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WIND ENERGY SCIENCE DISCUSSIONS

Offshore wind farm optimisation: a comparison of performance between regular and irregular wind turbine layouts

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Abstract. Layout optimisation is essential for improving the overall performance of offshore wind farms. During the past 15 years, the use of yield optimisation algorithms has resulted in a transition from regular to more irregular farm layouts. However, since the layout affects many factors, yield optimisation alone may not maximise the overall performance. In this paper, a comparative case study is presented to quantify the effect of the wind farm layout on the overall performance of offshore wind farms. The case study was performed to investigate two performance indicators: power performance, using yield calculations with WindPRO and wake-induced tower fatigue, using the Frandsen model. It is observed that irregular wind farm layouts have a higher annual energy production compared to regular layouts. Their power production is also more persistent (less sensitive) to wind direction, improving predictability and thus market value of power output. However, one turbine location in the irregular layout has a 24% higher effective turbulence level, leading to additional tower fatigue. As a result, fatigue-driven tower designs would require increased wall thicknesses, which would result in higher capital costs for all turbine locations. It is demonstrated in this study that layout optimisation using a minimum inter-turbine spacing effectively resolves the induced wake issue while maintaining high-yield performance.

1 Introduction

The share of wind energy in the electricity market is rapidly increasing (Musgrove, 2009; International Energy Agency, 2022). Offshore wind farms pose fewer geographical and social constraints than onshore wind farms, which leads to larger design spaces. The performance of an offshore wind farm indicates how efficient the system is at achieving its main objective (Tao and Finenko, 2016). Examining operational wind farms, a development of farm layouts over time can be recognised. Earlier wind farms show regular patterns such as the wind farms Horns Rev 1 (2002) (Akay et al., 2014) and Prinses Amalia (2008) (Stanley and Ning, 2019). Newer and larger wind farms show more variation in patterns such as the wind farms Horns Rev 2 (2009) (Ostachowicz et al., 2016) and Rødsand (2010) (Nygaard, 2014), and partial irregularity such as Anholt (2013) (Ostachowicz et al., 2016) and many more. A number of desktop optimisation studies even suggest fully irregular wind farms such as Research Layout 1 and 2 (Charhouni et al., 2019; Karouani and Elhoussaine, 2018) which are obtained from existing research as shown in Figure 1.

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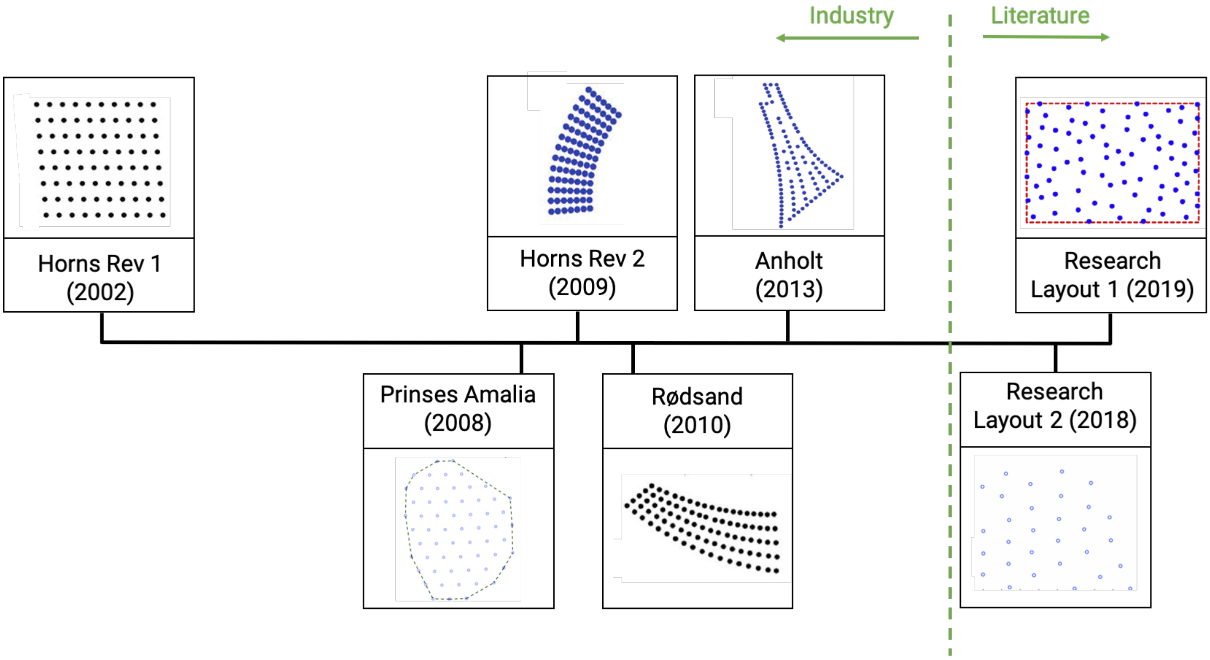

