Investigation of Wind Turbine Rotor Concepts for Offshore Wind Farms

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Abstract. Current plans in offshore wind energy developments call for further reduction of cost of energy. In order to contribute to this goal, several wind turbine rotor concepts have been investigated. Assuming the future offshore wind turbines will operate only in the offshore wind farms, the rotor concepts are not only evaluated for their stand-alone performances and their potential in reducing the loads, but also for their performance in an offshore wind farm. In order to do that, the 10MW reference wind turbine designed in Innwind.EU project is chosen as baseline. Several rotor parameters have been modified and their influences are investigated for offshore wind turbine design purposes. This investigation is carried out as a conceptual parametrical study. All concepts are evaluated numerically with BOT (Blade optimisation tool) software in wind turbine level and with Farmflow software in wind farm level for two wind farm layouts. At the end, all these concepts are compared with each other in terms of their advantages and disadvantages.

1. Introduction

Offshore wind energy has a lot of potential to convert the energy generation into more sustainable methods. In offshore wind energy, due to the complexity, especially going into deep seas, reducing the cost of energy remains to be the most challenging issue to be dealt with. Multi-disciplinary design and optimization is usually a way forward to include different disciplines to a design process directly. As a result of this, products or processes are optimized which lead to cost reductions eventually. Multi-disciplinary design and optimization is applied especially for large wind turbine developments [1]. During the design and certification of the current state-of-the-art offshore horizontal axis wind turbines, the harsh operating conditions of offshore environment are taken into account. However, the design is done for the optimum operation of a stand-alone wind turbine. In reality, the optimum operating condition of a wind turbine running in a wind farm is usually different than the stand-alone operation of the same wind turbine. Moreover, this operating condition can change from one wind farm to another. The purpose of this is usually to increase the energy output of a wind farm and/or reduce the maintenance costs for the entire farm instead of an individual turbine. As a result, offshore wind turbines in offshore wind farms do not operate exactly at their design conditions.

The current study is based on the assumption that future large offshore wind turbines are going to be used only in the offshore wind farms, not stand-alone. Following this assumption, a wind turbine is no longer a power plant by itself, but instead the whole wind farm consists of several wind turbines

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is a power plant. Consequently, improving the overall performance of the wind farm becomes more relevant than improving the performance of the individual turbine units in the farm. Maximising the energy output of a wind farm or reducing the costs taking into account different aspects is commonly investigated [2], [3], [4]. In those studies, parameters such as turbine locations, several farm-turbine control strategies, hub height, electrical infrastructure, overall costs, etc have been used but always with the existing turbine concepts. A turbine design and optimization for a specific wind farm operation has not been the part of that problem so far according to the authors of this paper.

The objective of this study is to investigate the possibility of designing the rotors of future very large wind turbines directly for the offshore farm operation. This investigation is done with a conceptual parametrical study in order to examine the effects of different rotor design parameters in turbine-level and in farm-level. By looking at these results, all concepts are assessed in terms of their potential in reducing the cost of energy.

2. Method
The baseline wind turbine chosen for this study is the reference wind turbine (RWT) used in Innwind.EU project which is a 10MW horizontal axis, variable speed, pitch controlled wind turbine [5]. Following the current trends in decreasing the power density as shown in Figure 1, the radius of RWT rotor is increased from 89m to 103m to reduce power density from 400W/m$^2$ to 300W/m$^2$ keeping the capacity of the turbine as 10MW. Power output of a wind turbine is proportional to the third power of the wind speed, $C_p$ (power coefficient) and rotor area. Assuming that $C_P$ and wind speed is kept constant, although the capacity is kept as 10MW, the power output for the below rated wind speeds increases due to the increase in rotor radius which at the end increases the annual energy output of the wind turbine. In addition to the increased blade length, several other parameters such as rotational speed, tip speed, tip speed ratio and airfoils are modified to obtain different rotor concepts. The annual energy output and the axial loads of these concepts are compared with each other. After that, they are evaluated in an offshore wind farm. Horns Rev wind farm is selected for this purpose. Initially, the turbines in Horns Rev are replaced with the rotor concepts evaluated in this study by keeping the absolute distance between the turbines the same as in Horns Rev. Afterwards, the diameter-relative distances between the turbines are kept the same which results in larger farm layout.

