Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study.

G.J.W. van Bussel*, PhD; M.B. Zaaijer, M Sc.
Section Wind Energy, Faculty Civil Engineering and Geosciences,
Delft University of Technology, The Netherlands

SYNOPSIS

The DOWEC projects aims at implementation of large wind turbines in large scale wind farms. part of the DOWEC project a concepts study was performed regarding the achievable reliability and availability levels. A reduction with a factor of 2 with regard to the present state of the art seems fairly easy achievable. This is however not sufficient for application at more exposed sites. Availability levels are lower than targeted, but moreover the O&M cost turn out to be substantially higher than initially anticipated. The main cause for the high O&M costs is the rather frequent need for an expensive external crane vessel. A second design round is necessary to reconsider the reliability levels adopted for almost all concepts. Furthermore a more "farm like design approach" is needed to reduce major maintenance cost and increase availability.

INTRODUCTION

At present a relatively small amount of wind turbines have been placed in an offshore environment. Most of the projects so far have been realised in small farms in rather benign sites. The most recent project are two 2 MW wind turbines located in the North Sea 2 km in front of Blyth Harbour (U.K). It is probable that future large-scale offshore wind farms will be equipped with considerably larger wind turbines. Such large-scale wind farms will also comprise a substantial number of such large wind turbines (typically about 100). It is by no means evident that such large wind turbines will be scaled up versions of the presently applied onshore wind turbines. One of the reasons is that the offshore environment yields different loads and constraints, which may lead to another design solution. Another reason is that the scale of the farm, the economy of operating and the ease of maintenance of such a farm may dominate design choices. In The Netherlands a project is carried out by a number of industrial and research participants [1]. Within the framework of this DOWEC project, a concepts study is carried out. Part of it is an assessment of the opportunities and the drawbacks of the application of different designs of very large wind turbines for such large-scale offshore wind farms. Concepts of 5 MW wind turbines were defined and analysed upon their applicability in a large scale wind farms of 100 units located in the North Sea.

ANALYSIS OF THE O&M PROBLEM

Introduction

Apart from the size of future offshore wind farms there is another evident and important difference with on shore wind farms. Not only the installation is more difficult and more expensive but also building wind turbines offshore has a major impact on the accessibility for maintenance purposes. It may well be that the complete wind farm is inaccessible by boat or helicopter for a period of one or two months because of harsh weather conditions (wind and waves). And even when weather permits access to the turbines, the cost of offshore maintenance is far higher than the equivalent job on shore.

---

* **Authors Biography**
Dr. Gerard van Bussel is presently Associate Professor in Wind Energy at the Delft University of Technology. He has been working for more then 20 years in wind energy research. His present research interests cover rotor aerodynamics, offshore wind farm integrated design methods, and wind energy in the built environment. He is a member of the board of NEWIN and EWEA (the Dutch and the European Wind Energy Association respectively).
Michiel Zaaijer is presently research scientist in offshore wind energy at Delft University of Technology. His research focuses on dynamic behaviour of offshore turbines and integrated wind farm design methods. After his M.Sc. in physics in 1993 he has worked for several years as a researcher in the field of aircraft navigation

Lifting actions are performed relatively easy on land, but in an offshore environment require special, and therefore expensive and sometimes scarce equipment.

RAMS Terms and definitions

For a proper understanding of this paper it is useful to first clarify a number of terms that will be used frequently:

- **Reliability** of a system is the probability that the system will perform its tasks. This probability is usually determined as a percentage of time. For a wind turbine this indicates percentage of time it is producing the power that corresponds to the acting wind according to its nominal power curve.
- **Availability** is the probability that the system is operating satisfactorily. The major difference between reliability and availability is the O&M strategy of the system. A system can be very reliable: i.e. its failure frequency is extremely low, but when no maintenance or repair action is taken after a failure its availability becomes very poor.
- **Maintainability** is a more qualitative issue that addresses the ease of repair issue. It can though be expressed in terms of hours needed to complete a repair action.
- **Serviceability** regards in a similar way the ease of regular (scheduled) service.
- **Failure** is the termination of the ability to perform a required function of a system.
- **Accessibility** is the percentage of time that a (offshore) construction can be approached. Evidently the accessibility depends upon the equipment used.