Figure 1. Development of wind farm patterns over time. Left of the green dashed line are wind farm layouts operational in industry (Akay et al., 2014; Stanley and Ning, 2019; Ostachowicz et al., 2016; Nygaard, 2014), while right of this line are optimised layouts from literature studies (Karouani and Elhoussaine, 2018; Charhouni et al., 2019).

Sanchez Perez Moreno (2019) investigated the preliminary design of the layout, electrical collection system, and support structures of an offshore wind farm using two different optimisation approaches. The sequential approach neglects the interaction between the three selected performance characteristics, while precisely this is taken into account in the multidisciplinary design analysis and optimisation (MDAO) approach. The two approaches were used to optimise the total system levelised cost of energy (LCOE) of a regular and an irregular farm layout. The study focussed on the comparison of the two approaches and the interaction effects, not comparing the performance of the different geometric patterns. Chen et al. (2015) used a multi-objective genetic algorithm (GA) to maximise the wind farm efficiency and minimise its cost applying real wind conditions. Investigating one regular and three irregular layouts with identical total geographical area, the comparison suggested that irregular geometric patterns may perform better than regular layouts, yet no final conclusion was drawn in the study. The goal of maximising the energy extraction while minimising the cost was also pursued by Charhouni et al. (2019) comparing regular and irregular wind farm layouts. The resulting power, capacity factor and efficiency were all higher for the irregular layout, although it should be noted that a constant wind speed and direction was considered. For general validity of this conclusion, the different layout options need to be investigated also at variable wind speed and direction.

Three observations can be made for comparisons of wind farms with regular and irregular layouts conducted to date. First, the performance indicators for wind farms are not well-defined in the literature. An overview of all possible indicators and how

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they affect the overall performance is lacking. Also, the degree to which these indicators are influenced by the geometry of the wind farm is not investigated.

Second, the effects of optimised wind farm layouts on all performance indicators are either unknown or only partially investigated in the literature. The existing studies which include regular and irregular wind farm layouts focus on the performance of the optimisation tools. The aim of these optimisation studies is not to compare the overall performance of the regular and irregular wind farms.

Third, an optimisation of the farm layout inherently leads to an irregular pattern, as shown by most optimisation studies in the literature (Grady et al., 2005; Marmidis et al., 2008; DuPont et al., 2012; Shakoor et al., 2016). This is only logical given the enormous design space of irregular patterns with many local optima compared to regular patterns. A particle swarm optimisation (PSO) or genetic algorithm (GA) is, for example, unlikely to find a regular pattern. Based on the nature of the optimisation algorithms many studies are naturally biased toward irregular wind farm layouts.

The objective of this paper is thus to quantify the effect of regular and irregular offshore wind farm layouts on selected performance indicators by means of a comparative case study using state-of-the-art simulation tools and models. The paper is structured as follows. In Section 2, the selection of performance indicators is described. In Section 3, the power production of the different layouts is assessed and in Section 4 the wake-induced tower fatigue of the different layouts. In Section 5, the general applicability of the results is investigated with a sensitivity analysis of the performance indicators for the Borssele wind farm. Conclusions are presented in Section 6.

