Floating Off Shore Wind Turbines for Shallow waters

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Abstract

Bottom mounted Offshore wind turbines seem to have a promising future but they are restricted to shallow waters of Northern Europe. Many projects are planned or are in the phase of construction on the North Sea and the Baltic Sea. All projects that are planned have a water depth up to approximately 25 m.

The project reported in this paper investigated the technical and economical feasibility of floating wind energy systems in deeper waters, approximately 50 m and deeper. It is assumed that at a certain water depth floating wind turbines will have better economics than bottom mounted wind turbines.

Floating wind energy systems seem to have some advantages over bottom mounted wind energy systems, like e.g.

- lower cost installation (in a harbour);
- lower maintenance cost;
- lower removal cost.

But floating wind energy systems have their own technical challenges, like

- dynamic interactions between floater and wind turbine;
- floater conceptual design including mooring system, taking into account restriction w.r.t. stability of floater and wind turbine, minimizing wave induced motion, water depth, etc.

This paper summarises the activities performed for the so called FloatWind feasibility project performed during 2001-2002.

1 Introduction

The project “Feasibility study of and Determination of Boundary Condition for Floating Off Shore Wind Turbines”, in short FloatWind, is carried out by the project partners ECN, MARIN, TUD and Lagerwey the Windmaster under coördination of TNO. MSC performed the pre-design of the final concept to estimate weights and cost under contract with TNO.

In the 1990’s a number of studies have been performed to investigate the feasibility, technically and economically, of floating wind energy systems. The outcome mostly was that technically is seems to be possible but the cost are much to high. The cost estimates showed cost of more than 3 times the cost of wind energy on shore. However at that time bottom mounted wind turbines off shore were also thought of as a bridge to far. The cost estimates of energy generated off shore was about twice the cost on shore generated energy. Bottom mounted off shore wind energy can be exploited economically nowadays so it is time to investigate whether floating off shore wind energy is closing the gap.

2 Literature survey

This section reviews the recent floating off shore wind energy studies and includes an inventory of the more important reports and papers that will help the reader gain an understanding of the subject.

In the early 1990s several studies have been performed in the U.K. which have been reported at the BWEA/DTI seminar "Prospects of Off Shore wind energy". Two of the concepts evaluated here are:

- a single turbine on a spar-buoy, [1], investigated by Garrad Hassan and Technomare, kept at location by an eight point caternary moorings. The cost were estimated to be twice that of bottom mounted alternatives at that time.
- a Multi Unit Floating Off shore wind farm (MUFO),

investigated by WS Atkins (U.K.), [2], in cooperation with the University College of London, resulting in a number of analysis tools for floating off shore wind energy wind farm [3, 4].

The outcome of those studies was also that the cost was to high.

3 Terms of reference

To be able to compare the results of this study with known results of other studies it was chosen to use equal starting points as the initial DOWEC Concept study [5] has used with a few exceptions. These exceptions were the distance to shore and the water depth which were specific for the floating concept. Due to the shallow depth of a major part of the Dutch sector of the North Sea, see figure 1, it was decided to direct the feasibility study also to investigate the minimum depth for floaters. The data used througout the project is summarised in table 1.

