Application of an Advanced Cost Model in the Different Design Phases of an Offshore Wind Turbine

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ABSTRACT: The goal of the Dutch Offshore Wind Energy Converter (DOWEC) consortium is to develop concepts and technology in order to make large scale offshore wind energy economically feasible. The overall DOWEC development comprises of the design, the construction, and the prototype testing. Onshore testing of a 3 MW research and development prototype is scheduled for the end of 2002.
The DOWEC Concept Study aims at the choice of the optimal wind turbine concept. The wind turbine will not be treated as an isolated system. Designs of different wind turbine concepts will be evaluated as an integral part of the complete large-scale offshore wind farm. All significant properties like the structural loads, the power performance, the system reliability, the costs of the electric infrastructure, maintenance costs and installation costs is determined for the optimised designs. A quantitative ranking is then based on the cost of energy generated. Furthermore qualitative criteria like development risk and market potential will be taken into consideration when finalising the choice of concept.
An advanced cost model is being developed to facilitate the above evaluation on basis of estimated energy generating costs for each concept. The same methodology will also be used in the system and detail design phase.
This paper describes the DOWEC project in general, focusing at the cost modelling aspects including some preliminary results.

Keywords: Off-shore, Cost Analyses, Optimization

1 INTRODUCTION

At present most offshore projects are located in the Baltic seas. The more hostile North Sea wave conditions, the water depths and the distance to shore will lead to higher investment and operational costs. Application of the current megawatt plus designs is not likely to result in competitive yielding costs. Economic exploitation of the huge wind resource at the North Sea requires new wind turbine designs.

These costs can be reduced by economics of scale. In a large-scale farm with large machines the relative costs of the electric farm infrastructure, the foundation, the grid connection and the operation and maintenance costs are reduced significantly. Dynamic oscillations and constraints on structural integrity may hamper a straightforward up-scaling of the existing Megawatt plus designs. Additionally the given concept may not be optimal; although a concept may have proven itself to be competitive at onshore sites the different conditions offshore and the different cost breakdown of energy generated result in different optimal concepts for the offshore application.

In this paper the need and possibilities of an integrated approach of design and economic optimisation are explored.

2 THE DOWEC PROJECT

The DOWEC project is build up in three phases. The phase 0 in which a concept study has been carried out is finalised. At present the phase 1 is halfway. One of the goals for this phase 1 is the design, building and testing of a 3 MW prototype. The testing of the prototype is planned for September 2002. In another part of the phase 1 the 3 MW machine is taken as reference in a sensitivity study in which concept and system design variations are evaluated. Finally in the phase 1 knowledge and technology development is carried out in order to have a solid basis for the design of a large scale farm build up of 6 MW wind turbines. The phase 1 is finalised in 2003. In the DOWEC phase 2 the 6 MW is designed, built and tested. Marine testing is scheduled in the year 2008.

2.1 Terms of reference

At the start of the DOWEC study project the terms of reference were drafted. Basically the Terms of Reference, abbreviated as ToR, set out the starting point, the project goal and the constraints along the way. Some key figures in this document are:

- Turbine rating: 6 MW
- Farm size 500 MW
- Distance to shore: 3 locations at 20 km, 60 km and 100 km
- Water depth 15 to 30 m

Detailed site conditions, including wind and wave data from the NESS database, have been obtained for 2 locations. These data will be used for evaluation of structural integrity of the designs, for accessibility modelling and for yield calculation.

2.2 Integrated design approach

In the DOWEC study the evaluation of the different design options is embedded in an integral design approach. This implies that the wind turbine is treated as one of the components of the overall wind farm and that interactions with the other system components, viz. electric infrastructure and support structure, are taken into account. The evaluation of different designs is based on a calculation of cost of energy generated. The calculation includes installation, operation & maintenance and decommissioning aspects. Aspects like development risk and development time are difficult and therefore treated separately. Finally next to the cost of energy the value of energy for different concepts is taken into account as well. The Figure 1 visualises this integral design methodology.

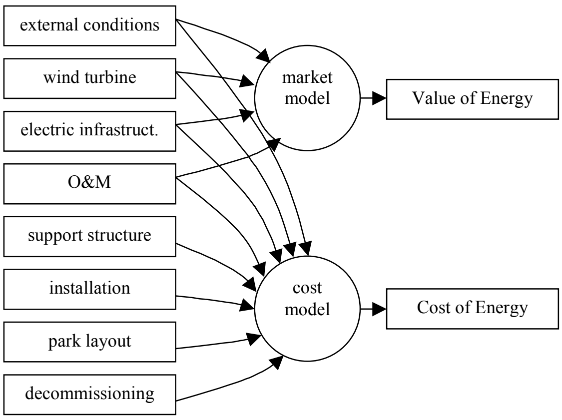

Figure 1: integrated cost model for the wind farm

It is clear that the above described design approach requires detailed experience and knowledge over a wide range of disciplines. The joined forces of a wind turbine manufacturer, a blade manufacturer, two offshore installation and dredging contractors and two wind energy research institutes in the DOWEC consortium offer the possibility to take all relevant aspects into account.