Availability of wind turbines

A large number of aspects play a role in the resulting availability of technical systems. Apart from properties of the machine regarding failure frequencies and service demand, also other "external aspects" place a role in the availability level that can be achieved. In the figure below this is shown in a schematic way.

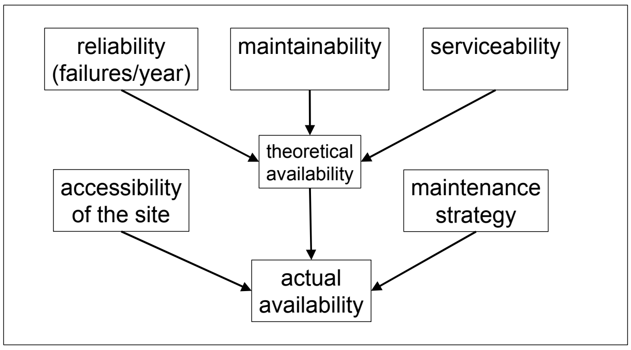

Fig. 1 Theoretical and actual availability

Nowadays commercial onshore wind turbines show very high availability levels. With a proper service organisation and by ensuring that regular maintenance actions are quick and can be performed in time the operators of modern wind turbines show actual availability levels of 98% or sometimes even beyond [2]. It must be stressed however that this is achieved through visiting a wind turbine about four times a year, either for regular service (usually twice a year) or for curing (repair) actions. In situations where both limited access and limited availability of maintenance equipment are at stake, such as for the offshore environment, this may easily lead to an unacceptable down time level. This makes it inevitable to assess the O&M demand of an offshore wind farm in conjunction with the other design parameters in order to achieve the required availability level against optimal cost expenditure. The latter being a trade of between investment costs in order to increase the reliability and the cost of maintenance actions to boost the availability to a high level. Since site accessibility always has a level below 100% for offshore conditions it is paramount to focus first on the decrease of the failure frequency of a an offshore wind energy system.

Reliability of components

Currently, there are a number of resources available that address failure rates of operational commercial (onshore) wind turbines [2,3]. The most useful source to obtain statistical information concerning failure classes of operational wind turbines turned out to [3]. These wind turbines operate on land but to a large extend in the coastal wind conditions of Northern Germany. Analysis of these data over the different type of turbines leads to an estimated total average of 2.20 failures per wind turbine per year. The DOWEC partners considered it reasonable to assume that such level can also be achieved for multi-megawatt wind turbines, at least when developed according to similar design lines as presently used on the current one megawatt scale. For the assessment of the different concepts to be defined later it was however necessary to elaborate the total failure frequency further, in order to come up with average failure frequencies for subsystems. In a workshop with experts from all the partners of the DOWEC team the following table was made up showing a distribution of the total failure frequency over the different components.

Component	Onshore failure frequency (failures/year)	Reduced failure frequency (failures/year)
Shaft & Bearings	0.02	0.02
Brake	0.05	0.05
Generator	0.05	0.05
Parking Brake	0.05	0.05
Electric	0.14	0.10
Blade	0.16	0.11
Yaw System	0.23	0.15
Blade tips	0.28	0.14
Pitch Mechanism	0.28	0.14
Gearbox	0.30	0.15
Inverter	0.32	0.16
Control	0.34	0.17
Total	**2.20**	**1.28**

Table 1 Estimated yearly averaged failure rates per component category

Note that in this table the hazardous external conditions that might lead to malfunctioning of the wind turbine, such as a lightning stroke, are internalised. This means that they are taken into account through an assessment of its impact on blades, blade-tips, pitch mechanism, bearings and electronics (the Inverter component and the Control component).