![Figure 1. Decreasing trend in power density with longer blades [6].](image)

BOT [7] software is used in the wind turbine level analysis. This software is based on ECN’s state-of-the-art BEM method used for blade designs which is coupled to an optimisation tool. It is used to calculate rotor performance and power production for a given Weibull distribution. In the wind farm level comparisons, Farmflow software is used [8] which solve the flow field developed within and around the offshore wind farms. Farmflow is based on a parabolised Navier Stokes solver coupled with an actuator disc method. The near wake effects are included by a free wake model and the
turbulence is modelled with a modified k-ԑ turbulence model. Since it solves the complete flow
domain including near wake and far wake, it is accurate and since it solves parabolized NS equations
instead of complete NS equations, it is fast. For these reasons, it is not only a very accurate tool for
ergy output estimations of wind farms but also a widely used tool for the decision making process in
wind farm development.

3. Rotor Concepts
The main rotor design parameters for seven concepts are shown In Table 1. In these seven concepts,
FFA series airfoils coming from Innwind RWT are used. For eighth and ninth concepts, the airfoils of
RWT (1) and Low solidity (3) concepts are replaced with ECN airfoils. No design or optimisation
effort is put in the concepts at this stage. Below, all rotor concepts are explained shortly. The chord
distribution and the blade root bending moments of the concepts are compared with each other in
Figure 2.

Table 1. Comparison of parameters chosen for the concepts.

| Name of concept | (1)RWT | (2)Upscale | (3)Low Solidity | (4)Upscale PS | (5) Higher Lambda | (6) Higher RPM |
|-----------------|--------|------------|-----------------|--------------|------------------|----------------|
| Capacity [MW]   | 10     | 10         | 10              | 10           | 10               | 10             |
| Tip Speed [m/s] | 89.6   | 89.6       | 103.6           | 113.5        |                  |                |
| Lambda          | 7.5    | 7.5        | 8.66            |              |                  |                |
| Rpm             | 9.6    | 8.31       | 9.6             | 10.53        |                  |                |
| Radius [m]      | 89.2   | 103        | 103             | 103          |                  |                |
| Power Density [W/m²] | 400    | 300        | 300             | 300          |                  |                |

- **Concept (1) RWT**: This concept is the reference wind turbine used in Innwind project. Throughout this study, RWT is used as the baseline configuration which all the results are compared to.
- **Concept (2) Upscale**: Rotor radius of RWT has been increased from 89m to 103m. Classical upscaling rules have been used in order to adjust the chord length proportionally, whereas the twist is kept as the same as RWT. Tip speed is unchanged, therefore rpm is reduced. As a result of increased radius and the chord lengths, blade root bending moment (BRBM) is increased.
- **Concept (3) Low Solidity**: This concept is motivated by the result of concept (2) Upscale. Local solidity of Upscale is reduced by interpolating the chord length between RWT and Upscale (2) in order to introduce the advantages coming from the slender blades such as less sensitivity to gusts, etc. Chord reduction with large BRBM is not desired since it makes blades more flexible and more expensive. Therefore, BRBM is reduced to the level of RWT by applying constant value of pitch angle. The same effect can be obtained by applying a constant value of twist along the blade. As a result of this action, local angle of attack values are reduced and therefore the local loads are reduced as well as BRBM. Another result of this is that the rotor no longer operates at it max Cp value. Therefore, overall increase in energy output of this concept is reduced compared to Upscale concept.
- **Concept (4) Upscale peak shaving (PS)**: This concept is based on the fact that the Low Solidity (3) concept is already operating in lower Cp value than max Cp in order to reduce BRBM. In reality, the similar effects can also be created by applying peak shaving to reduce the loads. The peak shaving in this concept is introduced by applying pitch angle to Upscale concept starting from 7m/s wind speed in order to reduce the BRBM significantly. In summary, this
rotor geometry is exactly the same as Upscale rotor where additional peak shaving is applied in operation.

- **Concept (5) Higher Lambda**: In this concept, the tip speed ratio value is brought to 8.5 from 7.5 which is approximately the aerodynamic optimum tip speed ratio value, assuming that better $C_p$ can be obtained. This is done by increasing the rpm value to 9.6 which the same as RWT. In order to keep the local loads unaffected, local chord lengths are reduced proportional to the rpm increase since $f_{local} = f \left( \frac{c_r}{c}, V_{local} \right)$ where $V_{local}$ is the local velocity the blade section experiences, $V_{local} \approx$ rotational speed. Twist is kept as in Upscale concept.