2 Selection of performance indicators

All performance indicators by which a wind farm has been assessed so far were inventorised using, among others, the works of Gonzalez et al. (2017) and Shafiee et al. (2016). The indicators were divided into four levels, as shown in Figure 2. To incorporate changes in energy price, instead of using the LCOE as an overarching key performance indicator, profit (positive net present value) was selected (Nissen and Harfst, 2019).

A multi-criteria decision analysis based on (1) affected by wind farm layout, (2) feasibility to research, (3) site independence, and (4) technical nature resulted in five sub-performance indicators. These were grouped into two performance indicator groups: (1) Power performance, including yield/wake losses, predictability and value on the electricity market, and (2) Wake induced tower fatigue, including wind turbine cost and component replacement cost.

To assess the performance of these indicator groups for the different layout categories, the regular and irregular farm layouts depicted in Figure 3 were selected from the work of Sanchez Perez Moreno (2019). For both layouts, the IEA Wind Task 37 reference wind turbine with 10 MW rated power and a rotor diameter of 190.8 m was used (Bortolotti et al., 2019). The degree of irregularity was quantified mathematically with (1) the sum of the distance to surrounding turbines in a radius of 10 rotor diameters (10 RD) for each turbine and (2) the minimum inter-turbine spacing. The number of turbines with the same unique sum of distances to their surrounding turbines with a tolerance of 0.001 RD was 66 for the regular wind farm layout and only

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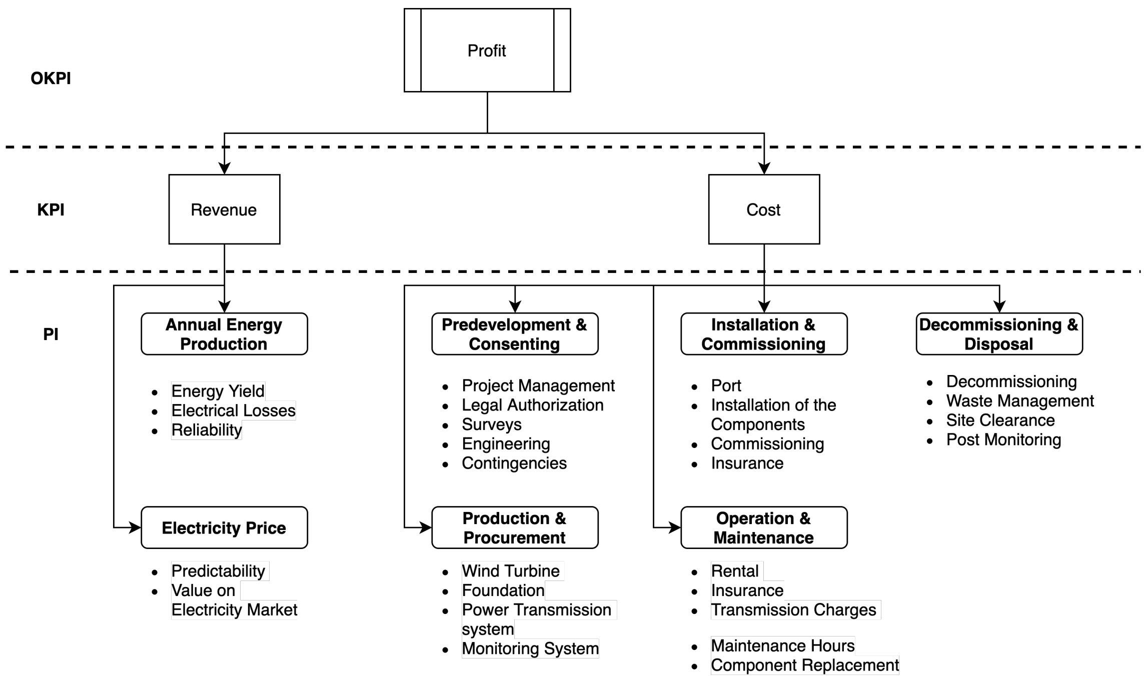
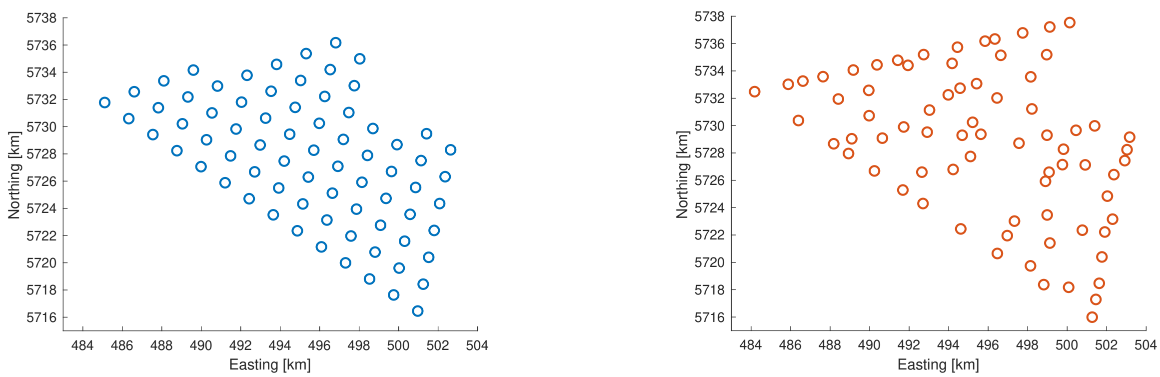


