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Disclaimer

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This report represents deliverable *Deliverable 4.3* “Integral impact of the results from WP1, WP2, WP3, and WP4 on the cost of energy at system level” of the TKI project “Design for Reliable power performance” (D4REL).

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Summary

Within the D4REL project the aim is to reduce the levelized cost of energy (LCoE) of an offshore wind turbine by 6.4%. This is realized by looking at the different parts of the wind turbine and analysing those to see where improvements can be done. Four technologies have been developed to reduce the LCoE. These are:

WP1: Electrical generator systems for reliability:
Aim: improving the availability of electrical generator systems by using modular conversion system concepts that are fault tolerant, re-configurable and self-healing.

WP2: Next Generation of Robust Offshore Blades:
Aim: generating the knowledge and design capability that enables the development of the next generation of larger and lighter offshore wind turbine blades that do not rely on failure prone features and thereby lower the cost of energy.

WP3: Reduction of uncertainties by integral substructure design:
Aim: realizing cost reduction in the support structure of offshore wind turbines while keeping a sound, safe and reliable design by using integral probabilistic structural design techniques; developing self-adaptive control algorithms dealing with constantly changing environmental conditions (e.g. water depth changes due to tides and/or scour, ice formation, etc.).

WP4: Self adapting control using system identification for robust control:
Aim: to improve the availability of offshore wind turbines by developing, (a) innovative adaptive controllers that optimize their performance using estimation of time-varying turbine parameters from system identification, and (b) condition based control that delays approaching failures by operating the turbine at reduced loading on parts with deteriorated condition.

In this report a quantitative analysis is performed on the impact of the developed technologies on the Cost of Energy (CoE). This is first done on component level, considering the individual developments in the different work packages (Chapter 2-5). Finally, in Chapter 6-7, the individual improvements are combined to arrive at an estimate of 3.8% of lower CoE on system level.

1. Introduction

D4REL is an R&D project aiming at developing innovative technology & tools for reducing uncertainty in both the design and operation of offshore wind farms.

Limiting the design uncertainty makes it possible to reassess and reduce the safety factors which are used in the design of wind turbines to account for the modelling uncertainty in the design process. More accurate modelling allows for lower safety factors, which in turn makes it possible to achieve less conservative (and, hence, cheaper) turbine design.

The operational uncertainty will be reduced by using fault tolerant and condition-based control methods. Fault tolerant control aims at accommodating simple, non-critical failures in the wind turbine by reconfiguring the control algorithm to prevent unnecessary shutdowns (missed production). Condition-based control, on the other hand, employs health monitoring techniques that signals an approaching critical component failure, and adapts the control algorithm to reduce the load of that component and delay/avoid failure. Hence, the fault tolerant and condition-based control methods will lead to less unplanned maintenance and higher supply certainty.

Improving the predictability of the performance of large offshore wind farms implies the development of tools and methods that assist the designer and operator/developer in achieving a reliable asset management of the offshore wind power plant. Key role in this target is the optimal operation of the wind turbine and the ability of the wind turbines to take the autonomous decisions for optimal operation. This project aims for a more reliable wind turbine with low performance uncertainties by:

- Improving the availability of electrical generator systems by using modular conversion system concepts that are fault tolerant, re-configurable and self-healing;
- generating the knowledge and design capability that enable the development of the next generation of larger and lighter offshore wind turbine blades that do not rely on failure prone features and thereby lower the cost of energy;
- realizing cost reduction in the support structure of offshore wind turbines while keeping a sound, safe and reliable design by using integral probabilistic structural design techniques;
- developing self-adaptive control algorithms dealing with constantly changing environmental conditions (e.g. water depth changes due to tides and/or scour, ice formation, etc.);
- substituting unplanned with planned maintenance by bridging the gap between existing condition monitoring and fault tolerant control schemes.

Altogether, reducing design and operational uncertainty is expected to have a significant contribution to the reduction of Cost of Energy (CoE) of offshore wind farms. In this report, a quantitative analysis is made of the impact of the technologies developed in the project on the CoE. This analysis is first performed on component level in Sections 2 - 5. Subsequently, the benefits on system level are analysed in Section 6.

