

OFFSHORE WIND FARMS

Analysis of Transport and Installation Costs

S.A. Herman

Abstract

A computer model that calculates the transport and installation costs of a wind farm has been composed and implemented in the OWECOP II model. The latter quantifies all costs of implementation of a wind farm, at a determined location on the Dutch Exclusive Economical Zone. Transport and installation are a part of it. The computer model is an Excel™ workbook that includes an input part, a database part and a calculation part.

Transport and installation costs have been derived based on known offshore techniques and they are structured according to possible wind turbine assembly procedures. Besides the cost of offshore equipment, also an estimation of delays due to bad weather and the use of several vessels simultaneously have been included. Other costs included are: Scour protection costs, costs of soil research, costs of electric cable installation and costs of removal of wind turbine / wind turbine components after their operational lifetime.

Chapters 2 and 3 of this report analyse the possible transport and installation techniques, based on state-of-the-art offshore equipment. Wind turbine mass estimation is realised in chapter 4. In chapters 5 to 6, the analysis of costs for respectively transport and installation is presented. Chapter 7 describes the cost model and its implementation in a spreadsheet. In chapter 8 some results are presented and the influence of some parameters is investigated. The conclusions and recommendations are presented in chapter 9.

The calculation of costs for transport and installation of offshore wind turbines as implemented in the OWECOP model, could be detailed by a deeper analysis of workable conditions (probability of work), and implementation of wind turbine sizes and dimensions related to the transport and installation vessels.

Keywords

Offshore, wind energy, transport, installation, costs, cost model, vessels, scour, removal, cable, weather window, Weibull, foundation, sea state, soil.

Acknowledgement

This work has been executed as part of a subsidiary Engine-program of ECN.

CONTENTS

LIST OF ABBREVIATIONS	7
1. INTRODUCTION	11
2. OFFSHORE TURBINE CONFIGURATIONS	13
2.1 General	13
2.2 Configuration 1	13
2.3 Configuration 2	15
2.4 Configuration 3	16
2.5 Configuration 4	17
2.6 Configuration 5	18
2.7 Configuration 6	19
2.8 Configuration 7	20
2.9 Configuration 8	21
2.10 Pro's and Con's of the Presented Configurations	23
3. OFFSHORE TURBINE TYPES, IMPACT ON DESIGN	27
3.1 Impact on Turbine Design due to Transport	27
3.2 Impact on Turbine Design due to Installation	27
3.3 Impact on Turbine Design due to Offshore Location	27
3.4 Impact on Turbine Design due to Maintenance	27
3.5 Impact on Turbine Foundation due to Vibration Induced by Waves	28
4. OFFSHORE WIND TURBINE DIMENSIONS AND MASS	29
4.1 General	29
4.2 Choice of Foundation Type	29
4.3 Load Cases	30
4.4 Estimation of Mass and Dimensions of Offshore Wind Turbines	32
5. ANALYSIS OF TRANSPORT COSTS	33
5.1 General	33
5.2 Impact of Turbine Design on Transport (Costs)	34
5.3 Impact on transport vessel design due to turbine configuration	36
5.4 Way of Transport to Location	38
5.5 Transport Steps	39
5.6 Cost of Transport Equipment	40
5.7 Estimation of Transport Time	40
5.8 Definition of Maximum Sea State Conditions for Transport	41
5.9 Probability of Non-Transport Sea State	42
5.10 Estimation of Transport Costs	43
5.11 Estimation of Savings Using Simultaneous Transport	44
5.12 The Use of Several Transport Vessels Simultaneously	45
5.13 Reparation of Paint Damages	45
6. ANALYSIS OF INSTALLATION COSTS	47
6.1 General	47
6.2 Analysis of Installation Strategy	47
6.3 Impact of Turbine Design on Installation Costs	49
6.4 Impact on Installation Vessel Design due to Turbine Configuration	54
6.5 Installation Steps	56
6.6 Cost of Installation Equipment	57
6.7 Estimation of Installation Time	57
6.8 Definition of Maximum Sea State Conditions for Installation	58
6.9 Probability of No-Installation Sea State	58
6.10 Estimation of Installation Costs	59
6.11 Combined Transport and Installation	60

6.12	The Use of Several Installation Vessels Simultaneously	60
6.13	Reparation of Paint Damages	61
6.14	Costs of De-installation	61
6.15	Costs of Installation of a Helicopter Platform	63
6.16	Cost of Soil Research	63
6.17	Cost of Scour Protection	63
6.18	Cost of Cable Installation	65
7.	INTEGRATION OF TRANSPORT AND INSTALLATION COSTS INTO THE COST MODEL	69
7.1	General	69
7.2	Cost Model Spreadsheet Characteristics	69
7.2.1	Input Section	69
7.2.2	Database Section	70
7.2.3	Transport and Installation Calculation Section	70
7.2.4	Other Calculations Section	75
8.	EVALUATION OF RESULTS	77
8.1	General	77
8.2	Transport and Installation Costs	77
8.3	Scour Protection Costs	80
8.4	Cable Installation Costs	82
8.5	De-Installation Costs	83
9.	CONCLUSIONS AND RECOMMENDATIONS	85
9.1	Conclusions	85
9.2	Recommendations	86
10.	REFERENCES	87

APPENDICES

Appendix A.	Breakdown of Mass and Dimension Estimation of an Offshore Wind Turbine
A.1	Introduction
A.2	Tower
A.3	Foundation
A.4	Rotor
A.5	Nacelle
Appendix B.	Material properties of steel type S235J2G3, S275J2G3 and S355J2G3
Appendix C.	Probabilistic Estimation of Benign Weather for Transport, Installation and Maintenance Purposes
C.1	Introduction
C.2	Probability of Exceeding a Wave Height
Appendix D.	Typical Transport and Installation Vessels

LIST OF SYMBOLS

Name	Unit	Explanation
A_{anode}	[m ²]	Cross section of a cathodic protection anode.
A_{bottom}	[m ²]	Area of construction to be protected against corrosion in the sea bottom.
$A_{\text{projected_x}}$	[m ²]	Projected area of turbine tower for wind load calculations. It applies from top of tower down to section X.
A_{subm}	[m ²]	Submerged area of construction to be protected (includes splash zone).
A_x	[m ²]	Cross section of steel material at section X.
B_{tr}	[N]	Buoyancy of submerged part of tripod foundation.
C	[m, m/s]	Scale parameter of a Weibull probability distribution. The units are depending on the considered data.
C_{anode}	[A*h / kg]	Anode capacity; Zn = 820, Al = 950-2800 & Mg = 1100.
C_D	[-]	Drag coefficient.
C_m	[-]	Inertia coefficient.
$\text{Cost}_{\text{scour}}$	[€]	Scour protection costs.
Cost_1	[€]	Cost of transport / installation of one unit to / into its final location.
Cost_{100}	[€]	Cost of transport / installation of hundred units to / into their final location.
delivery	[A]	Current delivery of the anode in Amperes.
$D_{\text{foundation_x}}$	[m]	Diameter of foundation at section X. In the case of a jacket or a gravity base it is equal to the diameter of the central column at that section.
D_{mean}	[m]	Mean tower diameter.
$D_{n,50}$	[m]	Nominal diameter of rocks used in scour protection.
d_{pile}	[m]	Diameter of pile of foundation.
D_{rotor}	[m]	Rotor diameter.
$D_{\text{rotor_ref}}$	[m]	Reference rotor diameter.
d_{scour}	[m]	Diameter of substructure (monopod or central column of a tripod) used to calculate the required quantity of rock for scour protection.
D_{shore}	[km]	Distance to shore from a central point in the wind farm.
$D_{\text{tower_x}}$	[m]	Tower diameter at section X.
F_0	[N]	Force acting on a central column of a tripod.
F_{current}	[N]	Current force acting on foundation.
F_{drag}	[N]	Drag force acting on foundation due to wave loads.
F_{inertia}	[N]	Inertia force acting on foundation due to wave loads.
F_m	[N]	Couple force that replaces moment M_0 at node location of a tripod foundation.
f_{mat}	[-]	Material factor for stress calculations.
$F_{\text{wind_rotor}}$	[N]	Force acting on rotor of considered wind turbine.
$F_{\text{wind_rotor_ref}}$	[N]	Force acting on rotor of reference wind turbine.
$F_{\text{tower_x}}$	[N]	Wind force acting on the tower of the wind turbine at section X
F_1, F_2, F_3	[N]	Forces acting on the braces of a tripod foundation.
g	[m/s ²]	Gravity constant, taken as 9.81 m/s ² .
H	[m]	Wave height.
H_{max}	[m]	Maximum wave height.
$H_{\text{max_n}}$	[m]	Maximum node height for a tripod foundation with respect to sea bottom.
h_{min}	[m]	Minimum depth of piles in the sea bottom required to withstand external loads on foundation.
$H_{\text{min_n}}$	[m]	Minimum node height for a tripod foundation with respect to sea bottom.

Name	Unit	Explanation
h_{node}	[m]	Height between sea bottom level and node location of a tripod foundation.
H_{ref}	[m]	Reference wave height.
H_s	[m]	Significant wave height.
H_{top}	[m]	Height at top section of the tower.
H_x	[m]	Height of the turbine tower at section X.
H_1, H_2	[N]	Force acting on horizontal braces of a tripod foundation.
k	[-]	Shape parameter of a Weibull probability distribution; Wave number.
K_a	[-]	Active pressure coefficient of the soil.
K_p	[-]	Passive pressure coefficient of the soil.
l_{anode}	[m]	Length of a cathodic protection anode.
L_x	[m]	Length of tower between top and considered section X.
M	[kg]	Mass of substructure.
$M(x)$	[Nm]	Bending moment at section X.
M_0	[Nm]	Moment acting on a central column of a tripod.
M_{ob}	[€]	Mobilisation Costs of vessels. Often also given by a fixed number of days multiplied by the day-rate Q.
n_{anode}	[-]	Required number of anodes for cathodic protection of submerged structures.
N_{day}	[1/day]	Number of substructures that can be transported / installed in one day by a determined vessel.
N_{owec}	[-]	Number of owecs in a wind farm.
N_{sim}	[-]	Number of substructures that can be transported simultaneously on one vessel.
N_{vess}	[-]	Number of vessels involved in one operation (transport / installation).
p	[-]	Number of points investigated in soil research.
$P()$	[-]	Probability of occurrence.
p_{el}	[V]	Electric potential of corrosion protection anodes, equals 200 mv for zinc and aluminium and 400 mv for magnesium.
Q	[€]	Day-rate of Vessels.
R	[Ω]	Electric resistance of a corrosion protection anode.
t_{delay}	[days]	Delay time of operation (transport / installation) due to bad weather conditions.
t_{fixed}	[days]	Fixed time between transport / installation of a vessel.
t_{life}	[years]	Required lifetime of cathodic protection
T_p	[s]	Peak period of waves.
t_{work}	[days]	Normal operation time (transport / installation) of vessels.
T_z	[s]	Zero up-crossing period of waves.
$V(z)$	[m/s]	Wind speed at height z.
V_{current}	[m/s]	Current speed of sea water.
V_{e50}	[m/s]	Extreme wind speed for a 50-year return period.
V_{hub}	[m/s]	Wind speed at hub height of wind turbine.
Vol	[m ³]	Volume of submerged construction used to calculate the buoyancy of the structure.
WD	[m]	Water depth.
$WD_{\text{ref_min}}$	[m]	Minimum water depth reference level.
$WD_{\text{ref_max}}$	[m]	Maximum water depth reference level.
W_{li}	[hr]	Benign weather window of length i hours.
W_x	[m ³]	Section modulus of section X.
w_t	[m]	Wall thickness.
W_{tripod}	[N]	Dry weight of tripod foundation. It includes rotor, nacelle and tower.

Name	Unit	Explanation
W_{tripod}^*	[N]	Effective weight of tripod foundation.
z	[m]	Vertical coordinate, $z=0$ at MSL , positive upwards.
z_{hub}	[m]	Vertical coordinate of the hub of a wind turbine.
α	[deg]	Angle of tripod construction on a vertical plane.
β	[deg]	Angle of tripod construction on a horizontal plane.
γ	[-]	Wave parameter of a JONSWAP distribution.
δ_1, δ_2	[m]	Shortening / elongation of horizontal braces of a tripod foundation.
ϕ	[rad]	Friction angle of the soil.
η	[-]	Usage factor on material. It depends on the load combination considered.
ω	[rad/s]	Radial frequency of sea waves.
ρ_{air}	[kg/m ³]	Air density.
ρ_{el}	[Ω m]	Specific resistance of anodes (cathodic protection).
ρ_{steel}	[kg/m ³]	Steel density.
ρ_{water}	[kg/m ³]	Sea water density.
σ	[N/mm ²]	Material stress, tension, compression or Von Mises.
$\sigma_{allowable}$	[N/mm ²]	Allowable stress in material.
σ_{eq}	[N/mm ²]	Equivalent stress (Von Mises).
σ_{yield}	[N/mm ²]	Yield stress of material. It depends on the quality and on the plate thickness considered.
σ_1, σ_2	[N/mm ²]	Principal stresses in material.
τ	[N/mm ²]	Shear stress in material.
τ_{cap}	[N/mm ²]	Capillary stress of sea water.

LIST OF ABBREVIATIONS

Abbreviation	Full Text
AHT	Anchor Handling Tug
COG	Center of Gravity
DP	Dynamic Positioning
EEZ	Exclusive Economical Zone
EWM	Extreme Wind Model
HAT	Highest Astronomical Tide
HVAC	High Voltage Alternate Current
LAT	Lowest Astronomical Tide
MER	“Milieu Effect Rapportage” – Environmental Report
MSL	Mean Sea Level
MT	Metric Tonnes
OWEC	Offshore Wind Energy Convertor
PDF	Probability Distribution Function
ROV	Remote Operating Vehicle
ULS	Ultimate Load State
WD	Water Depth

SUMMARY

An investigation of the transport and installation costs of offshore wind turbines has been carried out and implemented in the OWECOP II model of ECN.

The OWECOP model quantifies all costs of a wind farm at any location on the Dutch Exclusive Economical Zone (EEZ) and its Energy Production, and translates these to Levelised Production Costs (LPC). The transport and installation costs were estimated in OWECOP I as a percentage of the total investment.

Transport and installation costs have detailed further based on known offshore techniques and they are structured according to possible wind turbine assembly procedures. Besides the cost of offshore equipment, also an estimation of delays due to bad weather and use of several vessels simultaneously have been included.

Other costs included are: Scour protection costs, costs of soil research, costs of electric cable installation and costs of removal of wind turbine / wind turbine components after their operational lifetime.

The cost model is an Excel™ workbook and consists of an input part, a database part and a calculation part.

The calculation of costs for transport and installation of offshore wind turbines as implemented in the cost model, could be detailed by a deeper analysis of workable conditions (probability of work) and implementation of wind turbine sizes and dimensions related to the transport and installation vessels.

1. INTRODUCTION

Objectives of Report

This report intends to summarise all aspects to be considered during transport and installation of offshore wind farms in order to quantify the costs of such operations in a pre-design stage. Based on this summarisation, a cost model is built. Where applicable all not considered aspects and simplifications are mentioned.

This report is also meant as a basis for design and for cost analysis of a wind farm at a determined location.

The input parameters for the analysis of transport, installation, operational and maintenance costs are:

- Required wind farm electric power and grid connection structure, including the location of connection points and type;
- Environmental data of the wind farm location; water depth (variations), wind wave and current statistics (preferably correlated);
- Installation and maintenance infrastructure; i.e. location of main harbours from where the works may be carried out;
- Economic parameters.

Based on the above-mentioned input, the costs of transport, installation, operation and maintenance of some offshore wind turbine designs are analysed. Based on these costs, an optimum design is derived. All license costs that may be necessary to perform transport, installation, operation and / or maintenance of the wind farm are not included into this model.

For the realisation of a wind farm offshore, several steps must be considered. A rough classification of these steps could be:

- | | |
|----------------|--------------------------------|
| - Preparation | - Feasibility |
| | - Environmental research (MER) |
| | - Permits |
| | - Request for quotations |
| | - Bids |
| | - Negotiations |
| | - Contract |
| | - Financing |
| - Engineering | - Morphology research |
| | - Design |
| | - Certification |
| | - Procurement |
| | - Fabrication |
| | - Testing |
| - Installation | - Transport |
| | - Installation |
| | - Commissioning |
| - Operation | - Operation |
| | - Maintenance |
| - Removal | - Decommissioning |

In this report the transport, installation, operation and maintenance costs as mentioned above are analysed.

In the path of the cost analysis, eight different configurations of offshore wind turbines are presented in chapter 2 of this report. Chapter 3 briefly analyses the possible impact on the design of wind turbines due to their way of installation offshore.

In order to determine the costs of transport and installation, the mass of the wind turbine offshore is estimated for different types of foundations. These results are presented in chapter 4. In chapters 5 and 6, the analysis of costs for respectively transport and installation are presented.

Chapter 7 describes how the analysis of transport and installation costs is integrated into a cost model. In chapter 8 some results are presented and the influence of some parameters is analysed. The conclusions and recommendations are presented in chapter 9.

2. OFFSHORE TURBINE CONFIGURATIONS

2.1 General

The major impact on the configuration of an offshore wind turbine construction is the way of installation. Due to the dimensions of a wind turbine with a capacity between 3 to 5 MW combined with its mass, the transport to location and handling of such a vulnerable structure must be taken into consideration in the design phase.

Four major components of an offshore wind turbine structure can be considered:

- Wind turbine foundation (monopod, jacket or gravity base)
- Wind turbine tower, excluding nacelle
- Nacelle, complete with gearbox and main shaft
- Wind turbine rotor

These three components offer several possible installation alternatives:

1. Installation of the four components separately, i.e. starting with the foundation, then the tower, next the nacelle and finally the rotor
2. Installation of foundation first, followed by the tower together with the nacelle and finally the rotor
3. Installation of foundation first, followed by the tower and finally the nacelle together with the rotor
4. Installation of the pre-assembled foundation and tower (one component), followed by the installation of the nacelle and finally the rotor
5. Installation of pre-assembled foundation and tower, followed by the pre-assembled nacelle and rotor
6. Installation of pre-assembled foundation, tower and nacelle (one component), followed by the rotor
7. Installation of foundation first, followed by the pre-assembled wind turbine tower, nacelle and rotor
8. Installation of complete assembled offshore wind turbine

Notes:

- The installation of all submerged cabling is expected to take place after the installation of the wind turbine, which includes a cable connector. In this way, the turbine is connected to the network cabling after the structure is put into location. Another possibility is to design the cabling as an integral part of the foundation. Both possibilities have no influence on the above presented installation alternatives. Installation of the cabling is discussed in chapter 6.18.
- The installation alternatives presented do not include large sub-constructions going beyond the normal dimensions of a wind turbine, as a helicopter landing structure, which could be considered present for maintenance purposes.

2.2 Configuration 1

Installation of major components separately

When every component of a wind turbine is installed separately, more components of the same type could be transported together to their offshore location. This depends on the transport capacity of the considered vessels. Transporting several foundations together, for instance, would diminish their transport costs and installation time. On the other hand, a rather large stock of foundations must be present at the shore waiting for transport increasing storage costs.

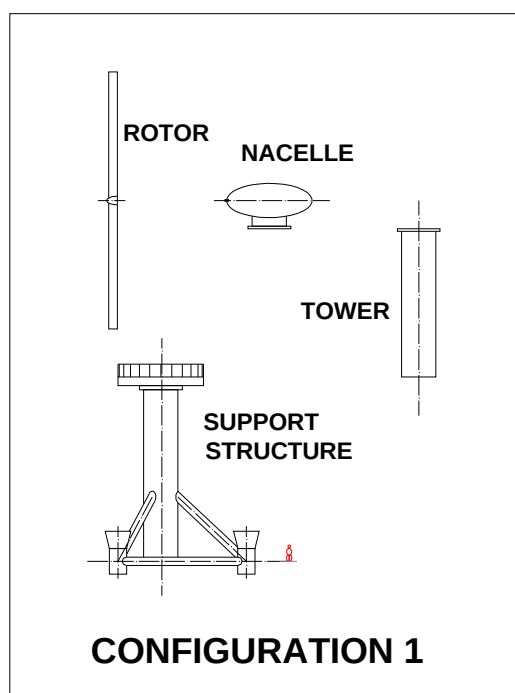


Figure 1. Configuration 1.

Installing the foundations separately could also lead to the use of smaller installation vessels (size and lifting capacity). In that case, however, the installation vessels would have to go to the installation site more often.

Due to the height of the tower (about 87 metres for a 5 MW turbine), it is thinkable that the tower may consist of two or more parts. In that case, transport and installation of the towers is much easier using smaller installation vessels. The installation time increases however considerably.

Several nacelles may be transported together to the site. The lifting capacity of the vessels may be such that 287 MT at about 92 m hub height (5 MW turbine) may be lifted. The transport and installation of the rotors presents more complications. For the size of the wind turbines considered large rotor diameters - up to 126 metres - are necessary. Their transport is not only constrained by their size; vulnerability against damage must also be taken into account. A possible transport option is to have more rotors placed horizontally on top of each other (not in contact with each other), resting on a modular transport frame. The use of rotors having different blade parts is not considered because of the required accuracy during their assembly.

The mounting of the nacelles offshore is time consuming. The installation time needed is comparable to the installation time of a turbine tower in one piece. Handling and mounting of the rotors offshore are also to be considered: the mounting of large rotors offshore requires qualified personnel working at large altitudes under difficult conditions. Small movements and a small breeze are then always present and it is crucial not to drop any component into the sea.

Wind turbine size [MW]	Nacelle mass [MT]	Hub height, resp. to MSL [m]
2	95	69
3	155	78
4	219	85
5	287	92

2.3 Configuration 2

Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

This configuration is very similar to configuration 1. By pre-assembling the tower and the nacelle before their installation, some considerable installation time may be avoided.

The transport aspects of the turbine towers are comparable with the transport aspects considered for the foundations. Care must be taken not to damage the nacelles. For this reason, transport of more than two towers simultaneously on one vessel seems unlikely, unless they are transported vertically.

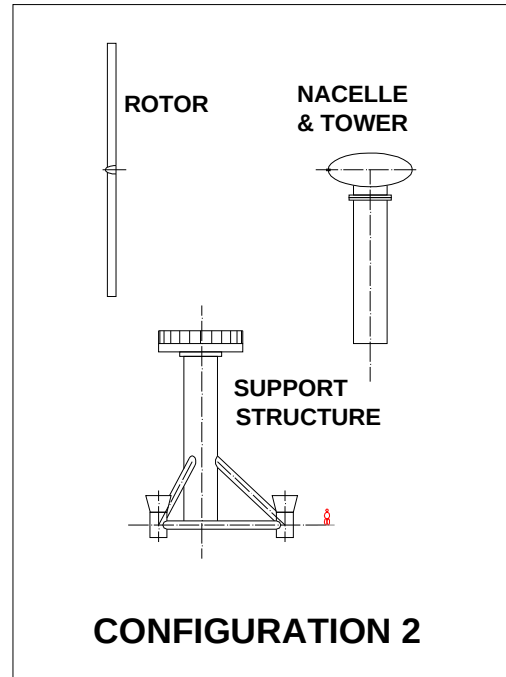


Figure 2. Configuration 2.

The required transport space on vessels increases slightly compared with configuration 1. The maximum mass to be lifted increases up to 507 MT at approximately 92 metres hub height (5 MW wind turbine, monopod) when compared with configuration 1. This could be a limiting factor for installation vessels.

Wind turbine size [MW]	Nacelle & tower mass Monopod [MT]	Nacelle & tower mass Tripod [MT]	Hub height, resp. to MSL [m]
2	245	234	69
3	343	335	78
4	424	419	85
5	507	523	92

2.4 Configuration 3

Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

The transport and installation of the support structure and of the turbine tower are similar to the procedure described in configuration 1.

The transport of a pre-assembled nacelle and rotor could lead to logistic problems in handling and supporting of the structure during transport. It seems unrealistic to consider the multiple transport of pre-assembled nacelles and rotors due to the special transport frames that it would be needed. This possibility is not considered in the cost model.

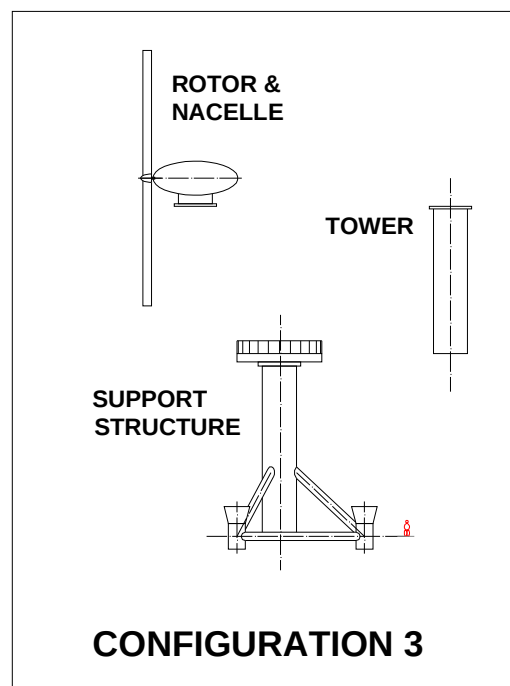


Figure 3. Configuration 3.

The offshore installation of the pre-assembled nacelle and rotor means that about 387 MT should be able to be lifted to about 92 metres hub height (5 MW wind turbine). This lifting condition is similar to the one described under configuration 2 and could be a limiting factor for installation vessels.

Wind turbine size [MW]	Nacelle & rotor mass [MT]	Hub height, resp. to MSL [m]
2	126	69
3	207	78
4	294	85
5	387	92

2.5 Configuration 4

Installation of pre-assembled foundation and tower, followed by nacelle and rotor

This configuration is similar to configuration 1. A difference is that the pre-assembled structure is considerably larger unless it is subdivided into flanged sections. Installation of pre-assembled monopod-tower structure is not possible.

To avoid any possible damage, the transport of several units simultaneously should take place vertically. This option seems however unlikely for monopod foundations.

In the case of a jacket, the foundation and the tower should be designed integrally in order to limit onshore pre-assembling time. More jackets-tower combinations may be transported vertically to the site and installed in position after each other. The transport characteristics of this option are similar to those presented previously.

The installation of the rotors is similar to configurations 1 and 2.

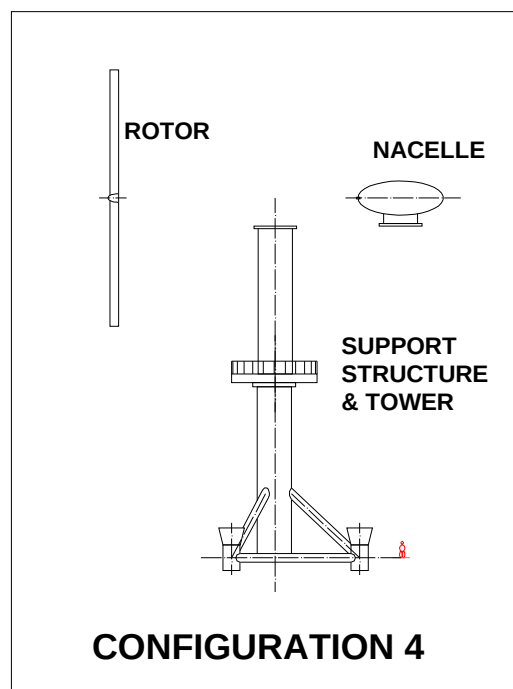


Figure 4. Configuration 4.

The maximum mass of the structure to be transported / installed is approximately 450 MT.

Wind turbine size	Support str. & tower (Tripod, no piles)	Top height, resp. to MSL
[MW]	[MT]	[m]
2	318	~66
3	361	~75
4	387	~82
5	447	~89

2.6 Configuration 5

Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

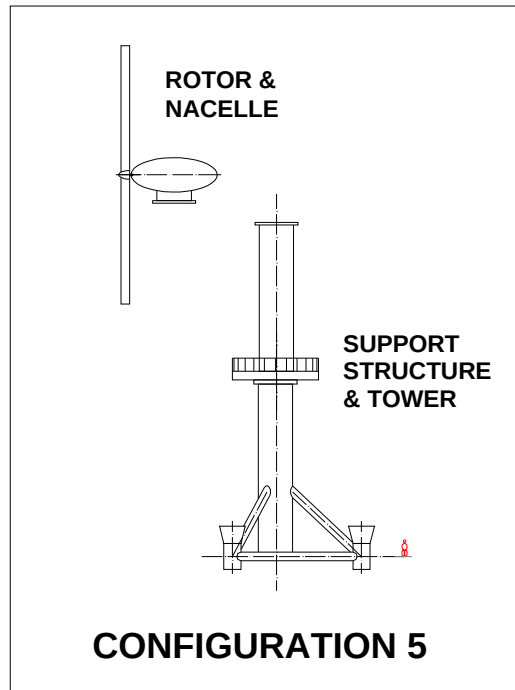


Figure 5. Configuration 5.

This configuration is a combination of configurations 3 and 4 presented before. The considerations presented there for pre-assembled support structure and tower, and for pre-assembled nacelle and rotor are applicable.

Wind turbine size [MW]	Nacelle & rotor mass [MT]	Support str. & tower (Tripod, no piles) [MT]	Hub height, resp. to MSL [m]
2	126	318	69
3	207	361	78
4	294	387	85
5	387	447	92

2.7 Configuration 6

Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

As an option to the configuration 5 as presented above, the pre-assembled support structure and tower can be added with the nacelle on top. A pre-assembled assembled support structure, tower and nacelle may be transported in the same way as explained for configuration 5. The installation mass of this combined structure arises however up to more than 730 MT (5 MW turbine). This mass must be lifted to about 95 metres height above MSL for its installation.

On the other hand, the installation time is reduced considerably compared to previous configurations where one or two flanged junctions must be connected offshore (tower-support structure junction and tower-nacelle junction).

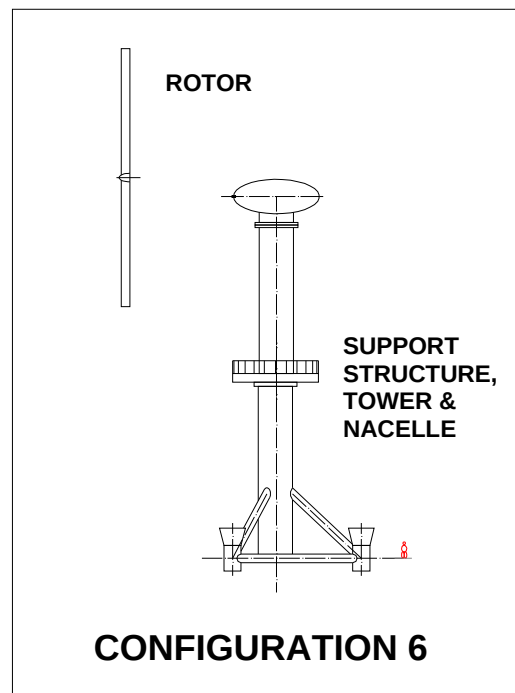


Figure 6. Configuration 6.

An extra difficulty when installing the turbines on jacket constructions is the sensitivity of the complete tower (with nacelle) to vibration caused by driving the installation piles. The construction should be analysed for this specific loading.