Figure 2. Breakdown of performance indicators. OKPI = overarching key performance indicator, KPI = key performance indicator, PI = performance indicator consisting of sub-performance indicators.



(a) Regular farm layout

(b) Irregular farm layout

Figure 3. Regular and irregular wind farm layouts from Sanchez Perez Moreno (2019) consisting of 74 turbines with a rated power of 10 MW at Borssele.

5 for the irregular farm layout. The minimum inter-turbine spacing was 2.73 RD for the irregular wind farm layout compared to 8.88 RD for the regular wind farm.

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The following two sections will present the analyses of performance indicator groups (1) and (2), respectively.

3 Performance indicator group (1): power performance

The annual energy production (AEP) was analysed in WindPRO, computing the absolute difference between regular and irregular wind farm layouts. The wind climate imported to WindPRO was obtained from Riezebos et al. (2015). The data was extrapolated to hub height using the power-law wind profile with a power exponent α of 0.08. The WindPRO calculation shows a higher AEP of approximately 0.66% for the irregular wind farm layout, corresponding to approximately €700 000 according to the average European Power Exchange (EPEX) price in the Netherlands between 2007 and 2020. The individual turbine performance shows that the difference in AEP is not caused by the outliers (best-performing and worst-performing turbines) but by the average-performing turbines in the wind farm. Relating the performance and positions shows that the distribution of the lower performing turbines is more evenly spread for the regular wind farm than for the irregular wind farm as becomes apparent from Figure 4.

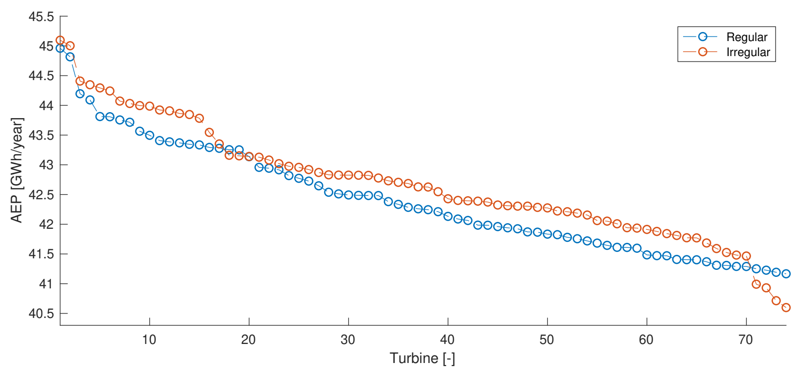

Figure 4. Individual turbine AEP for the regular and irregular wind farm layouts arranged from high performance to low performance.