It was realised from the beginning that the on shore level of failure rates (2.20 failures yearly) was not adequate for offshore application, so an effort was made as well to assess improved components. Per component category the following types of improvements (with respect to ‘average’) are considered:
- selection of the most reliable implementation (e.g. an electric yaw/pitch system in stead of an hydraulic system)
- adding redundancy to (sub-)components
- using MIL-specs components

This resulted in an estimate of reduced average failure frequencies that can be achieved when rather simple measures are taken to modify the current onshore designs, see column 3 of table 1. Evidently there is a cost penalty related to such increase in reliability. This will vary from component to component but, according to the DOWEC experts, will be in the order of 25 (blades) to 100% (blade tips, pitch mechanism, control).

Maintainability

Maintenance (repair) actions have to be taken about two times a year, as could be deduced from the state-of-the-art failure frequency. Usually a repair action is taken by a crew of two persons that drive to the failed wind turbine with a service van. At the spot they enter the wind turbine and try to determine the cause of the failure and either start their repair action or come to the conclusion that extra equipment and/or spare parts are needed for the repair action. The extra equipment can either be "sky-work" utensils or a crane for heavier lifting operations. The repair time can be anything between an hour (a simple inspect and reset action) to some days, when an exchange of a major component turns out to be necessary.

Reduction of maintenance effort is essential when locating wind turbines offshore. At first there is the cost issue. Offshore work is between 5 to 10 times more expensive than work on land. A second example stressing the need reduction of maintenance demand is the so-called cranage problem. A standard onshore wind turbine requires a lifting operation every 3 to 5 years. The day rate for general purpose lifting equipment from the offshore oil and gas industry is at least a factor 10 higher than a land based crane for similar lifting heights. One of the reasons is that such an offshore crane will be substantially over-dimensioned in terms of lifting weight. Take with that the fact that also mobilising and demobilising such crane, which may well cost several days, must also be paid for, makes is inevitable to reconsider the design of the wind turbine with respect to its maintenance demand, when located offshore.
An alternative for large-scale offshore wind farms (typically of the order of some hundreds of megawatts) may well be to purchase a special purpose crane vessel as maintenance hardware equipment. Such equipment might be used during

installation as well. Furthermore it can serve as a permanent basis for the maintenance crew. When the design of the wind turbine is sufficiently adapted it might be even used as a maintenance base where complete nacelles including blades can be overhauled and prepared for replacement of another failed turbine. This maintenance solution was proposed in the Opti-OWECS study, for a 100-unit wind farm using 3 MW turbines, ref [4].

Serviceability

The service demand of the presently manufactured wind turbines in terms of man-hours is in the order of 40 to 80 hours [5]. Service visits are paid regularly and usually (except in the more demanding first year) about every 6 months. Often a more intensive service action has to be taken every five years. At that service shut down, which will take around 100 man-hours, some major components are overhauled and worn out parts are replaced. It will be clear that reduction of the number of service visits to wind turbines in an offshore wind farm must be aimed at. It is virtually impossible to get any significant reduction for the present onshore wind turbines, but in the design process that the DOWEC teams tries to implement a significantly more challenging target has been set.

Promising offshore wind turbine design lines

Taking the current wind turbine designs and their maintenance and service demand into consideration it is clear that future offshore wind turbine designs need to be seriously reconsidered in terms of their adaptation for the marine environment. Without going into too much details a number of promising design lines can be described:

- One design philosophy may be to <u>reduce</u> the <u>number of components</u> to a minimum. This will reduce the number of possible failure modes and therefore lead to a more reliable turbine, which is also easier to maintain and to service. A two bladed fixed pitch direct drive wind turbine would be a good choice within such a philosophy.
- A second approach may be to adopt a <u>modular design</u> line. In such case the modules should be designed and located such that easy maintenance and service is assured. Furthermore the exchange of faulted modules must be possible in a quick and easy way, in order to keep downtime low, and thus keep the availability on the required level.
- A third possibility is a design line using <u>integrated components</u> provided these integrated components are easy to service. However their maintenance will probably be difficult and long lasting. Therefore such integrated component approach should make use of highly reliable components resulting in low failure rates.
- The fourth design line described here adopts an <u>integral exchange</u> philosophy. As soon as a failure is detected an integral part of the wind turbine, which may well be a complete nacelle including blades is replaced. Repair can then take place at a location with a (better) controlled environment and provided with all necessary repair equipment