Wind turbine size [MW]	Support structure, tower and nacelle (Tripod, no piles) [MT]	Top height, resp. to MSL [m]
2	413	~72
3	516	~81
4	606	~88
5	733	~95

2.8 Configuration 7

Installation of foundation, followed by pre-assembled tower, nacelle and rotor

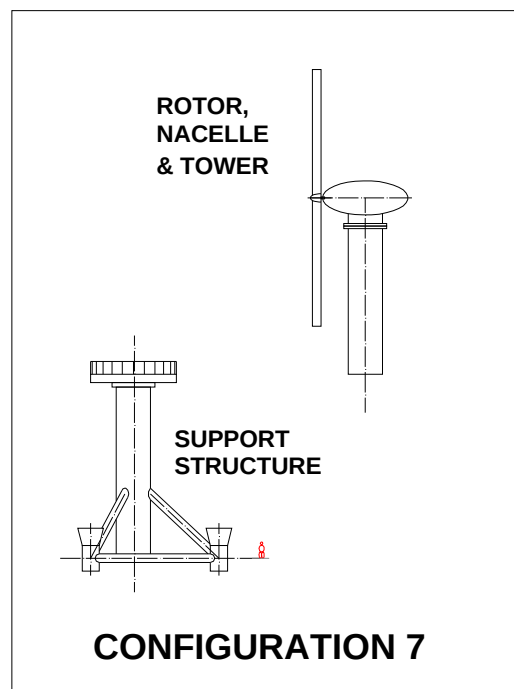


Figure 7. Configuration 7.

The approach is to install the foundation first and separately the pre-assembled tower, nacelle and rotor together. On behalf of the transport logistics (the size of vessel and way of transporting), a transport load case must be considered including wind loading for the turbine tower together with the (static) rotor.

The way of transporting the pre-assembled combination should be vertical: every assembly should be mounted temporarily on a foundation made on the vessel (for instance a large pin, either at the inside or at the outside of the tower). This means that an installation vessel should be adapted for this purpose. The total installation time is then probably long because the transportation speed is relatively low.

A second option for transport of the pre-assembly is a free-hanging transport. The maximum mass to be transported / installed rises to about 625 MT (5 MW turbine, tripod support structure). To install this pre-assembly, it must be lifted up to approximately 95 m above MSL (about 105 m lifting hook height).

The installation of the pre-assembled tower, nacelle and rotor presents also some difficulties: the handling of the assembly must be done in such a way that damage of the rotor does not take place. The tower-rotor assembly must be lifted from the temporary support, exposing at least one blade of the rotor to possible damage if the assembly is spinning around its vertical axis, either by the lifting cable or by the crane boom. The control of the stability of the assembly during installation is difficult to achieve.

Moreover, when the assembly is lifted up it would tend to lean over in such a way that the centre of gravity hangs exactly under the lifting point. Because the centre of gravity (COG) is located rather high, the assembled structure should be held in position by auxiliary lines in order to enable its installation.

Wind turbine size [MW]	Rotor, Nacelle & Tower mass (monopod) [MT]	Rotor, Nacelle & Tower mass (tripod) [MT]	Hub height, resp. to MSL [m]
2	275	264	69
3	394	386	78
4	499	494	85
5	608	624	92

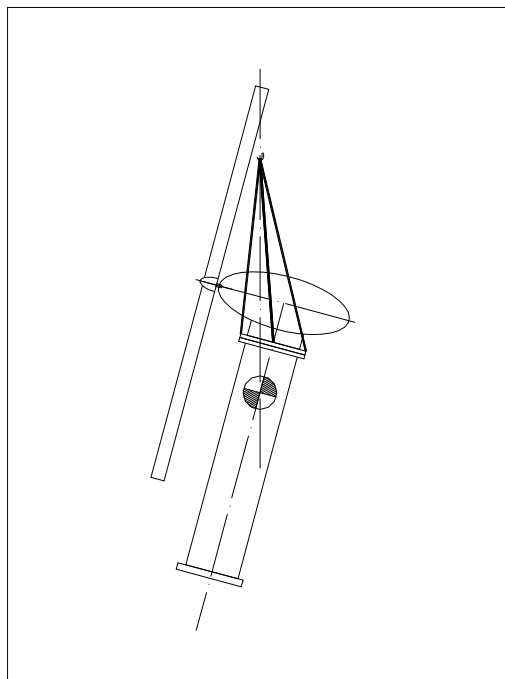


Figure 8. Inclination of pre-assembled structure due to position of COG.

A structural analysis of the sensitivity of the complete tower (with nacelle) against vibration, caused by driving the installation piles when the turbines are mounted on a jacket construction, should be performed during the design phase for this turbine.

2.9 Configuration 8

Installation of complete pre-assembled offshore wind turbine

This installation method is only applicable for jacket and gravity base assemblies. The idea is to transport one or maximum two wind turbines at a time to the location offshore, to lift a fully assembled wind turbine in one movement and to install it.

The installation of such a structure probably requires purpose built vessels, but the use of a self-elevating platform vessel (jack-up) may also be considered. The estimated mass of a complete assembled structure, based on a jacket foundation, may rise up to 834 MT. Based on a gravity base foundation the mass may be even more. A major problem would be the height at which the whole structure must be lifted (height of top of nacelle from vessels' deck is ± 95 m for a 5 MW turbine).

An analysis of the sensitivity of the complete tower (with nacelle) against vibration, caused by driving the installation piles when the turbines are mounted on a jacket construction, should be realised similar to configurations 6 and 7.

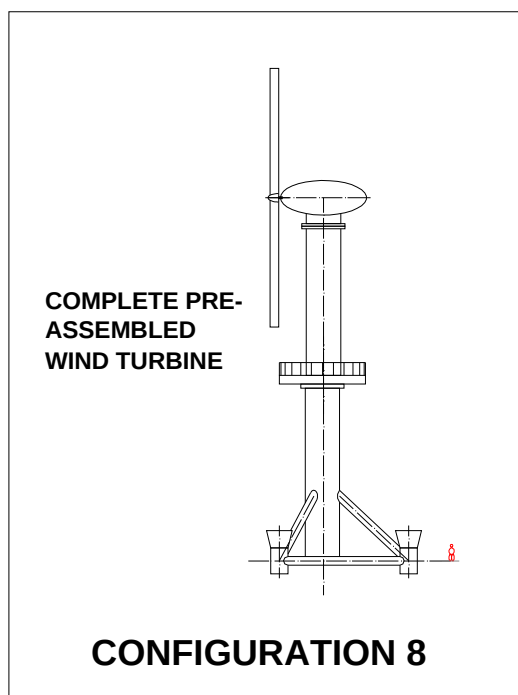
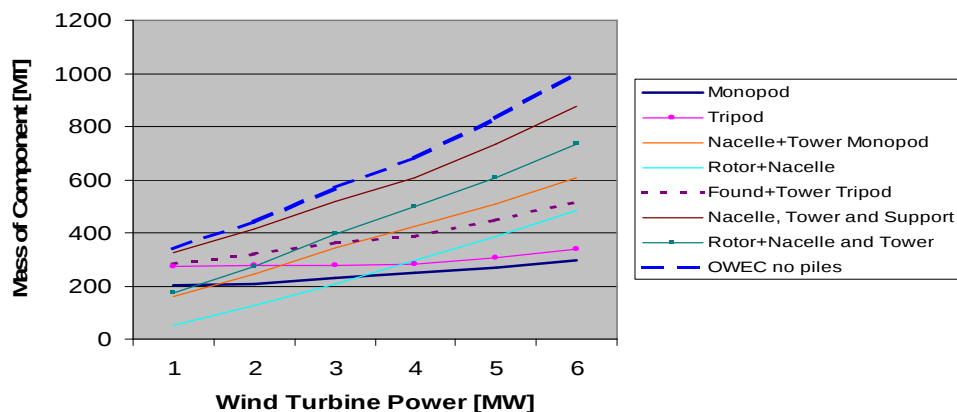


Figure 9. Configuration 8.

In the same way as presented in configuration 7, the installation must be carried out in such a way that damage of the rotor does not take place. The whole assembly must be lifted from the tower structure, exposing at least one blade of the rotor to possible damage if the assembly is spinning around its vertical axis. The control on the stability of the assembly during installation is easier to achieve than in configuration 7 because of the width of the jacket base. In addition, the assembly would incline less than the assembly of configuration 7 would, because the centre of gravity is located at a lower position.

Wind turbine size [MW]	Complete OWEC [MT]	Hub height, resp. to MSL [m]
2	443	69
3	567	78
4	681	85
5	834	92

Mass of OWEC components



2.10 Pro's and Con's of the Presented Configurations

The following summary is based on a 5 MW offshore wind turbine. The estimated dimensions and masses are based on results from a spreadsheet based on the formulas of Appendix A. A schematic drawing of this OWEC is given in Figure 10. Here a tripod foundation is illustrated, but the dimensions are also valid for a monopod foundation.

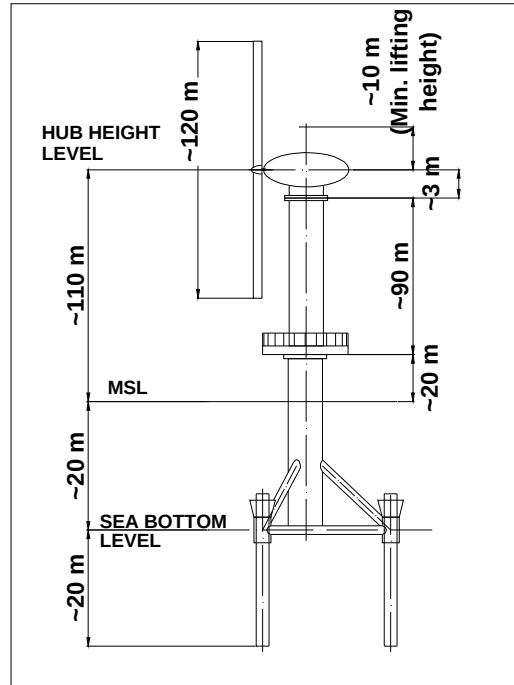


Figure 10.

Configuration 1. Installation of major components separately

Pro's

- Installation of monopods can be achieved within short intervals.
- Relatively low mass of components (up to 300 MT approximately) to be lifted up to a height of approximately 105 metres from MSL (height of lifting hook).
- More rotors could be transported on one vessel.
- Short transport time if more components of the same type are transported together.
- The use of smaller installation vessels if installed separately.

Con's

- Large installation time.
- High personnel risk during installation of rotor and nacelle components.
- Difficult handling / mounting of tower, nacelle and rotor components.
- Vulnerability of rotor during installation offshore.
- Several (small) installation vessels required or a short number of vessels leaving from and to the site frequently.

Configuration 2. Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

Pro's

- Installation of monopods can be achieved within short intervals.
- More rotors could be transported on one vessel.
- No offshore installation time required for the nacelles.

Con's

- High personnel risk during installation of rotor.

- Difficult handling / mounting of rotor components.
- Vulnerability of rotor during installation offshore.
- Relatively high mass of components (up to 510 MT approximately for a monopod) to be lifted up to a height of 105 metres from MSL (height of lifting hook).
- Several installation vessels required or a short number of vessels leaving from and to the site frequently.
- Larger installation vessels required when compared with configuration 1 (size and lifting capacity of pre-assembled tower-nacelle structure).

Configuration 3. Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

Pro's

- Installation of monopods can be achieved within short intervals.
- No offshore installation time required for the rotor.
- Less difficulty in handling and mounting of nacelle-rotor assembly when compared with configurations 1 and 2.
- Relatively low mass of components (up to 390 MT) to be lifted up to a height of 105 metres from MSL (height of lifting hook).

Con's

- High personnel risk during installation of nacelle-rotor assembly.
- Most probably only one nacelle-rotor assembly can be transported at time.
- Large installation time for junctions of tower and nacelle.

Configuration 4. Installation of pre-assembled foundation and tower, followed by nacelle and rotor

Pro's

- Integrated design of foundation and tower possible if jacket design is chosen.
- Transportation of pre-assembled foundation and tower can be achieved vertically (standing) diminishing the required transport space on a vessel and using less number of transport vessels.

Con's

- Monopod foundation is not possible in this configuration.
- Relatively high mass of components (up to 450 MT approximately) to be lifted up to a height of 100 metres from MSL (height of lifting hook).

Configuration 5. Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

Pro's

- No offshore installation time required for the rotor.
- Less difficulty in handling and mounting of nacelle-rotor assembly when compared with configurations 1 and 2.
- Integrated design of foundation and tower possible if jacket design is chosen.
- Transportation of pre-assembled foundation and tower can be achieved vertically (standing) diminishing the required transport space on a vessel and using less number of transport vessels.

Con's

- Monopod foundation is not possible in this configuration.
- Relatively high mass of components (up to 450 MT approximately) to be lifted up to a height of 100 metres from MSL (height of lifting hook).

Configuration 6. Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

Pro's

- No offshore installation time required for the nacelle or for the turbine tower.

Con's

- Monopod foundation is not possible in this configuration.
- High personnel risk during installation of rotor.
- Relatively very high mass of components (up to 730 MT approximately) to be lifted up to a height of 105 metres from MSL (height of lifting hook).
- Extra load case for the nacelle due to installation vibrations.

Configuration 7. Installation of foundation, followed by pre-assembled tower, nacelle and rotor

Pro's

- Installation of monopods can be achieved within short intervals.
- No high personnel risk.
- No difficulty in handling and mounting of rotor components.

Con's

- Purpose built (or adapted) large transport / installation vessel(s) required.
- Relatively very high mass of components (up to 625 MT approximately) to be lifted up to a height of 105 metres from MSL.
- Extra load cases for transport of pre-assembled tower, nacelle and rotor of turbines.
- Vulnerability of rotor to damage during installation.

Configuration 8. Installation of complete pre-assembled offshore wind turbine

Pro's

- Very short installation time.
- Small chance of damage to the construction due to handling.
- No high personnel risk.
- No difficulty in handling and mounting of rotor components.
- Low vulnerability of rotor during installation offshore.
- Construction availability of wind turbine maybe to the same level as required installation time (one assembly every week).

Con's

- Monopod foundation is not possible in this configuration.
- Only one (maximum two) assemblies can be transported at a time to the site.
- Large transport and installation vessel(s) required (maybe purpose built or adapted vessels).
- High mass of assemblies, about 835 MT, to be lifted over a large height (105 m height of lifting hook), i.e. big strong cranes required.
- Extra load case analysis due to installation vibrations.

3. OFFSHORE TURBINE TYPES, IMPACT ON DESIGN

3.1 Impact on Turbine Design due to Transport

Each of the configurations presented in the previous chapter will affect the wind turbine design. The way of transport shall influence for instance the number of lifting eyes and required reinforcements in the construction. The same applies to transport by means of towed construction instead of normal barge transport. Temporary (removable) construction parts must be taken into account during the design phase.

Another consideration would be the parking of blades when transporting the tower together with its rotor or the use of retractable rotor blades to minimise the physical transport space.

All these considerations will have an impact on the design costs of offshore wind turbines and will affect the transport costs as well. A cost estimation difference is made in chapter 5 of this report when considering these issues.

3.2 Impact on Turbine Design due to Installation

Besides the transport, considerations presented above, the way of installing the wind turbine offshore shall have an impact on the design of the structure. Some examples are:

- The parking of blades when installing the pre-assembled tower and rotor;
- Bolted connections with their fatigue problems;
- The choice of flanged connections;
- The choice of the location of the working platform connected to the structure.

All these considerations will have an impact on the design costs of offshore wind turbines and could influence the installation costs as well. A cost estimation difference is made in chapter 6 of this report when considering these issues.

3.3 Impact on Turbine Design due to Offshore Location

The location of the wind turbines offshore affects the choice of the material quality, corrosion protection and lightening protection. These choices will have an impact on transport and installation costs only through a change in the total mass of the construction and through a change in the sensibility of the construction during handling. Therefore, they will not be considered in this report.

Some examples of the impacts on turbine design have already been analysed in [1].

3.4 Impact on Turbine Design due to Maintenance

There are two aspects to be considered regarding the impact on design in regard to maintenance:

- Impact on design of the offshore construction in order to minimise maintenance.
- Safety of personnel during maintenance.

To analyse the impact on design it is necessary to establish a difference between heavy and light maintenance, based on the mass of the components to be replaced if necessary.

For light maintenance, no design changes are expected that would affect the transport or the installation.

For heavy maintenance, internal lifting equipment could be considered to lift turbine parts up and to lay them down on a platform at the lower end of the turbine tower. Another possibility is the use of helicopters to lift these heavy parts, where a helicopter platform should then be necessary.

Even though the turbines for an offshore location are specifically designed not to require much maintenance, they must be designed to receive personnel during calm / harsh weather conditions safely.

Due to the size of the expected offshore wind farms and due to the expected number of wind turbines in a farm, it is supposed that spare components will be off-the-shelves and therefore there will be no delay in the manufacturing process of spare components.

The access to (each) wind turbine may be realised in one of the following three ways:

- By maintenance vessels.
- By helicopter.
- Using both alternatives, maintenance vessels and helicopter.

All three possibilities are restricted by their operational conditions: the maximum sea state or wind speed/visibility conditions.

The impact on the wind turbine design related to maintenance, may be resumed by the following requirements:

- A lay-down platform for heavy maintenance equipment.
- A mooring platform to accept the maintenance vessels.
- Internal railing and platforms for climbing of maintenance personnel.
- Internal platform in conditioned nacelle for maintenance purposes.
- An external helicopter platform including ladders, railing and ancillaries in order to enter the nacelle.

All above-mentioned items will increase design costs, slightly increase construction mass (and thus transport and installation costs) and slightly increase the sensitivity of the construction during handling. An exception forms a helicopter platform. If installed separately, it may result in a substantial increase of transport and installation costs.

All these factors are taken into account in the calculation of transport and installation costs.

3.5 Impact on Turbine Foundation due to Vibration Induced by Waves

The impact of vibration induced by waves on the turbine foundation, like the avoiding of wave frequency in the range of natural frequency of the foundation, is not accounted for.

4. OFFSHORE WIND TURBINE DIMENSIONS AND MASS

4.1 General

To estimate the mass and dimensions of the tower and foundation of the OWEC a rough analysis of the stresses present in the structure is carried out.

The loads considered for the analysis are the result of a correlation between quasi-static wind, wave and current loads. For each load case considered, this correlation is analysed in chapter 4.2.

It must be noticed that this calculation is done with the only purpose to estimate the mass and the dimensions of such a construction in order to facilitate an estimation of the transport and installation costs. The real dimensions of an offshore wind turbine follow from a much more elaborated load analysis.

The following considerations must be taken into account when calculating the stresses in the steel structure:

- The maximum allowable stress in the material is given as a factor of the yield stress. This factor is defined for operational (a) and temporary (b) conditions respectively as 0.6 and 0.8, see reference [2], part 3, chapter 1, chapter 6 (C 200).
- For elastic design, a material coefficient must be used for steel structures. The coefficient used equals 1.15, see reference [2], part 3, chapter 1, chapter 6 (B 200).
- The stress used for calculation is the equivalent stress as formulated by Von Mises in Equation 1:

$$\sigma_e = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 * \sigma_2 + 3 * \tau^2}$$

see reference [2], part 3, chapter 1, chapter 6 (D 103).

- The structural members must also be designed against buckling. The criterion used to avoid buckling on the tower is given by $D/wt > 175$. As an alternative, the critical moment working on the construction may be considered using a formula for combinations of vertical load and bending moment (see ref. [4]).
- The yield stress of a material varies with the plate thickness. The considered material in this analysis is S355J2G3 (Euronorm) with a minimum yield stress of 335 N/mm² for wall thickness below 63 mm. In appendix B, three typical steel materials with their properties are presented, namely: S235J2G3, S275J2G3 and S355J2G3.

4.2 Choice of Foundation Type

Some basic foundation types are considered for offshore wind turbine applications:

- Gravity bases (concrete plates and grouted caissons)
- Guyed turbine towers
- Monopods (driven pile, drilled pile, suction pile)
- Jackets (tripods, lattice towers, or similar designs)
- Suction caissons
- Floated foundations

Gravity bases have been used already in several wind farms in the Danish waters. These farms include relative small offshore wind turbines in relatively shallow waters. The installation time for these farms was not very critical due to the limited number of turbines and the purpose of

the farm (gain experience). For these reasons they are of limited relevance when considering large wind farms in deeper waters as in the North Sea.

Gravity bases could be either transported on transport barges or be self-floating (hollow) structures that may be grouted once installed. In most cases, gravity bases need a sea bottom preparation before being put into place.

Monopods have been used very frequently for onshore and offshore wind farms. Due to their relative low mass and small dimensions, they are considered as the most cost effective foundation solution at this moment. Stability problems appear when water depths increase. Driven piles are mostly used in sandy sea bottoms. To prevent that the monopod foundation loses clamping load at its base, scouring of the seabed must be prevented. As an alternative, the monopod foundation is driven deeper.

Hard sea bottoms as rock and clay may need the use of drilled instead of driven piles. Suction piles are considered an option, although they have not been applied up to now.

Jackets (tripods and lattice towers) are considered necessary for deeper waters. Both type of structures make use of smaller driven (or drilled) piles than monopods, three as a minimum, and need sea bottom preparation or another aligning technique to ensure tower verticality when finally installed. Lattice towers may be lighter than jackets, but requires much more welding work. An optimum has not yet been found, although it is claimed by KEMA that their lattice tower design leads to minimum costs [5].

Instead of using driven or drilled piles, the use of suction piles is possible. Suction piles may be removed after use by inverting the installation procedure. Besides, instead of considering separate suction piles, a suction caisson may be used. A suction caisson is a large diameter suction pile that could be used as a base for monopods. The transportation to location of suction piles or a caisson could simply be self-floating.

At the time of this writing, no technical information about suction caissons and their respective design loads is known, reason why they won't be considered here.

In this report only monopod, tripod and gravity base foundation types will be considered. Other foundation types are not further investigated.

The mass of monopod, tripod and gravity base structures is analysed. The costs of transport, installation operation and maintenance of wind turbines placed on any type of foundation are well analysed. If in the future a different type of foundation becomes realistic, it could be analysed on the same terms.

4.3 Load Cases

Two different load cases are considered in the analysis of the offshore structure of a wind turbine: operational loads and extreme wind loading. Fatigue loading, frequency analysis due to dynamic loading or accidental loads due to, for instance, a barge collision are not included into this analysis.

Operational Loads

Operational loads are the maximum loads acting on the wind turbine structure when the turbine is working. As a basis of design, the cutout wind speed (25 m/s at hub) is considered to yield the dimensioning operational loading.

The cutout wind speed is considered a steady wind speed, which implies that the wind loads will induce wave loading. For the estimation of the wave loads, a wave height equal to the significant wave height at a determined location with a 1-year return period is used.

The third load component in the analysis is the sea current. Compared with the wind and the wave loads the loading from current is very low, but it will not be neglected.

In the case of operational loads, waves and wind directions may be assumed parallel because the waves considered are induced by the steady wind condition. The current will be assumed to be in the same direction as the wind and waves. This conservative assumption means that the full current load will act in addition to the other two.

The distributed loads considered and the stresses found in the structure are presented in the figures. Note that both tower diameter and wall thickness of the tower vary linearly from the top (hub height) up to the connection point between the tower and the foundation.

No dynamic amplification factor has been used in the analysis because the loads considered are scaled up values that were derived from a dynamic analysis for an existing wind turbine [6].

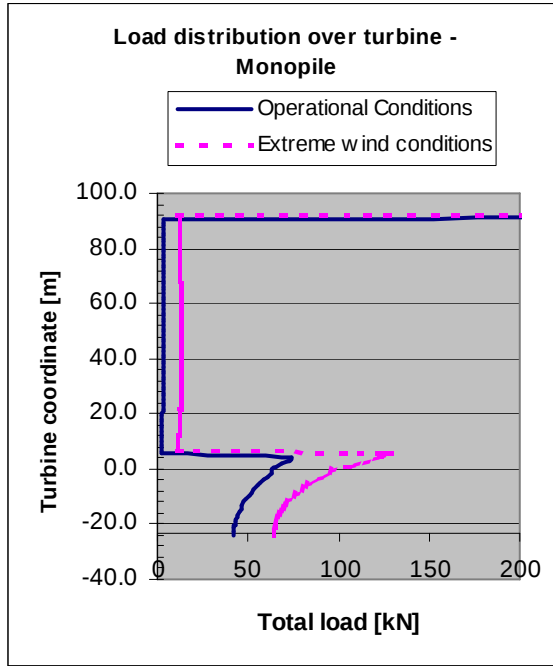


Figure 11

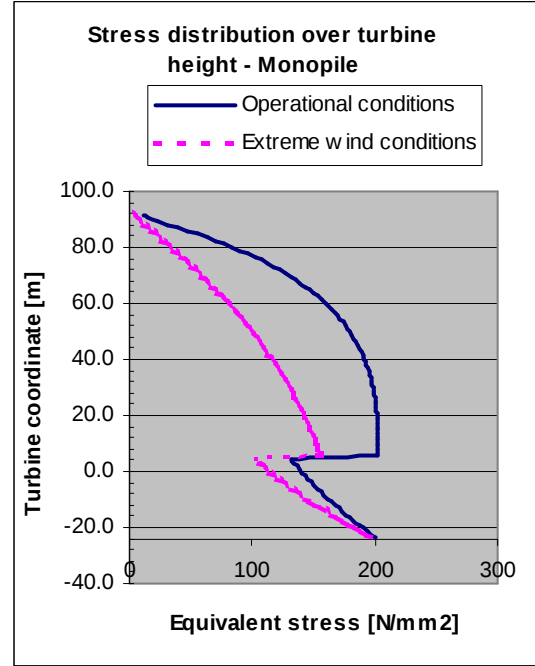


Figure 12

Extreme Wind Loading

Extreme loading refers here to the extreme wind speed having a probabilistic 50-year return period. In this case, for each 10 minutes average speed above 25 m/s, the wind turbine is disconnected (idle). The horizontal load acting on the rotor is related to the horizontal load of a reference turbine.

For the considered turbine for a mean wind speed of 56 m/s (3 seconds average peak wind speed of 70 m/s), the axial load is 84 kN. This load is up-scaled for the considered turbine according to Equation 2:

$$F_{wind_rotor} = F_{wind_rotor_ref} * \left(\frac{D_rotor}{D_rotor_{ref}} \right)^2$$

The corresponding wind speed acting on the tower is described as follows:

- At hub height a wind speed of 70 m/s is present ($=V_{e50}$).
- The wind profile acting on the tower diameter is given by the extreme wind model (EWM), according to [7], Equation 3:

$$V(z) = V_{hub} * \left(\frac{z}{z_{hub}} \right)^{0.11}$$

The correlation between wind speed and wave loading is taken to be parallel. The used height for the waves is the maximum wave height of the spectrum, determined for a given scatter diagram according to the JONSWAP formula, Equation 4:

$$H_{\max} = 1.8 * H_s$$

The current speed is assumed to deviate by 30 degrees from the direction of wind and waves. A brief analysis shows that the current speed is not relevant for the determination of the stresses and may as well be disregarded.

Other extreme load cases have not been investigated.

4.4 Estimation of Mass and Dimensions of Offshore Wind Turbines

In the following summary, two offshore wind turbines are considered: a 3 MW and a 5 MW turbine. It is not the intention of this study to do an in depth analysis of mass and lengths of turbines, but to present a breakdown of mass and dimensions as a help tool for doing costs analysis. A breakdown of the mass and dimension of the wind turbine, as used in this report, is analysed in Appendix A.

The following parameters are used as a base for the estimation:

- The water depth in which the OWEC is installed is 20 metres;
- A minimum clearance between the tip of the blades and sea water level (MSL) is 20 metres;
- The wind turbines have a specific power of 400 W/m² rotor area;
- The rotors of the OWECs have 3 blades;
- The mass of the blades is estimated using the up-scaling of blade mass as presented in reference [8], $M=0.10 \times (D_{\text{rotor}})^{2.63}$, D_{rotor} in [m] and M in [kg];
- The mass of the nacelles is estimated with the following empirical formula derived in reference [8], $M=2.6 \times (D_{\text{rotor}})^{2.4}$, D_{rotor} in [m] and M in [kg]. The gross of the data used to derive this formula is based on small turbines (diameter of rotor under 40 m), so its validity is still doubtful.

The results derived are presented in the following table:

Turbine type	Turbine part	Dimensions [m]		Mass [MT]
3 MW turbine	Monopod foundation	Length	49.3	~230
	Tripod foundation	Base x h	(15x15) x 28.7	~279
	Tower	D_tower x h	4 x 72.5	~185
	Nacelle	D x L	unknown	~155
	Rotor (3 blades)	D_rotor	98	~50
			Total Monopod Total Tripod	~625 ~665
5 MW turbine	Monopod foundation	Length	50.3	~270
	Tripod foundation	Base x h	(15x15) x 28.7	~310
	Tower	D_tower x h	4.5 x 86.7	~230
	Nacelle	D x L	unknown	~290
	Rotor (3 blades)	D_rotor	126	~100
			Total Monopod Total Tripod	~875 ~930

Table 1. Mass and dimensions of a 3 MW and a 5 MW OWEC.

Despite the fact that the dimensions and mass of the wind turbine are known, they are not further used in the estimation of the transport and or installation costs. The dimensions and mass are calculated to get an idea of the structures to be transported/installed. Based on this information, the transport and installation vessels are determined.

5. ANALYSIS OF TRANSPORT COSTS

5.1 General

The costs of transport of (sub-)structures related to wind energy converters and associated items offshore depend on several factors. Some of the factors are:

- Cost of hired equipment for transport
- Number of items to be transported, short and long term
- Dimension of substructure to be transported
- Sensitivity of substructure for damage during transport
- Delays due to weather conditions
- Costs of insurance

All above-mentioned factors are interrelated. In this section, each considered factor is treated independently from the others and is considered a lump sum.

The types of structural components to be considered are:

- Foundation
- Turbine tower
- Nacelle
- Turbine rotor

Besides, combinations of the components may also be considered:

- Transport of previously pre-assembled tower and nacelle (Configuration 2)
- Transport of previously pre-assembled nacelle and rotor (Configurations 3 and 5)
- Transport of previously pre-assembled foundation and tower (Configurations 4 and 5)
- Transport of previously pre-assembled foundation, tower and nacelle (Configuration 6)
- Transport of previously pre-assembled tower, nacelle and rotor (Configuration 7)
- Transport of the turbine as a whole (Configuration 8)

In addition, there are also different options for the foundation:

- Gravity base
- Guyed turbine tower
- Monopod
- Jacket, tripod design
- Jacket, lattice design

Finally, the way of anchoring a foundation to the sea bottom may be achieved by the mass of the foundation itself or by the use of drilled, grouted, driven or suction piles.

When considering the involved transport costs many combinations of constructions, assembly methods and anchoring methods are possible. Vessel capacity and costs are estimated, based on expertise of senior engineers in the offshore industry.

In the following paragraphs, the impact of the turbine design on the transport costs is discussed first. Secondly, the impact on transport vessels due to a chosen turbine design is presented. Thirdly, the transport costs for the configurations are discussed. Finally, the impact on the costs due to bad-weather delays is analysed. Costs of insurance have not been included in this report.

All derived costs have been deducted for the year 2001.

5.2 Impact of Turbine Design on Transport (Costs)

In all configurations, flanged sub-sections are mentioned. In chapter 6.2 of this report, the impact of this design on installation is discussed.

The turbine design could have a major influence on the transport costs to the offshore location. Examples of this are the choice for two or three blades for a rotor, or the design of a retractable blade for transport purposes.

For the analysis of the transport (costs) of the presented configurations, the following general assumptions are made:

- 1 The rotor of the wind turbine consists of three (non-retractable) blades.
- 2 The boat landing (platform) is located at mean sea level.
- 3 The foundation of the turbine ends at a certain height above mean sea level.
- 4 The required maintenance platform is a part of the foundation (at the upper end) or it is a part of the turbine tower (at the lower end).
- 5 The foundation of the turbine does not include any other external maintenance platform.
- 6 The offshore turbine does not include a helicopter platform on top. If such a platform is required, it is transported (and installed) separately. The necessity of a helicopter platform and cost is not analysed.