- **Concept (6) Higher RPM**: In this concept, rpm value and tip speed ratio is increased as well as the tip speed. Similarly, local chords are reduced as in Higher Lambda (5) concept proportional to the increase in blade local velocity. Twist is kept as in Upscale concept.

- **Concept (7) Higher RPM peak shaving (PS)**: The same rotor geometry and parameters as Higher RPM concept, with a peak shaving applied in operation. This time, the peak shaving is applied only to limit the max BRBM of Higher RPM concept to the BRBM of RWT.

- **Concept (8) RWT ECN airfoils**: In this concept, RWT concept is used except the FFA airfoils in the RWT blade is replaced with ECN airfoils. The chord distribution remains unchanged whereas the twist distribution is slightly modified in order to bring the local angle of attack values to the new airfoils’ optimum operating value.

- **Concept (9) Low Solidity ECN airfoils**: In this concept, Low solidity concept is used and again the FFA airfoils are replaced with ECN airfoils.

![Figure 2](image-url) (a) Chord distribution of the concepts (Upscale and Upscale PS are on top of each other and Higher RPM and Higher RPM PS are on top of each other). (b) BRBM values of concepts (Upscale, Higher Lambda and Higher RPM are on top of each other)

### 3.1. ECN airfoils

ECN airfoils are developed by applying Multidisciplinary Design Optimization (MDO) approach. A combination of Genetic Algorithm (GA) [9] and Gradient Based Algorithms (GBA) [10] has been implemented and coupled with the ECN panel code RFOIL [11], while the airfoil shape is parameterized with third order Bezier curves. A complete discussion about ECN airfoils can be found in [12],[13].

In the present work, the ECN-G1 airfoil series has been used. A work dedicated on ECN airfoils for wind farm operation is in preparation. However, the following figures are meant to give an idea of this series performance and help the reader to understand the differences coming from the airfoils. The lift and aerodynamic efficiency performance of the ECN-G1-25 airfoil are compared with the FFA-W3-241. The data are RFOIL simulations at 12 million Reynolds number and free transition.
The aerodynamic efficiency is quite similar to the FFA airfoil value, although the angle of attack range for optimal performance is wider. The real difference is the lift performance. The ECN-G1 series aims to achieve high lift performance; in this way, it could be possible to reduce chord and obtain slender blades. Also, in this series, good structural properties have been preferred while ensuring satisfactory aerodynamic characteristics.

4. Analysis Conditions and Assumptions

In the wind turbine level analysis, steady state analyses are performed. Wind turbine dynamics are not calculated and structural design and blade deformations are not taken into account. Longer and more slender blades with faster rotational speeds tend to be more flexible and/or structurally more challenging. Therefore they are more costly, even if the design loads are reduced. In reality, the benefit of the concepts used in this study can only be quantified after the cost increase due to the increase in blade length is taken into account which will reduce the benefits of the increase in the energy output. During this work, reducing or limiting the blade root bending moments and axial force outputs are used as methods to reduce the mass of the rotor and increase the reliability therefore reducing the costs of the turbine units.

Horns Rev wind farm consist of 80 wind turbines of 80m rotor diameter. For the analysis, the wind measurements between years 2000 and 2004 at 62 m heights are used [14]. Wind rose and average Weibull distribution is shown in Figure 4 (a) and (b) respectively. When replacing the wind turbines in this wind farm with 10MW wind turbine concepts, new hub height rises to 119m. At this hub height, the average wind speed is normally higher which ends up higher energy output. The wind data is not corrected for the new hub heights. By this way, the increase in the energy output due to the higher average wind speeds is excluded from the comparisons of different rotor concepts. The turbulence intensity value is taken as constant 7% for the entire analysis. This is done in order to eliminate the effect of changing turbulence intensity from the results. In addition to these, analyses are performed between 4 m/s and 25m/s for every 1m/s and between 0 to 360 degrees wind directions for every 30 degrees. 30 degree bins are normally somewhat large to be able to capture all the wake effects accurately. However, it is accepted sufficient for this parametrical study and chosen in order to limit the computational effort.