DEFINITION OF CONCEPTS

The DOWEC concepts project team decided beforehand upon the exclusion of Direct Drive machines. The main reason for it was the clear preference of the industrial partners within DOWEC not to mix up possible advanced rotor and control concepts with a choice for a power conversion concept, which was unfamiliar to them. Further it was agreed that not too many restrictions had to be taken into account beforehand. Therefore both 2 and 3 bladed machines, up wind and down wind operation as well as constant speed and variable speed were taken in consideration. Apart from the wind turbine itself also the support structure (everything below the yaw bearing) was an integral part of the development of the concepts. After a number of design considerations the concepts presented in table 2 were selected.

	Base Line	**Advanced**	**Robust**	**Stall-teeter**	**Smart-stall**	**Direct Drive**
Power control	active stall	pitch	passive stall	passive stall	smart stall	pitch
Nr. of blades	3	3	2	2	3	3
Rotor speed	constant/ double speed	partially variable	constant/ double speed	variable speed	variable speed	variable speed
Inverter	none	30%	none	full	full	full
Tower	tubular tower	tubular tower	tubular tower	truss tower	tubular tower	tubular tower
Foundation	piles	piles	monopile	gravity based	piles	piles
Rotor position	up wind	up wind	up wind	down wind	up wind	up wind
Hub	fixed	fixed	fixed	teeter	fixed	fixed

Table 2 DOWEC concept choices plus the Direct Drive alternative

Because of the more general interest of the researchers at TU Delft participating in the concept evaluation they kept the Direct drive machine as an extra option in their evaluation, hence the addition of the last column of table 2.

The Base Line concept implies a rather straightforward active stall design; a more or less scaled up version of current 1.5 to 2 MW Danish designs. Because of the size of the machine and its control system it is considered not suitable to use a monopile as its support structure. The Advanced concept represents the current trend of manufacturers to adopt variable speed pitch control. The Robust design concept aims at reduction of components and systems. No active power control, hence no blade pitching bearings and two blades only. A monopile support structure was adopted for this concept, mainly not to abandon such support structures already in the conceptual design phase.
The Stall-teeter design is inevitable coupled with two blades, having a teeter hinge at the hub, and is the most probable candidate to adopt down wind operation, together with a truss tower. The Smart-stall concept is most probably the most advanced wind turbine design, adopting variable speed with passive pitch control towards stall. This advanced design is then, most logically, combined with the base line support structure option. The Direct Drive concept, evaluated parallel to the DOWEC project team concept choices is in fact similar in its control concept to the Advanced concept, albeit that evidently a full variable speed option, inherently coupled to the direct drive generator and its advanced power converter, is implemented in this concept.

RAMS ASSESSMENT OF THE CONCEPTS

Reliability of the concepts

The reliability of the wind turbine concepts will be assessed using the reduced failure frequencies for the components given in table 1. Specific concepts will then yield different total failure frequencies. For instance, omission an inverter reduces the failure frequency by 0.14. The assessment is however not a straight forward implementation application of the failure frequencies for the components given in this table, because also the (positive or negative) effects the concept choice might have on certain component reliability levels was taken into account. An example of this more detailed level of assessment of the failure frequencies is the number of failures of the pitch mechanism. It will be larger for (positive) pitch control than for active stall (negative) pitch control, due to the higher number of anticipated pitch actions. The resulting reliability levels for the six concepts are shown in figure 2 below.