2. Electrical generator systems for reliability (WP1)

2.1 Modularity in Generator Systems

POWER electronic converters have been shown to be a major contributor to the failure rates of wind turbine drivetrains. This makes addressing their failures and improving their availability an important route towards reducing cost of energy. One method of doing this is through the addition of modularity in the converter system. Modularization is a design approach that decomposes a system into a number of ‘modules’ or components. The motivations behind the use of this concept have been diverse: from increasing manufacturability in machines, and standardization of parts for the supply chain, to improving part load efficiency and system reliability. For wind turbines, this concept is attractive from the perspective of improving the availability of the turbine system predominantly in two ways. First, the introduction of fault tolerance, where the faulted module is bypassed and the remaining system continues operation with the same or a lower rating. Second, the increased maintainability of such a system, by making failed modules easier and cheaper to replace.

It can be concluded that:

- For systems with continuous repair, modularity does not improve availability. In fact, modularity would increase the cost of repair as it would involve a higher number of maintenance visits.
- For systems with periodic repair, improvement in availability comes with some form of over-rating and modularity.
- As wind turbine systems often run at partial loading conditions, they are well suited to take advantage of this to improve availability without the need for either over-rating or redundancy.
- The improvement in availability reduces with each increment in the number of modules. The improvement after the number of modules exceeds 10-20 becomes insignificant.
- Extreme modularity is a viable option when it can lead to a reduction in failure rates and hence offer an improvement in the availability of the system.

According to the study by Carroll et al.[1], approximately 44% of the failures in the fully rated converters are due to the cooling system. With the introduction of extreme modularity, it is possible to implement thermal management for the converter using passive cooling. It can be hypothesised that this change would result in a maximum possible reduction of the failure rate by approximately 44% as it eliminates a failure mode.

But it must be noted that the failures considered in the paper are for the first five years of operation (so they include infant mortality rates), also the failure rates for the converters are quite high (0.593 failures per turbine per year).

As a result, an improvement of the availability of the generator system by 5% is estimated. Since the contribution of generator failures to the overall downtime of a turbine (7.3%) is around 16%, an overall increase in availability by 0.06% is estimated.

2.2 Converter Topologies for Improved Lifetimes

Conventional control schemes for wind turbines are based on the extraction of maximum energy from the wind. However, considering the cost of maintenance for far offshore wind turbines, it is important to look at reliability oriented design and control strategies that look to maximize the availability of the wind turbines rather than maximize the power production at each instant.
Existing topologies like the NPC, A-NPC, H bridge, T-type are compared from the point of view of reliability based on developed drivetrain, power semiconductor loss and thermal models.

It has been found that in a comparison of different three-level topologies, the 3L-ANPC and the 3L-T2C show the highest lifetimes. When a component over-rating is considered, the 3L-NPC topology shows a large improvement and the lifetime performance is comparable to that of the overrated topologies. However, the loss performance of the 3L-ANPC remains marginally better than the other cases considered in this study.
In conclusion, the use of over-rating; be it in the form of overrated topologies (like the ANPC and the T2C), or the use of overrated components, is successful in improving the lifetime performance of converters. However, the improvement offered by overrated topologies over the use of overrated components is not significant and it is unlikely to replace the current practice of using overrated components.

2.3 Dynamic Thermal Management

Junction Temperature and Junction Temperature Cycling are two major driving factors of failure mechanisms in power semiconductors. Previous studies have shown that active control concepts such as power sharing, reactive current circulation, DC-link regulation, modulation strategy, and active gate control can successfully increase the lifetimes of the power semiconductors in converters by reducing junction temperature cycling. Another possibility is the use of controlled dynamic cooling to reduce the amplitude of temperature cycles.
The dynamic thermal management system uses the modulation of the flow rate to reduce temperature cycling amplitudes. When junction temperature reduces, the system reduces flow rate, thus making the cooling system less efficient, thereby reducing the amplitude of the cycle.

It can be concluded that:

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[1] J. Carroll, A. McDonald, and D. McMillan, “Reliability comparison of wind turbines with dfig and pmg drive trains,” IEEE Transactions on Energy Conversion, vol. 30, no. 2, pp. 663–670, 2015.