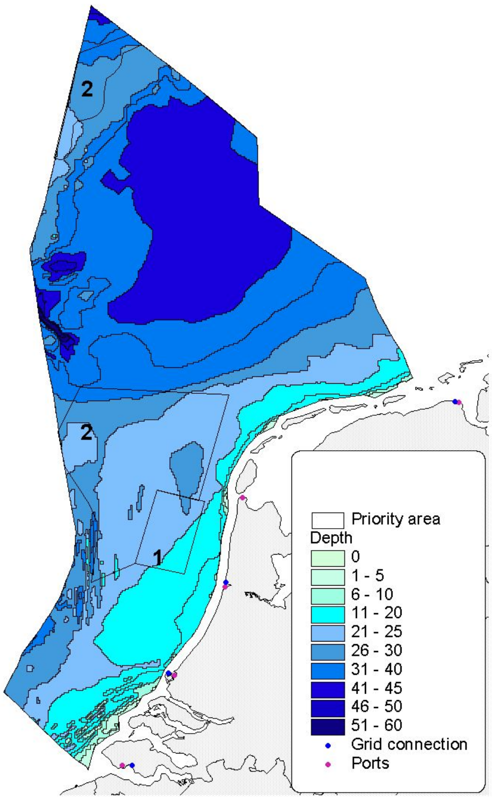

Figure 1: Bathymetric map of Dutch continental shelf

It was decided to calculate the cost of energy conform the procedure outlined in [6]. In short the cost of energy is calculated as the Levelized Production Cost, meaning that it is assumed that there is no variation in Energy Yield or Operation and Maintenance cost during the life time of the project.

The levelized productions cost (LPC) is determined as follows

$$\mathrm{L}PC = \mathrm{I}/\left(a \cdot AUE\right) + \mathrm{TOM}/AUE$$

Table 1: The terms of Reference

Location	North Sea
Water depth	Aronund 50 m
Distance to shore	more than 50 km
Weibull wind speed parameters 10 m height	Vave = 9 m/s k = 1.8
Wind shear profile	determined from a roughness height of 0.0001 m
Turbulence description	IEC I15 = 0.12 a = 3
Wind farm turbine spacing	Approximately 8 Diameters apart.
Wind farm array efficiency	95%
Turbine data General	Rated Power = 5 MW Diameter = 115 m Hub Height = > 80 m # blades = 3
Yaw system	nacelle only
Electrical system	Direct Drive generator
Floater/Submersible	single wind turbine 3-5 wind turbines
Water conditions	defined by Marin i.e. wave spectrum characteristic wave height and frequency etc.
Soil conditions(for mooring)	sand
Economic parameters	Real Interest rate 5 % inflation rate 0 % economic lifetime 20 y

In which:

a	Annuity factor	-
AUE	Annual Utilized Energy	kWh
I	Investment including possible interest during construction	€
TOM	Total (levelized) annual "downline cost"	€

This results in

$$\mathrm{L}PC = \mathrm{C}aptialCost + \mathrm{O}perationalCost$$

4 Generation of concepts

4.1 Introduction

A multi-disciplinary development effort as this FloatWind project is largely a knowledge acquisition activity. Therefore use has been made of the QUAESTOR knowledge based system of Marin [7] as the modelling environment. In the knowledge base relations between design parameters are assembled. These relations can be simple algebraic formulation or a complex computer code to determine the response of a (sub) system subjected to certain external conditions. For this project both kinds of relations have been used.

4.2 Concept generation

A number of design options have been investigated qualitativly at the start of the project. The main questions are

- single or multi wind turbine floaters;
- weather vaning floater or yawing wind turbines.

These two design options are related because when the choice would be to have multiple wind turbines on a single floater the weather vaning options would prevail to prevent that wind turbines operate in each other wake.

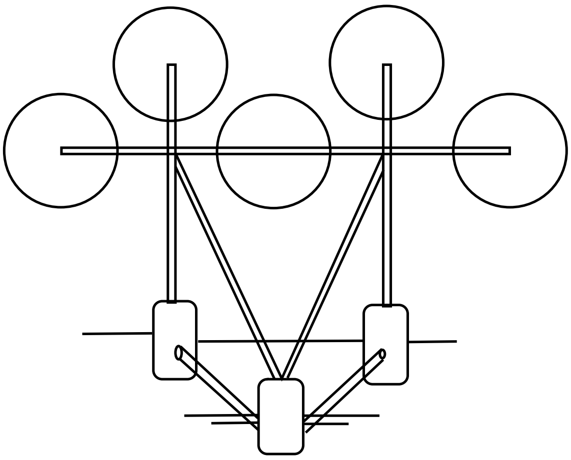

Figure 2: Multi rotor triple floater concept, developed by Lagerweij/Heerema

Multi rotor concepts would create the option to create wind energy systems of say 3 to 5 times the rated power of a single wind turbine, see figure 2, which would have the opportunity to combine several sub systems in the centre of the platform for a higher rated power resulting in better economics. Also from a maintenance perspective the largest system will have advantages. However the floater will also become exessively large to create sufficient stability. Only a two rotor option in a T-shaped arrangement, seems to give acceptable dimensions, masses and cost, see figure 3.