In addition to these assumptions each configuration as presented in chapter 2 is analysed:

Configuration 1: Installation of major components separately

Because all parts of the wind turbine are installed separately, all foundation(s) may be installed first. The foundations include a boat landing (platform) at the upper end, or at least a protection against vessel collision and a maintenance platform, just below the possible connection flange level. This part must be protected during transport.

The transport to location of the monopods may be done using a transport barge or they may be towed (floating).

If transported on a barge, the lengths of the monopod may be inconveniently large (about 50 metres in one piece). It seems improbable that this pile will be cut in pieces for transport and be welded together before installation. This means that a transport area on a barge will be needed of at least 50 metres long if the pile is made out of one piece. Even if the pile is transported inclined by an angle of 15 degrees, the needed length will be still 48 metres. The pile design must include lifting points able to carry a load that varies between 200 and 300 MT. Flanged sub-sections could be an option, provided that the flange remains above sea bottom level after installation of the pile.

If the piles are towed to location, their design must include watertight compartments or attachment points to external compartments. Probably two towing tugs will be needed for self-floated transport. The transport of more than one pile at a time by this method is not unthinkable.

The transport to location of jacket foundations will be slightly different: they may be transported upright. The minimum transporting areas of one unit will be limited by its base size, i.e. for a configuration of three piles at a radius of 8 metres, a triangular area of about 14 metres triangle size is needed (approx. 40 m²) or by the size of the maintenance platforms. This means that no special design of a jacket is needed to satisfy the transport limitations.

The transport of gravity base foundations may be achieved in two ways: self-floated or on a transport barge. If self-floated, grout is needed on the basement of the gravity base after its positioning on the location. This grout must be transported separately. The transport of a gravity base on a barge is similar to the transport of a jacket.

The foundation of a guyed turbine tower will probably be a slender monopod.

The following points need to be considered for the transport of the towers for this configuration:

- The mass of the towers varies between 120 and 220 MT for the 1 MW – 5 MW range

- The length of the towers is also considerable, being between 52 and 87 metres long.
- The towers may include a maintenance platform, located at the lower end.

It is expected that the towers will be transported horizontally, supported in order to avoid damage, on barges with at least 90 metres long transport area. Another option is to subdivide the tower into flanged sub-sections. The tower design must include lifting points. No other special features are expected for the design of the wind turbine towers.

The rotor diameter may be as much as 126 metres, for the 1 MW – 5 MW range. This means that very large and/or wide barges should be used to transport a three-bladed rotor, unless the blades are retractable or the blades may protrude from the transport barge. In the latter case possible loading during transport must be investigated at forehand. Two bladed rotors do not need any special design consideration, if there is a transport barge long enough to support a 126 meters rotor diameter.

Another option is to transport the blades of a rotor separately and to connect them to the hub prior to installation. In this case, the transport barge will not constitute any restriction, but the connection of the blades to the hub must be such that a straightforward installation in offshore environment can take place.

Configuration 2. Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

The considerations for this configuration are similar to configuration 1. The differences are:

- The tower-nacelle assemblies have a mass varying between 160 and 520 MT for 1 MW to 5 MW respectively.
- The length of the tower-nacelle assemblies is also considerable (approximately between 60 and 95 metres, including nacelle).

It is expected that the assemblies will be transported horizontally, supported in order to avoid damage, on barges with at least 100 metres long transport area. Protruding of assemblies from barges is an option. Towers subdivided into flanged sections, like the case of the foundation discussed previously, are possibly but then special measures would be needed for the electric cables.

Configuration 3. Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

This configuration is very similar to configuration 1. The only difference is the pre-assembled nacelle and rotor structure. It seems unlikely that the pre-assembled nacelle-rotor structures may be stapled for transport. This means that one transport vessel must be used for each pre-assembly.

Configuration 4. Installation of pre-assembled foundation and tower, followed by nacelle and rotor

If only the transport aspects are considered, it seems unrealistic to choose for transport of pre-assembled foundation-tower structures for monopod configurations. If this is the case, the transport barges for a 5 MW turbine should have a working area with a length of at least 140 metres, unless the combined pile-tower structure may protrude from the barge or it is made out of flanged sub-sections. The construction also includes a boat landing and a maintenance platform that must be protected during transport. This means that the whole structure must be supported on several points (because it may not be placed on the working area). For configuration 4, it seems more logical to transport the foundation and tower separately (maybe on the same barge) and to connect the parts before installation.

For a jacket construction, the transport of a standing combined foundation-tower structure seems realistic, if the rigging of such a structure is adequate. No special design features are required on the wind turbine for the transport of this configuration.

The analysis of transport of a rotor for this configuration is similar to configuration 1.

Configuration 5. Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

See configuration number 3 for analysis of transport of pre-assembled foundation and tower, and configuration 4 for the analysis of transport of pre-assembled nacelle and rotor.

Configuration 6. Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

The considerations of configuration 4 as presented before are also applicable for this configuration. Only the total mass of the pre-assembled structure will be higher.

Configuration 7: Installation of foundation, followed by pre-assembled tower, nacelle and rotor

The analysis of the transport of the foundations alone is similar to the case as presented in configuration 1.

The following considerations are applicable for transport of the tower, nacelle and rotor together:

- Because the parts are already assembled, it is not realistic to consider stapling of several structures on a barge, due to the mass and dimensions of the whole.
- The transport of one assembled unit alone, in flat position, would take a large required working area for transport purposes.
- The flat position of one unit makes it vulnerable to damage while loading on a transport barge.
- It will be almost impossible to support and to rig the combined structure if it is set upright.
- If the vertical transport of the combined structure is achievable, large transport environmental loading will arise due to its height.

Because of all above-mentioned reasons, it seems unrealistic to consider the transport of a pre-assembled tower and rotor unit in one piece unless very special transport barges are designed for this purpose. Flanged sub-sections are possible, although some of the above mentioned considerations still apply.

Configuration 8: Installation of complete pre-assembled offshore wind turbine

A complete pre-assembled wind turbine unit can only be transported to the location in case a jacket structure or a gravity base is used as a foundation. For a monopod, the same restrictions are applicable as for a pre-assembled tower-nacelle-rotor structure discussed under configuration 7.

5.3 Impact on transport vessel design due to turbine configuration

Based on the previous analysis, the following transport vessel design considerations are made:

Configuration 1: Installation of major components separately

The only design consideration applicable to the transport vessels in this case, is the possible manufacture of a rack or platform that extends beyond the limits of a normal transport barge. This rack should be designed to support the big rotor diameters on top of it. In this way, no need of reinforcement of the rotors is necessary, and no special or expensive transport vessels are

required. This possibility would be subjected to local legislation because of the extended lateral dimensions during transport.

If more rotors are to be transported simultaneously, these platforms must also include the possibility of being piled up.

Configuration 2. Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

The difference with configuration 1 is the difficulty to transport a nacelle that is assembled to the turbine tower.

If the pre-assembly is to be transported horizontally, special supports are needed in order to keep the nacelle free from interaction with the deck of the transport vessel. Probably no more than one pre-assembled tower and nacelle structure would be transported simultaneously in one vessel.

If the pre-assembly is to be transported vertically, transport vessels with special features are required in order to keep the pre-assemblies safe in vertical position under the action of the transport loads. Special transport vessels are not considered into this cost model.

Configuration 3. Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

This configuration differs from configuration 1 in the space on the transport vessel that the pre-assembly requires for its transport. The transport of this pre-assembly is possible, but it seems that a space frame would be required therefor. Moreover, the pre-assembly is very sensitive to damage during (de-) embarkation. If these technical issues were solved, probably no more than two pre-assemblies would be transported simultaneously in one vessel.

Configuration 4. Installation of pre-assembled foundation and tower, followed by nacelle and rotor

This configuration is considered only when the support structure is not a monopod. If that's not the case, its transport will be similar as discussed under configuration 1, only the height will be more and thus an adapted rigging method would be needed.

Configuration 5. Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

This configuration is a hybrid variant of configurations 3 and 4. All considerations presented there are valid. No other special requirements are necessary.

Configuration 6. Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

No special vessel designs are required for this configuration. The transport of the rotor(s) may occur in the same way as for configuration 1.

Configuration 7: Installation of foundation, followed by pre-assembled tower, nacelle and rotor

The transport of the foundations may occur similarly to configuration 1. The transport of the combined tower, nacelle and rotor seems impossible without adapting an existent transport vessel or even without a new vessel design.

If transported horizontally, similar considerations as presented under configurations 2 and 3 are applicable. In this case, the pre-assembly will be even more sensitive to damage than when compared with configuration 3. Besides, only one pre-assembly could be transported in one vessel.

If the pre-assembly is to be transported vertically, transport vessels with special features are required in order to keep the structure safe in a vertical position under the action of the transport loads. More than one pre-assembly could then be transported simultaneously in one barge. Special transport vessels are not considered into this cost model.

Configuration 8: Installation of complete pre-assembled offshore wind turbine

The transportation of pre-assembled wind turbines (in one piece) is only possible in case of the use of a jacket structure or a gravity base as foundation. In these cases, a special transport barge is expected to be required.

The aspects that are important for determination of an adequate transport barge are:

- Maximum working area of an erected wind turbine.
- Maximum external loading acting on the structure during transport.
- Minimum required rigging for transport and available space to realise this rigging.

Special designed transport vessels are not considered in this report.

5.4 Way of Transport to Location

The transport of the wind turbine (parts) to the location offshore can be realised by means of tugs towing the floated structure or by transport on a transport barge.

Floating transport may only be applied for turbine parts that comply with the following requirements:

- They are not sensible for damage due to water ingress; this applies only for foundation parts and turbine tower parts without nacelle,
- They have sufficient buoyancy; applying extra buoyancy to the structure is not considered an economic option. This implies that, if towed, these parts must include watertight compartments (additional steel), using for instance removable covers.

Based on the considerations as stated above, only the support structures of the offshore wind turbines are considered adequate for floated transport. Floated transport of combinations of foundation with other components or even floated transport of a complete wind turbine could be achievable, but it is not included as an option in the cost model.

Another problem that arises when considering towable structural parts is their installation once the offshore location is reached: the structures must include facilities to position them on their bases. This particularly applies to tower parts.

For towed transport, two towing tugs would be needed to transport the structure to its location offshore. In case of barge transport, the required equipment depends on the combination of transport and installation by the same barges. The following equipment is identified for transport purposes:

Separated transport and installation

- 1x towing tug
- 1x cargo barge
- 1x assistance tug (optional)

Or

- 1x crane barge with enough cargo area
- 1x assistance tug (optional)

Combined transport and installation

- 1x self-elevating work vessel (jack-up)

Or

- 1x construction vessel

(Sub)structure	Self-floated transportation	Barge transportation
Configuration 1: Monopod foundation	YES	YES
Jacket foundation, tripod design	NO	YES
Jacket foundation, lattice design	NO	YES
Gravity base foundation	YES	YES
Guyed turbine foundation	YES	YES
Turbine tower	NO	YES
Nacelle	NO	YES
Rotor	NO	YES
Guyed turbine tower	YES	YES
Configuration 2: Turbine tower and nacelle	NO	YES
For other components see Configuration 1		
Configuration 3: Rotor and Nacelle	NO	YES
For other components see Configuration 1		
Configuration 4: Monopod foundation and tower	NO ¹	NO
Jacket foundation and tower	NO	YES
Gravity base foundation and tower	YES ²	YES
Guyed turbine foundation and tower	NO	NO
For other components see Configuration 1		
Configuration 5: see configurations 3 and 4		
Configuration 6: Monopod foundation, turbine tower and nacelle	NO	YES
Jacket foundation, turbine tower and nacelle	NO	YES
Gravity base foundation, turbine tower and nacelle	NO	YES
Guyed turbine foundation, turbine tower and nacelle	NO	YES
Configuration 7: Turbine tower, Nacelle and Rotor	NO	YES
For other components see Configuration 1		
Configuration 8: Complete pre-assembled wind turbine	NO	YES

Table 2. Overview of transportation means for the different substructures.

5.5 Transport Steps

For each of the steps in the process of transportation to the site, a lump sum is estimated when applicable.

For transport of towed structures, the following procedure is applicable:

- Transport of structure from fabrication hall to quay ±0 k€ ³
- Rent of quayside ±200 k€ ⁴
- Lift the structure from quayside into the water ±0 k€
- Connect the structure to a towing tug ±0 k€

¹ A pre-assembled monopod support structure - turbine tower does not satisfy the requirements mentioned above.

² This floated option should be investigated. It is assumed here to be possible.

³ The transport cost of the substructure to the quayside is mostly a part of the substructure's price.

⁴ Estimated price for a three months period.

- Transport to offshore location see specification

For transport on a transport barge the steps are:

- Transport of structure from fabrication hall to quay ± 0 k€
- Rent of quayside ± 200 k€
- Loading of structure from quayside on transport barge ± 0 k€
- Transport to offshore location see specification

5.6 Cost of Transport Equipment

In the cost model 6 types of vessels are considered for transport and installation. The author of this report does not know some of these costs and therefore they have been estimated. An overview of the costs of these vessels is given in the next table:

Equipment	(De-)mobilisation Costs ⁵	Operational Costs ⁶ (day-rate)
Towing tug		
Cargo barge		
Jack-up		
Construction vessel		
Crane barge (sheer leg)		
Crane barge (derrick)		

Table 3, Cost of transport equipment

5.7 Estimation of Transport Time

The transport time can be subdivided into the following steps:

- Mobilisation of transport barges to the transport quay ± 3 days
- Loading of structures from the quay onto the vessel ± 0.5 day
- Transport time to site ± 0.25 day
- Time for anchoring on site (if applicable) 0 ⁷
- Time for unloading of structure ± 0.5 day
- Mobilisation time back to the quay ± 0.25 day

For the calculation of transport costs, the mobilisation time is not considered because most companies charge a lump sum for the mobilisation of their equipment. The other times are all together equal to 1.5 day. This 'fixed' time multiplied by the day-rate of the vessel is added into the cost calculation formula.

In the list above, the time needed by the transport barges to moor, in order to remain stable during unloading of the transported structures, is neglected. This will differ depending on the transport vessel used, especially when the use of one vessel for a combination of transport and installation is preferred.

The costs of transporting the wind turbines are estimated based on the in chapter 2 presented configurations. Depending on the vessel used, transport of all turbine substructures separated may be less expensive than a whole wind turbine at once. Based on these configurations, twenty different turbine substructures may be identified.

Two parameters are defined to quantify the costs of transporting the turbine substructures: Nsim_tr and Nday_tr.

⁵ Prices are not given here, see Ref [3]. Mobilisation costs are also given as a number of days (preparation time) multiplied by the day-rate.

⁶ Prices are not given here, see Ref [3].

⁷ Time for anchoring is neglected. From discussions with offshore experts, it seems that this time will be less than 3 hours for a large vessel. Anchoring is then done by assistance tugs.

Nsim_tr represents the maximum number of substructures that can be transported simultaneously on a vessel. Nday_tr represents the maximum number of substructures that can be delivered to their final location within one day by a vessel. These two parameters are further explained in section 5.11.

As an example, the value of these parameters is presented in the next table for three of the identified 20 turbine substructures. The dimensions of the substructures and their mass have not been taken into account. Special transport vessels are also not considered.

The mentioned transport times do not include delays because of bad weather conditions. The transport capacity (number of units that can be transported with one vessel) have been estimated based on the considerations given in chapter 5.3.

Substructure	Transport equipment	Simultaneous transport capacity (units)	Transport capacity ⁸ per day
	Cost model parameter →	Nsim_tr	Nday_tr
Monopod foundation	2x towing tugs	2	2
	1x cargo barge & 1x tug	4	2
	Jack-up	10	1
	Construction vessel	8	1
	Sheer leg	0	0
	Crane barge	0	0
Jacket foundation, tripod or lattice design	2x towing tugs	0	0
	1x cargo barge & 1x tug	1	1
	Jack-up	4	1
	Construction vessel	2	1
	Sheer leg	0	0
	Crane barge	1	1
Complete pre-assembled wind turbine (jacket foundation)	2x towing tugs	0	0
	1x cargo barge & 1x tug	1	1
	Jack-up	1	1
	Construction vessel	1	1
	Sheer leg	0	0
	Crane barge	0	0

Table 4, Transport of turbine substructures

Example:

The transport of 20 monopods with one cargo barge and tug, takes $20/4 = 5$ travels from shore to site because this transport combination can transport 4 units simultaneously (Nsim_tr = 4). The number of days working at sea will be $20/2 = 10$, because this transport combination is able to transport 2 units to the site in one day (Nday_tr = 2). The total working time is then $10 + 5 \cdot 1.5 = 17.5$ days.

5.8 Definition of Maximum Sea State Conditions for Transport

To analyse the availability of transport barges, it is possible to distinguish two types of maximum sea states:

- a maximum sea state for travelling to location and
- a maximum sea state for stable floating condition on the site, i.e. during the transshipment of the structures from the transport to the installation vessel.

⁸ This parameter represents the number of turbine substructures that can be transported from the quay to the offshore location, or from one location to another, in good weather conditions. It is estimated to be valid up to 40 km from the shore. It has been estimated independently from the substructure's dimensions and mass.

For reasons of simplicity, only the most unfavourable Sea State of the transport vessels is used to quantify the workability.

Equipment	Lifting capacity [MT]	Transport capacity [MT]	Maximum sea state [m]	Minimum draft [m]
Towing tug	0	0	1.5	1.5
Cargo barge	0	10,000	1.5	2.5
Jack-up	2,000	10,000	2.0	4.0
Construction vessel	3,000	20,000	2.0	4.0
Crane barge (sheer leg)	800	500	1.5	2.5
Crane barge (derrick)	800	500	2.0	3.5

Table 5, Maximum sea state conditions of transport vessels

Based on the operating sea state statistics, the probability of transport for the considered transport vessel can be estimated.

In the previous table the transport capacity of the vessels is given. Because the mass of a complete wind turbine is not expected to exceed 1,500 MT, it is assumed that the vessels may transport the structures as specified in table 4. In other words, the influence of the substructure's dimensions on the transport capacity of the vessels is not further used in the cost model. The cost model also assumes that the water depth where the wind farm is located exceeds the values of the minimum draft of the vessels, thus this parameter is also not used.

5.9 Probability of Non-Transport Sea State

To transport (and install) offshore wind turbines, (heavy) floating vessels are required. These vessels can travel to the location under certain maximum conditions. The environmental parameters describing these maximum conditions are waves, currents and wind. Not only their magnitude and direction are required, also their interaction is important.

The costs related to non-operational time while waiting for good weather to transport offshore wind turbines would be, depending on the type of contract, changeable to the installing party or to the contractor. In any case, they may be added as a lump sum to the normal transport costs.

Two parameters are important in order to determine the probability of benign weather for the transport of structures:

1. The probability that a specific wave height is not exceeded.
2. The probability that a weather window of sufficient length exists, with a maximum wave height, to carry out the transport process non-stop.

Once these two probabilities are found, the probability of transporting the structure to its offshore location is found by multiplication, i.e.:

Equation 5

$$P(\text{transport}) = P(H \leq H_{ref}) * P(\text{benign})$$

H	=	wave height	[m]
H _{ref}	=	reference wave height	[m]
P(benign)	=	Probability of occurrence of a minimum window length needed for transport	[-]

The total time needed for transport including bad-weather conditions may then be calculated as follows:

Equation 6

$$t_{total} = t_{work} + t_{delay}$$

For transport vessels, the only parameter that counts in the decision of travelling or not is the Sea State, i.e. the probability that a specific wave height is exceeded. Neither the wave direction, nor the influence of wind and current (load or direction) are relevant. Very strong winds are always correlated to high waves.

The probability of exceeding a wave height at a given location and the probability of occurrence of good-weather windows is further explained in 0. For simplicity, in the cost model it is assumed that the probability of occurrence of a good-weather window is equal for any case to 70%, $P(\text{benign})=0.7$. Using the formulas derived in 0, the cost model may be expanded in the future.

It is important to notice that the probability distribution may be taken for the whole year or only for the summer period. Figure 13 shows an example of (median) wave height distribution for a region in the EEZ of the Netherlands for the whole year [9]:

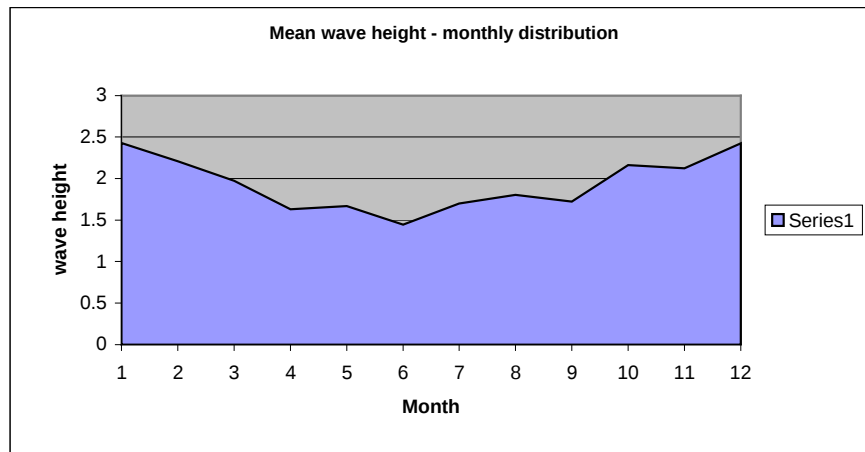


Figure 13

It is clear that in some months (in this case those between April and September) the mean waves will be smaller than for the winter months period. In the cost model, the Shape parameter (k) and the Scale parameter (c) of a Weibull distribution are used as input.

5.10 Estimation of Transport Costs

The transport costs of one substructure, are given by the next formula.

Equation 7

$$Cost_1 = Mob + t_{total} * Q$$

Bad weather will cause a delay in transport time. The extra costs involved are a direct consequence of this waiting time. If the day-rate for using a particular equipment is given by the parameter Q , the total cost per day of ' t_{work} ' days plus ' t_{delay} ' days delay due to bad weather conditions is $(t_{work} + t_{delay}) * Q$. The cost of using the equipment becomes:

Equation 8

$$Cost_1 = Mob + (t_{work} + t_{delay}) * Q$$

The delay time can be related to the working time and their probability of occurrence as follows:

Equation 9

$$\begin{aligned}
 t_{total} &= t_{work} * \left(1 + \frac{t_{delay}}{t_{work}}\right) = t_{work} * \left(1 + \frac{P(delay)}{P(work)}\right) = t_{work} * \left(1 + \frac{1 - P(work)}{P(work)}\right) \\
 \Rightarrow t_{total} &= t_{work} * \left(1 + \frac{1}{P(work)} - 1\right) \\
 \Rightarrow t_{total} &= t_{work} * \frac{1}{P(work)}
 \end{aligned}$$

The estimated costs are then given by:

Equation 10

$$Cost_1 = Mob + \left[\frac{t_{work}}{P(work)} + t_{FIXED}\right] * Q$$

For transport cost analysis purposes, in the equation above $P(work)$ must be substituted by $P(transport)$. In the equation above, the parameter t_{work} represents the time (in days) required to transport one structure using one vessel. Note that in the equation the fixed time t_{FIXED} is added in accordance to section 5.7. This extra time accounts for the transport vessel to load the structure onto the vessel, to position / moor along the wind turbine to be installed and to mobilise to the harbour or to the next location.

5.11 Estimation of Savings Using Simultaneous Transport

Good-weather conditions

The table presented in chapter 5.7 includes the costs of transport of one foundation at a time (1x). When considering a wind farm however, the simultaneous transport of more foundations may reduce the overall transport costs of foundations. This cost reduction is estimated, considering the maximum number of structures of each type that can be transported simultaneously (N_{sim} , units [-]) and the maximum number of structures that can be delivered to their final destination per day (N_{day} , units [1/day]).

The algorithm used to estimate the transport cost of 100 structures using only one vessel, is then given by:

Equation 11

$$Cost_{100} = \frac{100}{N_{sim}} * \left(\frac{N_{sim}}{N_{day}} + t_{FIXED}\right) * Q + Mob$$

In this algorithm, the factor $100/N_{sim}$ represents the number of travels of the vessel. This number is rounded up to the next integer. Besides, the ‘fixed’ time, as explained before in section 5.7, is included every time the transport barge comes back to the departure harbour or quay for transport of more structures. This extra time is chosen independently from the distance of the wind farm to the shore, because it is supposed that the wind farms will all be located not further than approximately 30 km from the coast.

Example.

A barge can transport 4 structures at a time ($N_{sim}=4$) and can transport 2 of these 4 structures in one day to their final location ($N_{day}=2$). The cost of transporting these 4 structures to their location takes $(4/2+1.5)$ days. Transporting 100 turbines, it will take $(100/4)*(4/2+1.5)$ days. The total costs involved amounts then $(100/4)*(4/2+1.5)*Q + Mob = 87.5Q + Mob$. This means that almost 88 days are required to transport 100 turbines with one vessel to their location offshore, if assuming good-weather conditions continuously.

Bad-weather conditions

When including the bad weather conditions to the formulas above, it is found that:

Equation 12

$$Cost_{100} = \frac{100}{N_{sim}} * [\frac{1}{P} * \frac{N_{sim}}{N_{day}} + t_{FIXED}] * Q + Mob$$

being $P = P(\text{transport})$ the probability of transport due to unfavourable weather conditions (see chapter 5.9). In the cost model the number $(100/N_{sim})$ is rounded up to the next upper integer.

5.12 The Use of Several Transport Vessels Simultaneously

When several transport vessels are used simultaneously, the derived formula must be modified with the number of times that each vessel must travel. The number of turbines that must be transported is divided by the number of vessels used (N_{vess}). The number of transport days required by each vessel remains unchanged, but the costs per day must be multiplied by the number of vessels used. The mobilisation costs must also be multiplied by the number of used vessels.

The equation then becomes:

Equation 13

$$Cost_{100} = \frac{100}{N_{vess} * N_{sim}} * [\frac{1}{P} * \frac{N_{sim}}{N_{day}} + t_{FIXED}] * N_{vess} * Q + N_{vess} * Mob$$

Moreover, after simplification, it becomes:.

Equation 14, transport costs.

$$Cost_{100} = \frac{100}{N_{sim}} * [\frac{1}{P} * \frac{N_{sim}}{N_{day}} + t_{FIXED}] * Q + N_{vess} * Mob$$

On the same way as in the formula derived before, the number $(100/N_{sim})$ is rounded up to the next upper integer.

5.13 Reparation of Paint Damages

During the transportation of offshore constructions, the paint of parts of the structure may be damaged. In principle, the costs involved are insured. For the analysis of the transport costs as presented here, it should be necessary to consider the repair time of the structure before installation as a percentage of extra time, allowing a repair team to work on the vessel. This estimation of extra time due to paint damage is not accounted for.

6. ANALYSIS OF INSTALLATION COSTS

6.1 General

The analysis of installation costs is realised similar to the transport costs analysis. Vessel capacity and costs have been estimated, based on the expert opinions of senior engineers in the offshore industry.

In the following paragraphs, the installation strategy will be discussed followed by the impact of the turbine design on the installation costs and by applicable on installation vessels. The analysis continues with the installation steps and costs, specified for the different structures and available vessel in a similar way as in chapter 5. Finally, the extra costs due to bad-weather delays and savings due to the use of several vessels simultaneously are analysed. Costs of insurance are not included.

6.2 Analysis of Installation Strategy

Capacity of Installation Vessels

When considering the installation of a wind farm, one may expect that the cheapest installation strategy is to embark as many substructures as possible at the same time and go to location to install them. In this way, time and costs for going back and forth to the location would be saved. When considering this, it must not be forgotten that in order to install as many structures as possible at the same time, the structures must be available.

The following aspects play a role:

- The manufacturers must construct and assemble as many wind turbine parts as possible in a short time and maintain them on stock.
- There must be enough space available at the quayside of the harbour to maintain the optimum stock required for installation. Space at the quayside is expensive.
- The stock at the quayside of the harbour must be filled with new components when they have been taken away by the transport barges.
- At the time of departure from the harbour, there should be a good-weather window expected long enough to install several units next after each other. If a good-weather window is not present, extra costs for rented installation equipment and costs forthcoming from the rent of the quayside will be present.

All these considerations are included into the model in order to derive an optimum, i.e.:

- A continuous process takes place during installation;
- There is enough stock of turbine parts available for installation;
- The maximum capacity of the transport and installation barges is accounted for.

The extra time due to the probability of equipment not being operational is taken into account. This extra time is the result of a particular sea-state. Examples of delay time that are not accounted for are the non-availability of vessels, damage of vessels, lack of personnel, etc.

Pre-Installation of Electric Cables

Another aspect that must be considered in the installation strategy is the installation of the electric cables between the wind turbines, between wind turbines and the farm power collection facility and between the farm power collection facility and the shore.

If the electric cables are pre-installed, before the wind turbine foundations are placed, they will be sensible to damage. Examples are:

- The cables may be damaged by the foundation itself during their installation.
- The mooring lines of the installation (or transport) vessels may damage the cables.
- The movement of the water (and thus the soil) by the installation vessels may expose the pre-installed cables. Later they may be damaged due to this exposure.

If the electric cables are not pre-installed, then the possibility of damaging the installed wind turbines during cable installation exists. The installation of the cables may require soil preparation, cable laying and erosion protection. These aspects force the barges used for cable lay, to operate very carefully between the installed turbines and if necessary deploying their mooring lines manoeuvring between the units.

Despite all these considerations, the cost model supposes that the installation of the electric cables takes place after the foundations (or the complete turbines) have been installed, without extra delay for manoeuvring or anchor deploying.

The Use of Flanged Sub-Sections for Installation

As discussed previously in chapter 5, the transport of large wind turbine sections may constitute a logistic problem. As an option, the division of the large turbine components (like for instance the tower) into flanged sub-sections may facilitate their transport. When considering this option the following aspects are of importance:

- Flanged sub-sections are only applicable for foundation parts located above the sea bottom level or for the tower of the wind turbine. Although theoretically an internal connecting flange for a pile is possible, a flanged pile is not considered as an option.
- The flanged sub-sections, once transported to location, should be connected to each other before installation to minimise the installation time.
- The connecting time of bolted flanges is large. Because the magnitude of the flanges, the loads involved and the probably large number of bolts involved, a special bolt installation sequence must be realised. This installation sequence comprises:
 - The hydraulic pre-tensioning of three bolts at the time (separated 120 degrees from each other) to 30% of the final pretension.
 - The subsequently pre-tensioning of the other bolts of the flange to 30% of the final tension.
 - The repetition of the first two steps for tensioning loads up to 60%, 90% and finally 100% of the final tension.

For reasons of simplicity, the time required for the connection of the flanges is neglected. This assumption is based on the fact that once the components are bolt-connected to each other (not yet pretensioned) the installation vessel leaves the location and continues its work on the next location. The pretension procedure continues without the presence of the vessel holding the structure.

- The costs of offshore tensioning of bolts may be large due to the time that the personnel is involved.
- The environmental conditions offshore for connecting the flanged sub-sections to each other may be unfavourable.
- The installation of the electric cables going through the tower (and possible through the foundation part) may be difficult to achieve, for instance due to minimum curvature of the cables and sensitivity to damage.
- The continuity of internal ancillary components in the turbine tower such as ladders and hand railing.

If it is supposed that the technical aspects mentioned above are overcome, the extra installation time due to the existence of a flanged connection may be estimated to be 0.5 days for each flanged connection. This time includes the positioning of flanged structures respect to each other.