2.3 Staged design approach

The design of the wind farm and its components is divided into a number of stages. In the concept design phase a functional decomposition is established and the main functional principles of the system are chosen. In the system design phase the main specifications of the system components and its interactions are defined. In the detail design phase the components are designed into detail up to specification for ordering or manufacturing.

The above design phases are applicable on wind farm level but also on wind turbine level.

In the DOWEC-project the application of the cost method is applied in every design phase. Also detailed design aspects may be evaluated on cost of energy basis.

3 COST MODEL

In the cost model for DOWEC information will be provided by several disciplines, using sub-models. Therefore, a breakdown of costs and energy yield is made to match these sub-models and the aim of the total cost model. This breakdown is then used to calculate Levelised Production Costs.

The breakdown of costs is simply a division into costs of sub-components and -activities. Provided that all sub-components and -activities are represented in the breakdown, the total costs can be recalculated as the summation of the components, attaining the accuracy associated with the sub-models.

The costs and efficiencies of the components are a function of the design of the wind. Because of the interactions in the wind farm (during its lifecycle), there are also interactions in the design process and in the evaluation of the design (e.g. to assess O&M costs and availability). The design can have different levels of integration, but usually the interactions involved in the design process exceed the boundaries of the components in the breakdown.

These interactions are not automated in the cost model, but consistency is ensured by procedures for the design team that operates the sub-models.

4 SOME ILLUSTRATING RESULTS

4.1 Stall or pitch in relation to spacing

The choice between stall controlled and pitch to vane controlled turbines has attracted the attention of wind turbine engineers for decades. Up to now the different concepts have been evaluated on turbine level only. In the offshore case the choice calls out for a more comprehensive evaluation. The electric system, maintenance demand and the grid requirements have to be taken into account. Wake losses play a role as well, as will be discussed here. The large-scale wind farms and the low ambient turbulence offshore make the aerodynamic array losses a far more significant design aspect than in the onshore case. In principle the spacing in a wind farm also influences the electric losses in the cable, the cable costs and the costs of cable installation. However, it appears that the differential influence of these cost components is insignificant. The costs of installation are determined by the time needed for the installation. The installation time of a cable inside the park is dominated by the installation time needed at either ends of the cable, viz. the tie-in at the turbines and platform(s). A length increase from 800 to 1200 m results in a minor cost increase. A cable with higher rating can compensate for the higher cable losses for longer distances. The difference in cable costs is only a minor part in the overall investment costs. Conclusively the optimum park layout aiming at minimum cost of energy generated will have a very large spacing and any difference in the wake effects between a stall and a pitch-regulated turbine will fade away. However, space limitations will also exist offshore. In such cases the lower axial force coefficients of a pitch to vane machine results in a better aerodynamic array efficiency compared with a stall controlled machine, see Figure 2. When the spacing is fixed by other design requirements the difference in aerodynamic array efficiency has a direct effect on the annual energy yield and thus on levelised production costs. In Figure 2 the aerodynamic array efficiencies for for a stall machine and pitch to vane machine are given for different spacing. The data is taken from a Dutch study on electric and control aspects in large offshore farms, ref. [1].

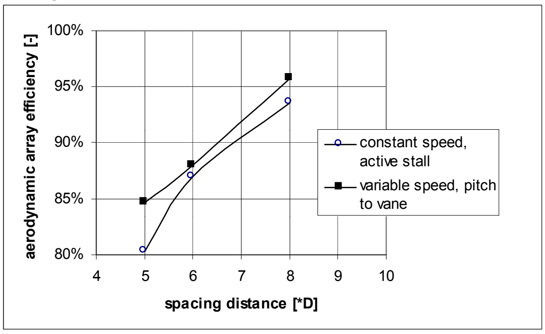

Figure 2: aerodynamic array efficiencies as function of spacing for a stall and a pitch to vane concept

4.2 The variable speed range

The huge investment costs of variable speed systems has hampered the implementation of variable speed concepts. The rapid decrease of the costs of power electronics, the more stringent grid requirements and the introduction of new generator systems have led to a bigger market share for variable speed systems. The new generator systems offer variable speed operation for lower investment costs. The doubly fed asynchronous generator offers variable speed operation with AC/DC/AC conversion of only a part of the rated power. The operational speed range of such a system is proportional to the rating of the inverter power fed to the rotor. The maximum deviation from synchonous speed is: $\Omega_{\text{deviation}} = \Omega_{\text{sync}} \cdot \frac{P_{\text{converter}}}{P_{\text{rated}}}$.