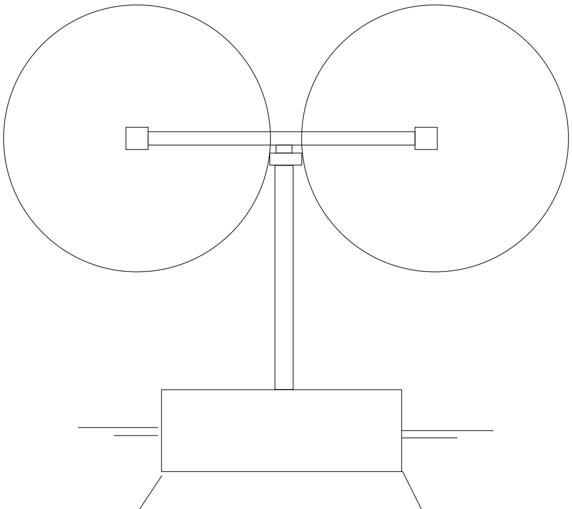

Figure 3: Two turbines on one floater

Weather vaning of the floater for the multiple wind turbine option leaves the problem how to keep the rotors in the wind when a single off centre rotor could not operate for some reason. Other problems are:

- the delivering of the electrical power to the fixed grid in the wind farm. This connection should have the ability to rotate and still be water thight. This type of equipement is available but is rather expensive certainly for the rated power of the multi rotor floaters.
- when the current and the wind direction are not in the same direction a passive system will mean that the wind turbine can have large yaw miss alignments especially at lower wind speeds an active system is more expensive and has a higher failure rate.

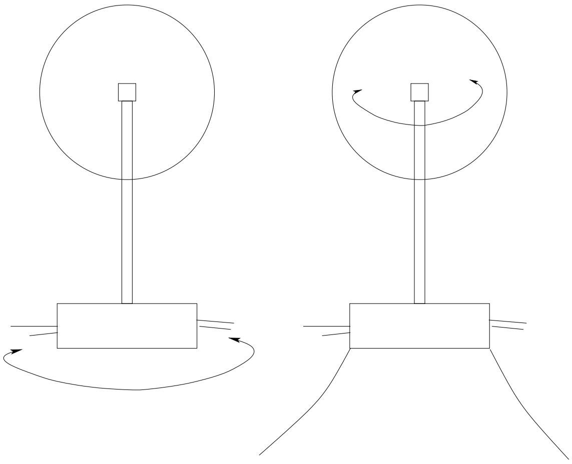

Figure 4: The difference between a yawing wind turbine or a weather vaning floater

A none weather vaning floater however needs a mooring system that is capable to keep the floater from rotating when the turbine is yawing. A spread mooring systems is capable to prevent this rotation and is also quit common so this is not really a problem. In a larger wind farm it is even possible to design a mooring system in such a way that cables are interconnect the floaters.

4.3 Floater design

The floater concepts investigated are

- single cylindrical floater (pill- box or buoy), see fig. 5;
- single cylindrical floater with a tension leg instead of spread mooring;
- single floater with a low connection tension leg 8;
- inverted spar with a buoy with pretension
- spar buoy with spread moorings
- triple floater with tubular truces, with and without damping plates;
- quadruple floater with truces
- four leg jackup with a single wind turbine.

4.3.1 Single cylindrical floater with or with out skirt

The floater is a simple vertical cylinder, held in position by a spread mooring. This concept was the starting point in the discussions. The stability range requires ballast water to achieve sufficient draft. Initial stability requires a diameter