Two different farm layouts are considered for evaluating the concepts. In the first layout, the absolute distance between the turbines is kept the same. Consequently, the distance between two concepts are reduced from 7D to 2.7D in east-west direction. In the second layout, the diameter-relative distance between the turbines is kept constant. In this layout, since the rotor diameter is increasing from 80m to 180m or 206m depending on the concept, the size of the farm is increased.
5. Results

5.1. Wind Turbine Level Comparisons

Wind turbine level comparisons are shown in Figure 5, Figure 6 and Table 2. As expected, the rated wind speed is reduced from 11m/s to 10m/s with the increased blade length.

**Upscale, Higher Lambda and Higher RPM:** These concepts produce higher axial force than RWT for the below rated wind speeds according to Figure 5 (a). In terms of maximum axial force, it is 10.7%, 11.4% and 11.1% more than RWT value respectively, as shown in Table 2. $C_p$ values of these concepts are very similar to each other and to RWT, except the concepts reach rated speed earlier than RWT. Annual energy productions of these three concepts are increased only due to the increase in radius which is 11% in average. In summary, with Upscale, Higher Lambda and Higher RPM concepts, it is possible to increase the maximum energy output, however, this increase immediately reflects in higher loads.

**Low Solidity, Upscale PS and Higher RPM PS:** Maximum axial forces generated by these concepts are less than the RWT value. 11.7% reduction is from Higher RPM PS and 17% is from the other two. For Upscale PS and Higher RPM PS concepts, axial force at the below rated wind speeds are also higher than RWT value as shown in Figure 5; only the maximum value is reduced. The reduction in maximum axial force is obtained by keeping the same maximum BRBM value of RWT turbine, as explained in section 3. Therefore the advantage of Low Solidity, Upscale PS and Higher RPM PS concepts is that they have the same BRBM value of RWT, but the maximum axial force is reduced significantly. In terms of annual energy production, Low Solidity, Upscale PS and Higher RPM PS are still able to generate more energy than RWT, due to the longer blades. However the overall increase is less compared to Upscale, Higher Lambda and Higher RPM concepts. This comes from the fact that maximum $C_p$ operation of these concepts is limited or reduced, as compared in Figure 5 (b), in order to reduce the BRBM. By looking at the increase in annual energy yield, these concepts can achieve 5.2% to 9.9% increase in energy production and this is obtained with 11.7% to 17% reduction in axial force, with the same maximum BRBM values.

**Concepts with ECN airfoils:** RWT ECN airfoils concept has 4% reduction in the maximum axial force value with a slight increase in annual energy production and Low Solidity ECN airfoils keeps all the advantages of Low Solidity concept and gives more energy output.

In summary, Low Solidity, Upscale PS, Higher RPM PS and RWT ECN Airfoils and Low Solidity ECN Airfoils have potential for further investigations.
Figure 5. (a) Axial force comparisons of the concepts (b) \(C_p\) comparisons of the concepts. (In (a) and (b) Upscale, Higher Lambda and Higher RPM are on top of each other)

Figure 6. (a) Axial force of the concepts with ECN airfoils. (b) \(C_p\) values of the same concepts in (a).

Table 2. Comparison of the results in turbine-level.

|                | \(\Delta AEP\) [% compared to RWT] | \(\Delta\text{Max. Axial Force}\) [% compared to RWT] |
|----------------|------------------------------------|---------------------------------------------|
| (2) Upscale    | 10.8                               | 10.7                                       |
| (3) Low Solidity | 5.2                               | -17.0                                      |
| (4) Upscale PS | 8.0                                | -17.0                                      |
| (5) Higher Lambda | 11.2                             | 11.4                                       |
| (6) Higher RPM | 11.4                               | 11.1                                       |
| (7) Higher RPM PS | 9.9                              | -11.7                                      |
| (8) RWT ECN Airfoils | 0.1                          | -4.0                                       |
| (9) Low Solidity ECN Airfoils | 5.5                      | -17.0                                      |
5.2. Wind Farm Level Comparisons
The results of the wind farm level comparisons are given in Table 3 in terms of annual energy yield and farm efficiency. The farm efficiency here is defined as the ratio between the actual annual energy production of the farm and the annual energy production in case no wake effects are present. This means 100% efficiency stands for a case where there are no wake effects.

Absolute distance between turbines is kept (2.7D): According to Table 3, usage of longer blades gives at least 10.5% more annual energy than RWT. The best performing wind farm is the wind farm with Higher RPM PS concept which generates 11.6% more energy than RWT case. Although due to the peak shaving, annual energy is reduced for a stand-alone wind turbine, in a wind farm with such layout; this concept gives the best energy output. In addition, the annual energy productions of the other concepts are very close to each other. Low Solidity concept having several advantages such as having a more slender blade and lower BRBM generates 10.5% more energy than RWT case. Similarly, the concepts with peak shaving, whose have significant load reductions, give the best energy output with lower loads for this farm layout. This is mainly because of the higher efficiency values coming from operating with less wake effects.