An optimum rating of the converter can be found by a cost-benefit evaluation. A high inverter rating has the following benefits:

- Better aerodynamic performance at low wind speed due to less deviation from optimum lambda control.
- Better aerodynamic performance around rated wind speed due the increased possibility to store kinetic energy from gusts.

The disadvantages of a high inverter rating are:

- Higher investment costs.
- Higher electric losses.

In a limited study the above issue has been addressed. The investment cost of the inverter increased only slightly as function of the speed range. This was caused by the fact that in the model a relative big part of the inverter power is dedicated to power factor control. For each inverter rating the power control parameters have been tuned and the blade twist distribution has been optimised. Two different strategies to change speed ranges have been evaluated; one keeping the synchronous speed constant and one keeping the maximum speed constant. In the Figure 3 the results are visualised.

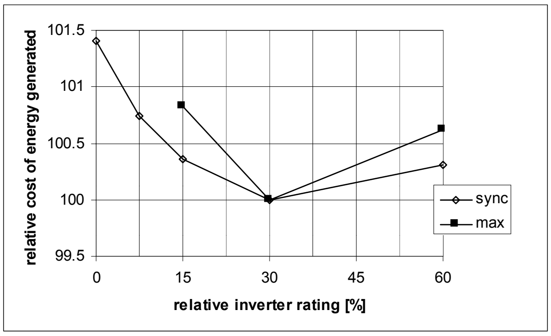

Figure 3: Relative costs of energy for different inverter ratings in a rotor fed asynchronous generator

From the Figure 3 it can be concluded that a variable speed range of ±30% around synchronous speed gives an optimum balance between costs and benefits. With this speed range optimum lambda control can be fulfilled almost over the complete wind range below rated wind speed.

The above analysis of the optimum speed range may be complicated by the interaction with tower design. A monopile support structure seems an economic option for many North Sea locations. The first conceptual design of scour protection shows that the costs for a 3 MW machine amount up to 10% of the overall investment. These costs may be avoided. The monopile may be dimensioned without scour protection. The additional costs for the monopile structure and the installation may be lower than the costs of scour protection. The occurrence of scour holes also requires additional attention for the cable connection and for shifts in the natural frequency of the tower modes. The latter item may require that the forbidden speed zones in the operational range shift. In this case a larger speed range, viz. a larger inverter rating, may be economic.

4.3 The support structure

Detailed designs of support structures, including costs and installation procedure, will be established in the DOWEC project. Because the design is very time consuming careful preselection of promising options is required. Within the DOWEC project a variety of locations is considered to set external conditions, such as water depth, composition of the soil and wind and wave climate. At these locations a large range of turbine concepts is evaluated, including an optimisation of the key parameters. This means that the costs and dynamic behaviour of the support structure needs to be known as a function of many variables. Therefore, an engineering model is being developed at Delft University of Technology, automatically generating a pre-design of the support structure, ref [4]. This pre-design is used to estimate dynamic behaviour, costs and duration of tasks relating to the support structure. The engineering model distinguishes between conceptually different elements, such as gravity base and pile foundations, mono-towers, tripods and lattice towers.

Figure 4 shows results as a function of water depth and of hub height. The variation of support structure costs with water depth exemplifies the assessment of concepts for a given turbine at various locations. At first sight, the monopile appears to be in favour for all water depths. However, the breakdown of the structural design and costs reveal several issues for further investigation. For example, the pile diameter of the monopile increases to values that are not suitable for conventional driven installation, as assumed in the cost model. The large increase in tripod costs can be contributed to the manufacture costs of the braces. The governing design load is the moment due to the hydrodynamic force on itself and several methods could be investigated to alleviate this moment and thus reduce costs.