Figure 5 shows the persistence of power to wind direction, i.e. the extent to which power production varies with wind direction, measured in degrees, for a certain wind speed. The maximum power drop is quantified as the maximum uninterrupted decrease of power for an increase or decrease in wind direction. This maximum power drop decreases by 73.7 % for the irregular wind farm compared to the regular wind farm layout. The orientation of turbine rows in the wind farm with regular layout is driving for the angle at which the power drops occur as well as for their magnitude. More turbines in a row correspond to a larger power drop. It is expected that a wind farm layout with a higher persistence to wind direction will lead to a decrease in prediction errors. This will likely result in lower imbalance costs. A rough estimation based on historical imbalance cost data shows that the imbalance cost would amount to approximately 1.6 % of the AEP revenue. The difference between the imbalance cost of the regular and irregular wind farm would then become visible within this 1.6 %.

The analysis for persistence to wind direction was executed using a constant mean wind speed of 9.5 m/s. This simplification likely overestimates the power drops as a function of wind direction because the time-dependent change of wake losses in the

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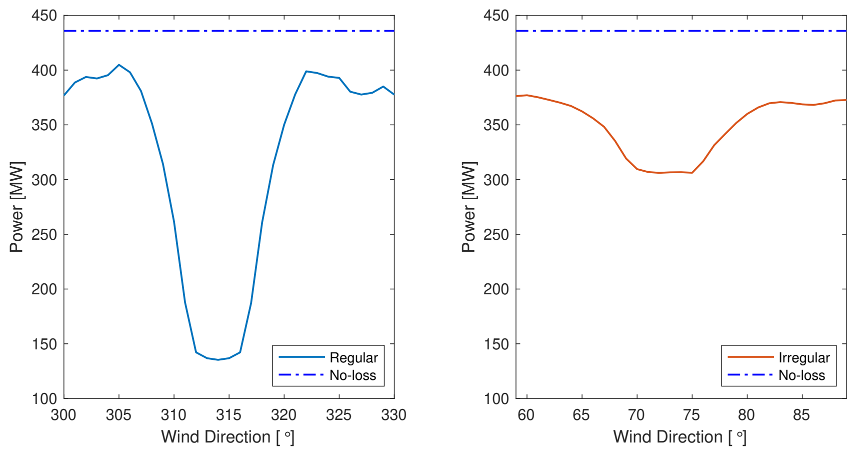

(a) Regular farm layout

(b) Irregular farm layout

Figure 5. Power output of wind farms with regular and irregular layouts at a wind speed of 9.5 m/s as functions of wind direction, zoomed in on the wind directions with the highest power drops.

wind farm was not included. Additionally, the wind speed is just below the rated power, which means that the wake losses play a significant role. For higher wind speeds (+ 15 m/s) the effect of wake losses diminishes or even disappears completely.

Based on the analysis and assumptions in this section, the irregular wind farm layout performs better for all three sub-performance indicators analysed: the energy yield, predictability, and value in the electricity market. The importance and value of persistence to wind direction will increase as the impacts of wind power on power system operation increase with the very large growth foreseen in the next decades. The idicator predictability and value in the electricity market do require a much more extensive analysis for proper quantification.

4 Performance indicator group (2): wake-induced tower fatigue

The layout of a wind farm and the wind environment determine to what degree downstream turbines are affected by the wakes of upstream turbines. Especially for offshore farms, these wake effects are driving for the wind turbine fatigue loading (Thomsen and Sørensen, 1999). With low terrain roughness and low ambient turbulence intensities, the effect of wakes is higher than in onshore wind farms. Multiple studies confirm that one of the fundamental parameters which determine the wall thickness of the tower design is fatigue (Igwemezie et al., 2018; Frandsen, 2007; Thomsen and Sørensen, 1999; Frohboese and Schmuck, 2010). Therefore, the layout of the farm will affect the cost of the towers.