- As most wind turbine converters today use liquid cooling for the power semiconductors, the use of controlled dynamic cooling could play a significant role in reducing stresses and increasing lifetimes.
- The dynamic thermal management based on control of junction temperature performs better than when case temperature is used. However, estimating/measuring the junction temperatures is difficult, while case temperature can be measured directly.
- It is indicated that using such a system could reduce the damage of the power semiconductor between 0 – 40% depending on the conditions considered.

It is indicated that using such a system could reduce the damage of the power semiconductor between 0 – 40% depending on the conditions considered. Further simulations and experiments are currently ongoing to see how different parameters can affect this. As this aspect has not completely been studied, therefore, a conservative figure for lifetime improvement (maybe 10-20%) should be considered. Notice that this effect on lifetime is only for wear-out failures of power semiconductors.

As lifetime extension is difficult to include directly into the cost model, it will be assumed that the total number of failures in the converter during the extended lifetime remains equal to that of the currently used converters, meaning that an extension of the lifetime by 15% is translated into a similar increase of the availability of the converter. Since the contribution of converter failures to the overall downtime (7.3%) of a turbine is around 2%, an overall increase in availability by 0.02% is estimated.

3. Next Generation of Robust Offshore Blades (WP2)

The quest for robust and higher power output at reduced costs per offshore wind turbine drives the design towards increasingly larger rotor diameters that have positive influence on the usage of the electrical grid (by larger capacity factor) and wind farm power production. To counter the increased mechanical loading in extreme off-design conditions these increasingly larger rotors have relatively small solidity. The much more slender rotors therefore have to be equipped with relatively thicker profiles in the rotor blades. The drawback of thicker blade sections is that the use of these rotors is accompanied with relatively large uncertainties in performance. This is motivating the application of vortex generators (VG) and thick trailing edges. These techniques are also not without risk; the modelling of rotors with vortex generators and thick trailing edges is a challenge in itself. The entire wind energy sector would be greatly assisted when reliable models for the use of vortex generators and thick trailing edges would be available.

In this work package Siemens is collaborating with ECN and TU Delft in the theoretical model development and practical implementation of these flow device models in the RFOIL blade section design code. Siemens will perform extensive wind tunnel measurements together with the TU Delft PhD researcher and bring in the project the results of previous wind tunnel experiments. The knowledge and experience of the Siemens CFD modelling group will be put to use in this work package.

The overall objective of the work package ‘Robust Power Performance’ is to generate the knowledge and design capability that enables the development of the next generation of larger and lighter offshore wind turbine blades that do not rely on failure prone features and thereby lower the cost of energy. More specifically this work package is to enable the accurate and reliable simulation of the effects of vortex generators and thick trailing edges on wind turbine performance by extending the existing airfoil design tool RFOIL with new models for the effect of vortex generators and thick trailing edges on airfoil aerodynamic performance that are validated against experimental data. From numerical and wind tunnel experiments flow field data will be obtained and analysed to create a vortex generator model that will be implemented in RFOIL. Partners in this work package ECN, Siemens, and TU Delft make sure that a practical solution for industry is developed that is based on solid scientific research.

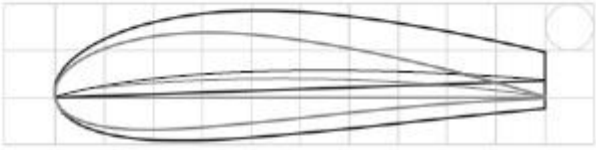
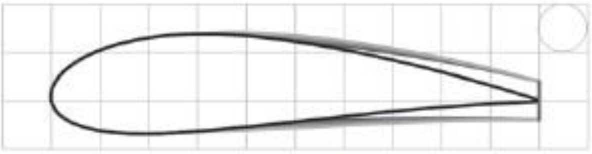
3.1 Vortex generators

The expected major effect of properly designed vortex generators (VGs) is increased energy production from the rotor.
The yield improvement will depend on the initial blade design and the soiling conditions of the blade (and therefore may be related to siting conditions), amongst other factors. Some studies suggest improvements on the order of 1-3% AEP may be expected. Keeping all else unchanged; this suggests a 1-3% decrease in the CoE assuming that the costs of VGs are nearly zero. VGs are especially effective at mitigating roughness-induced performance losses. Therefore, in this report an average value of 2% is used.