In the cost model, it is assumed that no flanged connections are present. The extra costs of connecting the flanges to each other before installation of the structure is assumed to be compensated by the use of larger transport vessels to the offshore location.

6.3 Impact of Turbine Design on Installation Costs

Similar to the analysis as presented in chapter 5.2, the following paragraphs present an analysis of the impact of the turbine design on installation costs.

For the analysis of the installation costs of the presented configurations, the general assumptions similar to chapter 5.2 are valid:

- 1 The rotor of the wind turbine consists of three (non-retractable) blades.
- 2 The boat landing (platform) is located at mean sea level.
- 3 The foundation of the turbine ends at a certain height above mean sea level.
- 4 The required maintenance platform is a part of the foundation (at the upper end) or it is a part of the turbine tower (at the lower end).
- 5 The foundation of the turbine does not include any other external maintenance platform.
- 6 The offshore turbine does not include a helicopter platform on top. If such a platform is required, it is transported (and installed) separately. The necessity of a helicopter platform with its cost impact is analysed separately.

In addition to the assumptions made above every configuration as presented in chapter 2 is analysed:

Configuration 1: Installation of major components separately

Monopod Foundation

A monopod foundation with a diameter up to approximately 4 metres may be driven or drilled into the sea bottom. Monopod foundations of larger diameters for use in the oil and gas industry have been installed using other techniques in waters of the North Sea [10], but costs of such ways of installation are unknown to the author of this report.

If the pile is manufactured including flanged subsections, an extra installation step must be included, i.e. connecting the flanges. Handling of larger and/or heavier constructions is in general more time consuming than the time needed for shorter and/or lighter substructures. In the cost model, the installation time is independent of dimensions or mass of the considered monopod.

An engineering problem is present when considering the location of the maintenance platform of a monopod wind turbine.

- If the maintenance platform is part of the foundation, the flange that connects the foundation with the turbine tower is located higher than 15 metres above mean sea level. The platform must then be located at a water-splash free zone. This makes the foundation very large.
- During the driving process of the pile in the ground, if the platform is a part of the foundation, then it will be subjected to heavy vibrating loading, which need to be accounted for.

The reason of considering the maintenance platform as a part of the foundation, is that this platform may serve during installation as a working platform, facilitating the installation personnel to connect the foundation and the tower of the wind turbine to each other. When no working platform is present as a part of the foundation, the connection of the flange must take place using an offshore working crane, making the installation time and the installation costs higher. As an option, a temporary working platform may be considered as part of the foundation. This last named platform will be relatively small, making it less vulnerable to

vibration loads during installation of the foundation. The platform can also be attached to the foundation after installation.

In the offshore wind farm of Horns Rev, Denmark, the design of the foundation includes a transition piece between the pile and the connecting flange in order not to damage this platform while piling. For more details see reference [11].

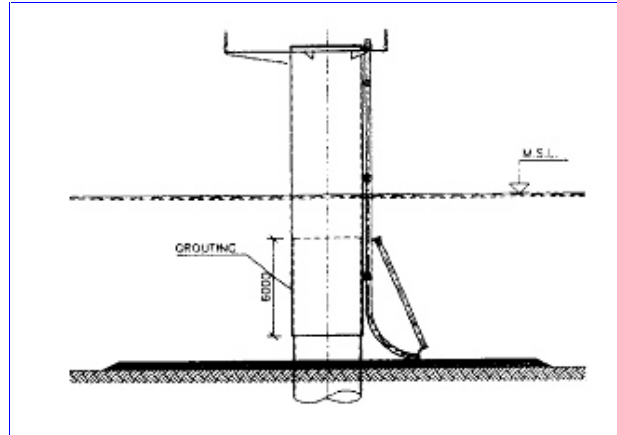


Figure 14. Transition piece between the pile and the platform at Horns Rev, Denmark.

In the cost model, the engineering solution considered is that the flange between foundation and tower is bolted using an offshore crane or temporary working platform. The flange can be as close to the water level as five metres above MSL. The permanent maintenance platform forms a part of the turbine tower.

Another important engineering consideration is the design of the flange that connects the foundation with the turbine tower with an extension on top of it. In this way, the flange is not damaged during the driving process of the pile into the bottom. In the cost model, this installation problem is supposed to be solved by an adequate flange design.

Once the foundation of the offshore wind turbine is installed, the installation barge may continue installing other foundations or other components of the same unit. At the end of the monopod foundation installation, a cylindrical tower piece, about five metres above of sea level, will wait for installation of the other components. On top of the foundation, a flange connection (to connect the tower) is visible. The installation of the electric cables is analysed in chapter 6.18.

Guyed Turbine

The foundation of a guyed turbine will probably be a slender monopod. Its installation is described before. In addition to the considerations for the foundation, the anchoring points of a guyed turbine must be considered.

At least three anchoring points are necessary for the guys. These points must withstand all loads acting on the turbine. The anchoring point will probably be similar to the foundation: a small monopod driven into the seabed, probably not so deep as the foundation self. Other technical feasible solutions are also possible: suction piles, gravity bases, etc.

In the cost model three anchoring points are considered. The foundation of each anchoring point is thought to be a monopod. The installation time required to install all anchoring points is estimated to be equal to the installation time of a (small) monopod, because the operation can take place sequentially.

Jacket Foundation

The installation of a jacket foundation requires the following installation steps:

- 1 Prepare seabed. The levelling of seabed under the three piles to achieve straight wind turbine could be necessary. Instead of levelling the seabed, the jacket may be levelled afterwards (step 7).
- 2 Lift the foundation from its transport barge (may be the same vessel used for installation).
- 3 Position the foundation on its location.
- 4 Lift a foundation pile, hold it on position and drive it to a certain depth (less than the maximum) into the ground.
- 5 Repeat the last step for the other two piles
- 6 Drive all three piles subsequently to their final depth.
- 7 Level the jacket foundation to obtain verticality according to required tolerances. If this step is present in the installation sequence, then the preparation of the seabed (step 1) is not necessary.
- 8 Fix the jacket to the piles by overpressure or welding techniques.

If suction piles are used instead of driven/drilled piles, the installation sequence is similar.

It is not likely that a jacket foundation will be manufactured including flanged subsections, so this is not considered here.

A temporary platform during installation is not necessary for a jacket foundation. Because the foundation is not driven into the ground a maintenance platform is also not submitted to heavy vibrations and may be used as a working platform during installation.

Once the jacket foundation of the offshore wind turbine is installed, the installation barge may continue installing other foundations or other components for the same unit. When the installation of the foundation is finished a cylindrical tower piece (in case of a tripod design) or a lattice construction, about 20 metres above sea level, will wait for installation of the other components. On top of the foundation, a flange connection (to connect the tower) is visible. Just under this flange, a maintenance platform is located. The installation of the electric cables is analysed in chapter 6.18.

In case that the verticality of the foundation is not yet satisfactory, the verticality of the complete turbine may still be achieved using filling material between the tower-foundation connection flanges.

Gravity Base Foundation

The installation of a gravity base foundation requires the following installation steps:

- 1 Prepare seabed. The levelling of seabed under the complete gravity base is indispensable.
- 2 Lift the foundation from its transport barge (may be the same vessel used for installation).
- 3 Position the foundation on its location.
- 4 Grout the base using grout material like sand, gravel or most probably concrete. For grouting purposes, a special barge is required.

The installation of a massive pre-fabricated concrete gravity base has been used as foundation for wind farms in the Baltic Sea. These wind farms are located in very shallow waters and the turbines of the farm are relatively small compared to today's standards. For larger sizes wind turbines and deeper waters, a gravity base is not considered a feasible option. The transport and installation of a pre-fabricated concrete gravity base would mean the handling of a very large and heavy construction. In the cost model, gravity bases as foundation are considered for comparison purposes only. The gravity bases are grouted after the foundation is on its position.

Wind Turbine Tower

The installation of the wind turbine tower requires the following installation steps:

- Lift the wind turbine tower from its transport barge (may be the same vessel that is used for installation).
- Position the tower on top of the foundation. Use guiding pins to position the connecting flanges properly.
- Connect the flanges using pre-tensioning bolts.

In favourable weather conditions, this operation would take a couple of days depending on the size of the tower structure and depending on the installation vessel considered.

The electric cables of each turbine are assumed already present in the inside of the tower for future connection. The only difference between the wind turbine tower of a configuration using a monopod or a jacket foundation, is the position of the maintenance platform on the tower.

Installation of the Rotor

The rotor (blades + hub) may be installed using one of the following three options:

- The rotor arrives at the location in one piece and is installed in one piece.
- The rotor blades and the hub arrive at the location separately. Before installation on the hub of the turbine tower, they are connected to each other. The rotor is then installed in one piece.
- The rotor blades and the hub arrive to the offshore location separately. They are also installed to the turbine tower separately.

Installation of the rotor in one piece requires that a working platform is made available at hub height during installation. This platform may be a part of the crane boom. The rotor is then connected to the nacelle using several (special) bolts. Bolt pre-tensioning is also required. Access to the connection point is realised from inside the nacelle.

For the offshore installation of the rotor in one piece, it must be realised that it must be connected under great precision at a large altitude. Even in the case of benign wind conditions, the suspended rotor will tend to move at a certain frequency. To avoid these movements the rotor must be held on position by additional supports. The realisation of such precise work offshore is difficult and time consuming.

In order to optimise transport space, the blades could be transported separately from the hub to the offshore location. Once on the location, the blades are connected to the hub and finally the complete rotor is installed onto the nacelle.

If this is the case, extra time and great precision is needed to install the rotor to the nacelle offshore. Precisely supporting and turning of large turbine blades is difficult and time consuming, especially offshore.

The last mentioned option implies separate installation of the blades onto the hub at great height. The installation of the rotor in this way would take very long compared with installation of the complete rotor at once.

For the purpose of cost modelling, the installation of the rotor to the nacelle is considered to take place in one piece (first option), by means of a crane boom of an installation vessel. From the same installation vessel, the rotor is supposed to be prevented from spinning.

Configuration 2. Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

The installation of this configuration is similar to the installation of configuration 1 as described above. The connection of the nacelle to the tower structure before its installation will diminish the total installation time of the wind turbine.

Configuration 3. Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

Similarly to configuration 2, the installation of this configuration is comparable to the installation of configuration 1. The connection of the rotor to the nacelle structure before its installation will diminish the total installation time of the wind turbine. The stability of the assembly and the lock of the rotor while installing must be considered in order not to damage the rotor blades.

The installation of this configuration will depend on the crane capacity of the installation vessels.

Configuration 4. Installation of pre-assembled foundation and tower, followed by nacelle and rotor

The installation of this configuration is also similar to the installation of configuration 1. The connection of the tower structure to the foundation before its installation will diminish the total installation time of the wind turbine.

For a wind turbine with a monopod foundation, a combined installation of foundation and turbine tower is not possible.

The installation of a combined foundation and tower of an offshore wind turbine with a jacket foundation may be realised similarly to the installation of a jacket foundation alone. The mass and the height of the tower-foundation assembly are larger than the mass and height of the foundation under configuration 1. This means that larger installation vessels are required.

Gravity bases combined with the turbine tower have the extra complication of verticality problems. The verticality must be achieved during sea bottom levelling, because corrections afterwards are very difficult.

The verticality of the tower-foundation assembly must be achieved during the installation. There are no simple means of correcting an unachieved tolerance afterwards.

Configuration 5. Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

For this configuration, all considerations described for configurations 3 and 4 are applicable.

Configuration 6. Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

The installation of this configuration is similar to the installation of configuration 4 described above. The connection of the nacelle to the tower structure and foundation before its installation will diminish the total installation time of the wind turbine.

This configuration requires installation vessels with even larger crane capacities than configuration 4. This applies for the load to be lifted as well as for the height to be lifted to.

The installation of the rotor is similar to that presented under configuration 1.

Configuration 7: Installation of foundation, followed by pre-assembled tower, nacelle and rotor

The installation of the foundation is similar to that presented for configuration 1.

The installation of a pre-assembled turbine tower, nacelle and rotor is unlikely because of transport limitations. Besides, its dimensions combined with its mass are very large. Nevertheless, this possibility is considered here because a pre-assembly of tower and rotor just before installation of the combination is optional.

To install the tower, the nacelle and the rotor together a large installation vessel is required. The mass of such a pre-assembled structure may be up to 625 MT for a 5 MW wind turbine. The required lifting height may be as much as 105 meters above MSL (crane hook).

If the transport of a pre-assembled tower-rotor combination is not possible, but the installation of the pre-assembly is desired, the time involved in assembling the rotor to the tower offshore needs to be accounted for. The installation steps may then be resumed as follows:

- Lift the rotor from its seating and connect it to the nacelle 1 day minimum
- Lift pre-assembled nacelle-rotor combination and connect it to the tower 1 day minimum
- Lift pre-assembled tower, nacelle and rotor combination and connect it to the foundation 1 day minimum

Installation times depend on vessel used. Bad weather and other time delays are not considered.

Configuration 8: Installation of complete pre-assembled offshore wind turbine

The installation of a complete pre-assembled wind turbine may only be achieved if the foundation is a jacket or a gravity base type.

The installation steps for a wind turbine with a jacket foundation type are similar to the ones described under configurations A and B, only the mass and dimensions are larger. A mass of 835 MT for a complete wind turbine assembly is conceivable for a 5 MW turbine. Once installed, the verticality of the wind turbine cannot be corrected anymore.

The installation steps for a wind turbine with a gravity base foundation type are also similar to those described in configurations A and B. A difference is though that the wind turbine must be held in place during the grouting process. The verticality of the final assembly is then very difficult to correct if the sea bottom is not levelled properly. In case of a jacket, for instance, the turbine could be pulled from different sides with dynamic positioned (DP) steered tugs.

6.4 Impact on Installation Vessel Design due to Turbine Configuration

The installation analysis is made on the assumption that standard vessels are used for this purpose. Nevertheless, adjustments to the installation barges may be necessary. Other special built installation vessels, were being developed for installation purposes at the time of this writing. An example of this is the Mayflower installation barge, to be used for the wind farm Horns Rev in Denmark [12], see also Appendix D, figure 10.

In order to do their work properly, installation vessels must be safely moored. Deploying of the mooring lines is a time consuming task, especially if offshore constructions are already present. Examples of this could be the presence of the foundations of the wind turbines offshore, with installation vessels manoeuvring around them in order to subsequently install the towers and the rotors.

A way of reducing the time needed for mooring purposes, installation barges could moor in such a way that at least two turbine locations can be reached with one anchor deploying (see Figure 15). This reduced mooring time is not considered in the cost estimation.

In the following paragraphs, some other considerations are discussed.

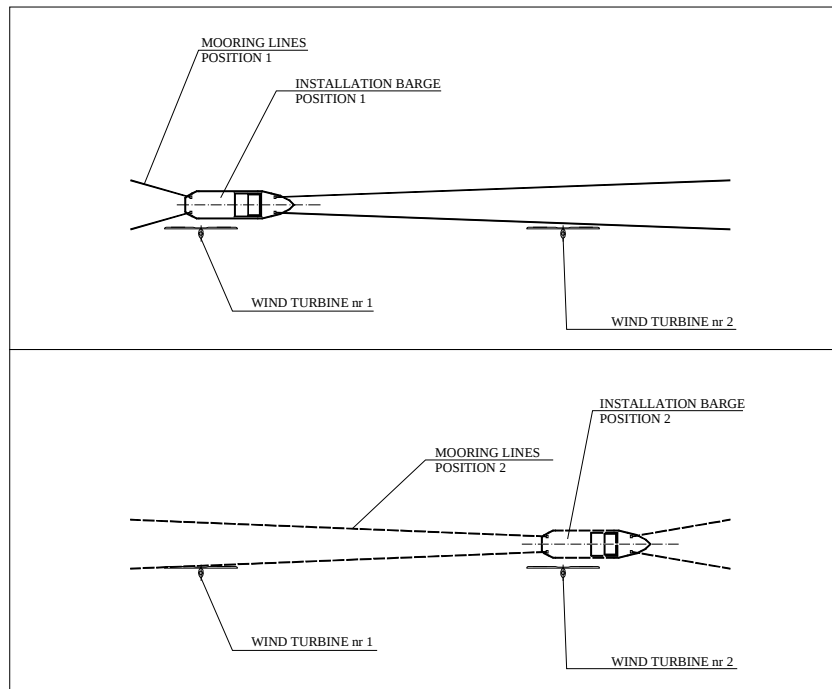


Figure 15. Installation vessel consecutively near turbine 1 and 2 without changing the mooring points.

Configuration 1: Installation of major components separately

No special features for the installation barges are required. In the case of installation of the rotor separately, care must be taken to hold the rotor in position without spinning in order to avoid damage. The minimum lifting height required for installation of the rotor in combination with its expected mass is achievable with state-of-the-art installation vessels.

Configuration 2. Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately

No special features on installation barges are required. For the rotor, similar considerations as described in configuration 1 are valid.

The minimum lifting height required to install a pre-assembled tower and nacelle structure in combination with its expected mass, could be a limiting factor for installation vessels.

Configuration 3. Installation of the foundation followed by the tower and finally the pre-assembled nacelle and rotor

No special features for the installation barges are required. For the rotor, similar considerations as described in configuration 1 are valid.

The minimum lifting height required to install a pre-assembled nacelle and rotor structure in combination with its expected mass, could be a limiting factor for installation vessels.

Configuration 4. Installation of pre-assembled foundation and tower, followed by nacelle and rotor

This configuration is similar to configuration 1, except that for monopod foundations installation of pre-assembled foundation and tower is not achievable.

The minimum lifting height required to install a pre-assembled foundation and tower structure in combination with its expected mass, could be a limiting factor for installation vessels.

Configuration 5. Installation of pre-assembled foundation and tower, followed by pre-assembled nacelle and rotor

All considerations as described in configurations 3 and 4 are valid. No other special features on installation barges are required.

Configuration 6. Installation of pre-assembled foundation, tower and nacelle, followed by the rotor

The installation of the rotor is similar to that presented under configuration 1. Compared to configurations 4 and 5, this configuration requires even more lifting capacity (combination of lifting height and related mass of structure). Monopod foundations are not possible to install for this configuration.

The installation of a pre-assembled foundation, tower and nacelle combination of a large wind turbine will probably present installation difficulties when sheer legs are considered as possible installation vessels. The largest sheer leg can lift up to 1400 MT but only to about 80 metres height. The corresponding outreach is then about 10 metres from the side of the vessel.

This means that this minimum required lifting capacity could be a serious limiting factor for installation vessels. One of the vessels that could realise this installation operation for large offshore wind turbines under this configuration is the 'Svanen'. This vessel is presented in Appendix D. Larger assemblies may also be installed with construction vessels and jack-ups. Construction vessels as the semi-submersible construction vessel 'Balder'[11], can lift 900 MT up to 84 m or 600 MT up to 95 m above MSL. This vessel, however, has a minimum draft of 11 to 27 metres depending on the loading. The water depth limits the use of this vessel. Besides, it is a very expensive unit due to its unique design. Finally, availability of this vessel is uncertain.

Configuration 7: Installation of foundation, followed by pre-assembled tower, nacelle and rotor

The installation of the foundation is similar as explained in configuration 1. No special features on installation barges are required in this case.

The installation of a pre-assembled tower, nacelle and rotor combination of a large wind turbine will probably present the same installation difficulties as described for configuration 6. The only difference is the sensitivity of the structure (blades) against damage. The same vessels mentioned above could perform the installation of these structures.

Configuration 8: Installation of complete pre-assembled offshore wind turbine

Due to the possible mass and dimensions of large wind turbines, it may be possible that with the existent installation vessels, the installation of these turbines is not achievable. In this case, special installation vessels may be required.

6.5 Installation Steps

The installation of an offshore wind turbine includes the following steps:

- Possible adaptation of vessel for specific installation procedure
- Mobilisation of equipment and personnel
- Installation of structure
- Mobilise scour protection equipment
- Apply scour protection
- Mobilise cable laying equipment
- Install electric cables
- Possible scour protection of (parts of) the electric cabling
- Demobilisation of equipment

The installation equipment will be different to the equipment needed for application of scouring and to the equipment needed for cable laying. Each installation equipment requires its own

mobilisation and demobilisation. Mobilisation of scouring and cable lay equipment can take place simultaneously with other activities.

The cost of each of these steps is analysed in the following paragraphs, depending on the structure to be installed and the installation equipment used.

6.6 Cost of Installation Equipment

The mobilisation costs and day-rates of the equipment used in the model have been already given in section 5.6.

6.7 Estimation of Installation Time

The installation time can be subdivided into the following steps:

- Mobilisation of installation equipment to the offshore location ± 7 days
- Anchoring time ± 1 day
- Loading of structures from the transport vessel ± 0.5 day
- Installation time see specification
- Mobilisation time to move to the next location ± 0.5 day
- Application of scour protection see specification
- Installation of electric cables see specification

For the calculation of installation costs, the mobilisation time is not considered because most companies charge a lump sum for the mobilisation of their equipment. The other times all together equal 2.0 days. This ‘fixed’ time multiplied by the day-rate of the vessel is added into the cost calculation formula.

Similar to section 5.7, the time involved for the installation process is given for the turbine substructures for each of the considered vessels. For simplicity, only two substructures of the 20 identified are presented here below.

Substructure	Transport equipment	Simultaneous transport capacity (units)	Installation capacity ⁹ per day
	Cost model parameter →	Nsim_tr	Nday_inst
Monopod foundation	2x towing tugs	2	0
	1x cargo barge & 1x tug	4	0
	Jack-up	10	1
	Construction vessel	8	1
	Sheer leg	0	2
	Crane barge	0	2
Jacket foundation, turbine tower and nacelle	2x towing tugs	0	0
	1x cargo barge & 1x tug	4	0
	Jack-up	6	1
	Construction vessel	4	1
	Sheer leg	0	0.5
	Crane barge	1	0.5

Table 6, Installation of turbine substructures

⁹ This parameter represents the number of substructures that can be installed in one day using the corresponding installation vessel. It is considered to be independent from the substructure’s dimensions and mass.

6.8 Definition of Maximum Sea State Conditions for Installation

The maximum Sea State conditions for installation barges are given in the next table:

Equipment	Lifting capacity [MT]	Corresponding lifting height	Maximum sea state [m]	Minimum draft [m]
Towing tug	0	0	1.5	1.5
Cargo barge	0	0	1.5	2.5
Jack-up	2,000	up to 150 [m] ¹⁰	2.0	4.0
Construction vessel	3,000	up to 90 [m] ¹¹	2.0	4.0
Crane barge (sheer leg)	800	up to 94 [m] ¹²	1.5	2.5
Crane barge (derrick)	800	up to 85 [m] ¹¹	2.0	3.5

Table 7, Maximum sea state conditions of transport vessels

Based on the operating sea states, the probability of the occurrence of installation for the corresponding vessel can be estimated.

The given lifting heights are approximately the heights of the hub level of wind turbines of 5 MW and larger. This means that such a turbine probably only can be installed using a jack-up or special designed vessels. Despite of this constraint, the cost model assumes that the installation of turbine substructures may be achieved using one of the last four mentioned vessels.

6.9 Probability of No-Installation Sea State

The analysis of the probability of down time due to sea state conditions is similar as explained in chapter 5.9. However, the probability of down time during installation depends on the equipment being used during the transport and installation handling.

If only one vessel is being used for both, transport and installation, the probability of working conditions are defined by the maximum operating conditions of the barge itself. If separate vessels are used for transport and installation, the probability of working conditions are defined by the lowest maximum operating conditions of the two vessels. The reason of this is that the structure to be installed must be lifted by the installation vessel from the transport vessel.

Another important aspect in the installation procedure is the need of mooring the installation vessel. If mooring (anchoring) of the vessel is required, the number of mooring lines and the normal mooring time must be known. The probability of good weather window must then be estimated.

In the cost model, the complications that may arise due to the required mooring space between the (partially) installed offshore wind turbines and the (pre-) installed electric cables are not considered.

Similar to the procedure presented in chapter 5.9, two parameters are important in order to determine the probability of having good weather for the transport of structures:

1. The probability that a specific wave height is not exceeded.
2. The probability that a weather window of sufficient length exists, with a maximum wave height, to carry out the installation process non-stop.

¹⁰ With respect to MSL

¹¹ Height measured from deck level of the vessel

¹² Height measured from deck level of the vessel, crane hook level.

Once these two probabilities are found, the probability of installing the structure at its offshore location is found by multiplication, i.e.:

Equation 15

$$P(\text{install}) = P(H \leq H_{ref}) * P(\text{benign})$$

H	=	wave height	[m]
H _{ref}	=	reference wave height	[m]
P(benign)	=	probability of occurrence of a minimum window length needed for installation	[-]

The total installation time due to bad-weather may then be calculated as follows:

Equation 16

$$t_{\text{total}} = t_{\text{work}} + t_{\text{delay}} = \frac{t_{\text{work}}}{P(\text{work})}$$

For installation vessels, the only parameter that counts in the decision of travelling or not is the Sea State, i.e. the probability that a specific wave height is exceeded. Neither the wave direction, nor the influence of wind and current (load or direction) are relevant. Very strong winds always are correlated to high waves.

The probability of exceeding a wave height at a given location and the probability of occurrence of a good-weather window are derived in 0. For simplicity, in the cost model it is assumed that the probability of occurrence of a good-weather window is equal for any case to 70%. With the formulas derived in 0, the cost model may be improved in the future.

6.10 Estimation of Installation Costs

The analysis of the transport costs including bad weather conditions, has been presented already in section 5.10. Similar to these results, the installation costs are given by the next equation:

Equation 17

$$Cost_1 = Mob + \left[\frac{t_{\text{work}}}{P(\text{work})} + t_{\text{FIXED}} \right] * Q$$

For installation cost analysis purposes, in the equation above P(work) must be substituted by P(install). In the equation above, the parameter t_{work} represents the time (in days) required to install one structure using one vessel. Note that in the equation the fixed time t_{FIXED} is added compared with Equation 10 of section 5.10 and in accordance to section 6.7. This extra time is needed to load the structure onto the vessel, to position / moor along the wind turbine to be installed and to mobilise to the harbour or to the next location. Barges that uses the DP principle (DP = Dynamic Positioning), do not need to moor and therefore they would use less time for installation. It is not known to the author of this report if large installation barges have this positioning system. This possibility is therefore not included into the cost model.

If we now consider the maximum number of structures of the same type to be installed in one day by the same vessel (N_{day}, units [1/day]), and the maximum number of structures to be transported at once (N_{sim}, units [-]), the installation costs of 100 structures becomes:

Equation 18

$$Cost_{100} = \frac{100}{N_{\text{sim}}} * \left[\frac{1}{P} * \frac{N_{\text{sim}}}{N_{\text{day}}} + t_{\text{FIXED}} \right] * Q + Mob$$

Note that if 3 days are required to install one structure and two structures may be transported in one embarkation, the parameter N_{sim}/N_{day} = 2/3 [units/day]. The probability P = P(install) is related to the number of days required to achieve the installation.

6.11 Combined Transport and Installation

Installation barges could also be used to transport the structures to the site. If that is the case, the mobilisation cost of the installation equipment is avoided. The time required to install a structure is however independent from the transport time, even if more structures are transported at the same time. In this way, the installation costs based on the time required for installation may be estimated independently.

In this case, the algorithm used to estimate the installation cost of 100 structures is given by:
Equation 19

$$Cost_{100} = \frac{100}{N_{sim}} * \left\{ \frac{1}{P} * \left(t_{FIXED_tr} + \frac{N_{sim}}{N_{day_comb}} + t_{FIXED_inst} \right) \right\} * Q + Mob$$

The mobilisation costs remain unchanged with respect to the previous equation because no extra vessels must be mobilised.

The parameter N_{day_comb} equals to the minimum between N_{day_tr} and N_{day_inst} because one vessel may not transport more structures to their final location without installing them.

In the above equation is $P = P(\text{work})$, the probability that the vessel may realise its operation, transport or installation. In the cost model the lowest probability P , $P(\text{transport})$ or $P(\text{install})$, is chosen. Note that not any vessel is adequate for transport and installation of offshore wind turbines.

6.12 The Use of Several Installation Vessels Simultaneously

If several installation vessels are used simultaneously, the derived algorithm must be modified with the number of vessels used. The use of several installation vessels implies the use of several transport vessels as well. Optimised combination of number of transport and number of installation vessels are not included in the cost model.

In the case that the vessel are used only for installation purposes, the cost of installing 100 structures using several vessels (N_{vess} , units [-]) is given by:
Equation 20, installation costs.

$$Cost_{100} = \frac{100}{N_{sim} * N_{vess}} * \left[\frac{1}{P} * \frac{N_{sim}}{N_{day_inst}} + t_{FIXED_inst} \right] * N_{vess} * Q + N_{vess} * Mob$$

$$\Rightarrow Cost_{100} = \frac{100}{N_{sim}} * \left[\frac{1}{P} * \frac{N_{sim}}{N_{day_inst}} + t_{FIXED_inst} \right] * Q + N_{vess_inst} * Mob$$

It can be seen, that the number of vessels used only influences the mobilisation costs.

In the case of using the same vessel for the transport and for the installation, the equation becomes:

Equation 21, combined costs of transport and installation.

$$Cost_{100} = \frac{100}{N_{sim}} * \left\{ \frac{1}{P} * \left[\frac{N_{sim}}{N_{day_comb}} + t_{FIXED_tr} + t_{FIXED_inst} \right] \right\} * Q + N_{vess} * Mob$$

For combined transport and installation the parameters N_{vess} and N_{day_comb} are defined as follows:

$$N_{vess} = N_{vess_tr} = N_{vess_inst}$$

$$N_{day_comb} = \min(N_{day_inst} ; N_{day_tr})$$

6.13 Reparation of Paint Damages

During the installation of offshore constructions, the paint of the structure may be damaged. In principle, the costs involved are insured. For the analysis of the installation costs as presented here, it should be necessary to consider the repair time of the structure before installation as a percentage of extra time, allowing a repair team to work on the vessel. The estimation of extra time due to the repair of paint damage is not accounted for.

6.14 Costs of De-installation

At the end of the service lifetime, all offshore wind turbines must be removed. It is possible that some components still will be re-used. Nevertheless, for conservatism the residual value is based on scrap value. This also means that there is no need of removing the wind turbines carefully.

The equipment that is used for removal, is as a minimum:

- A crane barge (or sheer leg) with enough capacity to reach the highest point at a minimum lifting capacity of approximately 20 MT;
- A large transport barge, to transport as much used components as possible without taking precautions for possible damage;
- Offshore crew able to dismantle the turbine offshore, by means of cutting the turbine in pieces when necessary;
- A crane barge (or sheer leg) with enough capacity to lift the entire foundation to an approximated height of 25 metres above MSL at a lifting capacity of approximately 300 MT;
- Submarine cutting equipment, to cut the used piles if required.

The costs of the offshore equipment are given in the following table:

Equipment nr.	Description of equipment	Day-rate ¹³
1	Crane barge (or sheer leg)	
2	Cargo barge (large working area)	
3	Cargo barge (normal working area)	
4	Towing tug	
5	Submarine cutting equipment ¹⁴	
6	Diver team	
7	Supply vessel	

Table 8. Cost of equipment.

The rotor blades may be removed in pieces, one blade at a time, in order to reduce the minimum lifting capacity at the required height. The removal times are estimated as follows:

Removal steps	Required offshore equipment	Minimum time required
Mobilisation	- ALL	±7 days
Rotor in one piece	- Crane barge 100 MT at 100 m height - Cargo barge (large working area) - Towing tug	±1 day
Rotor blades, separately	- Crane barge 15 MT at 100 m height	±2 days

¹³ Prices are not given here, see Ref [3].