Interestingly, while monopile foundation designs are optimised for individual locations within an offshore wind farm, typically only a single tower design is applied based on the turbine location with the highest turbulence intensity. Therefore a

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single, high-turbulence turbine location within a project impacts the wall thickness of all towers of that project, which implies a high-cost multiplication factor.

The effective turbulence intensity was quantified using the Frandsen model, which implies that the structural load ranges vary linearly with the turbulence intensity (Frandsen, 2007). The model was used to determine the damage-equivalent bending moment[1] at the tower bottom, $M_{YT,DEL}$, as a function of the varying wind and wake conditions in the farm. The bending moment is then related to the damage-equivalent stress σ_{DEL} and the tower wall thickness t via the following equation

$$\sigma_{DEL} \propto \frac{M_{YT,DEL}}{t}. \tag{1}$$

To maintain a constant damage-equivalent stress, the wall thickness of the tower thus needs to increase proportionally to the damage-equivalent load. This can be translated to an increased wall thickness required to support the increased load

$$t_{new} = t_{old}\left(\frac{I_{eff}}{I_a}\right), \tag{2}$$

where I_a is the ambient turbulence intensity and I_{eff} the effective turbulence intensity that can be evaluated as

$$I_{eff}(\bar{U}_a) = \left[\int_0^{2\pi} p(\theta|\bar{U}_a) I^m(\theta|\bar{U}_a)) d\theta\right]^{\frac{1}{m}}. \tag{3}$$

In this equation, p is the probability of a certain wind direction occurring at hub height, θ is the wind direction, $\overline{U}_a$ is the mean wind speed at hub height, I is the turbulence intensity in the wake, which consists of the ambient turbulence intensity and the wake-added turbulence intensity, and m is the Wöhler exponent of the material determined by the SN-curve. The effective turbulence intensity is driven by the minimum inter-turbine spacing in the wind farm. To compare the impact of the layout, the effective turbulence intensity was calculated for the individual turbines in the regular (blue) and irregular (red) wind farm layouts using a Wöhler exponent $m = 4$. The result is shown in Figure 6.

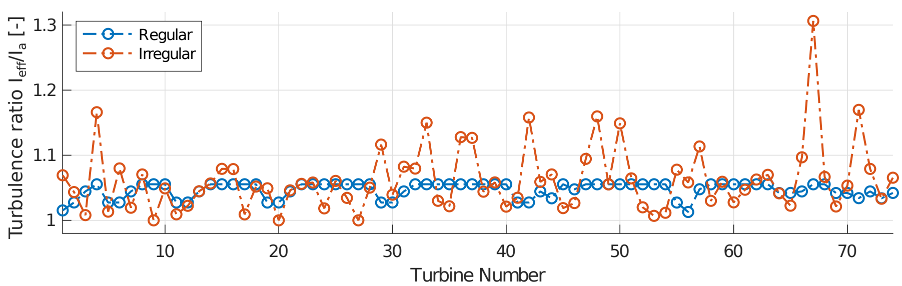

Figure 6. Effective to ambient turbulence intensity ratio I_{eff}/I_a for the different turbines in wind farms with regular (blue) and irregular (red) layouts due to wake-added turbulence using the Frandsen model.

[1]The damage-equivalent load is a load with constant amplitude and fixed frequency causing the same damage the actual variation of loads over a lifetime.

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As expected, the effective turbulence intensity levels are more constant for the regular wind farm layout. This means that wake-induced tower fatigue is similar for all turbines. For the irregular layout, however, a single outlier (in this case, turbine 67) can significantly increase tower steel for the entire project.