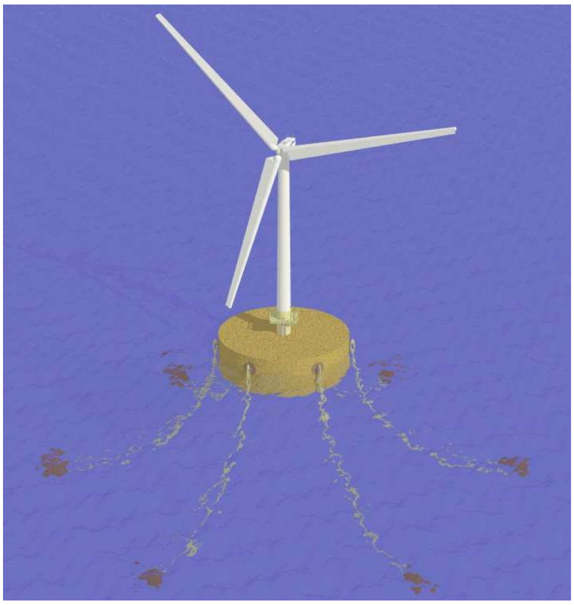

Figure 5: Pill box or buoy floater

of at least 37 m. In the above results, about 3100 t of water ballast is used to achieve a draft of 4. 27 m. This can either be stored in the pill box but this will require a lot of additional structure to prevent free surface stability loss. A more simple and effective solution is to introduce virtual ballast by constructing a buoy with a draft of about 1. 4 m and circular skirts fitted underneath the bottom of about 3 m height. This circular skirt will confine about 3000 tons of seawater and can be considered as a ballast tank without bottom. From a stability perspective, a completely filled ballast tank can be regarded as flooded space vice versa. Although feasible from a stability perspective, this concept is not feasible from a motion perspective; in particular the heave period (Tz) of about 9 seconds is right within the high energy range of the wave spectrum as well as the roll period T_ϕ which is critical with about 13 seconds. Both roll and heave period should be about 16 seconds and there is no way to achieve that with the single circular floater, i. e. it is not possible to fulfil stability and motion requirements at the same time. Therefore, the pill- box concept was concluded to be technically infeasible.

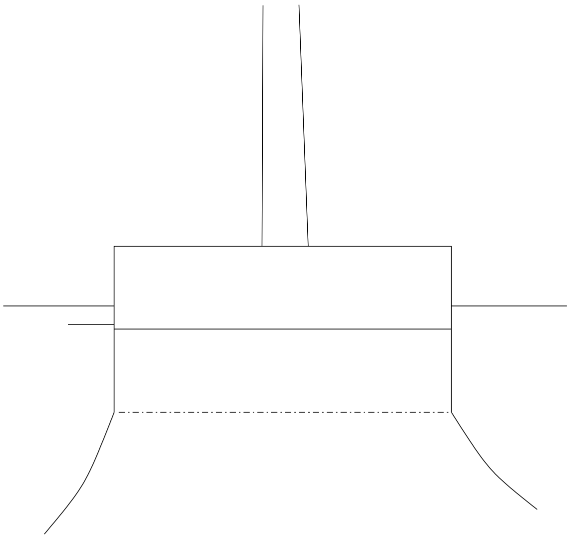

Figure 6: Floater with a skirt

4.3.2 Cylindrical floater with (low) tension leg

In order to fulfil stability requirements with a floater with a smaller diameter, it is an option to introduce pretension by means of a so-called tension leg. Next to this, the tension leg increases the vertical stiffness of the floating system, which reduces the heave period. In this way, the heave period can be moved out of the high-energy region of the spectrum. From a static stability point of view, this pretension can be considered as a point mass located at the connection point of the tension leg. In addition to the resulting downward shift of the virtual centre of gravity, the centre of buoyancy is also moved downward in absolute sense since additional buoyancy is required to compensate for the pretension.

