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An parametric investigation into the effect of low induction rotor (LIR) wind turbines on the levelised cost of electricity of a 1 GW offshore wind farm in a North Sea wind climate

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Abstract

In this report, the details of an investigation into the effect of the low induction wind turbines on the Levelised Cost of Electricity (LCoE) in a 1GW offshore wind farm is outlined. The 10 MW INNWIND.EU conventional wind turbine and its low induction variant, the 10 MW AVATAR wind turbine, are considered in a variety of 10x10 layout configurations. The Annual Energy Production (AEP) and cost of electrical infrastructure were determined using two in-house ECN software tools, namely FarmFlow and EEFarm II. Combining this information with a generalised cost model, the LCoE from these layouts were determined. The optimum LCoE for the AVATAR wind farm was determined to be 92.15 €/MWh while for the INNWIND.EU wind farm it was 93.85 €/MWh. Although the low induction wind farm offered a marginally lower LCoE, it should not be considered as definitive due to simple nature of the cost model used. The results do indicate that the AVATAR wind farms require less space to achieve this similar cost perfomace, with a higher optimal wind farm power density (WFPD) of 3.7 MW/km^2 compared to 3 MW/km^2 for the INNWIND.EU based wind farm.

Keywords: Offshore Wind; Low induction rotor; AVATAR; Levelised cost of electricity; Wind farm power density ;

1. Introduction

Recently, a new design for large multi-MW wind turbines that deviate significantly from the established design trends has emerged. These are characterised by high tip speeds, low solidity and larger than expected rotor diameters and are thought to be associated with the concept of low induction [1]. Low Induction Rotors (LIRs) offer many potential performance benefits for very large wind farms including a reduced wake effect and an associated increase in capacity factor. However LIRs are more expensive than the classical alternative due to the need for materials like

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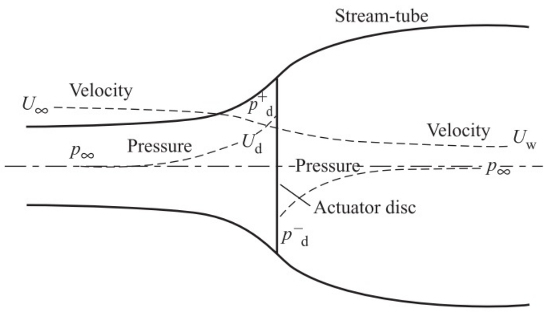

Fig. 1: Schematic representation of the actuator disc momentum theory.

carbon fibre. It is therefore unclear whether the benefits in performance of LIRs overcome this increase in cost. This is precisely the topic of the investigation carried out in this work.

1.1. *Wake effect*

One of the primary factors that affects the performance of wind farms both onshore and offshore is the wake effect of wind turbines. When the free stream wind flows through the rotor of wind turbine, kinetic energy is extracted from the flow and is converted to electricity. This process of extracting energy has two main impacts on the flow behind the wind turbine. First, the velocity of this downstream wind behind the turbine is reduced from its undisturbed upstream velocity just through the conservation of energy. Secondly, the turbulence intensity of flow in the area behind the wind turbine is increased. This region of reduced velocity and increased turbulence is known at the wake of the wind turbine. Actuator disc momentum theory is often used to mathematically describe the energy extraction process, the schematic of which is shown in Fig. 1. The rotor of the wind turbine is modelled as an actuator disc, which can be thought of as a semi-transparent, infinitely thin disc which exerts some axial force on the flow. The three conservation laws (mass, energy and momentum) are applied to a flow inside a 1-dimensional stream tube, where the air passing through the disc is considered separate from the free stream.

The velocity of the free stream flow is gradually reduced as it approaches to actuator disc. Correspondingly, the stream tube must expand and the static pressure increase as no energy has yet been extracted from the flow. As the flow passes through the disc the static pressure drops and the velocity continues to reduce. Finally, further downstream the pressure recovers to the original atmospheric value. Through these assumptions, the following equation is derived for the power coefficient C_p of a wind turbine:

$$C_p = \frac{P}{\frac{1}{2}\rho U^3 A} = 4a(1-a^2) \tag{1}$$

where P is the power, ρ is the density of air, A is the area of the rotor and a is the axial induction factor. The axial induction factor is defined as the fractional decrease in wind velocity between the free stream flow and the wind turbine. The maximum C_p therefore occurs at an induction factor of 1/3. This is precisely the induction around which conventional turbines are designed in order to maximise their power output. However this also leads to strong wake effects behind the turbine, which is a major consideration in the design of an offshore wind farm.