Conveniently, an irregular layout has a higher potential of increasing the minimum inter-turbine spacing. By strategically relocating a limited number of turbines, the wake-induced turbulence of those turbines (and thereby the tower design of all turbines) can be optimised, effectively resolving the issue. One of the turbines for each of the turbine pairs with inter-turbine spacing less than 4 RD is manually moved to satisfy a 4 RD separation constraint to show the result in wake-induced turbulence. The result is shown in Figure 7, resulting in a decrease of 10.4% of the maximum effective turbulence in the wind farm.

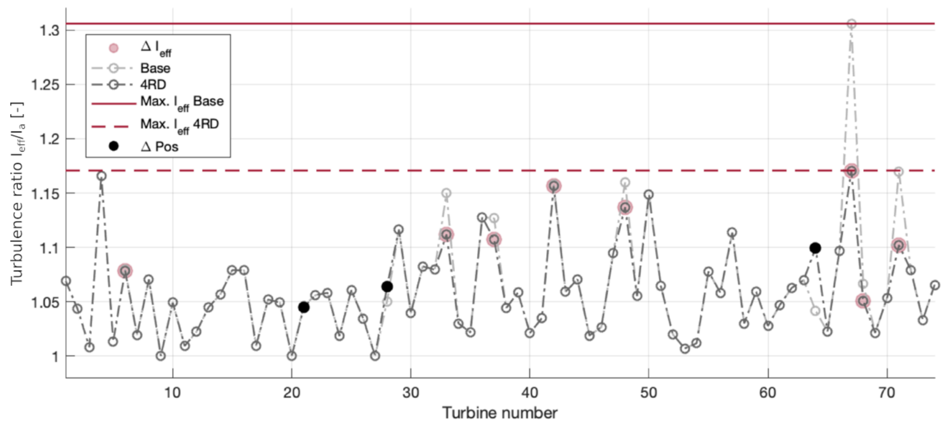

Figure 7. Effective to ambient turbulence intensity ratio I_{eff}/I_a of the original and increased inter-turbine spacing wind farm layout. The re-positioned turbines are denoted with a filled black dot. The turbines which are not re-positioned, but do experience a change in effective turbulence, are highlighted in red. The maximum effective turbulence value is indicated with the horizontal red lines for the respective layouts.

5 General applicability of results

The performance indicator group analyses in the first part of this study were performed for the Borssele wind farm with the original 10 MW IEA Wind Task 37 reference wind turbines. In this section, the global effect of the farm layout was investigated using sensitivity studies and additional layout cases with both MDAO and WindPRO. The sensitivity analysis served as a method to predict the outcome of the performance indicator group results for a change in rotor diameter size or wind climate. While this may not inform about the global effects of different layouts, it provided a first step toward evaluating the general trends of their effects. To assess this global effect of different layouts, the effect of other optimised wind farm layouts on the performance indicator group results was quantified. The results of the sensitivity studies are shown on the left-hand side of the red dashed line in Figure 8, and the additional layout case studies are shown on the right of this line. The changes to the conditions and layouts are explained in the discussion of the results below.

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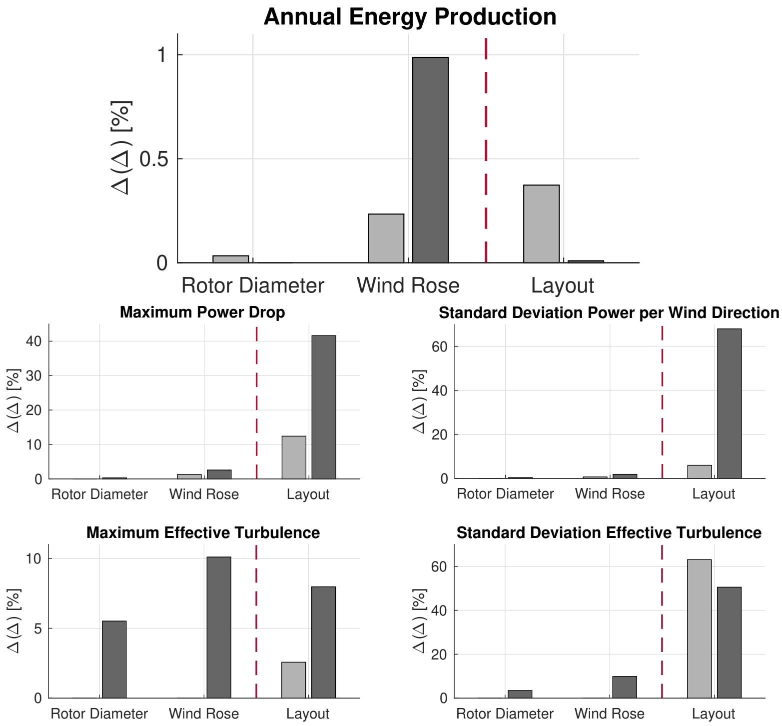