There are a number of additional benefits. These are however harder to quantify and are therefore not included into the CoE analysis. Some of them are listed below.

- Materials/Loads
  - VGs would increase root-contribution to blade loads slightly (by definition, VGs should delay separation, i.e. increase lift). One would think this increase is only a small fraction of the global load profile and is still well accounted for by the modest safety factors involved in the design. -> Cost increase
  - Reduction of flow separation on the inner blade region should be accompanied by a reduction in fatigue stress (flow separation is an inherently unsteady process). -> Cost decrease
- Maintenance/Installation
  - Although probably not a major issue, VGs are a retrofit device. Devices detaching during operation would be a costly fix. Smart strategies should be able to handle this - at least, the manufacturer probably has an idea how sensitive the success of the entire VG installation is to the failure of a few devices. -> Cost increase
  - VGs retrofitted to operating turbines would be costlier than installation during the manufacturing stage
- Safety Factors
  - Compared with very simple engineering models to assess the impact of VGs (such as extrapolation of polars), the improved models from D4Rel should reduce the uncertainties of the estimated improvements and require less conservative safety margins. Having said that, more experience and model improvements are required before any significant benefits are seen. -> Cost decrease
- Noise
  - Reduction of separated flow regions would also reduce turbulent noise sources. On the other hand, the devices themselves could generate tonal emissions. This can be practically thought of as an extra cost for design effort for acoustics considerations and might be especially relevant for onshore permitting due to noise regulations.

3.2 Thick trailing edges

 Figure 3. Cutting off Method	 Figure 4. Added Thickness Methods
Figure 1 a blunt trailing edge profile created by applying, in theory a larger chord, cutting of the profile at the original chord having overall a greater cross section	Figure 2 A thick or blunt trailing edge created by adding symmetrically thickness to the profile after the maximum profile thickness resulting a larger cross section.

With thick trailing edges, for a given airfoil geometry two options are available; see Figure 1 and Figure 2. Option 1 the chords can be reduced at the same relative thickness of the profile cutting the profile at e.g. at 90% of the chord. Option 2 is modifying the profile by adding symmetrically thickness to the profile from the chord position where the profile height is largest to the trailing edge. For both options the advantage is twofold, the blade structure can be made more efficiently having more material at a larger distance from the principle axis of the cross section. Another positive effect of the thicker profile is that the stiffness of the cross section increases, which is especially of interest for the long and more slender rotor blades applied in the new multi MW wind turbines.

Aerodynamically the effect of the thicker profiles is determined with the improved RFOIL tool. The results show that the lift curve is nearly identical to the original (thin) profile while the drag is higher. The stall behaviour of the blunt trailing edge airfoils is more robust enabling a more optimal twist angle distribution.

When the thick trailing edge profiles are applied at the blade tip the structural effects are reduced due to the fact that the loads at the outboard stations of the blade are relatively low. By applying the thicker profiles the required skin/wall thicknesses due to fatigue loads can be reduced but quite often the fatigue loads are not the design driving loads.

Modelling the thick trailing edge profiles on the D4Rel reference wind turbine, in ECNs BladOpt model, see report ECN-C--01-011[2], by increasing the 18% thick profiles at the tip to 20% and increasing the width of the spar inside the blade from 60% chord to 66% chord results in a minimal increase in weight (less than 1%) of the rotor blade compared to the weight of the reference blade. This is partly due to the fact that a minimum beam wall thickness of 3 mm is applied.

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[2] Bulder, B.H. et.al, 2001, ECN--C01-011, Theory and user manual BladOpt.

4. Reduction of uncertainties by integral substructure design (WP3)

To make offshore wind cost effective there is a need to reduce the cost of energy. The aim of this work package is to investigate where cost reductions in the support structure are possible while keeping a sound and safe design. Probabilistic design methods (structural reliability methods) are used to study whether there is any conservatism in the design of support structures.