¹⁴ Using a ROV = Remote Operating Vehicle

Removal steps	Required offshore equipment	Minimum time required
	- Cargo barge - Towing tug	
Nacelle in one piece	- Crane barge 300 MT at 100 m height - Cargo barge - Towing tug	±1 day
Nacelle in components	- Crane barge 50 MT at 100 m height - Cargo barge - Towing tug	±7 days
Tower in one piece	- Crane barge 250 MT at 100 m height - Cargo barge - Towing tug	±1 day
Tower in pieces	- Crane barge (250 MT divided by number of pieces) at 100 m height - Cargo barge - Towing tug	±1 day/piece
Foundation piles (includes monopod foundation)	- Submarine cutting equipment - Supply vessel + crew - Diver team - Cargo barge - Towing tug	±2 days/pile
Foundation (jackets or gravity base)	- Crane barge 300 MT at 25 m height - Cargo barge - Towing tug	±1 day
Demobilisation	- ALL	±7 days

Table 9. De-installation of structures.

The costs of the removal of one offshore wind turbine are derived here below, based on the following assumptions:

- There is a crane barge with capacity of 300 MT at 100 m height;
- The wind turbine has a monopod as foundation;
- The rotor, nacelle, tower and foundation are removed separately, but each of them in one piece;
- There are no delays in time due to bad weather conditions.

Removal steps	Required equipment	Required time ¹⁵
Mobilisation	- ALL	±7 days
Removal of rotor	- Crane barge - Cargo barge (large working area) - Towing tug	±1 day
Removal of nacelle	- Crane barge - Cargo barge (normal working area) - Towing tug	±1 day
Removal of tower in one piece	- Crane barge - Cargo barge (normal working area) - Towing tug	±1 day
Cutting-off monopod foundation	- Submarine cutting equipment ¹⁶ - Diver team	±2 days

¹⁵ Mobilisation not included.

¹⁶ Using a ROV = Remote Operating Vehicle

	- Supply vessel	
Removal of foundation	- Crane barge - Cargo barge (normal working area) - Towing tug	±1 day
Demobilisation	- ALL	±7 days

It is assumed that all turbine components are loaded onto a cargo barge and when the whole turbine is removed, the cargo barge travels to the shore. When the use of several offshore equipment simultaneously is preferred, the cargo barges may be loaded more effectively.

Based on above day-rates and time of operation, the demobilisation costs are calculated. In this calculation, the probability of benign weather condition has already been included. This probability is related to a weather window of two days, because the shortest activity takes at least one day to be realised.

If bad weather does not allow continuing with the removal works, the vessel just has to wait until it can continue its work. This delay has not been taken into account.

6.15 Costs of Installation of a Helicopter Platform

The costs of installation of a helicopter platform are not considered separately. In the cost model is assumed that these costs are included into the installation costs of a nacelle.

6.16 Cost of Soil Research

The costs of soil research should be added to the overall installation costs or they should be considered in the pre-design phase.

Soil research includes an investigation of the soil type up to penetration depth and the chance of early refusal. This research requires sound analysis. The offshore companies will need these results to estimate their installation time, required equipment and thus estimating their overall costs.

The costs depend on the number of points to be researched. For a squared area of say 100 km², one measurement at each corner of the area plus one in the middle would satisfy. In this report, 7 measurement points are considered. This applies for an area of any shape, but it is restricted to approximately 100 km². The time and costs involved into soil research are approximated by the formulas:

Equation 22

$$Time = 2 + 3 * p \quad [days]$$

$$Cost = Mob + Q * p \quad [kEuros]$$

In the above formulas is Mob = XXX¹⁷ [k€], Q = XXX¹⁸ [k€] and p = number of points to be investigated. The estimate for seven points where soil research is needed gives 23 days duration at 400 k€ total.

6.17 Cost of Scour Protection

A scour hole will develop at the base of the pile foundation, if a threshold current speed at that level is locally exceeded. The threshold current speed depends on the seabed material. While the scour hole deepens, the current speed decreases. An equilibrium point is reached at a certain maximum depth. If the threshold current speed is exceeded globally, the scour hole will be partially filled by seabed particles that are in suspension at that level.

¹⁷ Prices are not given here, see Ref [3].

¹⁸ Prices are not given here, see Ref [3].

For a jacket structure like a tripod, there are two types of scour holes that will develop in absence of protection:

- a) A local scour hole around each leg of the structure;
- b) A global scour deepness around the whole structure. This global deepness will be relatively less severe than the local scour hole.

Based on a case study for the DOWEC project (reference [14]), a maximum scour hole may be determined given a pile diameter, current speed and seabed material. The results show that a scour hole with a depth of approximately two times the pile diameter would develop if no scour protection were used.

For the scour protection of a gravity base or of a jacket, there is no rule of thumb that can be used. For this reason the dimensions of the scour protection of these structures is based on the tower diameter of the turbine in a similar way as for a monopod foundation.

For the cost model as presented here, a scour protection is included, based on the assumption that otherwise a scour hole will develop without the protection. The estimation of the costs is based on that derived in the DOWEC project, and it is resumed here.

Scour protection characteristics (reference [14]):

- Protection on top of seabed, no dredging required.
- Radius of scour protection equals 6x pile diameter in every direction excluding slope extension
- Slope at the end of scour protection is 3:1 (extension equals to 3x depth total layer)
- 3 rock layers
 - top layer: rock diameter, $D_{n,50} = 0.45$ m, 0.9 m layer thickness
 - filter layer 1: rock diameter, $D_{n,50} = 0.08$ m, 0.3 m layer thickness
 - filter layer 2: rock diameter, $D_{n,50} = 0.01$ m, 0.3 m layer thickness
- Total rock quantity 6500 MT for each unit for 25 m diameter of scour protection
- A side stone dumping vessel is used for the operation with a loading capacity of 980 MT.

Based on the referred scour protection characteristics, the following corresponding characteristics are considered in the cost model:

- Protection on top of seabed, no dredging required.
- Radius of scour protection equals 6x pile diameter plus 3x depth total layer
- 3 rock layers, total layer depth equals 1.5 metres
- Required scour protection rock quantity 10.5 MT/m^2
- A side stone dumping vessel is used for the operation

The realisation of scour protection is assumed to be applied immediately after the installation of the pile foundation is achieved, giving no time to the seabed to develop a scour hole.

Scour protection costs are sub-divided into mobilisation and demobilisation costs of offshore equipment and material costs. Mobilisation and demobilisation costs are appointed every time the scour protection may not be realised in a continuous operation. These costs are presented in reference [14] as follows (prices referred to year 2000):

Mobilisation and demobilisation costs:	Mob	= XXX per occurrence ¹⁹
Operational day-rate of stone vessel:	Q	= XXX per day ²⁰
Costs of rock material	$\text{rocks}_{\text{price}}$	= XXX [€/MT] ²¹

In the cost model the costs for scour protection, using one vessel, are estimated by:

¹⁹ Prices are not given here, see Ref [3].

²⁰ Prices are not given here, see Ref [3].

²¹ Prices are not given here, see Ref [3].

Equation 23

$$Cost_{scour} = Cost_{rocks} + Mob + Q * t_{work}$$

In this formula $Cost_{rock}$ represents the material costs. The parameter t_{work} represents the total time in days, that the stone dumping vessel must be operational.

Equation 24

$$t_{work} = travel_time + loading_time$$

$$\Rightarrow t_{work} = \left\{ \frac{2 * D_{shore}}{vessel_speed} + loading_time \right\} * \frac{1}{24} \quad [days]$$

The parameter D_{shore} represents the distance between the farm and the harbour on the shore where the stones are loaded onto the vessel. The loading_time parameter is vessel specific. In the cost model, this parameter is set to 3.5 hours.

The material costs are given by:

Equation 25

$$Cost_{rocks} = (V_{rocks} * \rho_{rocks}) * rocks_{price}$$

In the above formula, the density of the rock material is approximated by $\rho_{rocks} \approx 2.2 \text{ [MT/m}^3\text{]}$

Finally, the volume of rocks needed is approximated by the next formula:

Equation 26

$$V_{rocks} = \pi * R_{rocks}^2 * t_{layer} \approx \pi * (L_{pile} * \tan(35^\circ))^2 * t_{layer}$$

L_{pile}	[m]	=	length of the pile in the seabed
t_{layer}	[m]	=	thickness of scour protection layer, $\approx 1.5 \text{ [m]}$

Because the scour protection work may be realised while other wind turbines are installed at other locations within the wind farm, the overall time involved in the application of the scour protection is not considered in the model.

For planning considerations it must be observed that, during the application time of scour protection, no other installation operation may be realised to the same unit, i.e. the installation sequence is supposed to be:

- install foundation (if applicable);
- apply scour protection;
- install other components of wind turbine (not applicable for configuration 8);
- install cabling.

6.18 Cost of Cable Installation

The number of submarine cables present in the wind farm depends on the type of current to be delivered at the connection point on the shore.

The number of electric cables present between the transformer station and the shore when AC current is considered (3-phase HVAC) needs to be input by the user of the cost model. Further it is assumed that the cables do not lay together to avoid electromagnetic interference and to minimise the risk of damage by anchors of vessels. This means that the installation of three electric cables will take three times longer than the installation of one cable and that the installation costs will be about three times higher.

In addition, it is assumed that for DC current only one cable is required between the transformer station and the shore. No redundancy is assumed.

Finally, only one electric cable is accounted for between wind turbines or between wind turbine and transformer station.

The cable length from the shore to the transformer station is estimated from the distance in a straight line between the shore and the transformer station, increased by 25% to compensate for the avoidance of seabed corridors.

For the calculation of the required cable length within the wind farm, the following assumptions are made:

- A maximum of 5 wind turbine cables connected in a string.
- A maximum of 10 cable strings are connected to a transformer station.

The mean depth under the seabed at which the cables must be installed, is supposed to be 2 metres. This depth is taken arbitrarily, based on typical depths reached by the cable bury equipment. Scouring protection of the cables is not required. The placement of the electric cables into steel pipes to avoid exposure is not taken into consideration in the cost model. Cable crossing protection is evaluated as a lump sum times the number of cable crossings present.

Pre-installation of network cabling and/or cables to shore is not considered, i.e. the electric cables are installed once all foundations of the OWECs are installed, or even later when the complete OWEC has been installed. All cables are considered to include under water cable connectors. These connectors are of the “proven technology” type.

The connection of the cable ends to the transformer is realised using a hoist located on the transformer support platform. The connection steps may be resumed as follows:

- Pick the cables up from the sea-bottom using a hoist system of a support vessel and with the help of divers.
- Transfer the cables from the hoist of the support vessel to the hoist of transformer station.
- Connect the cables to the transformer station.

This procedure would take approximately three hours time for each cable.

The connection of the cable ends to the turbines is realised in a similar manner than for the transformer station. The difference will be that the turbines may not have a hoist system at a low level and that the support vessel must go from one turbine to the other. The total time for connecting a turbine is estimated to be 4 hours per cable (1/6th day).

Some typical electric cable characteristics are [16]:

cable diameter	=	100	[mm]
cable mass	=	40	[kg/m]
minimum bending radius	=	2	[m]
choice of current type	:	to be determined based on economics	

Equipment number	Description	Day-rate ²²
1	Directional drill installation for cable at shore side.	
2	Installation pontoon with cable and crane on board, also to help with directional drill process, deck area 80x25 metres.	
3	Cable bury pontoon, deck area 60x20 metres.	
4	2x trenching equipment, to be mounted on both installation pontoon and cable bury pontoon.	
5	60 MT Anchor Handling Tug (AHT) for assistance and handling of the anchors of the installation pontoon.	

²² Prices are not given here, see Ref [3].

6	35 MT Anchor Handling Tug (AHT) for assistance and handling of the anchors of the installation pontoon.	
7	Towing tugs.	
8	Diving team for control and assistance purposes	

Cable Installation Steps	Required equipment	Required time
- Installation of trenching equipment on pontoons	2, 3, 4	±14 days
- Mobilisation of equipment	2, 3, 4, 7	±6 days
- Positioning of the directional drill + cable pull installation at shore	1	assumed: 60 days
- Cable loading and transport to shore	2, 3, 4, 7	±15 days
- Cable head installation through pre-drilled pipe at shore	2, 4, 7	±1 day/cable
- Lay and bury cable from shore to transformer station, using AHT for anchor handling	2, 4, 5, 7	±2 km/day
- Connection of cable to transformer station	5, 8	±4 hrs/cable
- Lay of cable between transformer station and turbines and between turbines using cable lay vessel and AHT	2, 4, 7	±1 day/cable
- Bury of cable using digger and AHT	3	±1 day/cable
- Connection of cable to transformer station	5, 8	±4 hrs/cable
- Connection of cables between turbines	6, 8	±4 hrs/cable
- Demobilisation of equipment	ALL	±14 days

Note that some of the mentioned activities may take place simultaneously.

The combination of both above given tables leads to a total cost for each activity, depending on distance to shore, number of cables to shore, number of turbines or just lump sums. By ordering these sums depending on these parameters, the cable installation costs are calculated.

7. INTEGRATION OF TRANSPORT AND INSTALLATION COSTS INTO THE COST MODEL

7.1 General

The cost model is the implementation of the formulas as described in chapters 5 and 6 into an Excel™ spreadsheet.

The costs of transport and installation of wind turbine components are determined for the configurations specified in chapter 2 of this report. The derived costs are an optimum, i.e. a minimum value between a list of possibilities.

In the cost model, transport and installation costs are compared between two transport and installation methodologies:

1. Transport and installation of wind turbine (components) are realised by the same vessel. In this case, the calculation of transport and installation costs is given by Equation 21 given in section 6.12.
2. Transport and installation of wind turbine (components) are realised by different vessels. In this case, the calculation of transport and installation costs is given by the sum of transport and installation costs separately. Transport costs are calculated using Equation 14 of section 5.12. Installation costs are calculated using Equation 20 of section 6.12.

The transport and installation costs are given by the minimum value of the costs for these two methodologies. From this result, it is deduced which of the two methodologies is found the less expensive and which configuration type – according to section 2 – is the cheapest option for the chosen methodology.

7.2 Cost Model Spreadsheet Characteristics

The cost model spreadsheet consists of four sections:

- An input section;
- A database section;
- A transport and installation calculation section;
- A section where other costs are also calculated.

7.2.1 Input Section

In the input section, three types of input are required:

- Parameters for transport and installation analysis. These parameters are variable or “semi-variable”. Variable parameters are free to be input by the user within the respective (logical) boundaries. Semi-variable parameters are parameters that may be input by the user, but their value is more or less fixed. Example of this is the value of the “transport fixed time”, t_{fix_tr} which is derived in section 5.7 of this report (= 1.5 days).
- Parameters for scour protection costs. These parameters are used for the estimation of the costs of scour protection. The mobilisation costs of the equipment and the costs per unit are given as parameter to allow for updates of the model.
- Parameters for cable installation costs. These parameters depend on the electric configuration.

The input section of the spreadsheet is shown in the next figure:

PARAMETERS FOR TRANSPORT AND INSTALLATION ANALYSIS			
Probability of good weather for transport	P(benign)_tr	0.7	[-]
Probability of good weather for installation	P(benign)_inst	0.75	[-]
Number of turbines in wind farm	Nowec	100	[-]
Number of vessels used for transport	Nvess_tr	1	[-]
Number of vessels used for installation	Nvess_inst	1	[-]
Weibull shape factor for wave height	Kweibull	2	[-]
Weibull scale factor for wave height	Cweibull	1.6	[-]
Transport "fixed" time between turbines	t_fix_tr	1.5	[days]
Installation "fixed" time between turbines	t_fix_inst	2	[days]
Fundatie type	Monopod	4	

PARAMETERS FOR SCOUR PROTECTION COSTS			
Diameter of turbine tower	d_tower	4.5	[m]
Mob en demob costs of equipment	Mob_scour	165,000	[]
Installation costs per unit (per 6500 MT)	Q_scour	375,000	[]

PARAMETERS FOR CABLE INSTALLATION COSTS			
Number of electric cables to shore	Ncable	1	[-]
Number of turbines in a cluster	Ncluster	10	[-]
Distance of Wind Farm to shore	Dshore	40	[km]
Number of cable crossings (cable to shore)	Ncross	3	[-]

Figure 16

7.2.2 Database Section

The database section of the spreadsheet is a compilation of the following tables:

- Table 3, Cost of transport equipment (section 5.6);
- Table 4, Transport of turbine substructures (section 5.7);
- Table 5, Maximum sea state conditions of transport vessels (section 5.8 - only the given maximum sea state where the vessels are operational);
- Table 6, Installation of turbine substructures;
- Table 7, Maximum sea state conditions of transport vessels (only the given maximum sea state where the vessels are operational).

7.2.3 Transport and Installation Calculation Section

In the transport and installation section, the costs for transport and installation as presented in chapters 5 and 6 are calculated. The costs are the minimum costs of the two methodologies as explained before. Four calculations are made:

- Calculation of transport costs alone, according to Equation 14 of section 5.12;
- Calculation of installation costs alone, according to Equation 20 of section 6.12;
- Calculation of transport and installation costs together when using vessels for the combined operation, according to Equation 21 of section 6.12;
- Calculation of transport and installation costs separately, when using different vessels for each operation. These costs are equal to the sum of the first two mentioned calculations.

The overall calculation of Transport and Installation costs is explained using the following diagram:

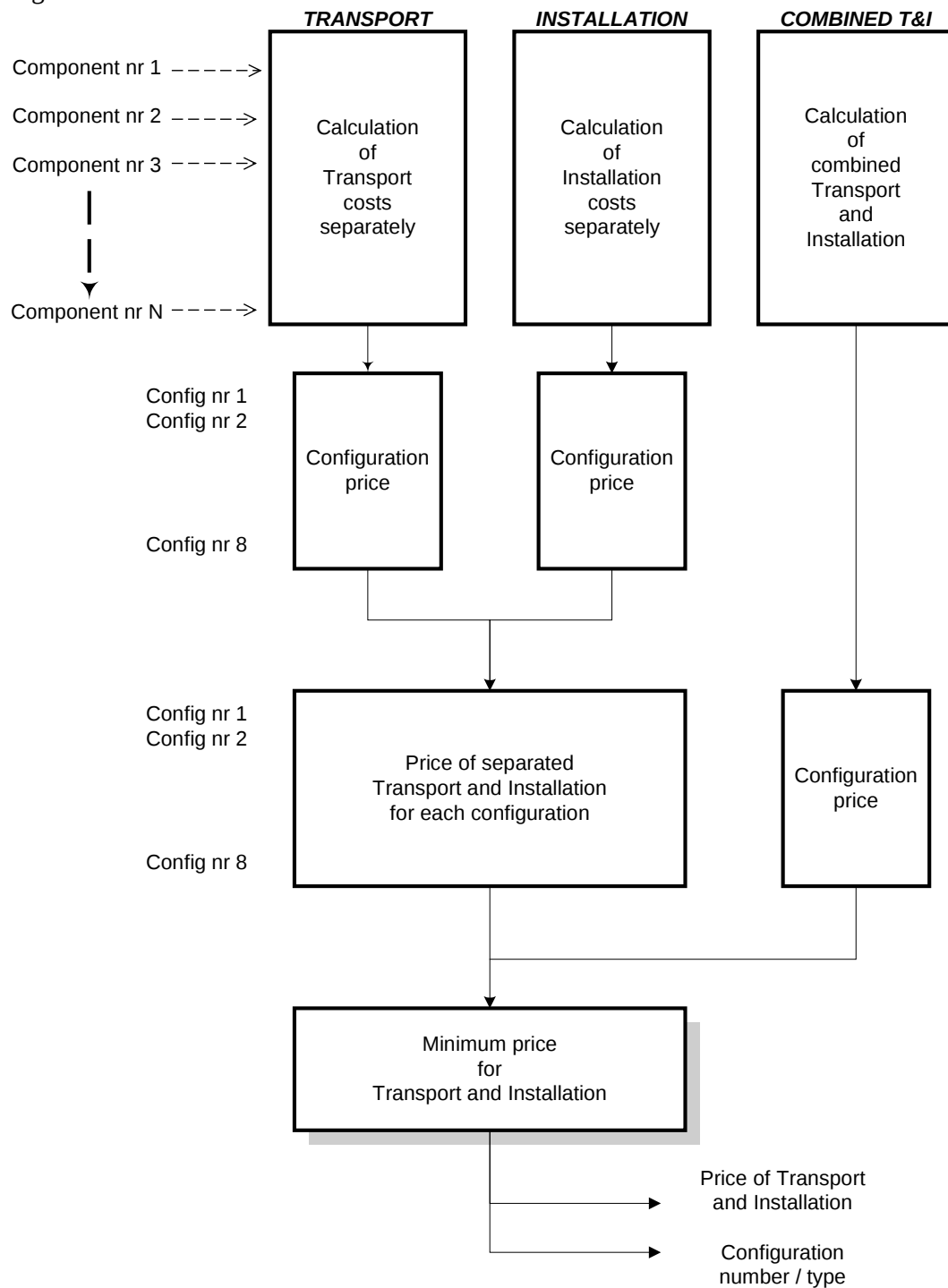


Figure 17. Diagram of calculation of overall Transport and Installation costs.

Given the presented configurations of section 2, the following wind turbine components / assemblies are defined:

- Wind turbine foundation
- Wind turbine tower
- Wind turbine nacelle

- Wind turbine rotor
- Guyed turbine (it assumes small monopod foundation)
- Tower and nacelle assembly
- Rotor and nacelle assembly
- Foundation and tower assembly
- Foundation, tower and nacelle assembly
- Tower, nacelle and rotor assembly
- Complete OWEC

For each of these components, the transport costs, installation costs and combined costs of transport and installation using the same vessels are calculated considering the available vessels.

Based on the calculated costs of transport and installation of the components, the transport and installation costs of the configurations are determined. The costs of separated transport and installation (using different vessels) are found by adding these costs to each other.

From the obtained costs, a minimum is obtained by comparison. The result allows also to determine which configuration type is the most cost effective.

Transport Costs

The calculation of the transport costs alone is explained using the diagram of Figure 18.

From the input sheet three parameters are taken: P_{benign_tr} and the shape and scale factors of the Weibull distribution of waves: $k_{weibull}$ and $c_{weibull}$. With these three parameters, the probability of transport is calculated.

For each wind turbine component / assembly, the transport costs are calculated considering every vessel available. The parameters N_{sim_tr} and N_{day_tr} give an indication if the transport using those vessels is possible or not ($N_{sim_tr} = 0$ means that the vessel cannot transport a component of this type and $N_{day_tr} = 0$ means that no component of that type can be transported to the location in one day).

If the parameters N_{sim_tr} or N_{day_tr} are equal to zero, a very large transport cost value (fault value) is obtained. This fault value is needed because the optimisation procedure searches for the minimum costs of transport between a number of possibilities.

The last step in the calculation is to verify if the foundation type as specified by the user equals to the foundation of the database from which the transport costs are derived. If that's not the case an extra parameter gets the value zero. From the analysis of the multiplication of this parameter and the value of transport costs for the determined vessel and turbine component, the actual costs of transport or a fault value is determined.

The optimum is found by comparison of transport costs for all configurations.

Installation Costs

The diagram of Figure 19 illustrates the calculation of the installation costs alone. This calculation is similar to the one for the transport costs.

From the input sheet, the wave parameters are taken. With these parameters, the probability of installation is calculated.

For each wind turbine component / assembly, the installation costs are calculated considering every vessel available, on a similar way as presented at the transport costs calculation: the parameters N_{sim_tr} and N_{day_inst} give an indication if the installation using those vessels is possible or not.

If the parameters N_{sim_tr} or N_{day_inst} are equal to zero, the 'provisory' installation costs are zero. The difference with the transport costs calculation is that the combined costs of transport and installation are derived partially from this result.

The last step in the calculation is to verify if the foundation type as specified by the user equals to the foundation of the database from which the installation costs are derived. If that's not the case an extra parameter gets the value zero. From the analysis of the multiplication of this parameter and the value of installation costs for the determined vessel and turbine component, the actual costs of installation or a fault value is determined. This fault value is needed because the optimisation procedure searches for the minimum costs of transport between a number of possibilities.

The optimum is found by comparison of transport costs for all configurations.

TRANSPORT COSTS

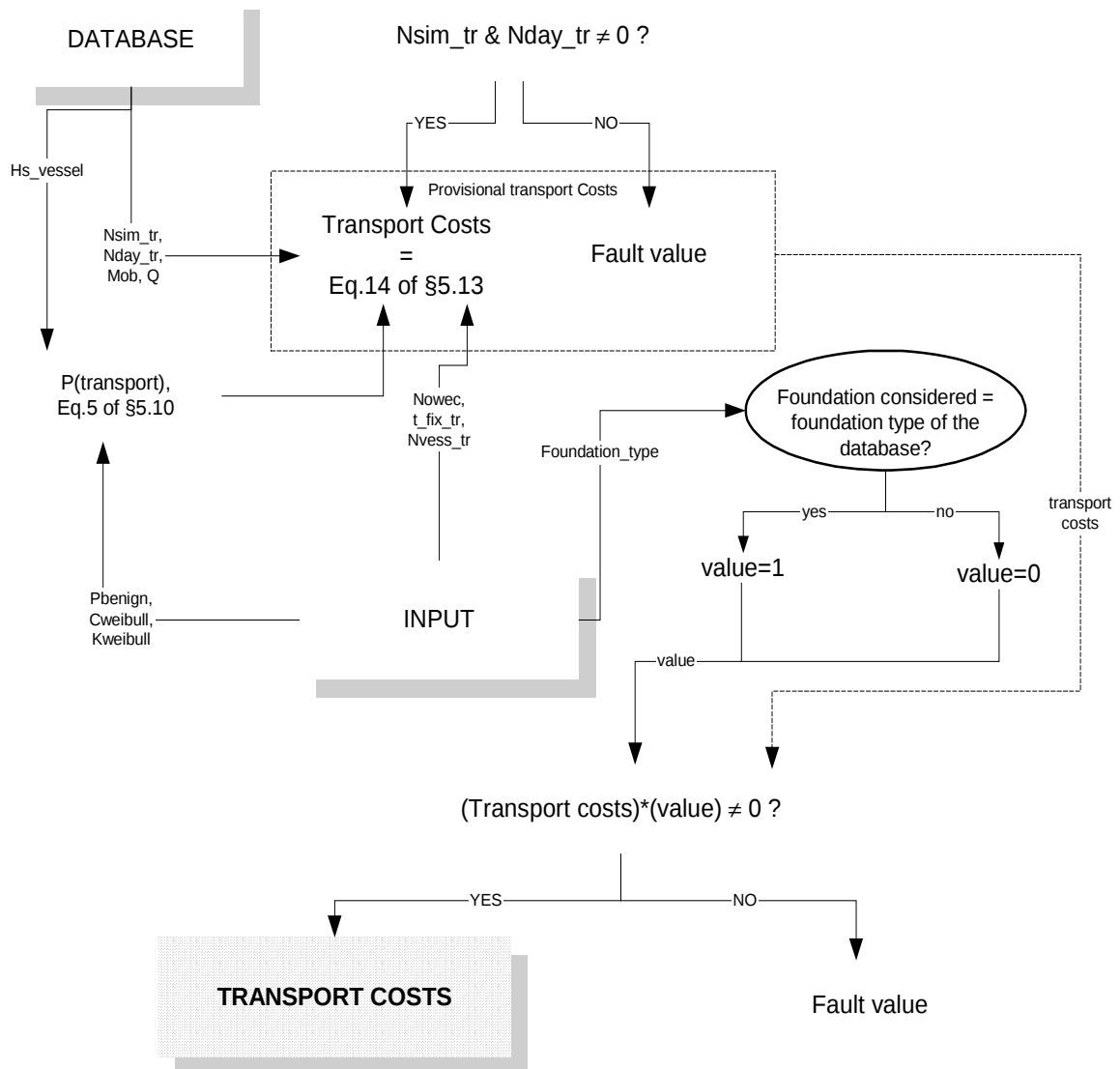


Figure 18. Transport costs diagram.

INSTALLATION COSTS

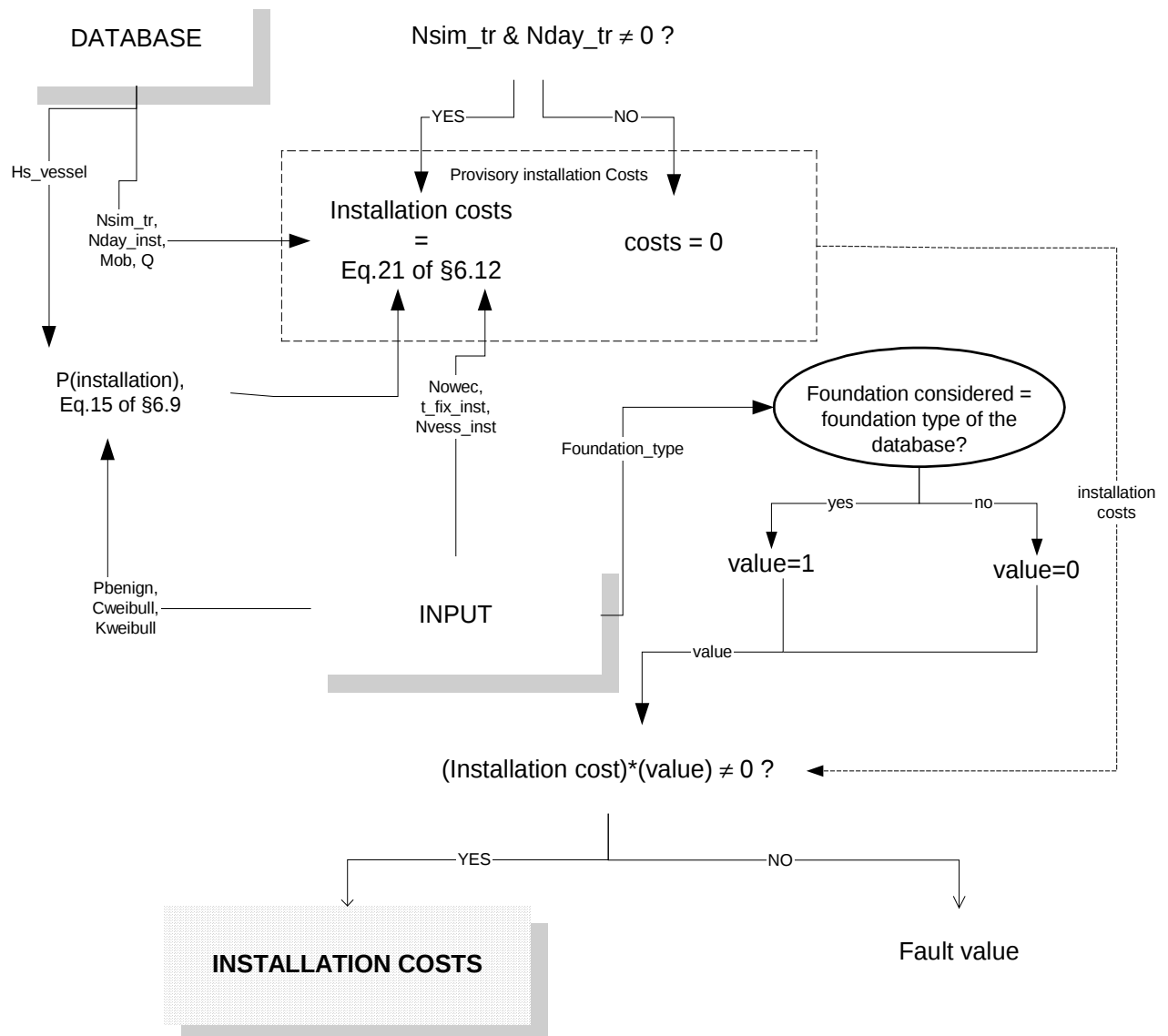


Figure 19. Installation costs diagram.