Diameter-Relative distance between the turbines is kept (7D): Larger distance between the wind turbines is usually preferred in the offshore wind farm designs in order to reduce the wake effects in the farm. Replacing the turbines in Horns Rev wind farm by the new concepts and keeping the diameter-relative distances between the turbines unchanged, minimum 13.25% increase in annual energy yield is obtained by larger rotor. Efficiency levels of all concepts are now closer to each other and this explains the limited annual energy increase in concepts with peak shaving and Low Solidity. Yet, considering the advantages of lower loads designs, these concepts have still potential for further investigations.

| Table 3. Comparison of the results in Farm-level given for two farm layouts. |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | Absolute distance kept (2.7D east-west) | Relative distance kept (7D east-west) |
|                                | ∆AEP [% compared to RWT] | Efficiency [%] | ∆AEP [% compared to RWT] | Efficiency [%] |
| (1)RWT                         | - | 71.98 | - | 85.83 |
| (2)Upscale                     | 10.78 | 71.84 | 13.25 | 87.57 |
| (3)Low Solidity                | 10.5 | 75.67 | 9.64 | 89.54 |
| (4)Upscale PS                  | 11.52 | 74.42 | 11.37 | 88.62 |
| (5)Higher Lambda               | 11.2 | 71.97 | 13.56 | 87.64 |
| (6)Higher RPM                  | 11.39 | 72.09 | 13.64 | 87.71 |
| (7)Higher RPM PS               | 11.6 | 73.15 | 12.9 | 88.24 |

5.2.1. Effect of Airfoils in farm performance
In the wind farm level comparisons shown in Figure 7, the effect of ECN airfoils is to increase the annual energy output between 0.07% and 0.23% depending on the farm layout considered. For RWT ECN airfoils concept, when the distances between turbines are large, the annual energy output is slightly reduced which is lower than the uncertainty level of the models that predict the wake effects. The increase in the annual energy yield is a very good outcome since the main purpose of using ECN airfoils is to reduce the price of the turbine unit. However, according to these results, there is also potential in increasing the energy output of the wind farm.
Discussions and Conclusions
Nine different 10MW horizontal axis wind turbine rotor concepts are evaluated in turbine and farm level. The concepts are created by reducing the power density of the wind turbines from 400W/m$^2$ to 300W/m$^2$ by increasing the blade length of RWT 10MW. Higher energy output coming from the increase in rotor diameter of the concepts calculated in the wind turbine level doesn’t necessarily show up in the wind farm level. Main conclusions and discussion points of this work are as follows:

- 15% longer blades for the same wind turbine helps immediately to increase the power output of a wind farm more than 10% independent of the distances between the turbines.
- Low Solidity concept or concepts with peak shaving have big potential for the future wind farm applications. Especially Low Solidity concept having the same BRBM as RWT with longer blades shows a lot of possibilities in terms of low cost wind turbine. However the feasibility and the actual cost reduction potential of these concepts should be investigated further in more details.
- Effect of peak shaving strategy in the power output of a wind turbine can be much less in a wind farm, since it reduces the wake effects at the same time.
- These results are strongly dependent on the chosen farm parameters and the accuracy of the models used. Nevertheless, they still indicate the potential of the integral design for future offshore wind farms.
- Preliminary results for the current ECN airfoils do not lead to a large gain in farm power output. However the latest studies are aiming to help to reduce the wake losses and to improve the structural efficiency of the blade.
- Larger distances between the turbines in future wind farms equipped with 10MW+ wind turbines will lead to higher costs in other aspects, such as electrical infrastructure and O&M. Moreover wind resource assessments based on the measurements done at only one location and applied for a layout of 10kmx13km wind farm might not be feasible anymore, although the change in wind conditions are somewhat limited in offshore.
- Wind turbine design and control, wind farm design and farm control even airfoil design should be done integrally in order to design&operate an offshore wind farm in the most optimum conditions for the reduction of CoE.

Acknowledgements
Authors would like to acknowledge European Union FP7 Innwind.EU project with project no. 308974 for partially funding this work.

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