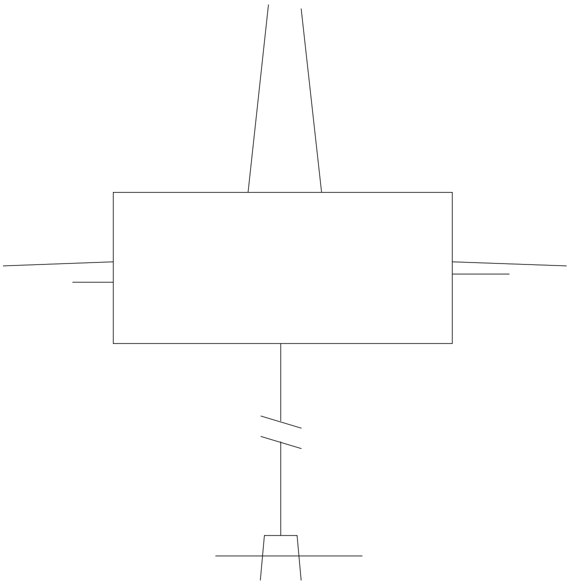

Figure 7: Cylindrical floater with a tension leg

Summarising, the tension leg concept is not suitable for the water depths considered in this study since not enough stability advantage is achieved by the pretension. For this concept, the only reason to introduce pretension is the reduction of the heave period, which is making the single floater into an infeasible concept.

4.3.3 Tri floater

4.3.4 Quadruple floater

The floaters are cylindrical as well as the truces, a spread mooring is applied. This concept is very similar to the triple floater concept. With equal floater dimensions, the distance between the floaters can be somewhat smaller. The steel weight of the quadruple floater is expected to be higher due to the larger amount of connecting structure between the four floaters, as is obvious from the comparison of the artist impressions from the triple and the quadruple floaters.