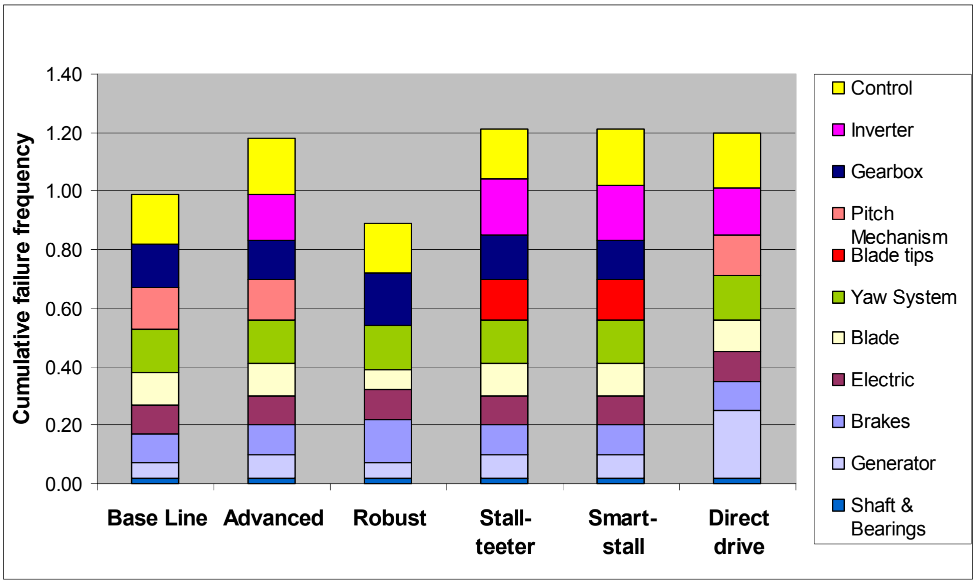

Fig. 2 Yearly (cumulative) failure frequencies of the concepts anticipated in the study

The reliability level ranges from 0.89 yearly failures for the Robust concept to 1.21 for both the Stall-teeter and the Smart-stall concept.

Concepts maintainability

The distribution of the reliability levels over the components does however not provide information about the maintainability of the concepts, i.e. about the character and the length of the repair actions that have to be taken in order to get the wind turbine in operation again. For the calculation of the availability and the costs associated with repair actions, such information is however inevitable. Thus the associated repair actions were assessed as well with respect to the concepts defined. The result is shown in table 3 below. With respect to the required maintenance action four categories were distinguished. Category 1 implies the most severe repair action and implies the use of an external (offshore) crane. The other categories require no other equipment than available at the wind turbine.

Maintenance categories	Base Line	Advanced	Robust	Stall-teeter	Smart-stall	Direct Drive
Cat. 1: Heavy components, external crane	0.17	0.17	0.14	0.18	0.17	0.18
Cat. 2: Large components internal crane	0.45	0.46	0.33	0.47	0.46	0.47
Cat. 3: Small parts, 48 hrs repair time	0.15	0.31	0.20	0.34	0.34	0.31
Cat. 4: Small/no parts 24 hrs repair time	0.22	0.24	0.22	0.22	0.24	0.24
Total yearly failure frequency	**0.99**	**1.18**	**0.89**	**1.21**	**1.21**	**1.20**

Table 3 Distribution of yearly failure rates over the maintenance categories for the 5 DOWEC concepts plus the Direct Drive concept

From table 3 it can be seen that statistically every wind turbine needs to be maintained with the use of an external crane every 5 to 7 years depending upon the concept chosen. The concepts are developed with the purpose to apply them in large-scale wind farms of typically 100 units. This means that 15 to 20 lifting action per year are requested to keep such a wind farm in operation. Since the DOWEC concept deals with 5 MW designs it must be anticipated that such a maintenance crane has do deal with significant hoisting heights (hub height is typically in the order of 100 m).