Costs of Combined Transport and Installation

The calculation of the costs of combined transport and installation are very similar to the procedures as explained above. The diagram is almost identical (see Figure 20), only the differences will be explained here.

- The parameter *Nday_comb* represents the number of structures that the vessel may transport or install in one day. Because the same vessel is used for both operations, the value of this parameter is obtained from the minimum of these values for transport and installation separately.
- The probability of install / transport a turbine component is also determined as the minimum of these values for transport and installation separately, because the probability parameter gives an indication of the workability of the vessel independent of the use of the vessel.

TRANSPORT and INSTALLATION COSTS USING THE SAME VESSELS

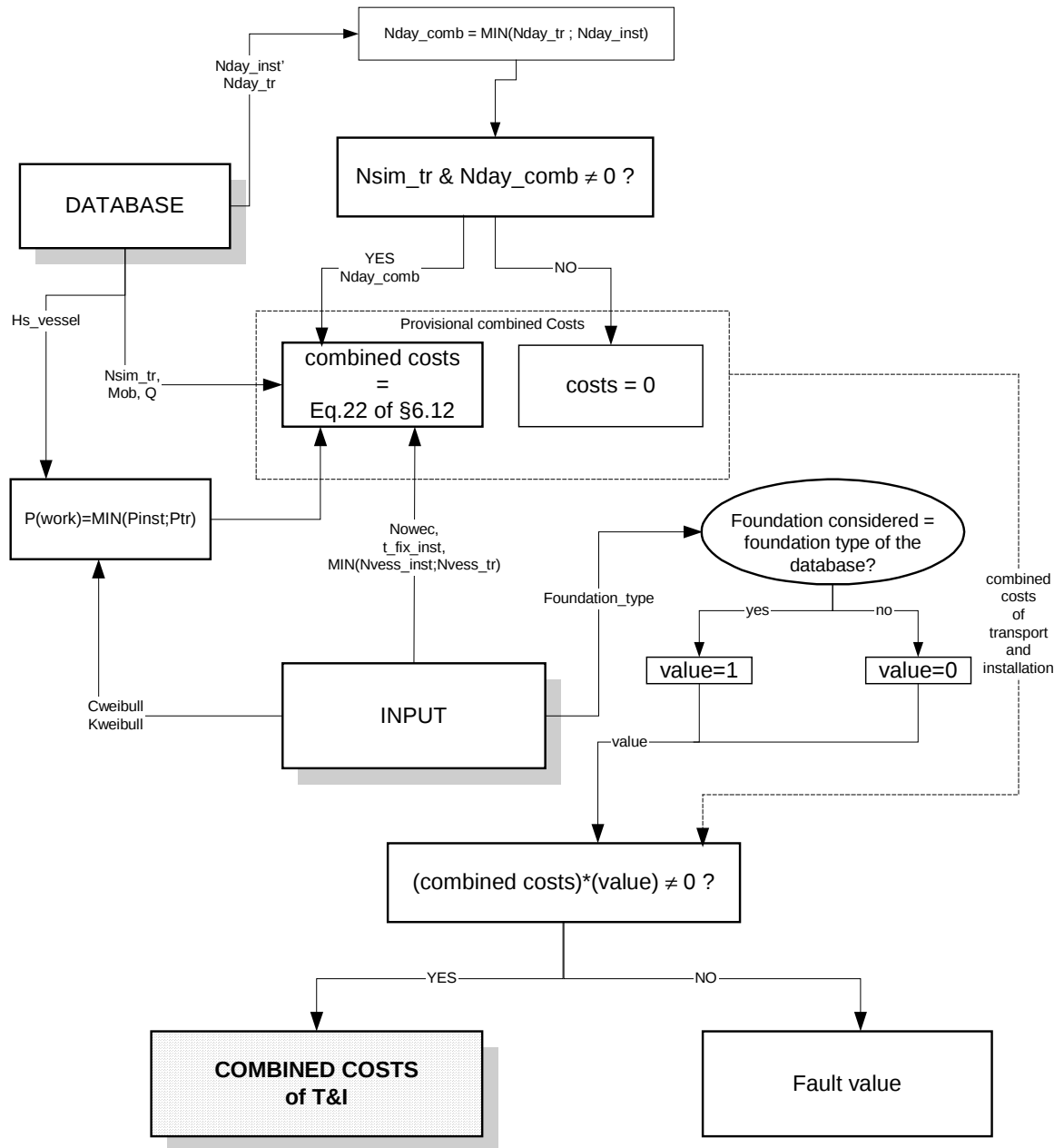


Figure 20. Diagram of the calculation of combined transport and installation.

7.2.4 Other Calculations Section

In the last section of the cost model, other calculations are realised. These are:

- Calculation of the scour protection costs. This calculation is done by means of an empirical formula derived from data of an offshore company specialised in this area. The formula used is given by Equation 23 of section 6.17.
- Calculation of costs of soil research. This calculation is done by means of an empirical formula derived from data of an offshore consultant. The formula used is given by Equation 22 of section 6.16.

- Calculation of cable installation costs. This calculation is done by means of a matrix combination of steps and installation equipment against equipment costs. The procedure used has been explained in section 6.18.
- Calculation of de-installation costs. This calculation is done by means of a matrix combination of removal steps and required offshore equipment against equipment costs. The procedure used has been explained in section 6.14.

8. EVALUATION OF RESULTS

8.1 General

In this section, some results obtained with the model costs are presented. The analysis is divided into the following:

- Costs of transport and installation
- Type of transport and installation strategy
- Analysis of optimum found configuration
- Influence of used parameters into the found transport and installation costs
- Influence of used parameters into the found scour protection costs
- Influence of used parameters into the found cable installation costs

The results obtained with the cost model have not been verified against existent wind farm configurations.

8.2 Transport and Installation Costs

The overall transport and installation costs of OWECS are presented in the next figure:

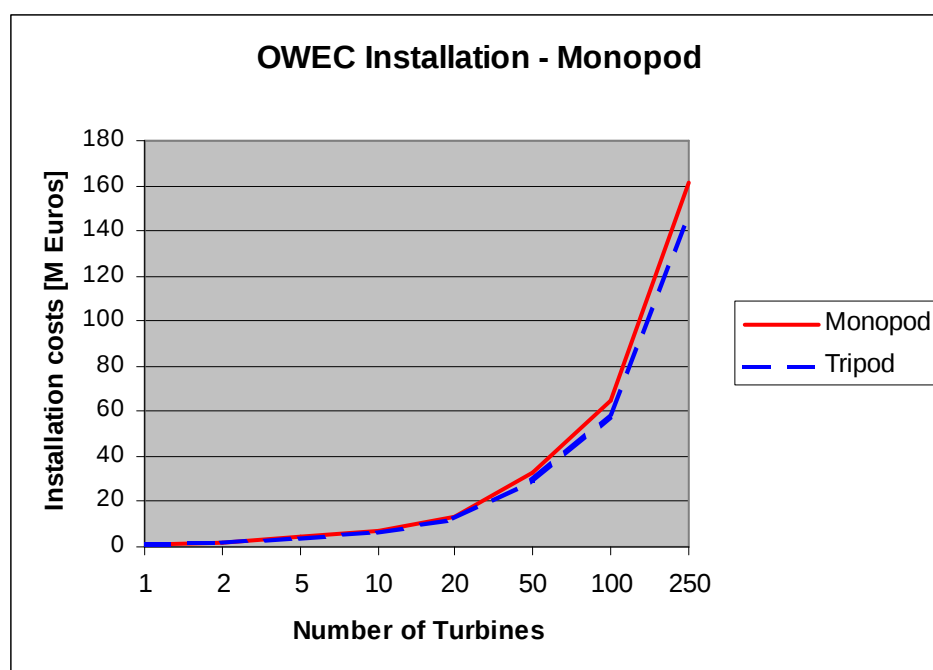


Figure 21. Overall transport and installation costs.

It can be seen that there is no big difference in overall transport and installation costs when a monopod type of foundation is compared with a tripod. The above graph is based on the next table of results:

COSTS [M €]	Number of OWECS to be installed							
	1	2	5	10	20	50	100	250
Monopod based OWECs	1.3	2.0	4.0	7.1	13.5	32.8	65.0	161.5
Jacket based OWECs	1.2	1.8	3.5	6.4	12.2	29.7	58.8	146.0

By doubling the number of OWECs to be installed, the overall transport and installation costs are not twice as much. In fact if comparing the above costs on a linear horizontal scale, it can be seen that the overall transport and installation costs increases linearly, see Figure 22:

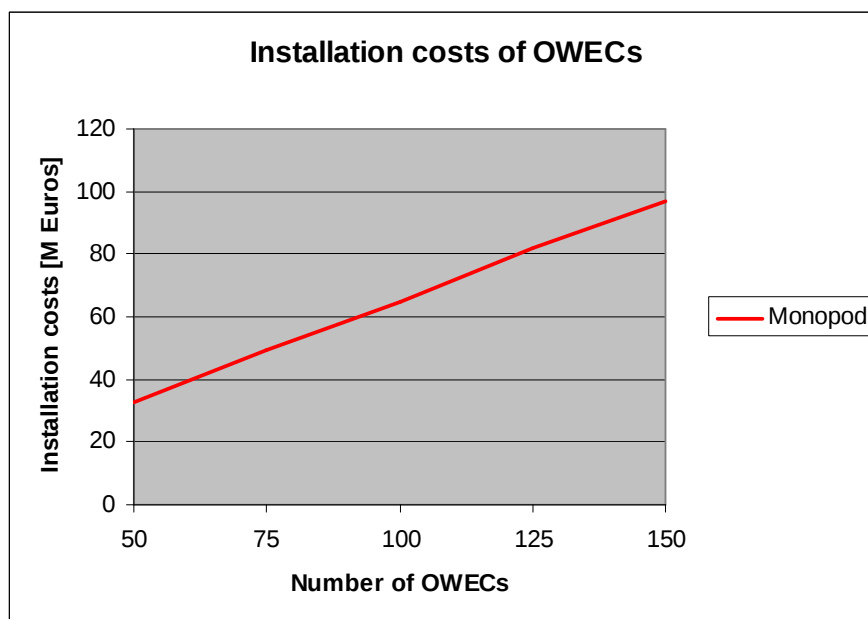


Figure 22. Overall transport and installation costs plotted on a linear scale.

Another interesting result, is that the overall transport and installation costs also increases linearly with increasing number of transport and installation vessels used, see Figure 23.

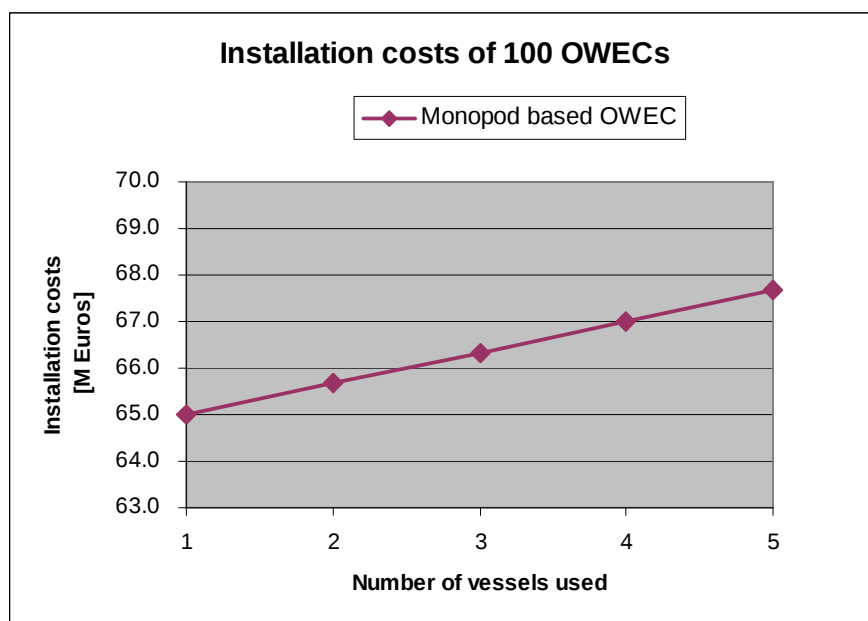


Figure 23. Cost of transport and installation of 100 wind turbines.

In the above graph, the number of transport vessels used equals the number of installation vessels used. The cost model allows however a distinction between the number of transport and the number of installation vessels to be given in order to optimise the costs involved.

The distance to the shore has not been taken into effect for the overall transport and installation costs of the cost model. For reasons of simplicity, it is assumed in the cost model that the travelling time for transport and installation vessels will not differ significantly if the wind farm is located between 10 and 50 km from shore.

The weather influence on the overall transport and installation costs is given by the Weibull shape and scale parameters (k_{weibull} and c_{weibull}) and by the user-specified probability of benign weather for transport and installation ($P_{\text{benign_tr}}$ and $P_{\text{benign_inst}}$).

The following table presents the influence of the Weibull parameters. They are obtained for a wind farm with 100 wind turbines using a monopod as foundation:

WEATHER PARAMETERS						
Costs in [M€]						
P(benign)_tr	0.7	0.7	0.7	0.7	0.7	0.7
P(benign)_inst	0.75	0.75	0.75	0.75	0.75	0.75
Kweibull	1.8	1.9	2	2.1	2.2	2.3
Cweibull	1.6	1.6	1.6	1.6	1.6	1.6
Overall Costs	66.34	65.99	65.66	65.34	65.03	64.73
Variation	1.0%	0.5%	0%	-0.5%	-1.0%	-1.4%
P(benign)_tr	0.7	0.7	0.7	0.7	0.7	0.7
P(benign)_inst	0.75	0.75	0.75	0.75	0.75	0.75
Kweibull	2	2	2	2	2	2
Cweibull	1.4	1.5	1.6	1.7	1.8	1.9
Overall Costs	61.31	63.35	65.66	68.23	71.04	74.08
Variation	-6.6%	-3.5%	0%	3.9%	8.2%	12.8%

From the table above, it can be noticed that variation of the scale parameter of the Weibull distribution hardly influences the overall transport and installation costs, while the shape parameter has a large influence.

In a similar way, the influence of the parameters that represent the probability of a benign weather window for transport and installation vessels, is presented in the next table. These values are also obtained for a wind farm with 100 wind turbines using a monopod as foundation.

WEATHER PARAMETERS						
Costs in [M€]						
P(benign)_tr	0.5	0.6	0.7	0.8	0.9	0.99
P(benign)_inst	0.75	0.75	0.75	0.75	0.75	0.75
Kweibull	2	2	2	2	2	2
Cweibull	1.6	1.6	1.6	1.6	1.6	1.6
Overall Costs	67.43	66.00	64.99	64.22	63.63	63.20
Variation	4%	2%	0%	-1%	-2%	-3%
P(benign)_tr	0.7	0.7	0.7	0.7	0.7	0.7
P(benign)_inst	0.50	0.60	0.70	0.80	0.90	0.99
Kweibull	2	2	2	2	2	2
Cweibull	1.6	1.6	1.6	1.6	1.6	1.6
Overall Costs	83.97	74.48	67.70	62.62	58.66	55.77
Variation	24%	10%	0%	-8%	-13%	-18%

It can be noticed that a variation of the probability of benign weather window for transport vessels has a minor influence on the overall costs, while the same variation of the probability for the installation vessels has a very significant influence into these costs. This may be explained by the fact that installation vessels generally need a relative long time to realise their job, so a

low probability of benign weather window will affect the total number of days necessary to install the wind turbine components/assemblies considerably.

Note that the probability of transport / installation is not given only to the above parameters, but it is also related to the probability of exceedance of a determined wave height (see for reference also Equation 5).

8.3 Scour Protection Costs

The scour protection costs obtained with the cost model are plotted in Figure 24, Figure 25 and :

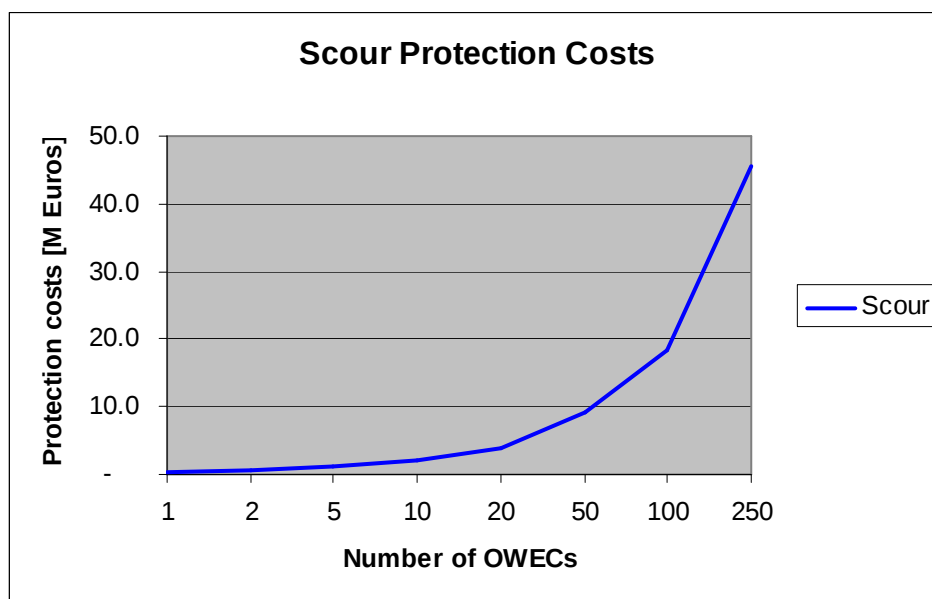


Figure 24. Scour protection costs.

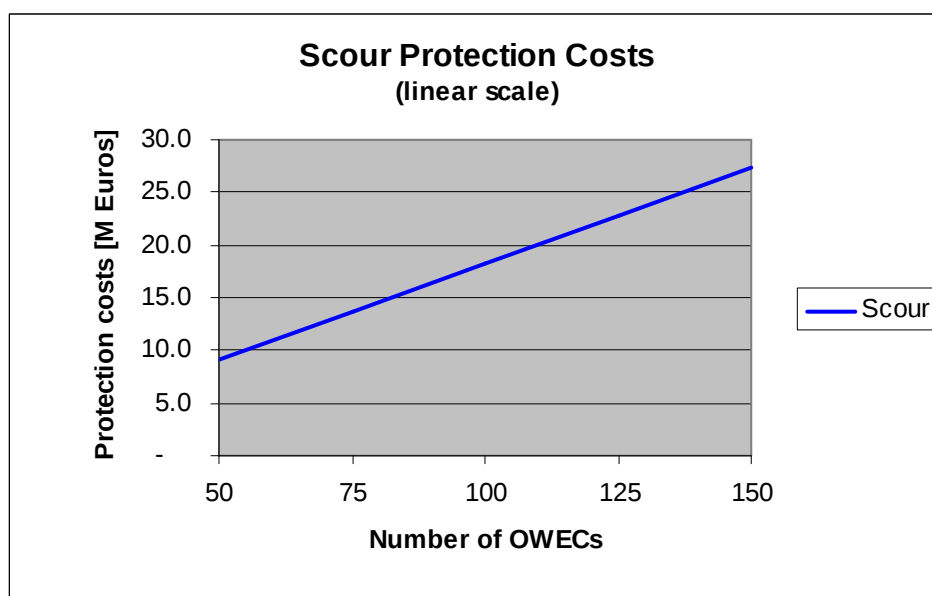


Figure 25. Scour protection costs (linear scale).

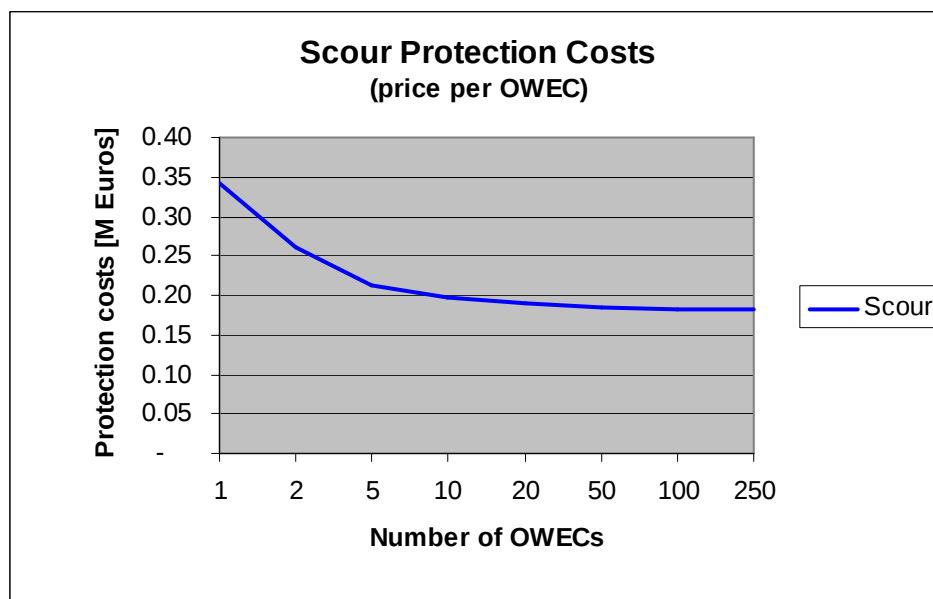


Figure 26. Scour protection costs, price per OWEC.

The scour protection costs are linear for a fixed diameter of monopod foundation (central column if tripod). For a variable diameter of monopod, the costs vary quadratically.

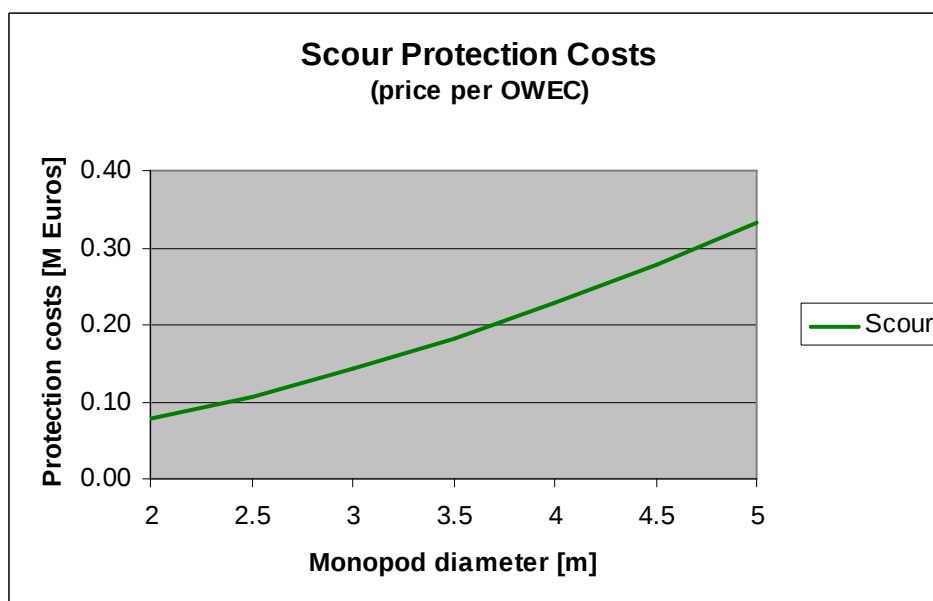


Figure 27. Scour protection costs, OWECs with variable diameter , price per OWEC

8.4 Cable Installation Costs

The costs of electric cable installation in a wind farm depend heavily on the number of wind turbines in the farm. The number of electric cables for electric connection to the grid onshore has a minor influence on these costs. The following two figures show these relations:

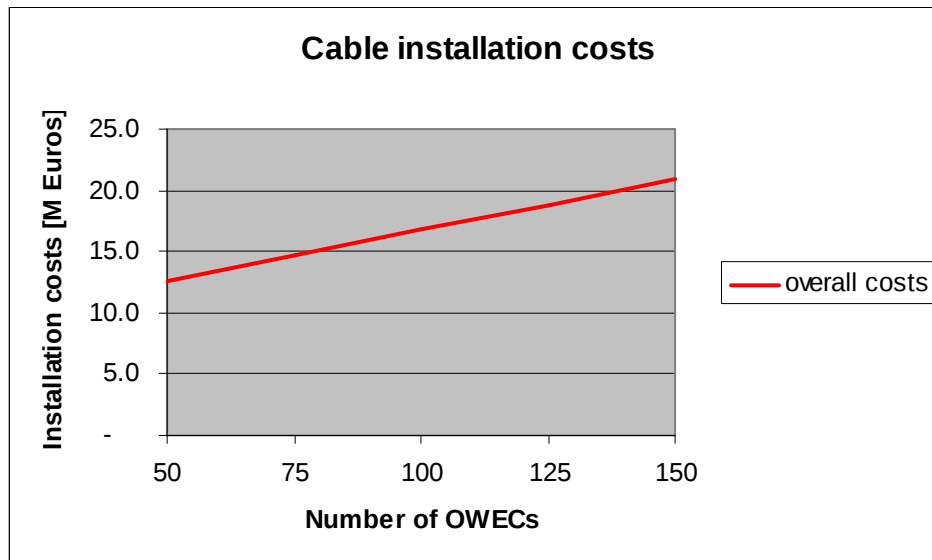


Figure 28. Overall cable installation costs, as function of the number of wind turbines present in the farm.

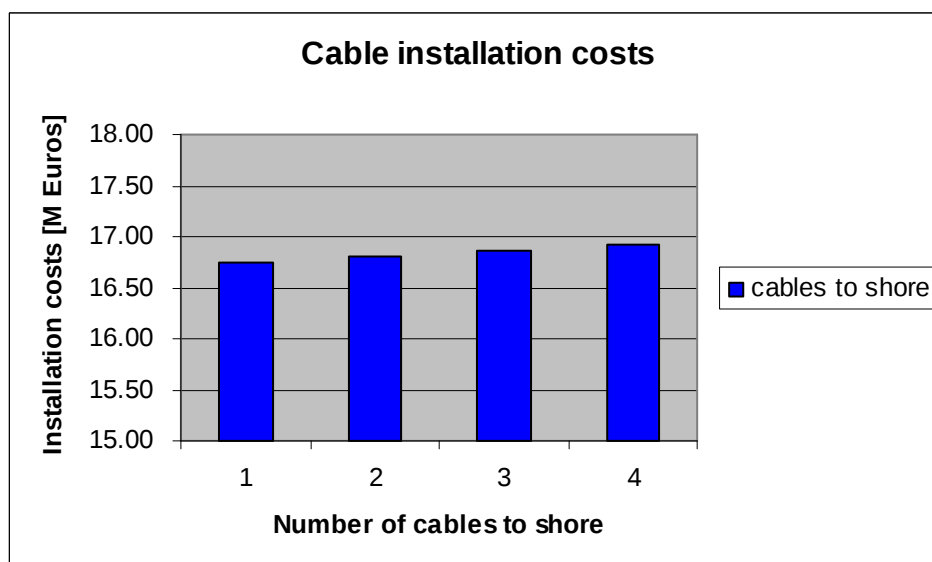


Figure 29. Overall cable installation costs, as function of the number of cable connections to shore.

The influence of the number of wind turbines connected in a cluster ($N_{cluster}$) and the influence of the distance between a central point of the wind farm and the shore (D_{shore}), is presented in the next table. These results are derived for a wind farm of 100 wind turbines and 1 electric cable for connection to the grid onshore:

Cable Installation Costs					
Ncluster [-]	5	8	10	15	25
Dshore [km]	40	40	40	40	40
total costs [M€]	16.79	16.76	16.74	16.73	16.72
Variation [-]	0.2%	0.1%	0.0%	-0.1%	-0.1%
Ncluster [-]	10	10	10	10	10
Dshore [km]	10	20	30	40	50
total costs [M€]	15.69	16.04	16.39	16.74	17.09
Variation [-]	-4.3%	-2.1%	0.0%	2.1%	4.3%

The influence of these two parameters is considered relatively low.

Finally, the variation in cable installation costs related to the number of cable crossings is neglected. The costs due to these crossings are incorporated into the cost model as a linear function depending on the number of crossings to be realised.

8.5 De-Installation Costs

The costs of removal of wind turbine structures after the end of their lifetime, but expressed in actual values, varies approximately linear with the number of wind turbines present in the wind farm. Only when the number of OWECs in the farm are low, the (de-)mobilisation costs play a relatively more important role into the overall de-installation costs.

The results found with the model are presented in the next figure:

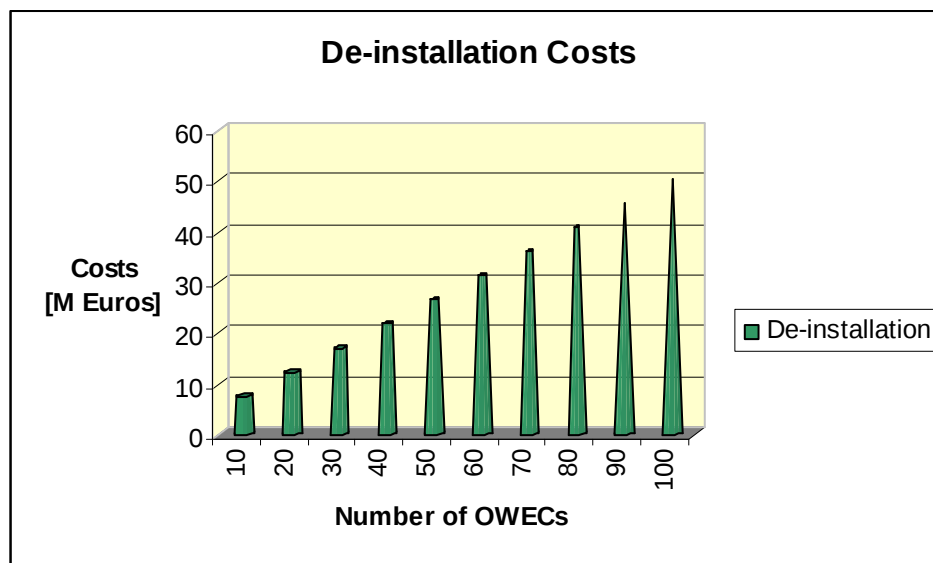


Figure 30. Costs of removal of OWECs after lifetime.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

1. The following costs items have been detailed in the OWECOP cost model:
 - Transport and Installation costs;
 - Scour protection costs;
 - Cable laying costs;
 - Costs of soil research;
 - Costs of removal of wind turbine (components).
2. For the implementation of transport and installation costs into the model, eight wind turbine installation configurations are investigated. These configurations are the result of combining four identified main parts of a wind turbine: rotor, nacelle, tower and support structure. For each configuration, the transport and installation costs, using separated vessels or using one vessel for both activities, are investigated. The cost model searches for an economic optimum between these configurations. For the activities to be performed during transport and installation, some known offshore equipment is used into the database of the model.
3. The calculation of the transport and installation costs include an estimation of the delay in transport and installation time due to high waves, at which some vessels cannot perform their activities. The estimation of these delays is based on a Weibull probability distribution of the wave height coupled to the maximum wave height at which the considered vessel may operate. For the estimation of the time delay, the Weibull variables of the probability distribution are user's input. Some known values of these variables for the Dutch EEZ are presented in one of the appendices of this report.