1.2. *Design problem of offshore wind farms*

The presence of upstream wind turbines within a wind farm and the associated wake creation causes the power of downstream turbines to be reduced due to the reduction in wind velocity. It is therefore of upmost importance for wind farm designers to minimse the wake effect so that the maximum possible energy can be generated. Furthermore, the more turbulent wind conditions means that the aerodynamic loading of downstream turbines is also affected.

Therein lies the primary design problem for wind farms. In order to minimise the wake interaction between successive rows of wind turbines (and to a lesser extent adjacent wind turbines) within a typical farm boundary, the rows of wind turbines should be spaced as far apart as possible. This allows for a greater recovery in the velocity of the wake which means the power, and hence the Annual Energy Production (AEP), of each successive downstream row of wind turbines is increased. However increasing the separation distance requires long electrical cables to collect and transport the energy generated which increases the capital costs of the electrical infrastructure. Longer cables also imply greater energy losses. Conversely, by reducing the distance between the wind turbines the cost is also reduced while the increased wake interaction means that the AEP will be lower.

A trade-off therefore exists between minimising the wake effect and maximising the energy yield from a given wind farm site. Therefore, it is important to be able to accurately model the wake effect so wind farms can be designed appropriately.

1.3. Wake Models

There is a wide variety of wake models that are still used today in the design of wind farms. They can be classified into two distinct categories, namely kinematic models and field models, which are also referred to explicit and implicit models respectively e.g. [2,3]. Kinematic models are based on self-similar velocity deficit profiles obtained from global momentum conservation where simple analytical expressions are often used. The near wake region is not distinguished from the far wake further downstream. Instead the velocity profiles are applied directly at the rotor plane. Conversely field models, which include Computation Fluid Dynamics (CFD) models, evaluate the complete flow field through a wind farm and a clear distinction between the near and far wake is made.

Simple kinematic models are often used in industry due to their low computational effort. However this comes at the expense of accurate modelling of the physical processes in the wake. Therefore a trade-off always exists between desired accuracy and computational time. The wake model used in this study which is incorporated into FarmFlow is a field model that solves the Reynolds Averaged Navier Stokes Equations (RANS). This approach decomposes the instantaneous velocity and pressure in the turbulent wake flow field into a mean and fluctuating component. The wake model is based on a 3D parabolised Navier-Stokes code, using a k-ϵ turbulence model to account for turbulent processes in the wake. The free stream wind speed is calculated using a boundary layer based on [4]. The wake model is often explicitly referred to as WAKEFARM and it originally based on the based on the UPMWAKE model developed at the Universidad Polytecnica de Madrid. The wind turbine is modelled as an actuator disc For the deceleration and expansion of the near wake, FarmFlow uses an axisymmetric vortex wake model to calculate the stream wise pressure gradients, which are prescribed as a source term in the flow equations [5].

The validation of FarmFlow against full scale wind farms [5] is of particular relevance for this study.. Calculations from FarmFlow are compared to measurements from EWTW as well as three offshore wind farms namely Horns Rev, Nysted and Offshore Wind farm Egmond aan Zee (OWEZ). It was found that the velocity deficits, turbulence intensities and power performance especially for wind turbine spacings larger than 5D apart agree very well with the data. However, for distances shorter than 5D the wake recovery is overestimated while for very large distances behind the rotor the generated turbulence intensity tends to be slightly overestimated.