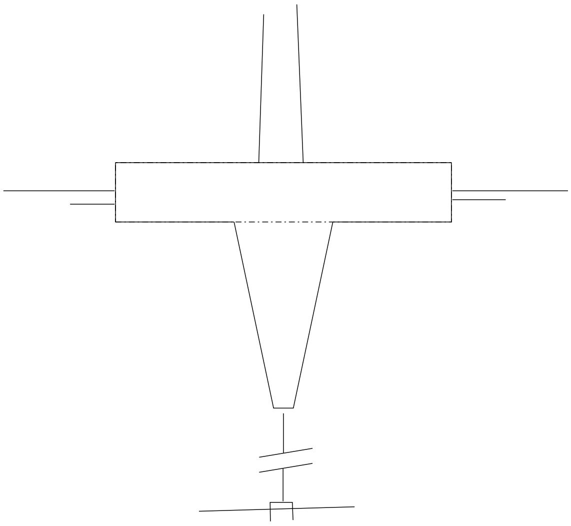

Figure 8: cylindrical floater with a low tension leg

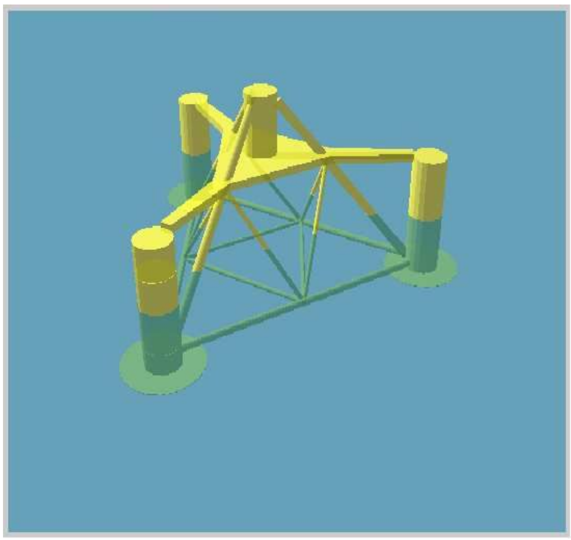

Figure 9: triple floater

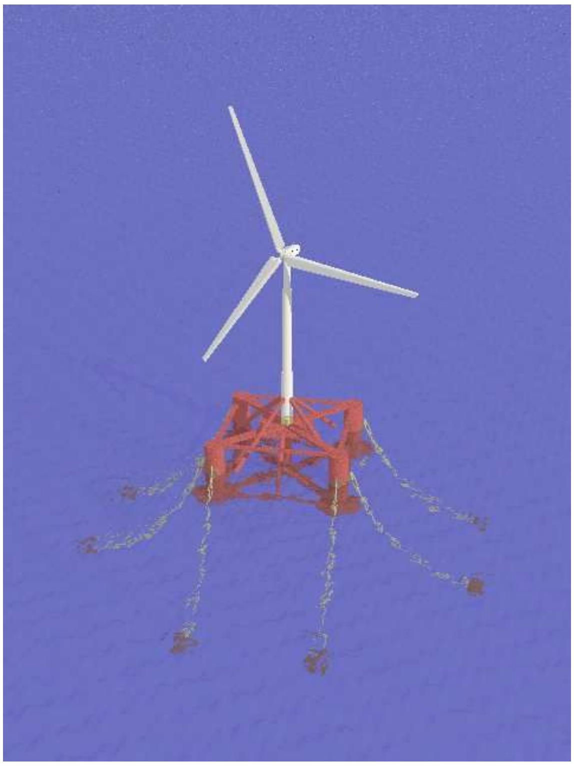

Figure 10: Quadruple floater

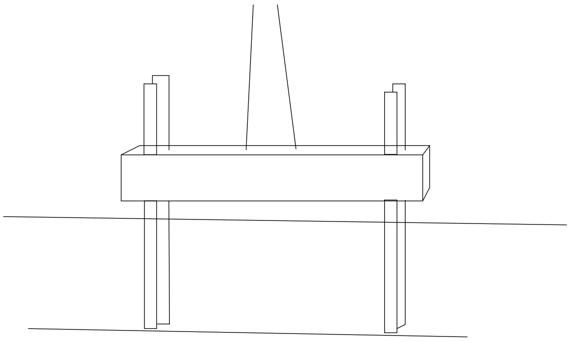

Figure 11: Four leg jackup with a single wind turbine

4.3.5 Jack up

The jack-up concept was proposed as an option to allow simple installation and convenient transportation to and from the wind farm. A jack-up concept eliminates wave-induced motions of the turbine and forms a stable foundation of a single or multiple turbine system. However, the jack-up concept has a major drawback: its cost. According to data provided by MSC, a jackup suitable to carry a single 115 m turbine will cost about M€12 which makes it totally impossible to apply the as a platform for wind turbines.

4.4 Electrical system

An important aspect in the determination of the feasibility of an offshore wind farm is the choice of the electrical system, necessary to collect the power in the farm and transport it to shore.

For this purpose, the EEFARM computer program, [8], is used to calculate the electrical and economic performanceof a number of electrical architectures and layouts. A single EE-FARM analysis gives the load flow (voltages, currents, active and reactive powers) in all system nodes as well as the electrical losses for all wind speed bins. EE-FARM also estimates the contri-bution of the electrical system to the kWh price, averaged over the life time of the wind farm. The economic evaluation is based on budget prices for the electrical components, received from manufacturers, and aerodynamic performance of the wind farm calculated by FYNDFARM [9]. Prior to the EEFARM calculations for Drijfwind turbine and wind farm layouts, a preliminary choice of the most promising electrical architectures has to be made, since a large number of suitable electrical architectures exist for the connection of large wind farms to shore. The preliminary choice will be based on the results of a case study in the ERAO project [2]. In this project EEFARM has been used to evaluate 13 electrical architectures for 2 wind farm sizes and 2 distances to shore. The calculations were based on a 5 MWwind turbine. Chapter

Figure 12: The chosen concept

3 summarizes the ERAO case study results and makes a preliminary choice. The two most promising electrical options, suitable for the Lagerwey turbine, will be evaluated for the Drijfwind 5 MWwind turbine and a farm size of 500 MW(100 turbines). These options are the Individual Variable Speed system (IV) and the Park Variable Speed system (PV). Two platform options will be considered: platforms with 1 or 5 turbines. The evaluation will take into account distances to shore between 50 and 200 km. Chapter 4 gives the Drijfwind results.