At this moment the design of support structures for offshore wind turbines is done in collaboration between the wind turbine manufacture and a specialized engineering company like Ballast Nedam or Ramboll. The support structure consists of a foundation, a sub-structure and a tower. The tower is designed by the wind turbine manufacture, while the foundation and sub-structure are designed by the engineering company. The structural design is verified by applying partial safety factors as prescribed in the standards of Germanische Lloyd or DNV. Partial safety factors are applied to compensate for uncertainties in the design process, and improved knowledge may help to reduce these factors and hence contribute to reduction in COE without compromising the reliability of the design.

As an alternative to applying (possibly conservative) partial safety factors, probabilistic design methods can be applied. In the past, probabilistic design methods were already used for wind turbines. For instance in the JOULE-III project PRODETO (PRObabilistic DEsign TOol) [1], the PhD-thesis of Veldkamp [2] and the work by Soerensen [3]. The focus in this work package will be on the support structure while taking the complete offshore wind turbine system in to account.

The optimisation is currently performed by reducing the mass as much as possible without getting utilisation ratio higher than 1 along the structure. In the current model, uncertainties in the material properties, loads dimensions etc. are taken into account by using safety factors. This might lead to an over-designed structure as there is no knowledge of the effects of the uncertainties on the loads. The new model should therefore take as an input the uncertainties of the before mentioned design properties and determine the probability of failure of the structure. An open source probabilistic tool, called Pyre, is therefore added to the model. This determines, based on the uncertainty, materials or loads, a probability of failure. Using the probability of failure as a constraint instead of the utilisation ratio, the uncertainties can be taken into account during the optimisation and thus create support structure with a lower mass. It was found that for the D4REL reference turbine a 6.7% cost reduction in the support structure can be achieved with this new design approach.

5. System Identification for Robust Control (WP4)

5.1 Adaptive tower damping

Offshore wind turbines operate in harsh, time-varying environmental conditions resulting in significant uncertainties during the design. More specifically, wind turbine manufacturers face the problem that the support structure modal parameters (such as frequency and damping) deviate significantly from their design values. Even more, these parameters also vary with time because of e.g., scour, formation of marine sand dunes and biofouling. As the true support structure frequency is not exactly known in advance, is time-varying and deviates from one turbine in the farm to another, a robust design of the support structure is required to ensure it can withstand the worst-case loading that may occur during its lifetime. Even more, the wind turbine controller, if tuned for a wrong support structure frequency, is not only expected to perform sub-optimally but might even increase the loads on the support structure. This leads altogether to conservative designs of the support structure with increased material costs and questionable reliability.

In Task 4.2.1 of the D4REL project, an adaptive control algorithm is developed that reduces the loads on the support structure in a worst-case sense in the presence of uncertainty in the support structure frequency. This parameter is assumed to be unknown during the design apart from a realistic possible range of variation, very slowly-varying and online-available (i.e., identifiable using measured data, for one possible approach). Given this setting, a control algorithm is developed that adapts its parameters based on the tower frequency, estimated by some means. The purpose is to achieve improved performance in terms of reduction of fatigue loads on the support structure when compared with conventional control where the controller is tuned for the nominal (design) value of the tower frequency. Based on a detailed analysis, the focus of this work is to put on the active fore-aft tower damping control loop as this loop suffers most by the considered changes in the tower dynamics. Damping of the fore-aft vibrations of the tower is achieved, as usual, by controlling the thrust force on the rotor by means of collectively pitching the blades based on the measured tower top acceleration.

The study has revealed that the current approach to tower damping control does not provide optimal fatigue load reduction performance when the natural tower frequency of the wind turbine is different from its nominal value, typically used for the design of the controller: whereas in some situations the DEL reduction is less significant than in the nominal case, several scenarios have shown that such an approach could even increase DELs when compared with open-loop operation. On the other hand, the proposed adaptive tower control strategy has been shown to bring guaranteed and satisfactory performance in almost all situations. This strategy allows for a reduction of fatigue loads on the support structure of up to 3%, which indicates that a reduction of the support structure costs of the same order can be expected by using the proposed adaptive control algorithm.