Service demand of the concepts

The targeted service demand of the DOWEC concepts is a visit once per 12 to 18 months. The service period is flexible in order to facilitate opportunity-based maintenance. With such maintenance strategy the regular service of the machines is carried out in combination with a failure that needs to be repaired. Since totalled failure frequencies are in the order of 1 failure per year such opportunity based maintenance strategy is adequate for the presently defined concepts. Still a more intensive service action has to be taken every five years in which some crucial heavy-duty components are overhauled.

Availability, O&M costs and cost of energy for the concepts

In order to make a comparison of some overall figures with respect to an offshore wind farm the availability and the energy yield of 100 unit wind farm equipped with the concepts developed so far was assessed. A preliminary study regarding the availability of the concepts, for a wind farm situated some 35 kilometres off the Dutch coast in north-west direction from the Rotterdam Harbour area, shows availability levels of 85 to 94%, depending upon the concept adopted. This study is performed using a Monte-Carlo simulation tool developed at TU Delft [6,7]. With this tool it is possible to simulate a 20-year period of wind farm operation including stochastic failure occurrence of the machines and weather conditions. It was clear that the availability level for the majority of the concepts was unacceptable (a preliminary target of 94% was set at the start of the concept study); the only exception being the Robust design. The reason for it was the anticipated accessibility level of the chosen site, which is on the average around 60% (dependent upon the season) and the fact that an external crane ship is never immediately available.

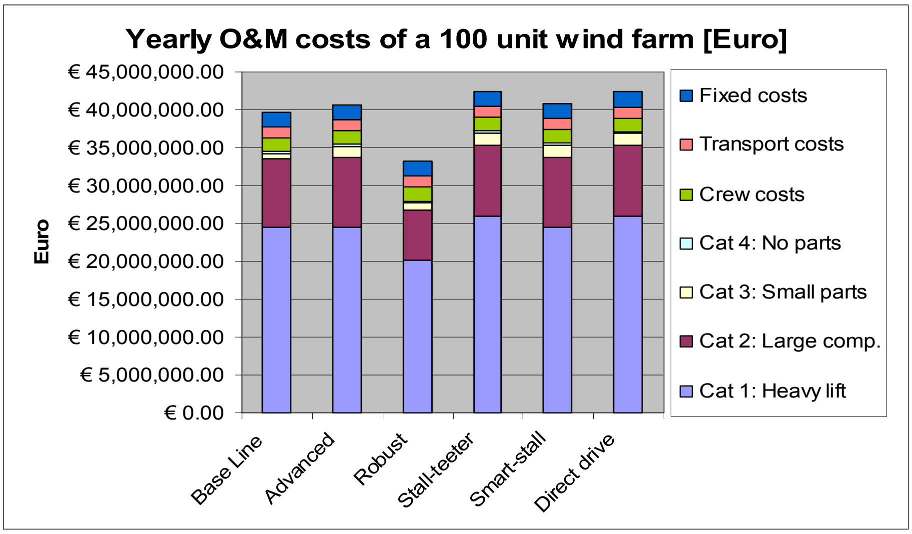

Fig. 3 Yearly O&M costs for a 100 unit wind farm equipped with the anticipated concepts

The yearly O&M costs were determined using a simple expert system [8]. This expert system comprises trend lines extracted from the Monte-Carlo simulation tool, and determines the availability and related O&M costs of a 100-unit wind farm as a function of the machine reliability, an average wind speed parameter, and the distance to shore. The result with respect to the O&M costs is shown in figure 3

The level of yearly O&M costs turns out to be about 4 to 4.5 % of the total wind farm investment, which is substantially higher than the challenging 2.4% for the Opti-OWECS design solution [4]. Two things can be noticed directly when looking to figure 4. Indeed the Robust design is most in favour with respect to the O&M expenses, but the most striking is the contribution of category 1 to the O&M costs. More than 50% of the average yearly expenses for O&M have to be paid for lifting operations using an external crane. This has a number of reasons. At first the external cranage demand of the concepts considered, which leads to15 to 20 lifting action per year for the wind farm, and second the type of crane vessel needed to perform hoisting operations at hub height (around 100 m). Figure 5 below taken from [9], shows the trend lines for the day rate of offshore crane vessels. It can be seen that at a hoisting height of around 85 m there is a sudden increase in day rate with a factor of 4, and evidently all external lifting operations for the DOWEC concepts have to be performed using the expensive crane vessels.