5 Evaluation of the concepts

5.1 Floater

Study to feasibility of and boundary conditions for floating offshore wind turbines 5-24 5.5 CONCLUSIONS Some initial calculations performed within the DRIJFWIND knowledge base show that the single pill-box buoy concept without pretension is not feasible as free floating buoy and requires buoy diameters as much as 37 m for a 115 m turbine. Smaller buoy sizes are only possible when a tension leg concept is applied. This implies to some extend that the single buoy/single turbine concept is not feasible at all since a tension leg concept does not allow the buoy + turbine to be towed to a harbour facility for maintenance. From a perspective of motions, the pill-box floater is not feasible since in particular the vertical motion response is within the high-energy region of the wave spectrum. The multi-floater i.e. triple-floater concept is feasible in terms of stability and its structural weight is smaller if compared to a single floater. However, the size of the structure becomes quickly too large for a single turbine. The requirement of a movable platform implies a requirement for stability afloat, say during the passage from shore to the wind farm. A hybrid solution could be a jackup, which is a fixed structure when on location and a floating one related to transport and maintenance. The jackup, however, is not feasible due to its high construction cost. The course approximations in the DRIJFWIND knowledge base allowed to rapidly focusing on the technically feasible concepts. In order to select/optimise the presented concepts in terms of both economical and technical aspects, it is absolutely necessary to fill in the white spots discussed in section 4.2. Based on the concept variations performed in DRIJFWIND, the triple floater concept was selected as basis of a point design, performed by MSC [MSC, 2002]. The DRIJFWIND knowledge base in QUAESTOR proved to be a useful tool to establish the focus of research performed within this project. The DRIJFWIND knowledge base forms an extendable and easy to maintain body of knowledge on floating wind farms and is open to extensions and enhancements that results from future research.

5.2 Electrical system

Conclusions

- Two electrical system types, Individual Variable speed (IV) and Park Variable speed (PV), have been investigated for the connection of a 500 MW floating wind farm to the high voltage grid. Based on the assumptions in this study the individual variable speed system with 150 V AC connection has the lowest price for a distance less than 160 km. Above this distance, the park variable speed system with a 141 kV DC connection is cheaper.

- The load flow calculations showed that it is possible to transport the full park power over a distance of 200 km with an AC cable without intermediate shunts.

- For a distance of 200 km the electrical losses of an AC connection are relatively high. For the conditions in this studie an AC connection will loose 14-20% of the total park energy at 200 km. A DC connection dissipates 7-12% at the same distance.

- For the contribution of the electrical system to price of the produced energy (LPC), the break even point for the two system types IV and PV is found at about 140 km distance. The difference in losses moves the break even point by 20 km in favour of the system with DC connection.

- Two platform options were compared: a single turbine platform and a five turbine plat-form. The differences in price are caused by a wider spacing of the five turbine platform, induced by the star layout. The spacing in the star layouts can be reduced, bringing the five turbine platform results close to the single turbine cases.

- Electrical system choice: Based on economics only, the best choice for the Drijfwind 500 MW wind farm will be the Individual Variable speed system for distances below 140 km and the Park Variable speed system for distance above 140 km. Differences in controllability and stability of the two options may influence the choice, but has not been investigated.

6 Maintenance cost

Another item which influences the cost of energy to a large extend is the operating and maintenance cost. Initially the objective included an option to perform large overhaul on shore and not at the site. The floaters would need to be shipped back to shore every 5-8 years depending on the mean time between large overhaul.

So the question is to what extent is it profitable to perform maintenance on site in comparison with on shore maintenance for which the floating platform needs to be shipped. Both strategies are dependent on weather windows but it was calculated that the case of the towing of the platform is more susceptible and hence that on site maintenance is preferable for practically all failure mechanisms. Specific on shore activities such as recovering of the platform or clustered activities within a substantial overhaul have been assumed to be unnecessary due to a maintenance free platform and the use of reliable components. The cost calculations assume the availability of exchange parts, the costs of which are managed by using renewed cost-intensive components that have failed. Efficiency measures such as opportunity based maintenance or implementation of clustered corrective maintenance actions, have not been incorporated in the model since the failure rates are limited. This factor therefore determines the maintenance costs only to a limited portion of the accuracy of estimation. Uncertainties with respect to the maintenance demand, resulting from the fact that no detailed design is present, are to be controlled by incorporating a RAM (Reliability, Availability and Maintenance) specification and assessment within the design phase of the final construction. In a RAM assessment the final design is evaluated with respect to its maintainability (with function loss during a specific time) and the resulting availability (capability to produce), by using the reliability performance data of the specific components. The reliability data that are applicable for supposedly maintenance free components in order to safeguard the assumptions made within this study, are determined by a failure rate of ultimately 4Œ10-4 (yr-1). This guideline in combination with availability criteria is applicable during the actual design phase. The maintenance costs for a platform are estimated to be 2.2% of the investment costs (offshore position: 100 km). This is equivalent to approximately 35% of the levelised production cost .