1.4. Economics of offshore wind

Wind energy like most renewable energy technologies is notoriously capital intensive. The capital expenditure (CapEx) is the biggest contributor to the life cycle costs of offshore wind farms. The trend of steadily increasing CapEx in recent years is due to number of factors including the increasing size and capacity of wind turbines. The other major contributor to the cost of offshore wind is the Operational and Maintenance (O&M) costs, which typically makes up about 20-30% of the LCoE [7]. The LCoE is is a widely used metric to assess the cost of electricity from different energy sources. LCoE represents the sum of all costs over the lifetime of a given wind project, discounted to the present time and levelised based on annual energy production, namely:

$$\begin{aligned} LCoE &= \frac{R \cdot CapEx + O\&M}{AEP} \\ R &= \frac{i}{1-(1+i)^{-N}} \end{aligned} \tag{2}$$

where i is the interest rate and N is the lifetime of the project. Offshore wind still remains about twice as expensive as its onshore counterpart. One of the key measures identified to reduce the cost of offshore is the development of much larger wind turbines specifically for the offshore environment [8].

1.5. Upscaling

Upscaling of conventional turbines designs does not guarantee that economies of scale can be achieved. This is down to the fundamental 'square-cubed' law of classical upscaling, whereby the power of a wind turbine increases in proportion to the second power but the mass increases in proportion the third power. Therefore, without improvements to blade technology or a change in the design principle, there is an upper limit to this classical upscaling approach.

This has led to the development of new turbine concepts such as the LIR. The basic principle behind the LIR concept is that optimising the rotor design for lower induction factors (i.e. lower nominal power coefficient) results in lower thrust and bending moments. Therefore the rotor diameter can then be increased until similar aerodynamic loads as the conventional design are reached and thus increased energy capture for the same rated power of turbine can be achieved [1].

The wind turbines used in this report are the INNWIND.EU Reference Wind Turbine (RWT) and the low induction variant developed as part of the AdVanced Aerodynamic Tools for lArge Rotors (AVATAR) and therefore named the AVATAR turbine. The basic characteristics of these turbines are shown in the Table 1 below.

Table 1: Basic characteristics of the INNWIND.EU and AVATAR wind turbines.

Wind turbine	Rated Power (MW)	Diameter (m)	Axial induction factor	WTPD (Wm^{-2})	Hub height (m)	Rated speed (ms^{-1})
INNWIND.EU	10	178.3	0.3	400	119	11.50
AVATAR	10	205.8	0.24	300	132.7	10.75

2. Methodology

2.1. General procedure

In order to investigate the differences between the INNWIND.EU RWT and the LIR variant AVATAR wind turbine, a 1GW wind farm in a 10x10 layout configuration is considered in a typical North Sea wind climate. This wind rose is shown Fig. 2.

The spacing between the turbines is varied using five fixed spacing ratios and range of CrossWind Direction (CWD) spacings. CWD refers to the spacing between adjacent wind turbines and Primary Wind Direction (PWD) refers to the spacing between successive turbines. The spacing ratio refers to the ratio of the turbine separation in the PWD (i.e. along wind turbine columns) to the spacing in the CWD (i.e. along wind turbine rows). Therefore a ratio of 1.0 corresponds to a square layout and as the ratio is increased the wind farm becomes more elongated in the PWD. Then, for each spacing ratio a range of CWDs are also chosen.

This allows the wind farm performance to be considered in two dimensions. First, *for each CWD spacing* the benefit of increased spacing in the PWD is investigated using the chosen spacing ratios. This is analagous to the traditional approach to wind farm design whereby the spacing between the wind turbines is iteratively adjusted until optimum positing is found. However this process has a complex interaction with the wind climate as each step increase in the PWD changes the relative positing of the turbines within the wind farm (e.g. wind turbines within the wind farm are moving in/out of the wake effect shadow of turbines in front). Therefore, using a range of CWD values *for each fixed spacing ratio*, the benefit of increased mutual distance between turbines is isolated from the benefits due to the complex interaction of the wind farm over the entire wind rose. This allows the benefits soley due to the greater amount of time for the wake recovery to be assessed independently.