Figure 8. Absolute percentage points change obtained from the sensitivity (left of the red dashed line) and additional case studies (right of the dashed red line). The absolute percentage points change are computed based on the layout pair relative performance compared to the base layout pair performance.

To study the sensitivity to the turbine size, the rotor diameter of the IEA Wind Task 37 reference wind turbine was down-scaled from 190.8 to 178.3 m. Comparing the two layouts then shows that the relative sub-performance indicator results between the irregular and regular layouts are only marginally affected by this size change. Following, the sensitivity to the wind rose was investigated, considering uniform and unidirectional wind roses. The sensitivity of the performance indicator group results to changes in the wind rose was no longer negligible. Especially the results for the sub-performance indicator effective turbulence changed significantly between the Borssele and the uniform wind rose.

It should be noted that the wind farm layout is not optimised for changes in input parameters, which is not realistic. WindPRO was utilised to develop an additional wind farm layout for the Borssele case study. Two additional optimisations for a change in rotor diameter showed that the farm layout does not change significantly as a function of this input change. On the other hand, the changes of the wind rose altered the optimised wind farm layout significantly.

Finally, the MDAO- and WindPRO-optimised farm layout pairs were compared. The aim of performing these additional case studies was to assess the global effect of these wind farm layouts on the performance indicator group results. We observed that the relative behaviour of the layout pairs (Base, MDAO, and WindPRO) is very similar. The largest difference is in the

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persistence to wind direction for the standard deviation as a function of wind direction. This sub-performance indicator result strongly depends on the size of the wind farm with regular layout.

Different analysis methods were implemented to assess the global effect of the wind farm layout on the performance indicator group results. It was found that regardless of the changes in layout cases, wind rose or rotor radius, the absolute inter-pair results are identical as to which layout outperforms the other. For example, in the base case, the irregular wind farm was found to perform worse on the maximum effective turbulence. The same negative behaviour was found with respect to the regular wind farm layout for a change in rotor diameter, wind climate and also for alternative wind farm layouts.

6 Conclusions

Irregular wind farm layouts outperform regular layouts regarding energy production, as overall wake losses are reduced. In the performed case study, an overall yield increase of 0.66% was found for the chosen layout pair. A notable finding was that the irregular layout also increases the persistence to wind direction, which means that the power output is less sensitive to fluctuations in wind direction. The maximum power drop of the irregular layout is roughly one-third of the maximum power drop observed in the regular layout. This characteristic of irregular layouts improves the predictability of the power output, reducing the impact of wind forecasting errors on power system operation and potentially increasing the value of power in the electricity market.

However, irregular layouts may increase the overall tower steel use. Using the Frandsen model, the irregular layout is found to generate 14 to 24% higher worst-case wake-induced turbulence levels. This results in higher fatigue loads, increases in tower wall thickness and therefore higher steel costs. By increasing the minimum spacing, the worst-case turbulence intensity is reduced by 10.4%, bringing the worst-case wake-induced turbulence within the range of the regular layout. This conclusion has general validity since irregular layouts inherently have at least a few turbines positioned with limited spacing. Although the use of irregular wind farm patterns increases energy yield, improving the performance of the wind farm as a whole requires caution to inter-turbine spacing to limit the negative effect of increased fatigue-loading.

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