7 Conclusion

Uncertainty in LPC The costs for the electrical infrastructure are based on budget prices for existing components. However, the prices can still vary within ś 10% due to competition etc.

The costs for the construction of the floater are the construction costs in 2002 of offshore constructions based on experience of MSC. The prices can vary within ś 10%.

The total maintenance costs are a ś 50% estimation.

Table 2: The economic performance data for the triple floater

Construction location	Europa		Asia	
Distance to shore	200 km	100 km	200 km	100 km
Grid Option	pv1	iv1	pv1	iv1
Floater + installation M€	4.500	4.500	3.500	3.500
Mooring cost M€	2.500	2.500	2.500	2.500
Turbine cost M€	2.875	2.875	2.875	2.875
Electrical infrastructure M€	3.710	2.710	3.710	2.710
Total Capital Investment M€	13.585	12.585	12.585	11.585
Annual O&M cost M€	0.299	0.277	0.299	0.277
Insurance Cost[1] M€	0.136	0.126	0.126	0.116
Annual downline cost M€	0.435	0.403	0.425	0.393
Energy Yield gross Wh	2.4600E+10	2.4600E+10	2.4600E+10	2.4600E+10
Wind Farm Efficiency	95.00%	95.00%	95.00%	95.00%
Electrical transport efficiency	91.30%	91.50%	91.30%	91.50%
Yield Netto Wh	2.1337E+10	2.1384E+10	2.1337E+10	2.1384E+10
interest	5.00%	5.00%	5.00%	5.00%
Economic Life Time years	20	20	20	20
annuity factor	12.462	12.462	12.462	12.462
Levelized Production Cost	0.071€/kWh	0.066€/kWh	0.067€/kWh	0.062€/kWh

The following conclusions have been drawn from the results of the study:

A literature study has been carried out and relevant literature has been gathered on a cd-rom.

The literature study is the basis for the boundary conditions and references for the floating turbine.

All the references, data, equations etc., are brought together in the knowledge based system Quaestor.

Quaestor has been used to analyse different floater concepts in a quick and easy manner.

The Quaestor analysis showed that the tri-floater concept looks feasible.

Motion response calculations for the tri-floater concept showed that the concept is technical feasible regarding motions.

A more thorough design of the tri-floater has been made. The strength, production and installation costs and mooring of the tri-floater are calculated.

The total investment costs of the tri-floater are approximately M€5. This is excluding the electrical system and maintenance costs.

Based on economics only, the Individual Variable Speed system is the best choice for distances below 140 km and the Park Variable Speed system for distances above 140 km.

The maintenance costs are calculated to be about 277 k€/year per 5 MWatt turbine. The availability is 91%.

It appears not to be cost effective to tow the floating turbine to shore for corrective maintenance.

The levelised production costs for a wind turbine 200 km of the coast build in Asia is 0.069 €, build in Europe 0.074 €

The levelised production costs for a wind turbine 100 km of the coast build in Asia is 0.064 €, build in Europe 0.068 €

8 Recommendations

The tri-floater has been designed for water depths of 50 m and more. However, it can also be used in water depths of

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[1] 1% of the total investment

40-45 m. This increases the area of the Netherlands continental shelf, which can be used for floating offshore wind energy, to at least 14%. (See figure 1).

In order to select/ optimise the presented concepts in terms of both economical and technical aspects, it is absolutely necessary to improve the Quaestor application by adding more data and equations.

For the choice of the electrical system, a second major aspect is the controllability and behaviour with respect to the (high voltage) grid. This should be done for a final decision.

It is recommended to use a RAM-spec during the design phase, which reduces the maintenance costs within 1 year for ten turbines already.

Reducing the maintenance costs can be achieved in the fastest way by reducing the failure rate of those processes that appear to contribute heavily due to the characteristics of the repair scenario (repair time, delay due to weather window and repair time needed).

9 Acknowledgement

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