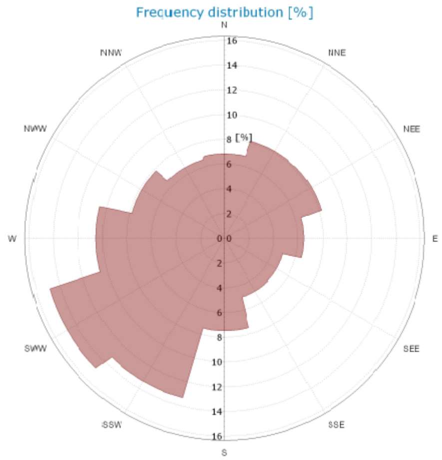

Fig. 2: The North Sea wind rose used in this study.

2.2. FarmFlow & EEFarm II

EEFarm II is electrical infrastructure tool developed by ECN which has been built in the Matlab-Simulink environment [5]. It allows electrical models for wind farms to be created and evaluated in terms of its electrical and economic performance. The value of EEFarm II lies in the extensive database of electrical components that has been created and built into a Simulink library. This database contains both the electrical parameters of each component as well as the cost, which for some components includes not only the capital cost but also the laying/installation cost.

Using EEFarm II an intra-array collection system was developed to estimate the cost and electrical losses for each wind farm layout configuration. When calculating the cable lengths for input into EEFarm II, some assumptions have to be made. To be consistent with the origin of the wind rose, a water depth of 25m and on overlength of 10% is assumed. The overlength is to account for any obstacles or sea floor level changes that may require the cable to be rerouted. Finally the height of the two-transformer platform is also assumed to be 25m. For FarmFlow, an average turbulence intensity of 7% for all wind directions is assumed. There will of course be a directional dependency in reality however 7% is a typical turbulence level for offshore wind farms and is considered reasonable. The atmospheric conditions are assumed to be neutral for all FarmFlow simulations which means there will be less mixing than in a real offshore environment.

2.3. Cost model

Estimating the cost of offshore wind farms is not straightforward, in particular for the high capacity turbines under consideration as a lot of the derived models are based on information from smaller turbines. For this study the procedure outlined on page 15 as part of a deliverable for the INNWIND.EU project [1] is followed. The cost models are largely based on the work from [9] and [10].

The cost of the INNWIND.EU blades is referenced as €1,343,803. However because the AVATAR blade makes use of carbon fibre layers, the cost estimation from the INNWIND.EU model has to be adjusted. Therefore, it is assumed that 1/3 of the AVATAR blade is made up of carbon fibre and that the carbon fibre is approximately 3 times more expensive that the INNWIND.EU composite. Therefore, the cost of the AVATAR blade would be 66% more expensive than an INNWIND.EU blade of the same size, which leads to the total cost of 2.57M€ for all 3 blades.

For the balance of plant costs, the aforementioned model uses costs designed for further offshore (e.g. jacket foundations). Therefore, a simple excel model is used to estimate the mass and cost of the monopile foundations for the turbines. This solver specifies the thickness of the monopile, transition piece and tower through a factor D/t, where D is the rotor diameter and t is the thickness of each of the respective components. The D/t ratios are constrained and varied within certain limits in order to achieve the minimum mass, where the natural frequency and constraints related to the fatigue stress are also included. Then, the costs of each of the components are determined using simple

€/kg values, namely €3.0/kg for the transition piece and €2.8/kg for the monopile. This resulted in a cost of 3.4M€ and 3.7M€ for the INNWIND.EU and AVATAR turbines respectively. The cost for transport and installation is quite broad in the literature. [11] estimates the cost of installation to be €546 per turbine (foundation, transition piece and j-tubes). The INNWIND model uses a value of approximately 1.6M€ for the installation. Furthermore, it is noted in [10] that for larger turbines, the price increases significantly due to premiums involved in moving such large structures. An installation cost of 1.2M€ is assumed reasonable for both turbines.

The cost of scour protection and the port and staging costs are the same values of 600k€ and 217k€ as used in the INNWIND.EU model. Furthermore, a decommissioning cost of 1.5M€ and development cost of 1.2M€ per turbine are also assumed. The cost of the electrical transmission system to shore of 500M€ is determined from the EEFarm II database. The intra-array collection system is also determined through EEFarm. The transformer platform is considered to be at the centre of the wind farm and the turbines are connected in strings of 5, ending at the middle-most rows. From here the cables are run along the most direct route to the transformer platform.