5.2 Condition based control

Offshore wind farms are expensive to maintain and it is difficult to achieve a similar availability to onshore farms. In D4REL, the possible benefit of condition based control is examined, where the controller is adapted to modify the loading of parts depending on their condition. This benefit is only examined in terms of annual energy production. Other, secondary benefits may be possible, but are not considered.

Literature indicates that the most relevant parts are the drive train, the blades and the pitch systems. Literature does not give a clear relation between loading and remaining life time of the components, so it is assumed that the remaining life time is inversely related to the loading of the parts.

An O&M case study into the maximum possible benefit of the condition based maintenance and condition based control shows that an AEP increase of up to 2% can be achieved. For the considered reference wind farm (consisting of 120 3MW wind turbines), this boils down to 72 M€ over the lifetime of the farm. However, this figure represents an upper limit on the achievable benefit as it is based on an idealistic scenario. More specifically, it is computed by assuming that CBM is applied to all turbine components and that the condition signal is always received enough in advance of the actual failure to allow for performing the O&M planning and waiting activities before the actual failure occurs. The calculation of a more accurate estimate of the achievable benefit requires more detailed data on the failure prediction capabilities of the condition monitoring systems, which was not available in this study. However, if for example CBM is applied to only 50% of the cases, and if the assumed percentage of the logistics/waiting time that the turbine remains in operation is reduced from 100% to 30%, the lifetime revenue increase would drop down to the more realistic value of 10.8 M€ (availability increase by 0.3%).

With respect to condition based control, two methods have been investigated: power down-regulation and a novel pitch reduction control. Both methods deliver fatigue load reductions at the expense of some power loss, but are complementary as they target different components. In terms of economic benefits, significant revenue improvements are estimated by combining condition monitoring systems with CBM and condition based control, ranging from 1.5-1.7 M€ (for the gearbox and the yaw mechanism) to 2.7 M€ (for the pitch system). This sums up to a total of 5.9 M€ additional revenue. This benefit is solely due to an increased availability by 0.17%. This benefit comes in addition to those from CBM, so that a total of 0.47% increase in availability is obtained.

6. CoE analysis on system level

This section provides a quantitative estimation of the benefits of the technologies, developed in the D4REL project, on the CoE on system level. To this end, the analysis made in the previous sections on component level is combined. These are summarized in Table 1.

Cost component	CAPEX		OPEX	AEP	
Technology	Blades	Support structure	O&M	Gross AEP	Availability
Generator modularity (Section 2.1)					0.06%
Converter topology (Section 2.2)					
Thermal management (Section 2.3)					0.02%
Vortex generators				2%	
Thick trailing edges		0%		0%	
Probabilistic design (Section 4)		6.7%			
Adaptive control (Section 5.1)		3%			
Condition based control (Section 5.2)					0.47%
Total		9.7%		2%	0.55%

Table 1 Quantitative analysis of the impact of the D4REL technologies on the CoE

7. Conclusions

This report describes the positive and negative effects of all innovations investigated in the D4Rel project. The investigations show that effects are based on improved availability, improved energy yield and decrease of the wind turbine cost (decrease of capital cost).

The overall effect shown is:

- on AEP is ~2.5% , based on 2% increase in AEP due to vortex generators and approximately 0.5% increase in availability.
- 9.7% reduction of the support structure CAPEX. The share of the support structure cost on the total required CAPEX of an offshore wind farm is approximately 20 – 25%, for water depth of approximately 30 – 35 m. This would then result in a total reduction of approximately 2%.

ECNs cost model shows that for large offshore wind turbines the LCoE is based on 55 – 65% on the capital cost and for 35 – 45% on the operational cost.
Applying these shares the total cost reduction due to D4Rel investigated innovations can be 1-(1-0.6*0.02)/1.025 resulting in approximately 3.6% cost reduction of the LCoE.

In the project plan, the expected impact was estimated at a total of 6% reduction of CAPEX, 4% reduction of OPEX, and 1.25% AEP increase. The total LCoE reduction target, set at the proposal stage, 1-(1-0.6*0.06-0.4*0.04)/1.0125=6.4%, proves to have been quite ambitious.

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