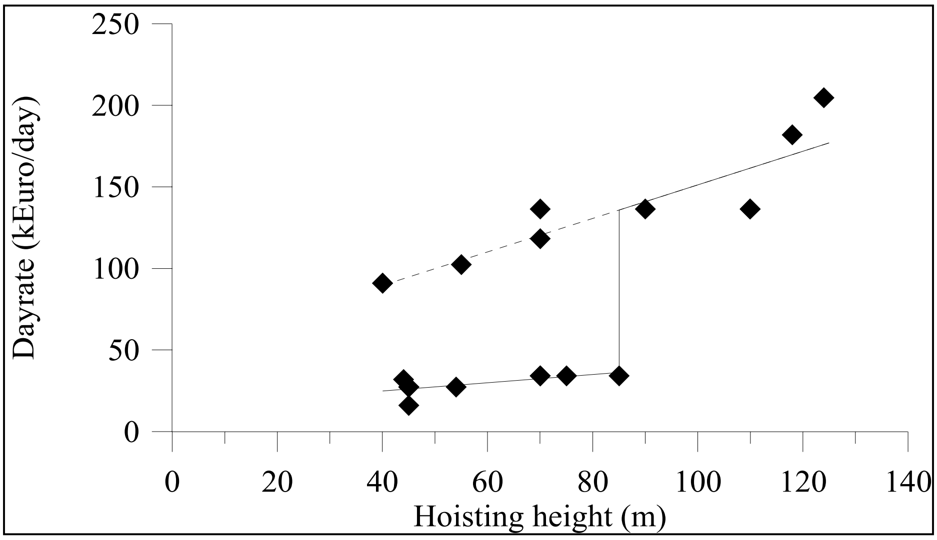

Fig. 5 Trend of day rate for crane vessels as a function of hoisting height

The cost of energy is usually determined with the LPC approach [10]. By adopting the standard 20 years economic lifetime and a yearly discount rate of 5% [11], the LPC of all concepts for the offshore location in consideration turned out to be higher than the target value of 5.5 Euroct/kWh set in the beginning of the concept study. The calculated LPC for the Robust Design wind farm however came quite close, thanks to its fairly low investment cost, its relatively low O&M costs and its high availability. These properties ruled out its 6.5% lower potential energy yield with respect to the Base Line concept and its 9% lower potential energy yield with respect to the Advanced and the Direct Drive Concept.

DISCUSSION

The results show that the concepts as presently defined are not yet suitable for further development. Definitely not when application in large-scale offshore wind farms on rather remote locations is targeted. The total level of reliability is still insufficient, although the Monte Carlo simulation for a wind farm equipped with Robust concept wind turbines showed an acceptable availability level of 94% on a fairly remote location.

The regular demand of a large external cane vessel is killing for the O&M costs and hence for the cost of energy (LPC) for all concepts. There are several ways to get over this problem. One way is to design the wind turbines such that they can completely rely on built-in facilities for exchange of components. This requests a further development of the concepts along a true modular design line.

Another approach might be to adopt the Opti-OWECS design solution approach, which includes the purchase of special purpose O&M hardware as part of the total wind farm investment. In that case a self-propelled jack-up platform was modified to perform the required lifting actions, but simultaneously serve as a maintenance base for the offshore wind farm. In this case the concepts can be further developed along the integrated component or integral exchange design lines.

CONCLUSIONS

1. Presently achieved reliability levels of onshore wind turbines is insufficient for application offshore

2. An increase with a factor of two of the reliability of wind turbines can be achieved against reasonable effort and costs, by choosing highly reliable components, selection of the most reliable implementation and introducing redundancy.