To determine the LCoE, an interest rate of 7.8% and a lifetime of 15 years are also assumed while the O&M costs are taken to be 4% of the CapEx. The purpose of using such a generic model is to illustrate the performance difference between both wind farms.

3. Results

The general performance benefits of the low induction AVATAR based wind farm over the conventionally designed INNWIND.EU turbine are consistent with expectations as well as with some similar work from previous studies. The capacity factor, and hence the AEP, are significantly higher for the AVATAR wind farms compared to the INNWIND.EU based wind farm. This is shown in Fig. 3 where the electrical losses in the collection system are already included. The AVATAR wind farms have approximately an 8% higher capacity factor than the corresponding layout configuration for the INNWIND.EU wind farm.

Other behaviours were also consistent with the LIR concept. For example the power output from the second and successive rows of wind turbines in the AVATAR wind farms were always higher than for the INNWIND.EU wind farms, which is a function of the lower axial induction.

For both the AVATAR and INNWIND.EU wind farms, the spacing ratio of 1.6 gave the minimum LCoE corresponding to spacing of 7.25Dx11.6D and 9Dx14.4D respectfully as is shown in Fig. 4 where cubic fits have been applied. The optimum LCoE for the AVATAR wind farm was determined to be 92.15€/MWh while for the INNWIND.EU wind farm it was 93.85€/MWh. These results would indicate that the LIR AVATAR turbines do offer a better cost solution in terms of the levelised cost, although the difference is marginal. It is worth noting that the results are of course highly sensitive to the cost model used. In particular, accounting for the relative cost differences between the turbines is important. Therefore, the rather crude estimation of the cost differences between the blades has an important impact. Nonetheless, these figures can be considered as a conservative basis from which the cost estimates can be improved. Furthermore, the assumptions of lifetime, interest etc. for the LCoE are somewhat generic and the lifetime of 15 years is also conservative.

An interesting point however is derived from the WFPD. The area enclosed by the optimal wind farm layout for the AVATAR turbine is lower than for the INNWIND.EU, with areas of 269 km^2 and 334 km^2. This corresponds to WFPDs of approximately 3.7 MW/km^2 and 3 MW/km^2. This implies that the INNWIND.EU based wind farms require more sea area in order to achieve similar levels of LCoE. This is of course related to the higher axial induction and stronger wake profiles that associated to conventional rotors over LIRs, which appears to make the LIR more advantageous from the view of (state) landowners.

4. Conclusions

Under two degrees of freedom, namely the Wind Farm Power Density (WFPD) and the Wind Turbine Power Density (WTPD), the benefits of the proposed shift to the Low Induction Rotor (LIR) concept was investigated. This was done by considering a 1GW wind farm made up of either 100x10 MW INNWIND.EU Reference Wind Turbines (RWTs), or its LIR variant the AVATAR wind turbine, in a range of layout configurations. Using two in house ECN software tools, namely FarmFlow and EEFarm II, the Annual Energy Production (AEP) and cost of the