In section 8, some results obtained with the cost model have been presented. Based on these results, the following conclusions are drawn:

4. The overall transport and installation costs are assumed not to be influenced by the size of the wind turbine components / assemblies. This assumption is of course not entirely correct. In some cases, it is conceivable that the size of the components has almost no influence on the transport costs.
Examples of this are:
 - The number of monopod foundations to be transported on a barge. When thinking about the diameters of the foundations, it is possible to transport more foundations on a barge when the diameters are relatively smaller. The differences will however be marginal. The length of the monopod foundations could have a strong influence on the chosen cargo vessel. However, if it is considered that the foundation will extend beyond the length limits of the barge, then no big differences in transport prices are to be expected.
 - The number of jacket foundations to be transported on a barge. Since it is assumed that the jacket foundations would be transported standing, small differences in the number of structures possible to be transported are expected. Nevertheless, cargo barges would transport one or two jacket foundations more or less independent of their sizes, because they would not differ too much from each other for the given megawatt size of the wind turbines.
5. The overall transport and installation costs are assumed not to be influenced by the mass of the wind turbine components / assemblies. This assumption is of course not correct. Crane capacity and crane capacity related to the height to be lifted, have a large impact in the choice of an offshore installation vessel. Nevertheless, it may be assumed that up to a

certain offshore wind turbine size, a standard lifting equipment would be hired at mean day-rate costs. The exact turbine size limit is not known. Based on existent offshore equipment like, sheer-leg vessels, the limit would be up to 4 to 5 MW turbine range.

6. The distance to the shore is considered not to be of influence on the overall transport and installation costs of the model. For reasons of simplicity, it is assumed in the cost model that the travelling time for transport and installation vessels will not differ much if the wind farm is located between 10 and 50 km from shore.
If 6 knots (11.11 km/h) is considered as an average travelling speed of a vessel, the actual travelling time will vary between 1 and 4.5 hours. The time that an offshore company will consider their vessel 'travelling' will probably be taken as 0.5 day. For wind farms with a large number of wind turbines, the travelling time could play a role in the overall transport and/or installation time.
7. The use of more transport and/or installation vessels increases the overall transport and installation costs of the wind farm. However, the economic profit of using several vessels simultaneously, will be visible when analysing the overall costs and revenues of the wind farm over its lifetime. The use of several vessels will mean that the wind farm will be sooner in operation. Therefore, the incomes of such a wind farm will also start earlier. It must be noticed that the use of more vessels simultaneously for one operation (transport or installation) only will probably not be an optimum. Nevertheless, the cost model allows this distinction.
8. The combined transport and installation of a wind turbine (done by the same vessel, avoiding double mobilisation costs) considers the transport and installation of all components of a wind turbine only. Transport and installation of some of the wind turbine components / assemblies by the same vessel are slightly overestimated: in this case, the mobilisation costs of the equipment are counted twice.
9. Prices used in the cost model are related to the year 2001. If other future years must be considered, an inflation rate for the years in between should be added. This feature has not been added to the cost model.
The cost model is build up in such a way, that by changing the mobilisation costs (Mob) and the day-rates (Q) to actual values, all costs get actualised.

9.2 Recommendations

Based on the results presented in section 8 and the conclusions presented here above, the following recommendations are given:

- Improve the estimation of probabilistic parameters $P_{\text{benign_tr}}$ and $P_{\text{benign_inst}}$ in such a way that there are not needed to be input by the user anymore. These parameters should be read or derived from known data of offshore sites.
- Improve the estimation of the Weibull shape and scale parameters k_{weibull} and c_{weibull} in such a way, that there is no need of input by the user anymore. These parameters should be read or derived from known data of offshore sites.
- Relate the size and weight of the wind turbine components / assemblies to the cargo and lifting capacity of vessels. By doing so, under- and overestimation of transport and installation costs would be avoided.
- Update cost parameters regularly, or, implement a feature to consider a yearly inflation rate instead of updating costs parameters.
- Update vessel properties regularly. The addition of (near) future vessels is also recommended, in order to investigate if such a vessel could be competitive in the market.

10. REFERENCES

In the following list of references, all references from the appendices have been included as well.

1. Heijdra, J.J. and Hendriks, H.B.; DOWEC Concept Study Task 11: Selection of feasible concepts. ECN-CX—00-040 / DOWEC-F0-T11-JH-00-10010/00-P. Petten, March 2000.
2. Kooijman, H.J.T. & Hagg, F.; OWECOP I: Modelling van Kosten en Potentieel van Offshore Wind energie in de Nederlandse Exclusieve Economische Zone van de Noordzee (NEEZ). ECN-Wind Memo-01-035. Petten, May 2001.
3. Herman, S.A.; Offshore Wind Farms, Transport and Installation Costs – Cost Tables. ECN-Wind Memo-02-007. Petten, february 2002.
4. Young, W.C.; *Roark's – Formulas for Stress & Strain*, 6th edition. ISBN 0-07-100373-8. Singapore 1989.
5. Rikken, J.F. & Klop, J.. *Studie naar goedkopere concepten voor de ondersteuning van een offshore windturbine*. KEMA Power Generation & Sustainables. Ref. nr. 99560396-KPS/SEN 00-3035. November 2000.
6. Kooijman, H.J.T.; *LW-C 1.5 MW wind turbine - Load set calculations and performance*. ECN-CX--00-120. Petten, December 2000.
7. International Electrotechnical Commission. *Wind turbine generator systems – Part 1: Safety requirements*. IEC 61400-1; Second edition 1999-02.
8. European Wind Energy Association; *Wind Energy – The Facts*. London, 1999.
9. Coelingh, J.P. (editor); *Long term wind speed climate & Temporary characterisation of wind and wave coupling – State of the art – general overview*; DOWEC-T56-JC-99-R01_D4-C. Petten, February 2000.
10. Genius Vos B.V./ DNS Dutch Northsea Services; *The Single Pile Platform*. Leaflet 1998.
11. Horns Rev, website of the first offshore windfarm in Denmark; <http://www.hornsrev.dk/Foundation>.
12. Mayflower Energy Ltd. Turbine Installation Vessel TIV-1. Website of Mayflower Energy Ltd: <http://www.mayflower-energy.com>.
13. Heerema Marine Contractors; *BALDER*. Leaflet.
14. Halfscepel, R.; *Concept study bottom protection around pile foundation of 3MW turbine*. Document number DOWEC-F1W1-RH-01-023/02. November 2001.
15. Pierik, J.T.G.; Damen, M.E.C.; Bauer, P.; de Haan, S.W.H.; *Electrical and Control Aspects of Offshore Wind Farms*. ECN-CX—01-083. Petten, June 2001.
16. Van der Stoel Cable, Submarine Cable Installation Contractors; CD-Rom with company profile, version 01-08-2000.
17. Det Norske Veritas; *Rules for the Classification of Fixed Offshore Installations*; July 1995.
18. Department of Energy – Offshore Installations; *Guidance on design, construction and certification*.
19. Verruijt, A.; *Laterally Loaded Pile*. Appendix of report “Waterdiepte begrenzingen aan de toepassing van een monopaal voor het Near Shore Windpark voor de Nederlandse kust”. TU Delft, March 1999.
20. Nederlands Normalisatie-instituut; *Richtlijnen voor de kathodische bescherming van stalen constructies buitengaats (inclusief pijpleidingen)*; Dutch norm, NPR 2727. February 1990.
21. Concerted Action on Offshore Wind Energy in Europe – Final Report CA-OWEE. December 2001.
22. de Swart, H.E.; *Windgolven*. Instituut voor Marien en Atmosferisch Onderzoek Utrecht, report nr. D97-9. Utrecht 1999.
23. Ministerie van Verkeer en Waterstaat; www.golfklimaat.nl. Water data.

APPENDIX A

Breakdown of Mass and Dimension Estimation of an Offshore Wind Turbine

APPENDIX A. BREAKDOWN OF MASS AND DIMENSION ESTIMATION OF AN OFFSHORE WIND TURBINE

A.1 Introduction

In this section, an estimation of the mass and dimensions of a wind turbine offshore is made. The calculation of the diameters and wall thicknesses resulting in the mass of the structure are done based on simplified quasi-static analysis of all environmental loads acting on the structure. The definition of the names used is presented in

Figure 31. For simplicity only a monopod foundation has been drawn. The dimensions in this figure are not to scale.

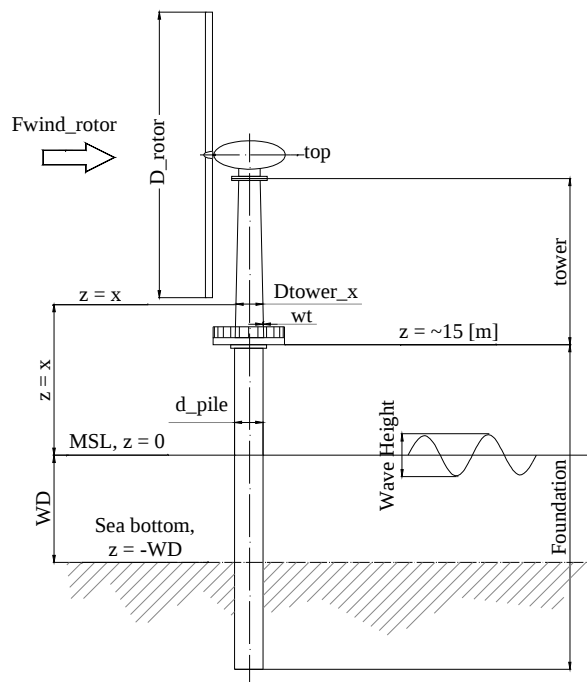


Figure 31. Schematic representation of a wind turbine offshore.

A.2 Tower

To calculate the mass of the tower the following external loads are considered for each load case (see chapter 4.):

1. Wind load acting on the rotor. This load is scaled from known data, based on a fatigue load analysis for a reference rotor. This load is scaled to the actual turbine diameter as follows:

Equation 27

$$F_{wind_rotor} = F_{wind_rotor_ref} * \left(\frac{D_rotor}{D_rotor_{ref}} \right)^2$$

2. Wind acting on the cylindrical tower. This load is the drag load calculated considering a wind speed, including wind shear, acting along the structure. The drag load is given by Equation 28:

$$F_{tower_x} = C_D * 1/2 * \rho_{air} * V_{wind}^2 * A_{projected_x}$$

C_D	=	1.2	[-]	drag coefficient for a cylinder
ρ_{air}	=	1.225	[kg/m3]	air density
$A_{projected_x}$	=	$D_{mean} * Lx$	[m2]	projected area for wind force from top to section x
D_{mean}	=	$0.5 * (D_{tower_top} + D_{tower_x})$	[m]	mean tower diameter at considered height
Lx	=	$H_{top} - H_x$	[m]	length of tower between top and section considered

The wind speed is according to the following table:

Load Case	Component	Wind speed
1, Operational	Rotor	$V = 25 \text{ m/s}$
	Tower	Normal wind profile, according to IEC 61400 [7]
2, Extreme	Rotor	$V = 56 \text{ m/s}$
	Tower	Normal wind profile, according to IEC 61400 [7]

For design purposes in the Ultimate Limit State (ULS) for design according to the Allowable Stress Method, DNV rules [Ref.17, Pt.3 Ch.1 Sec.5 G200] prescribe two load combinations as follows:

- a) $1.0 P + 1.0 L + 1.0 D$
- b) $1.0 P + 1.0 L + 1.0 D + 1.0 E$

Here are P = Permanent loads (like mass), L = Living loads (variable functional loads), D = Deformation loads and E = environmental loads (wind , waves, etc.).

With above mentioned external loads, the shear stress and the bending stress acting at each section are determined. Using these two stresses, the equivalent stress according “Von Mises” is then determined.

Equation 29

$$\sigma_{eq} = \sqrt{\sigma_b^2 + 3 * \tau^2}$$

σ_{eq}	[N/mm ²]	equivalent stress (Von Mises)
σ_b	[N/mm ²]	bending stress
τ	[N/mm ²]	shear stress

Note that the only principal stress present is the bending stress σ_b .

The bending stress is given by Equation 30:

$$\sigma_b = \frac{M(x)}{W_x}; \quad M(x) = F_{wind_rotor} * Lx + F_{tower_x} * \frac{Lx}{2}; \quad W_x = \frac{\pi * D_{tower_x}^2 * wt}{8}$$

and the shear stress by Equation 31:

$$\tau_x = \frac{F_{total}}{A_x}; \quad F_{total} = F_{wind_rotor} + \int_x^{top} F_{tower_x}; \quad A_x \approx \pi * D_{tower_x} * wt$$

The calculated equivalent stress (Von Mises) is then compared against the allowable stress. The allowable stress is equal to the yield stress of the material multiplied by the allowable factor. For the material S355J2G3 (high tensile steel), plate thickness less or equal to 63 mm, is the yield stress equal to 335 N/mm2. The material factor according to DNV is $f_{mat} = 1.15$ [Ref.17,

Pt.3 Ch.1 Sec.6 B200] and the usage factor for the given load combinations as described before are [Ref.17, Pt.3 Ch.1 Sec.6 C200]:

- a) $\eta = 0.6$ not including environmental loads
- b) $\eta = 0.8$ including environmental loads

The maximum allowable stress for load combination (b) is then given by Equation 32:

$$\sigma_{allowable} = \sigma_{yield} * \frac{1}{f_{mat}} * \eta = 335 * \frac{1}{1.15} * 0.8 = 233 \frac{N}{mm^2}$$

For the check of the design against local buckling, the failure modes that is used is that the ratio of diameter / thickness of the cylinder for each section must be at least 175, i.e. $D_{tower_x}/wt > 175$ [no reference].

The obtained maximum stress is compared against the allowable stress of the material. From this comparison, the diameter and the wall thickness of the tower are obtained at the optimum value.

The mass of the tower construction is then estimated by the volume of steel used multiplied by the density of steel ($=7850 \text{ kg/m}^3$). The mass of ladders and platforms inside the tower, a boat landing platform and a maintenance platform are also added to the mass of the tower.

A.3 Foundation

The foundation of the turbine is loaded by three different loads: wind load (from tower calculation), wave loads and current loads.

At the intersection point between tower and foundation, the bending moment and the shear force at that point are continuous and thus known from tower calculations. The wave and current loading are then superimposed.

The wave loads are calculated according to Morison, Equation 33:

$$F = F_{drag} + F_{inertia} ;$$

$$F_{drag} = C_D * 0.5 * \rho_{water} * V_{wave}^2 ;$$

$$F_{inertia} = C_m * \rho_{water} * \frac{\pi * D_{foundation_x}^2}{4} * a_{wave}$$

$$C_D = 1.25 \quad [-] \quad \text{drag coefficient of a cylinder}$$

$$C_m = 2.0 \quad [-] \quad \text{inertia coefficient of a cylinder}$$

The maximum wave speed and acceleration are given by Equation 34 and Equation 35:

$$V_{wave} = \omega * \frac{H_s}{2} * \frac{\cosh(k * (z + WD))}{\sinh(k * WD)}$$

$$a_{wave} = \omega^2 * \frac{H_s}{2} * \frac{\cosh(k * (z + WD))}{\sinh(k * WD)}$$

ω	[rad/s]	radial frequency of the wave
H_s	[m]	significant wave height
k	[-]	wave number
z	[m]	considered z-co-ordinate (z=0 at MSL, positive upwards)
WD	[m]	water depth

The radial frequency of the wave is a representative value for the known wave scatter diagram. For operational conditions, its value is determined from the representative zero up-crossing period T_z ($\omega = 2\pi/T_z$). T_z is respectively the corresponding T_z for the maximum significant

wave Hs obtained from the scatter. For extreme conditions the peak period Tp and the maximum wave height Hmax are used instead according to a JONSWAP distribution with parameter $\gamma = 3.3$ ($H_{max} = 1.8 * H_s$ and $T_p = 1.286 * T_z$).

The value of the wave number k is found from the dispersion theory for linear gravity waves [22], Equation 36:

$$\omega^2 = \left(g * k + \frac{\tau_{cap} * k^3}{\rho_{water}} \right) * \tanh(k * WD)$$

g	=	9.81	[m/s ²]	gravity constant
τ_{cap}	=	0.08	[N/m]	capillary stress of water
ρ_{water}	=	1025	[kg/m ³]	water density

The current load is determined using a drag component caused by the current speed, Equation 37:

$$F_{current} = C_D * 1/2 * \rho_{water} * V_{current}^2 * A_{projected_x}$$

C_D	=	1.2	[-]	drag coefficient for a cylinder
$V_{current}$	=	1.0	[m/s]	obtained from reference [18], section 11

From the obtained wave and current forces, superimposed to the wind forces, an equivalent stress can be obtained in the same manner as explained before in section A.2 (tower calculation). In the case of the tripod structure, the Morison equation has only been used on the central column and not on the braces of the structure. This means that these loads are expected to be negligible because of the small diameter of the members and low position with respect to the water depth. For shallow waters, these loads should however be taken into account.

Analogue to the calculation of the mass of the tower, the mass of the foundation is obtained by optimising the stress in the material when compared to the allowable stress. From here, the diameter and the wall thickness of the monopod (or central column if a tripod is considered) are derived.

The mass of the foundation is obtained from the volume of steel used multiplied by the steel density.

A.3.1 Monopod

The estimation of stresses and required diameter, wall thickness and thus mass of the monopod construction are determined with the above calculation procedure, considering the following:

- The required clamping depth of the monopod in the sea bed is calculated using a procedure as described in reference [19], and presented here shortly, see section A.3.3.
- The wall thickness between top of foundation and seabed varies linearly. The wall thickness at seabed level is determined under the condition that the allowable stress is not exceeded. The mass estimation includes a corrosion allowance of 3 mm extra wall thickness.
- The maximum pile diameter is taken to be 4.5 metres. Larger diameters are not possible to drive into the seabed using the state-of-the-art pile driving techniques. Therefore, the diameter of the construction between the connection point and the seabed (and beyond) is constant and equal to a maximum of 4.5 metres. Other installation techniques for monopods with diameters larger than 4.5 metres are known [10], but installation costs are not known to the author of this report.
- Just above the connection point between tower and foundation, the tower diameter may exceed 4.5 metres. In this case, a special interface between tower and foundation should be manufactured.

- The wall thickness of the pile under the seabed is assumed constant and equal to the thickness at seabed level. The mass estimation includes a corrosion allowance of 3 mm extra wall thickness.
- No extra calculations are made to prevent scouring at the monopod base. The assumption is made that scour protection is always applied.

A.3.2 Tripod Construction

The estimation of stresses, required diameter, wall thickness and mass of the tripod construction is determined with the above calculation procedure. The central column is considered to resist these loads up to the node under water where the braces of the tripod are connected to the central column, see Figure 32.

For the foundation below this point, an analysis is made considering the loads acting on the braces and on the pile supports.

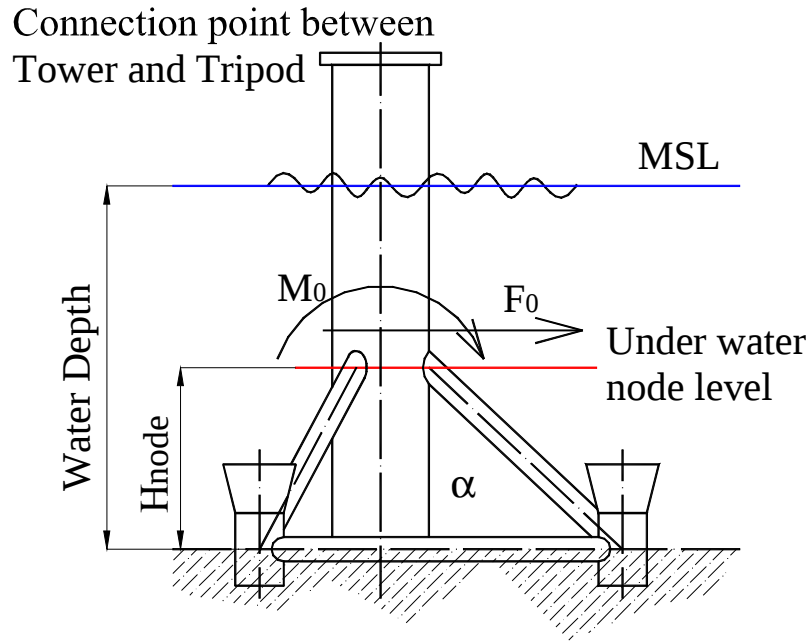


Figure 32: Tripod foundation.

The determination of the node position depends on the water depth (WD) according the following Equation 38:

$$\begin{cases} WD < WD_{ref_min} \rightarrow H_{node} = H_{min_n} \\ WD_{ref_min} \leq WD \leq WD_{ref_max} \rightarrow H_{node} = Linear \text{ in between} \\ WD > WD_{ref_max} \rightarrow H_{node} = H_{max_n} \end{cases}$$

$$\begin{array}{llll} WD_{ref_min} & = & 15 & [m] \\ WD_{ref_max} & = & 50 & [m] \end{array} \quad \begin{array}{llll} H_{min} & = & 5 & [m] \\ H_{max} & = & 20 & [m] \end{array}$$

The node location obtained in this way is shown in Figure 33

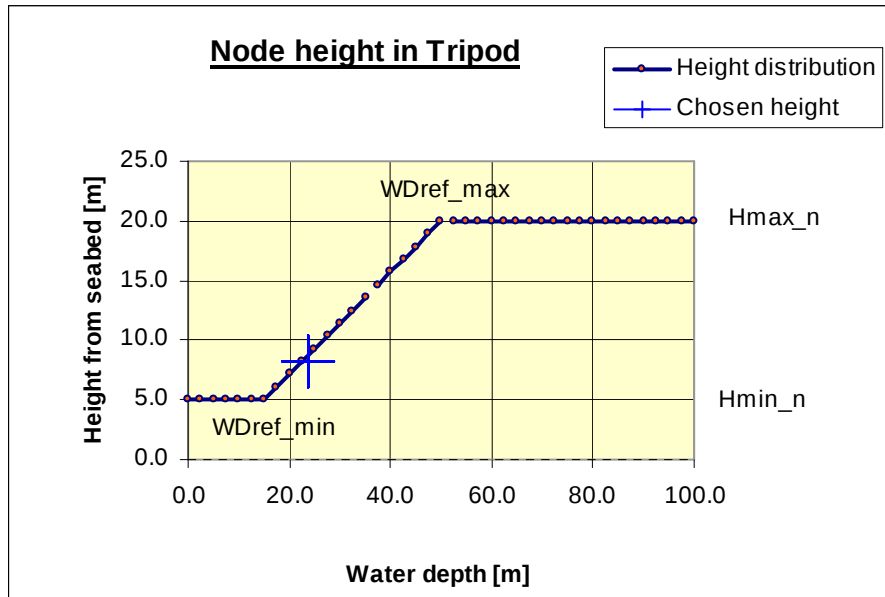


Figure 33

The tripod structure is considered to be loaded in the most unfavourable way, i.e. only one brace is being loaded under tension and the other two are being loaded in compression mode.

F_0 and M_0 are the load and the moment acting on the central column at the node location as result of all external loads working on the structure, i.e. wind, wave and current loads.

The load F_m is the result of translating the moment M_0 to a couple acting between the tripod node and the sea bottom, Equation 39:

$$M_0 = F_m * H_{node}$$

H_{node} is the height between sea bottom and node location.

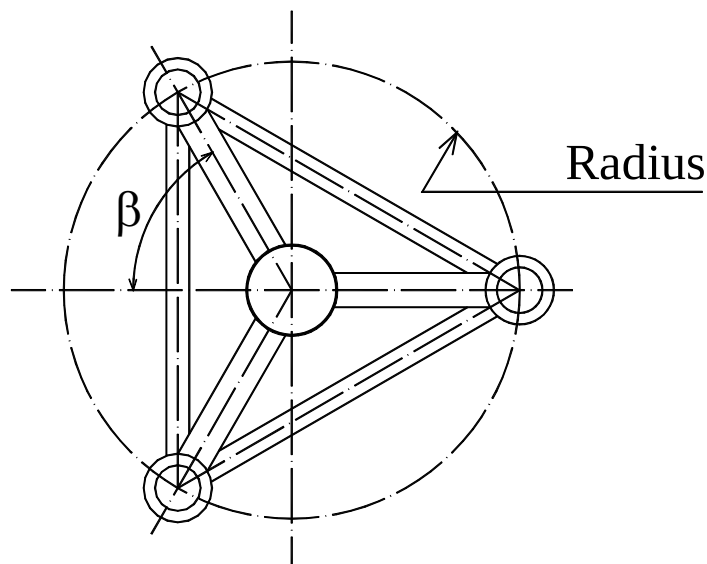


Figure 34: Tripod upper view.

For a symmetric tripod, the angle β defined in the figure equals 60 degrees.

The calculation of the loads in the members under this node is determined as follows:

Equation 40

$$\sum F_h = 0 \Rightarrow F_0 + F_m = F_1 \sin \alpha - 2F_2 \cos \beta \sin \alpha$$

Equation 41

$$\sum F_v = 0 \Rightarrow F_1 \cos \alpha + 2F_2 \cos \alpha = W^*$$

Equation 42

$$W_{tripod}^* = W_{tripod} - B_{tr} \quad ; \quad B_{tr} = \rho_{water} * Vol * g$$

F1, F2 and F3 represent the forces acting on the three braces. The equations assume that the brace nr.1 is in tension and the other two in compression mode. Because of symmetry, F2 = F3 = 2*F2 (see also Figure 34).

W_{tripod} is the mass of the turbine including rotor, nacelle, tower and the central column of the tripod construction. B is the buoyancy of the construction part that is submerged. The buoyancy depends on the volume of the construction under water, which for simplicity will be considered equal to the volume of the water tight central column under water.

From Equation 40 and Equation 41 presented above, the following relation is obtained for the force F₂, Equation 43:

$$F_2 = \frac{F_0 + F_m - \frac{W_{tripod}^*}{\cos \alpha} \sin \alpha}{2 * (\sin \alpha + \cos \beta * \sin \alpha)}$$

The angle b is as shown in Figure 34: Tripod upper view. Using equation (1), the following relation is obtained for the force F₁, Equation 44:

$$F_1 = \frac{F_0 + F_m - \frac{W_{tripod}^*}{\cos \alpha} \sin \alpha}{(\sin \alpha + \cos \beta * \sin \alpha)} + \frac{W_{tripod}^*}{\cos \alpha}$$

This load is further used to determine the wall thickness of the braces when their diameter is considered to be 0.5x the diameter of the central column. The other braces present in the design will be assumed to have a diameter equal to 0.375x the diameter of the central column (equal to 1.5 [m], when the central column has a diameter of 4 [m]).

To determine the loads acting on the horizontal braces at the sea bottom, the following equation of equilibrium of forces is used:

Equation 45

$$\sum F_h = 0 \Rightarrow F_m = H_1 + 2 * H_2 \cos \beta$$

where H₁ is the force of the horizontal brace in tension and H₂ (=H₃) is the force of the horizontal brace in compression. Both forces are considered to act along the members.

An extra equation is found when considering that the shortening of the brace 1 due to H₁ equals the shortening of both braces 2 and 3 together due to the forces H₂, Equation 46:

$$\delta_1 = \frac{H_1 * l_1}{A * E} \quad ; \quad \delta_2 = \frac{H_2 * l_2}{A * E} * \frac{1}{\cos \beta} \quad ; \quad \text{and} \quad \delta_1 = \delta_2$$

$$\Rightarrow H_1 * \cos \beta = H_2$$

Equation 47

$$\begin{cases} H_2 = \frac{F_m}{3} * \frac{1}{\cos \beta} \\ H_1 = \frac{F_m}{3} * \left(\frac{1}{\cos \beta} \right)^2 \end{cases}$$

Because H_1 then bigger is than H_2 by a factor $1/\cos(\beta)$, the horizontal braces are analysed for this force.

A.3.3 Depth of Piles in the Seabed

The calculation of the depth of the piles in the sea bottom is based on the theory as presented in reference [19].

The minimum depth $h_{\min}$ is determined using the following Equation 48:

$$\sigma_0 * h_{\min}^2 = \frac{6 * (F_0 * h_{\min} + M_0)}{h_{\min}}$$

F_0 and M_0 are respectively the lateral force and the moment force at sea bottom level

σ_0 is the reference stress of the sea bottom soil, given by Equation 49a, b and c:

$$\sigma_0 = (K_p - K_a) * \rho_{\text{water}} * g * d_{\text{pile}} \quad ; \quad K_p = \frac{1 + \sin(\phi)}{1 - \sin(\phi)} \quad ; \quad K_a = \frac{1 - \sin(\phi)}{1 + \sin(\phi)}$$

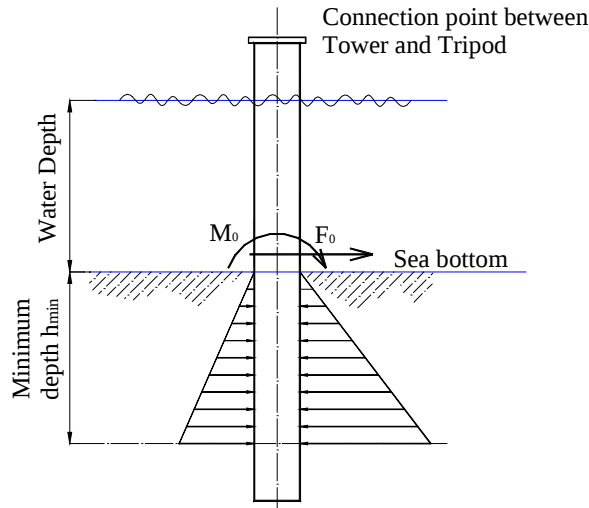


Figure 35: Pile loading

- K_p and K_a are respectively the passive and active pressure coefficients of the soil

ϕ	=	friction angle of the soil	[rad]
ρ_{water}	=	water density	[kg/m ³]
g	=	gravity constant	[m/s ²]
d_{pile}	=	pile diameter	[m]

If the friction angle of the soil (ϕ) is not known, the value of (K_p - K_a) as in the formula may be taken as to be 6.0. With this choice, the three-dimensional effect of the stresses on the soil has been taken into account.

The depth of the pile into the sea bottom must be increased by say 30% above the value found with the presented equation, in order to ensure that enough clamping of the pile is achieved.

An important consideration when calculating the required pile depth is the deflection that will occur at two loading points: the sea bottom level and the maximum height of the tower. The deflection may be found by considering the elastic deflection of the pile due to the loading and subtracting the effects of damping of the rotor and tower itself. This effect has not been considered in this report.

In the case of a monopod, it has been found that for a 5 MW turbine with 4 m pile diameter, a pile depth penetration into the soil of 22 metres is required. In the case of a tripod, the analysis has not been done, but the depth is estimated to be 15 metres.

The diameter and wall thickness of the pile is, in the case the foundation is a monopod, taken to be equal to the diameter and wall thickness at sea bottom level. In the case of a tripod construction, the diameter has been set to 1.5 metres, while the wall thickness is set to be 40 mm. These values must be verified.

A.3.4 Cathodic protection

A brief analysis of the cathodic protection is included here, in order to estimate the costs related to it. These costs will probably be a part of the overall engineering costs (construction) of the structure, like painting or similar. Therefore are not implemented into the cost model.

The wall thickness of any structure part that is submerged, must include cathodic protection with sacrificial anodes, see ref. [17], Pt.3, Ch.1, Sec.10 (B 103). The quantity of anodes depends on the lifetime and the number of squared metres to be protected [20]. For any structure part that is located in the splash zone a minimum corrosion allowance of 0.15 mm material wall thickness per year (3 mm in 20 years) must be added, see ref. [17], Pt.3, Ch.1, Sec.10 (B 104).

The calculation of quantity, mass and costs of anodes is given by Equation 50:

$$n_{anodes} = \frac{0.13 * A_{subm} + 0.03 * A_{bottom}}{delivery} ; \quad delivery = \frac{P_{EL} [V]}{R [\Omega]}$$

The parameter n_{anodes} is the number required of anodes in the construction depending on to the corrosion exposed zones.