3. A yearly failure frequency of around one for each turbine prevents the application of such designs for more demanding less accessible sites.

4. The DOWEC 5 MW concepts as presently defined are not adequate, for real offshore applications, with the Robust design concept as the only exception.

5. Availability levels at the design location (35 km off the Dutch North Sea coast) ranged from 85% to 94%

6. O&M costs of the DOWEC 5 MW concepts, around 4 to 4.5% of the initial investment, are beyond the level that was initially foreseen. Together with the fairly low availability levels this leads to energy costs above the targeted level of 5.5 Euroct/kWh for all concepts; the Robust design getting the closest to the target.

7. Implementation of a much more "farm like design approach" may overcome the current dilemma with respect to O&M costs and availability. A purchased special purpose-lifting vessel together with an integral exchange design line for large components might simultaneously reduce lifting costs significantly and increase the availability of the wind farm.

ACKNOWLEDGEMENT

Part of the work presented here is performed in the project ‘DOWEC concepts’, funded by NOVEM, the Dutch Agency for Energy and Environment, and is ongoing in the DOWEC project, funded by the Dutch EET-program.

REFERENCES

1. H.B. Hendriks e.a., DOWEC Concept Study, Evaluation of Wind Turbine Concepts for Large Scale Offshore Application, *Proceedings of OWEMES*, ENEA, Italy, April 2000.
2. MWEP Jahresauswertung 1996-2000, *ISET*, Kassel, Germany, ISBN 3-9805896- 6-8/5-X/n-n.
3. W. Eggersglüβ, Wind Energie IX-XI, *Praxis-Ergebnisse 1995-1999*, Landwirtschaftskammer Schleswig-Holstein, Osterrönfeld, Germany.
4. M.C. Ferguson (editor); M. Kühn; G.J.W. van Bussel; W.A.A.M. Bierbooms; T.T. Cockerill.; B. Göransson; L.A. Harland; J.H. Vugts; R. Hes, Opti-OWECS Final Report Vol. 4: A Typical Design Solution for an Offshore Wind Energy Conversion System, *Institute for Wind Energy,TU Delft, The Netherlands,* 1998, ISBN 90-76468-05-2.
5. Chr. Schöntag, Optimisation of Operation and Maintenance of Offshore Wind Farms, *Report IW-96-108R*, *Institute for Wind Energy, TU Delft, The Netherlands*, November 1996
6. G.J.W. van Bussel; Chr. Schöntag, Operation and Maintenance Aspects of Large Offshore Wind farms, *Proceedings of the 1997 European Wind Energy Conference,* Dublin, Ireland, October 1997, pp. 272-279.
7. Chr. Schöntag ; G.J.W. van Bussel, Optimisation of Operation and Maintenance, Opti-OWECS Final Report Vol. 2: Methods Assisting the Design of Offshore Wind Energy Conversion Systems, Part B, *Institute for Wind Energy, TU Delft, The Netherlands*, ISBN 90-76468-03-6
8. G.J.W. van Bussel; The Development of an Expert System for the determination of Availability and O&M Costs for Offshore Wind Farms, *Proceedings of the 1999 European Wind Energy Conference,* Nice, France, March 1999, pp. 402-405
9. M.B. Zaaijer, G.J.W. van Bussel, Toward selection of concepts for offshore support structures for large scale wind turbines, *Proceedings of MAREC 200: Marine Renewable Energy Conference*, Newcastle, U.K. March 2001
10. .J.O. Tande (edt); Estimation of Cost of Energy from Wind Energy Conversion Systems, *IEA Recommended Practices for Wind Turbine Testing* International Energy Agency, edition 1994.
11. A.R. Henderson; G.J.W. van Bussel, Offshore Wind Energy in Europe - the Current Status, *Proceedings of MAREC 200: Marine Renewable Energy Conference*, Newcastle, U.K. March 2001.