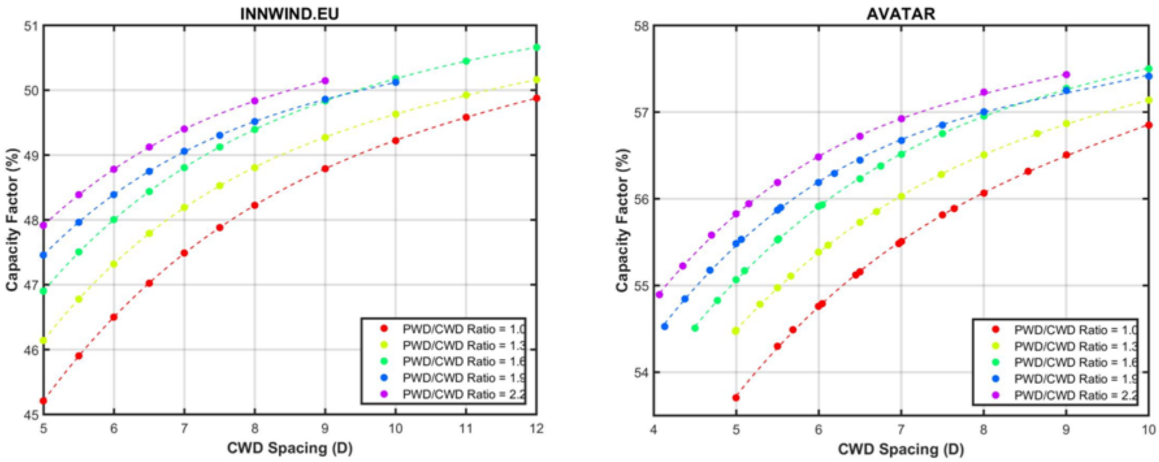

Fig. 3: Capacity factor for INNWIND.EU (left) and AVATAR (right) wind farms in all layout configurations including electrical losses.

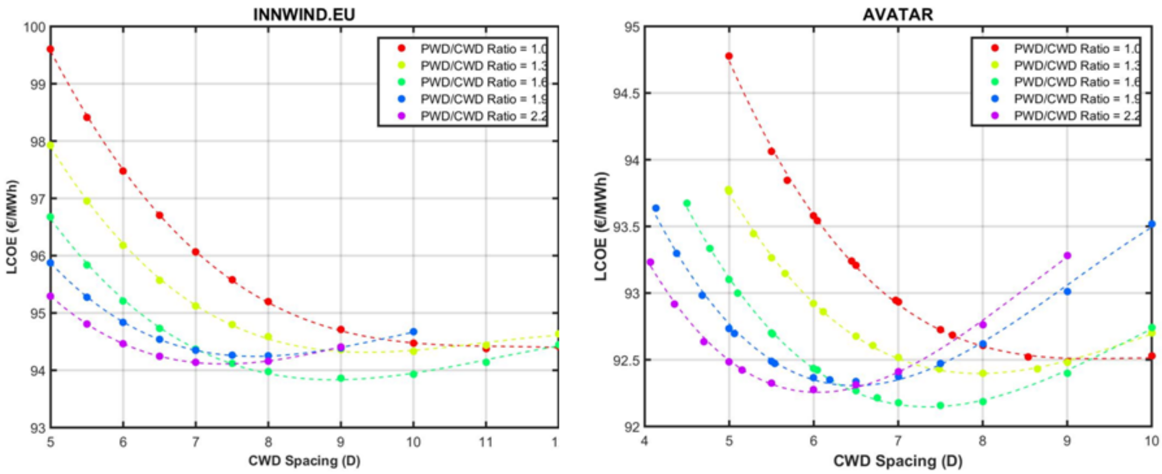

Fig. 4: Levelised cost of electricity (LCoE) for INNWIND.EU (left) and AVATAR (right) wind farms in all layout configurations including electrical losses.

electrical infrastructure could be accurately determined. FarmFlow is specifically calibrated to perform best at the turbines spacings typical of large scale offshore wind farms and although one single calculation can take up to 36 hours, the use of a batch version on the ECN cluster made this study possible. The results of this investigation demonstrates that the LIR concept does offer a cost benefit at the 1GW scale in terms of the Levelised Cost of Electricity (LCoE) of an offshore wind farm, although the benefit was marginal. The Levelised Cost of Electricity (LCoE) for optimal layout configurations of the AVATAR and INNWIND.EU wind farms was determined to be 92.15€/MWh and 93.85€/MWh respectively. It is important to note that the results are naturally sensitive to the cost model used, and due to lack of relevant available data, generic cost models were used and basic assumptions made it is difficult to draw strong conclusions. Although the cost of components for the INNWIND.EU project were determined using the same empirical relations, the biggest source of uncertainty arises from the assumptions made on the cost of the AVATAR blade. Therefore, more accurate cost modelling with reliable, up-to-date cost information could improve the validity of the results and she more light on relative cost difference between conventional and LIR turbines. Nonetheless, the optimal layout configuration of the AVATAR wind farm required less space than that of the INNWIND.EU, with WFPDs of 3.7 MW/km^2 and 3 MW/km^2 respectively. This indicates that despite the much larger rotor of the AVATAR turbine, the optimal spacing does not come at the expense of needing a larger area at sea.

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