A_{subm}	=	Submerged area of construction to be protected (includes splash zone)	[m ²]
A_{bottom}	=	Area of construction to be protected in the sea bottom	[m ²]
delivery	=	current delivery of the anode	[A]
P_{EL}	=	Electric potential, equals 200 mV for zinc and aluminium and 400 mV for magnesium	[V]
R	=	Electric resistance of the anode	[Ω]

The electric resistance of the anode R depends on the dimensions of the same, and it is calculated as follows, Equation 51:

$$R = \frac{\rho_{el}}{2 * \pi * l_{anode}} * \{ \ln(\frac{4 * l_{anode}}{r}) - 1 \} ; \quad r = \sqrt{\frac{A_{anode}}{\pi}}$$

ρ_{el}	=	specific resistance	$[\Omega \cdot m]$
l_{anode}	=	length of anode	$[m]$
A_{anode}	=	cross section of anode	$[m^2]$

The mass of anode material required to protect the construction for a number of years, is given by Equation 52:

$$Mass = \frac{t_{life} * delivery * 8760}{C_{anode}} * 1.2 \quad [kg]$$

t_{life}	=	required lifetime	$[years]$
8760	=	number of hours in one year (=365*24)	$[h]$
C_{anode}	=	anode capacity; Zn = 820, Al = 950-2800 & Mg = 1100	$[A \cdot h / kg]$
1.2	=	safety factor	

A.4 Rotor

According to reference [8] (figure 4.5.2), the mass of a rotor blade can be estimated using the scaling formula as follows, Equation 53:

$$Mass = 0.10 * D_{rotor}^{2.63} \quad [kg]$$

Above calculated mass must be multiplied by the number of blades present in the rotor design. There is no approximation made for the mass of the hub.

A.5 Nacelle

According to reference [21], the mass of a wind turbine nacelle may be approximated by Equation 54:

$$Mass = 0.017 * D_{rotor}^{1.9054}$$

where D_{rotor} in $[m]$ and m in $[kg]$. This is an empirical formula, derived from known data (onshore turbines), and must be verified for large offshore wind systems convertors.

APPENDIX B

Material properties of steel type S235J2G3, S275J2G3 and S355J2G3

APPENDIX B. MATERIAL PROPERTIES OF STEEL TYPE S235J2G3, S275J2G3 AND S355J2G3

Constructiestaal

Werkstoff Nr	1.0116	BS	Fe360 D1 FF
DIN	S235J2G3	AISI	A284 Gr.D
Afnor	E24-3	UNS	K02001
Euronorm	S235J2G3		

C	0.00	-	0.17 %	N	0.000	-	0.000 %
Cr	0.00	-	0.00 %	V	0.00	-	0.00 %
Mo	0.00	-	0.00 %	P	0.035 %		
Mn	0.00	-	1.40 %	S	0.035 %		
Ni	0.00	-	0.00 %	Co	0.00	-	0.00 %
Si	0.00	-	0.00 %	W	0.00	-	0.00 %

Overige elementen --

Overige informatie

Het stikstof moet gebonden worden door bijvoorbeeld $\geq 0,02\%$ Al.
 Een koolstofstaal dat ook bekend staat onder de aanduidingen S 235J2G3+CR, St 37-3 en St 7-3G.
 Normeringen:
 1652 Deel 2: Blank staal en constructiestaal.
 1623 Deel 2: Koudgewalste plaat en strip van koolstofstaal.
 1652 Deel 2: Blank staal voor algemene constructiedoeleinden.
 EN 10025: Warmgewalste produkten van koolstofstaal.
 17119: Gelaste en koudgedeformeerde profielbuizen t.b.v. algemeen constructiewerk.
 17121: Naadloze ronde buizen voor algemeen constructiewerk.
 17120: Gelaste ronde stalen buizen voor algemeen constructiewerk.
 17163: Stalen platen en strippen. Electrolytisch koudgewalste verzinkte staalplaten en strippen.
 5512 Deel 2: Materialen voor treinstellen. Algemeen constructiestaal.

Volledig gekalmeerd koolstofstaal (d.m.v. aluminium $\pm 0,020\%$).

De mechanische waarden luiden als volgt:

Treksterkte:

Bij de plaatdikte:

< 3 mm	360 - 510 N/mm ²
≥ 3 mm - ≤ 100 mm:	340 - 470 N/mm ²
> 100 mm - ≤ 150 mm:	340 - 470 N/mm ²
> 150 mm - ≤ 250 mm:	320 - 470 N/mm ²

0,2% Rekgrens:

Bij de plaatdikte:

≤ 16 mm	235 N/mm ²
> 16 mm - ≤ 40 mm:	225 N/mm ²
> 40 mm - ≤ 63 mm:	215 N/mm ²
> 63 mm - ≤ 80 mm:	215 N/mm ²
> 80 mm - ≤ 100 mm:	215 N/mm ²
> 100 mm - ≤ 150 mm:	195 N/mm ²
> 150 mm - ≤ 200 mm:	185 N/mm ²

Constructiestaal

Werkstoff Nr	1.0144	BS	Fe430D1 FF
DIN	S275J2G3	AISI	A573 Gr.70
Afnor	E28-3	UNS	K02601
Euronorm	S275J2G3		

C	0.00	-	0.18 %	N	0.000	-	0.000 %
Cr	0.00	-	0.00 %	V	0.00	-	0.00 %
Mo	0.00	-	0.00 %	P	0.035 %		
Mn	0.00	-	1.50 %	S	0.035 %		
Ni	0.00	-	0.00 %	Co	0.00	-	0.00 %
Si	0.00	-	0.00 %	W	0.00	-	0.00 %

Overige elementen --

Overige informatie

Het stikstof moet gebonden worden door bijvoorbeeld $\geq 0,02\%$ Al.

Een koolstofstaal dat ook bekend staat onder de aanduidingen S275J2G3+CR, St 44-3 en St 44-3G.

Normeringen:

EN 10025: Warmgewalste producten van ongelegeerd koolstofstaal.

1652 Deel 2: Blank constructiestaal.

17119: Gelaste koudgedeformeerde stalen t.b.v. algemeen constructiewerk.

17120: Gelaste ronde buizen voor algemene constructies.

17121: Naadloze satel buizen voor algemene constructies.

EN 10025: Warmgewalste producten van koolstofstaal.

Het materiaal is volledig gekalmeerd (m.b.v. aluminium $\pm 0,020\%$).

De mechanische waarden luiden als volgt:

Treksterkte:

Bij de plaatdikte:

< 3 mm	430 - 580 N/mm ²
≥ 3 mm - ≤ 100 mm:	410 - 560 N/mm ²
> 100 mm - ≤ 150 mm:	400 - 540 N/mm ²
> 150 mm - ≤ 250 mm:	380 - 540 N/mm ²

0,2% Rekgrens:

Bij de plaatdikte:

≤ 16 mm	275 N/mm ²
> 16 mm - ≤ 40 mm:	265 N/mm ²
> 40 mm - ≤ 63 mm:	255 N/mm ²
> 63 mm - ≤ 80 mm:	245 N/mm ²
> 80 mm - ≤ 100 mm:	235 N/mm ²
> 100 mm - ≤ 150 mm:	225 N/mm ²
> 150 mm - ≤ 200 mm:	215 N/mm ²
> 200 mm - ≤ 250 mm:	205 N/mm ²

Breekrek:

Constructiestaal

Werkstoff Nr	1.0570	BS	Fe510D1FF
DIN	S355J2G3	AISI	--
Afnor	E36-3	UNS	--
Euronorm	S355J2G3		

C	0.00	-	0.20 %	N	0.000	-	0.000 %
Cr	0.00	-	0.00 %	V	0.00	-	0.00 %
Mo	0.00	-	0.00 %	P	0.035 %		
Mn	0.00	-	1.60 %	S	0.035 %		
Ni	0.00	-	0.00 %	Co	0.00	-	0.00 %
Si	0.00	-	0.55 %	W	0.00	-	0.00 %

Overige elementen Al >= 0.020%

Overige informatie

Een koolstofstaal dat ook bekend staat onder de aanduidingen S355J2G3, (S355J2G3+CR), St 52-3 en St 52-3G.

Normeringen:

1652 Deel 4: Blank staal. Staalsoorten voor snel afkoelen en t.b.v. het harden.
 17119: Gelaste koudgedeformeerde stalen t.b.v. algemeen constructiewerk.
 17120: Gelaste ronde buizen voor algemene constructies.
 17121: Naadloze satel buizen voor algemene constructies.
 EN 10025: Warmgewalste producten van koolstofstaal.
 5512 Deel 1: Materialen voor treinstellen. Algemene constructiestalen.
 1623 Deel 2: Stalen platen en strippen. Koudgewalste plaat en strippen. Algemene constructiestalen.
 5512 Deel 2: Materialen voor treinstellen. Ongelegeerde koolstofstalen platen tot 3 mm dikte.

Mechanische waarden:

Treksterkte:

Bij de plaatdikte:

< 3 mm	510 - 680 N/mm ²
>= 3 mm - <= 100 mm:	490 - 630 N/mm ²
> 100 mm - <= 150 mm:	470 - 630 N/mm ²
> 150 mm - <= 250 mm:	450 - 630 N/mm ²

0,2% Rekgrens:

Bij de plaatdikte:

<= 16 mm	355 N/mm ²
> 16 mm - <= 40 mm:	345 N/mm ²
> 40 mm - <= 63 mm:	335 N/mm ²
> 63 mm - <= 80 mm:	325 N/mm ²
> 80 mm - <= 100 mm:	315 N/mm ²
> 100 mm - <= 150 mm:	295 N/mm ²
> 150 mm - <= 200 mm:	285 N/mm ²
> 200 mm - <= 250 mm:	275 N/mm ²

De trekstaven zijn in de lengterichting genomen.

APPENDIX C

Probabilistic Estimation of Benign Weather for Transport, Installation and Maintenance Purposes

APPENDIX C. PROBABILISTIC ESTIMATION OF BENIGN WEATHER FOR TRANSPORT, INSTALLATION AND MAINTENANCE PURPOSES

C.1 Introduction

In order to estimate the benign conditions for transport, installation and maintenance purposes, two probabilistic calculations are needed:

1. The probability of non-exceedance of a specific wave height, and
2. The probability of a benign weather window, within the previous condition.

Besides, if for maintenance purposes a helicopter is considered, the probability of exceeding a specific wind speed must be analysed in a similar way as the probability of exceeding a specific wave height.

C.2 Probability of Exceeding a Wave Height

This probability is estimated using a Weibull approximation of a known scatter diagram. Some scatter diagrams of the Exclusive Economic Zone of the Netherlands (Dutch EEZ) have been derived from [23].

The available data is a compilation of measurements of environmental parameters of nine locations in the Dutch EEZ, see also Figure 36:.

Name	Code	Co-ordinates		Geographical co-ordinates		Water depth [m]
		x	y	NB	OL	
K13a platform	K13	10,176	583,334	53°13'04"	3°13'13"	30
Schiermonnikoog Noord	SON	206,527	623,483	53°35'44"	6°10'00"	19
Eierlandse Gat	ELD	106,514	587,985	53°16'37"	4°39'42"	26
IJmuiden munitiestortplaats	YM6	64,779	507,673	52°33'00"	4°03'30"	21
Noordwijk meetpost	MPN	80,443	476,683	52°16'26"	4°17'46"	18
Euro platform	EUR	9,963	447,601	51°59'55"	3°16'35"	32
Lichteiland Goeree	LEG	36,779	438,793	51°55'33"	3°40'11"	21
Schouwenbank	SWB	11,244	419,519	51°44'48"	3°18'24"	20
Scheur west	SCW	7,797	380,645	51°23'32"	3°02'57"	15

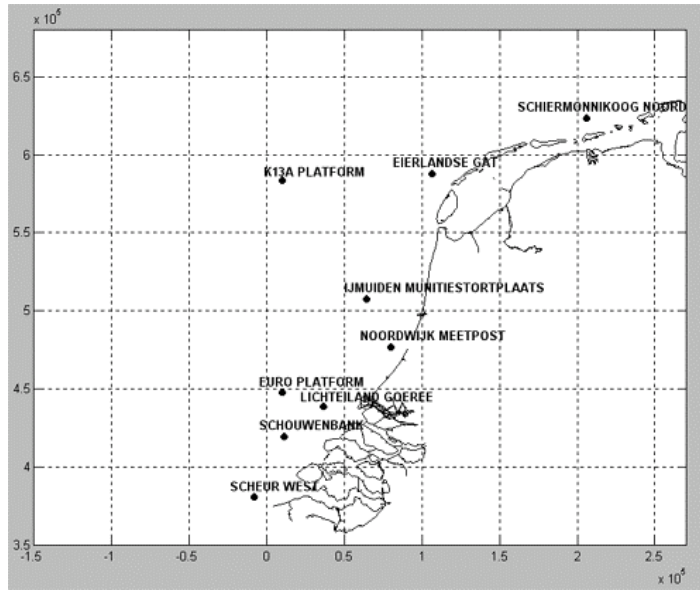


Figure 36: Location of the nine measuring points in the Dutch EEZ.

Voids in the data sets have been filled up by Rijkswaterstaat with measurements and extrapolations from other data sources. Wind and wave data are compiled simultaneously.

From the scatter diagram of each location, a Weibull approximation of the probability density function (PDF) is derived. This procedure is as follows:

The probability of exceeding a wave height at a given location, may be approximated by a Weibull distribution, Equation 55:

$$P(H \leq H_{\text{ref}}) = 1 - e^{-\left(\frac{H}{c}\right)^k}$$

k and c are respectively the shape and the scale parameter of the Weibull distribution. The PDF is approximated by a linear equation as follows, Equation 56:

$$\begin{aligned} P &= 1 - e^{-\left(\frac{H}{c}\right)^k} \Rightarrow (1 - P) = e^{-\left(\frac{H}{c}\right)^k} \\ \Rightarrow \ln(1 - P) &= -\left(\frac{H}{c}\right)^k \Rightarrow -\ln(1 - P) = \left(\frac{H}{c}\right)^k \\ \Rightarrow \ln(-\ln(1 - P)) &= k * \ln\left(\frac{H}{c}\right) \\ \Rightarrow \ln(-\ln(1 - P)) &= k * \ln(H) - k * \ln(c) \end{aligned}$$

Thus the Weibull distribution is approximated by the equation $Y = A * X + B$ if

$$X = \ln(H)$$

$$Y = \ln(-\ln(1 - P))$$

$$k = A$$

$$B = -k * \ln(c) \rightarrow c = \exp(-B/k)$$

An example of fitting the data with a Weibull distribution is shown in Figure 37: Weibull fitting.

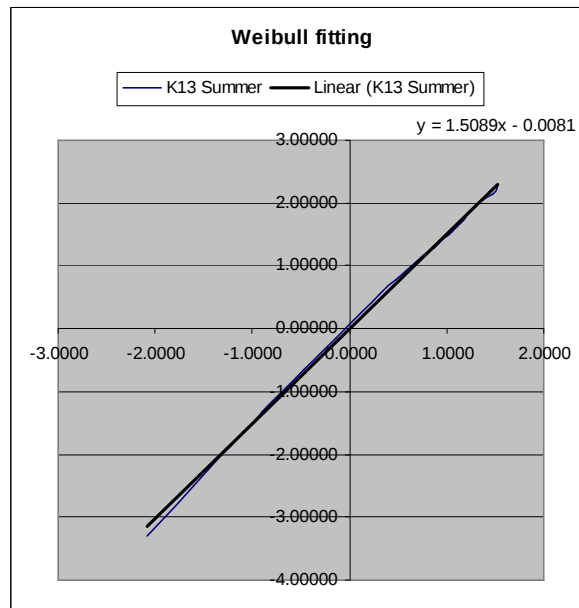


Figure 37: Weibull fitting.

This procedure has been repeated for all nine offshore locations. The results are presented in the table below:

Offshore location	Code	Co-ordinates						Weibull parameters			
		NB			OL			Summer		Whole year	
		deg	min	sec	deg	min	sec	k	c	k	c
Eierlandse Gat	ELD	53	16	37	4	39	42	1.4792	0.9552	1.3969	1.2948
Ijmuiden Munitiestortplaats	YM6	52	33	0	4	3	30	1.4273	0.8910	1.3585	1.2083
Meetpunt Noordwijk	MPN	52	16	26	4	17	46	1.4232	0.7674	1.2840	0.9743
K13a platform	K13	53	13	4	3	13	13	1.5089	1.0054	1.4825	1.4229
Euro platform	EUR	51	59	55	3	16	35	1.5892	0.9293	1.5244	1.2232
Schiermonnikoog Noord	SON	53	35	44	6	10	0	1.4360	0.4920	1.3369	0.5984
Lichteiland Goeree	LEG	51	55	33	3	40	11	1.6047	0.9743	1.3769	1.1209
Schouwenbank	SWB	51	44	48	3	18	24	1.4587	0.8408	1.4372	1.0381
Scheur West	SCW	51	23	32	3	2	57	1.4690	0.7072	1.4329	0.8355

Figure 38 shows an example of a Weibull fitting for the wave heights of the K13 platform in the summer period.

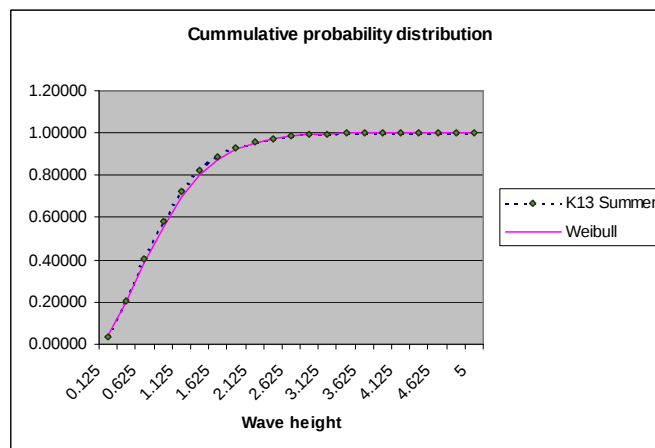


Figure 38

Probability of benign weather window

A benign weather window is a window of time where the considered vessel is able to work. If for instance a minimum of 3 days is required for a certain activity, every weather window larger than 3 days is accounted.

This probability is given by Equation 57:

$$P(\text{benign}) = \sum_{i=k}^N P(WL)_i * P(\text{effective})_i$$

$P(WL)_i$ is the probability of a particular weather window length. This probability depends on the wave height considered. $P(WL)$ actually means “the probability that a certain weather window occurs given a particular wave height”. In the above formula, k represents the weather window number that is equal or longer than the minimum weather window required to realise the operation.

$P(\text{effective})_i$ represents the probability of effective time of operation. The probability of realising the operation depends on which moment the decision is taken to start with the operation.

To illustrate this, let's assume that a weather window has a length of 5 hours wherein it is needed to realise an operation that takes 3 hours time. If the decision of starting the operation takes place during the 1st or 2nd hour, the activity may be realised. But if the decision of starting the operation takes place during the 3rd, 4th or 5th hour, it will not possible to realise the operation because lack of time.

The probability of realising an operation of 3 hours within a window length of 5 hours is given by 1-3/5.

In general terms, the probability of carrying out an activity of length X within a weather window of length WL_i is given by Equation 58:

$$P(\text{effective})_i = 1 - \frac{X}{WL_i}$$

The probability of a benign weather window, where an operation may take place is then given by Equation 59:

$$P(\text{benign}) = \sum_i P(WL)_i * (1 - \frac{X}{WL_i})$$

Example:

$$WL_{\text{ref}} = 2 \text{ [h]}$$

Length WL [h]	Occurrences Qi	Probability P(WL)	P(effective) Pi	P(benign) P(WL)*Pi
1	19	0.2088	0.0000	0.00
2	25	0.2747	0.0000	0.00
3	20	0.2198	0.3333	0.07
4	15	0.1648	0.5000	0.08
5	12	0.1319	0.6000	0.08
	91	1		0.23 = P(benign)

APPENDIX D

Typical Transport and Installation Vessels



Figure 39. Typical Towing Tug.

Source: Sea Heavy Lifting (SHL); Internet site: <http://www.shl.com>



Figure 40. Typical jack-up vessel.

Source: Transocean Sedco Forex; Internet site: <http://www.deepwater.com>



Figure 41. Derrick barge.

Source: Global Industries Ltd.; Internet site: <http://www.globalind.com>



Figure 42. Typical Construction vessel.

Source: Saipem S.p.A.; Internet site: <http://www.saipem.it>



Figure 43. Typical Sheer Leg Vessels (right side of the picture).
 Source: Smit International; Internet site: <http://www.smit.com>



Figure 44. Typical Side Stone Vessel.
 Source: Van Oord ACZ; Internet site: <http://www.vanoordacz.nl>



Figure 45. Typical Remote Operating Vehicle (ROV).
 Source: Van der Stoel Cable, Submarine Cable Installation Contractors;
 CD-Rom with company profile, version 01-08-2000



Figure 46. Installation of rotor at Middelgrunden wind farm.
 Wings and hub are raised horizontally until they can be tilted into vertical position. Then they are elevated to a height of 75 meters before they are mounted onto the nacelle.
 Source: Middelgrunden Internet site: <http://www.middelgrunden.dk>



Figure 47. Special Installation barge for the gravity base support structure at Middelgrunden. When the barge is in place by Middelgrunden, several anchors are layed out, they are used to manouvre the barge so the turbine is in the right spot, it must be within 25 cm of the calculated position.

Source: Middelgrunden Internet site: <http://www.middelgrunden.dk>

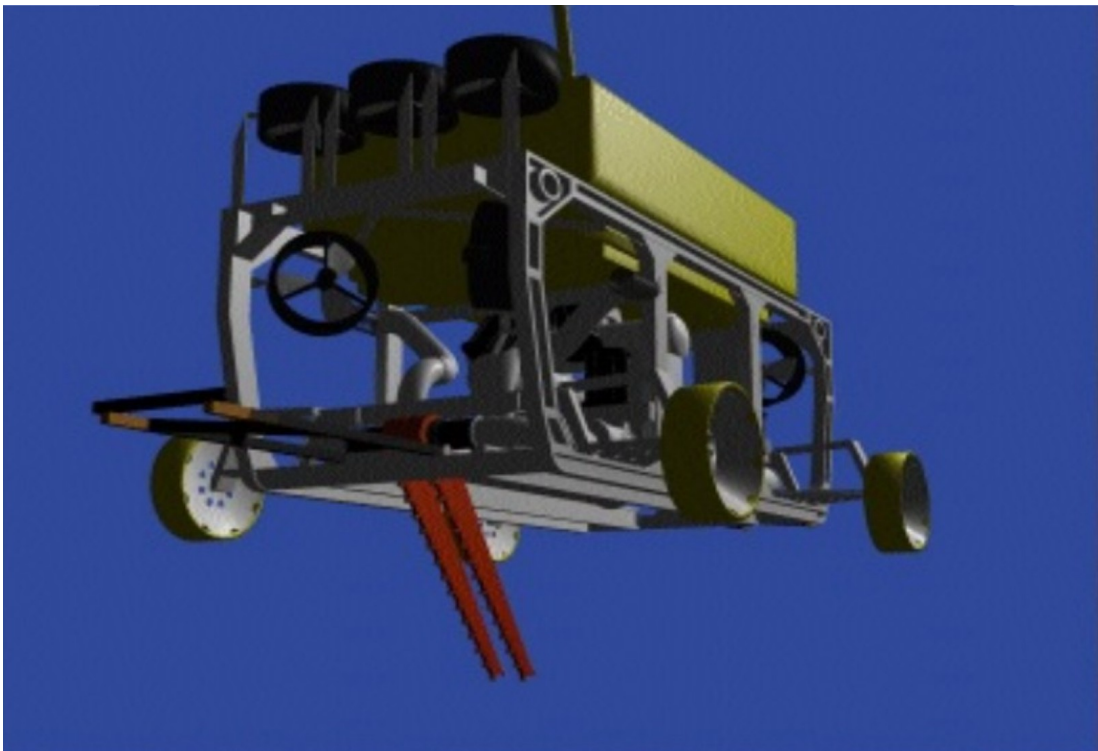


Figure 48. Typical Cable Trencher Vehicle.

Source: Van der Stoel Cable, Submarine Cable Installation Contractors; CD-Rom with company profile, version 01-08-2000

11. SPECIAL INSTALLATION BARGES

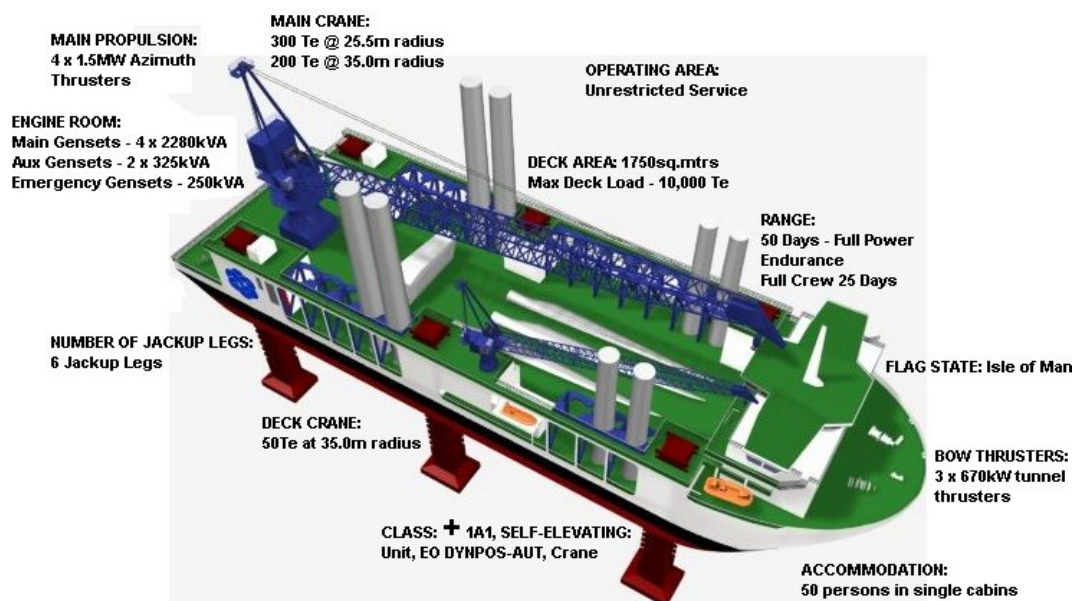


Figure 49. Turbine Installation Vessel TIV-1.

The vessel will have the following characteristics:

1. GENERAL

- Class: DNV +1A1, Self-elevating Unit, EO DYNAPOS-AUT, Crane
- Number of Jackup Legs : 6
- Flag State: Isle of Man
- Operating Area: Unrestricted
- Range 25 Days - Full Crew / Deck Load
- Length: 130.50 metres; Breadth: 38.00 metres; Depth: 8.00 metres

2. CARGO & ACCOMMODATION CAPACITY

- Type / Number: Offshore Wind Turbines / 10
- Maximum Payload: 3,000 Te Jacking
- MAIN Crane - Max Capacity
 - 300 Te @ 25.5 metres
 - 250 Te @ 29.5 metres
 - 240 Te @ 30.5 metres
 - 200 Te @ 35.0 metres
 - 50 Te @ 80.0 metres
- Auxiliary Crane 50 e @ 35.00 metre radius
- Accommodation: 50 Single Berths 2.6 Utilities: Hospital-Recreation

3. OPERATING CONDITIONS

- Service: Unrestricted (as per DNV Rules)
- Jacking Operations: 3.0 metre maximum wave
- Jacked Survival 100 Year Storm (Force 12 Beaufort Scale) 50 year wave 14.0 metres
- Minimum Operating Depth 10% Cargo: 2.25 metres
- Minimum Operating Depth 100% Cargo: 3.25 metres
- Max Operating Depth: 35.00 metres (increase possible)

4. PERFORMANCE

- Transit Speed: 10.5 Knots +
- Jacking Capacity: 2500 Te per leg; Holding Capacity: 3500 Te per leg
- Jacking Speed: 1m/min
- Maximum Draught Loaded: 3.0 metres
- Maximum Draught Lightship: 2.4 metres

Source: Website of Mayflower Energy Ltd: <http://www.mayflower-energy.com>.

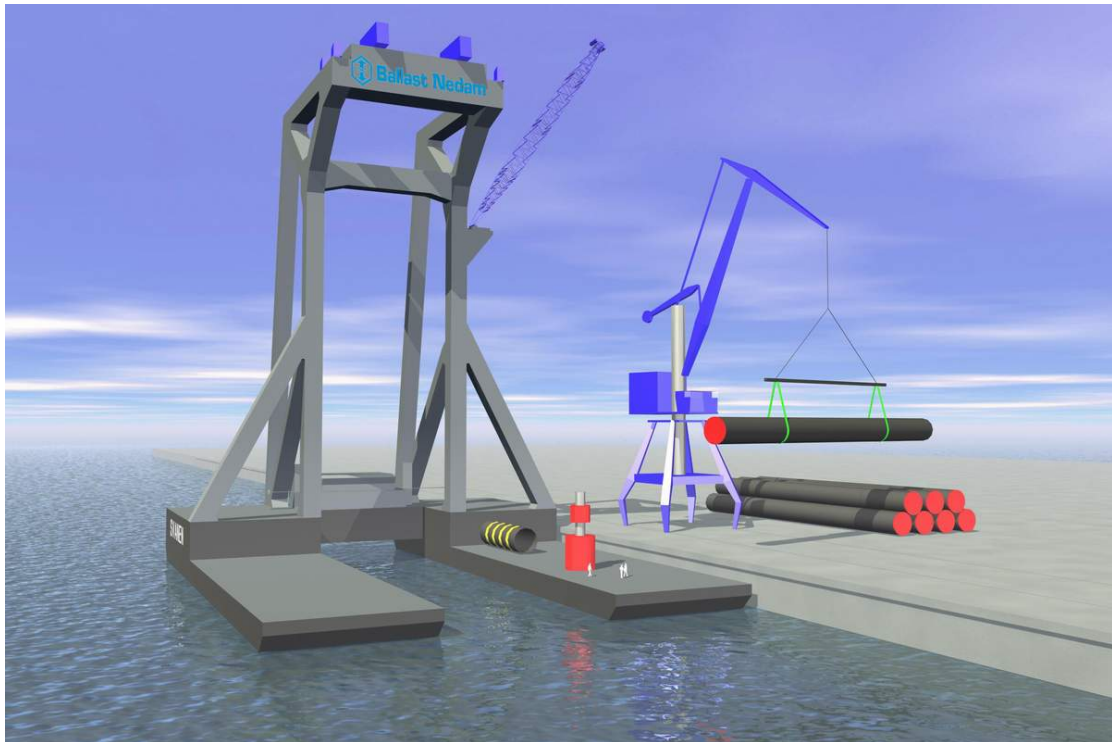


Figure 50. Very Heavy Lifting Vessel, The Svanen.
 Artist impression of the Svanen while loading wind turbine components for transport offshore.
 Courtesy: Ballast Nedam; <http://www.ballast-nedam.nl>.



Figure 51. Very Heavy Lifting Vessel, The Svanen.
 Artist impression of the Svanen while installing a tower-nacelle-rotor assembly of a wind turbine on its support structure offshore. Courtesy: Ballast Nedam; <http://www.ballast-nedam.nl>.



Figure 52. Very Heavy Lifting Vessel, The Svanen.
The Svanen in action during the transport of a bridge piece. Courtesy: Ballast Nedam;
<http://www.ballast-nedam.nl>.