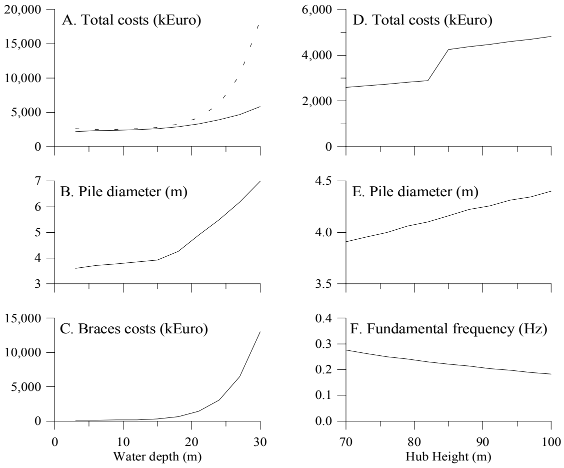

Figure 4: trends of support structures for 5 MW turbines based on an engineernig model (reference hub height 72 m, water depth 15). Graphs A to C show influence of depth, graphs D to F show influence of hub height.

4.4 The blade design

A blade design, for a turbine with pitch to vane power control, optimised for maximum energy yield is straightforward. With respect to part of the design variables, the optimum appears to be rather flat or in other words the design may deviate from the optimum design without losing too much energy yield, see Figure 5. This freedom can be used to adapt the blade design in order to meet blade-manufacturing requirements and/or to reduce structural loading.

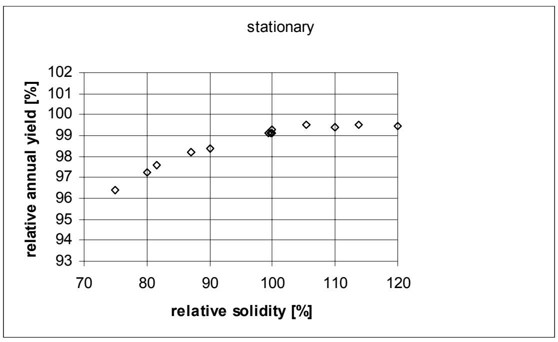

Figure 5: stationary annual yield as function of rotor solidity; 100% solidity refers to the optimum value

A comprehensive aerodynamic parameter sensitivity study has been carried out, ref [2]. The aim is to find a rotor blade geometry that combines a high annual energy capture with relatively low values for the extreme blade root and tower base moments. The manufacturing requirements and wishes have been used as constraints in the optimisation process. A total number of 29 configurations has been evaluated. Stationary and dynamic annual energy yield has been calculated, but also a full design load spectrum has been calculated for each configuration. Part of the variations was focussing at the chord distribution. Figure 5 shows the annual energy yield of different configurations as function of the solidity. This figure shows relative values; all values are divided by the corresponding value of the reference design. This reference design is the result of a, stationary, optimisation towards maximum energy yield. The figure shows that relatively large deviations from the optimum design are possible without loosing significant yield.

Figure 6 also shows the influences of the calculation methods. In the process of the design it is quite common to calculate the power performance of the design with a stationary model. The calculation may be improved by application of a correction factor for the influence of turbulent wind, ref. [3]. The most accurate calculation is also the most time consuming. The yield can be calculated by time simulation of the wind turbine behaviour using an aeroelastic model including simulation of the pitch and power control and using a stochastic wind field as input. The different methods show differences in the resulting annual energy yield for the same design. But, more important the optimum for maximum energy capture is different and the slope of the yield versus solidity curve is different, the rather flat optimum no longer exists. Both these differences are of influence when optimising the design towards minimum cost of energy. The inclusion of dynamic simulation in the optimisation complicates the optimisation process in many aspects. Not only the computation time increases significantly but also the design effort. Each blade design with an adapted chord distribution needs optimisation of the twist distribution. In the case of a dynamic calculation also mass and stiffness distribution has to be defined and the control setting has to be adapted to the new rotor characteristics.

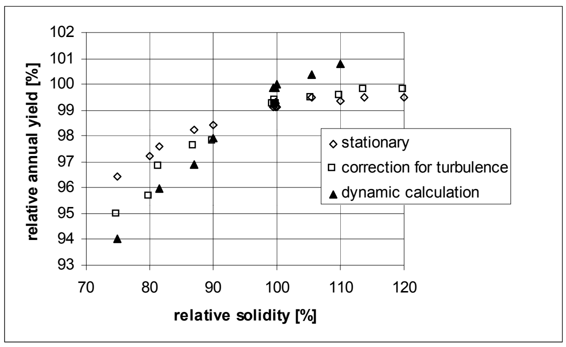

Figure 6: annual yield as function of rotor solidity; 100% solidity refers to the optimum value

5 CONCLUSIONS

The feasibility and the need for an integrated design approach in the different design phases of an offshore wind farm are demonstrated with respect to economics. In this process the wind turbine is treated as a key component in the farm. Further development of designs and models is required in order to be able to more accurately model the expected costs of energy and in order to reduce these costs.

Acknowledgement

The work presented here has been substantially funded by the EET-program of the Dutch Ministry of Economic affairs.

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