A Practical Optimization for Offshore Wind Farm Layout

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Abstract: the evenly distributed offshore wind resource calls for regular placement of wind turbines which is adopted in most offshore wind farms. However, the optimizations of offshore wind farm layout by most academic researchers often lead to irregular arrangement which cannot be standard for engineering practice. An optimization strategy called WindMax for regular turbine layout is put forward. 3 widely cited case studies and a factual offshore wind farm study were carried out to show the effectiveness and its potential for offshore wind power engineering application.

Key words: offshore wind farm   optimization   regular layout

1. Introduction

The layout optimization is a persistent pursuit for wind energy development which tries to determine the optimal locations of wind turbines by maximizing and/or minimizing a single objective or multiple objectives, while satisfying certain constraints [1]. This problem has been investigated in many studies with different problem formulations and using various optimization algorithms [2]. Mosetti, Poloni and Diviacco first systematically optimized turbine positions in a wind farm by a genetic algorithm (GA) [3]. Their work was further improved by Grady, Hussaini and Abdullah [4], Marmidis, Lazarou and Pyrgioti [5], and Wan, Wang, Yang, et al. [6]. However, all these optimization methods can hardly be used in offshore wind farms.

Offshore wind farm features evenly distributed wind energy resource, which requires uniform placement of wind turbines. Actually, a common practice for offshore wind farm layout is the regular arrangement of wind turbines, such as Horns Rev, London array and its neighboring offshore wind farms etc. Moreover, the whole layout of Horns Rev wind farm can be configurated by a basic parallelogram arrangement with each vertex standing for a location of wind turbine as shown in figure 1.

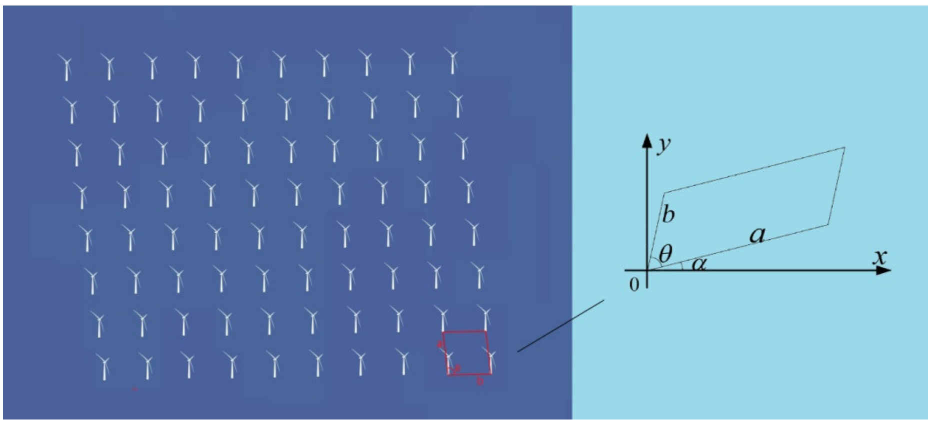


Fig. 1: configuration of Horns Rev offshore wind farm layout

Take the example of London array, which still is the largest offshore wind farm in the world, and its neighboring offshore wind farms, the basic configurations of these wind farms can be described by figure 2. Located in the adjacent area and given the similar wind resource, why these four offshore wind farms layouts are so different, and the questions that whether there is an optimal layout for this area and how to get the solution should be investigated.

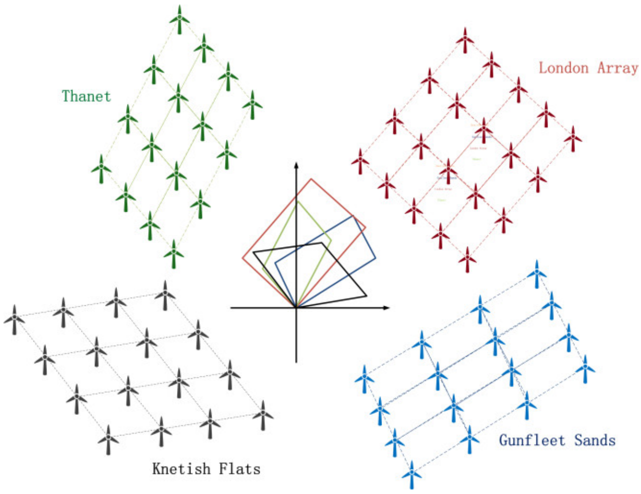


Fig. 2: configuration of London array and its neighboring offshore wind farms layout

2. An optimization strategy for regular layout

Upon the idea of regular arrangement of wind turbine, a wind power utilization maximization strategy (WindMax) features uniform parallelogram arrangement for wind turbine location presented to maximize energy production. A uniform layout of wind farm with staggered equally-spaced wind turbines arrangement can be described with parameters of a parallelogram, namely the two adjacent sides a and b, the angle θ between them, and the orientation angle of α, as shown in right side of figure 1. With each vertex standing for a wind turbine, the turbine position for row m+1 and column n+1 can be expressed with following formula under polar coordinate system.

$$\begin{cases} \rho_{mn} = \sqrt{(ma)^2 + (nb)^2 + 2mnab\cos\theta} \\ \gamma_{mn} = \arctan\frac{nb\sin\theta}{ma+nb\cos\theta} + \alpha \end{cases}, (m, n \in Z) \qquad ------ \quad (1)$$

In above formula, the radius ρ_{mn} and azimuth γ_{mn} are determined by four parameters of a parallelogram, the lengths of a and b, the angle θ, and the orientation angle α. With such scheme, WindMax translates the layout optimization into geometry optimal value finding.

Aiming at wake loss minimization, WindMax performs an explicit enumeration of all admissible solution within various parallelogram parameters space to find the optimal layout. The flow chart is shown in figure 3. For each positional relationship between the wind turbines, the wake effects can be easily assessed for favorable 360 degree direction with wind data and wind turbine parameters input. The wind direction resolution is chosen as to get the fine optimal solution, It has been found that the choice of bin size for wind direction is crucial for layout optimization and the choice of using bin size of 1 m/s for wind speed and 1° for wind direction is recommended, so that reliable and consistent optimization results can be obtained [1].

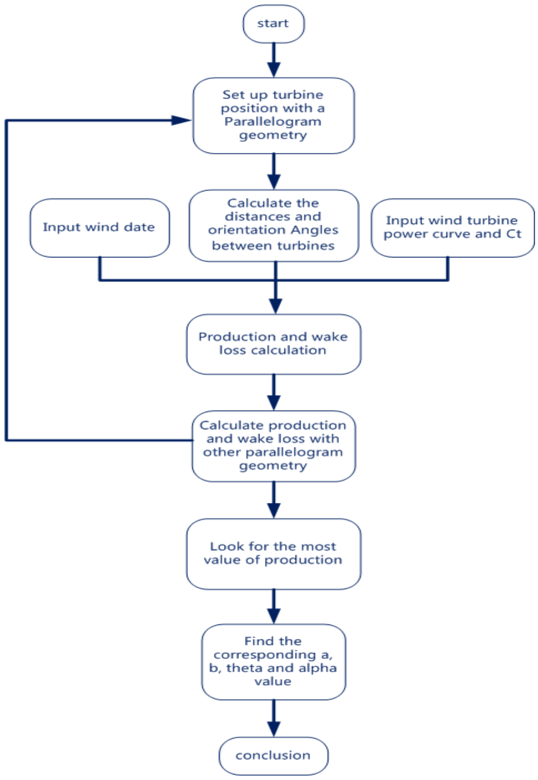


Fig. 3: WindMax flow chart for offshore wind farm layout optimization

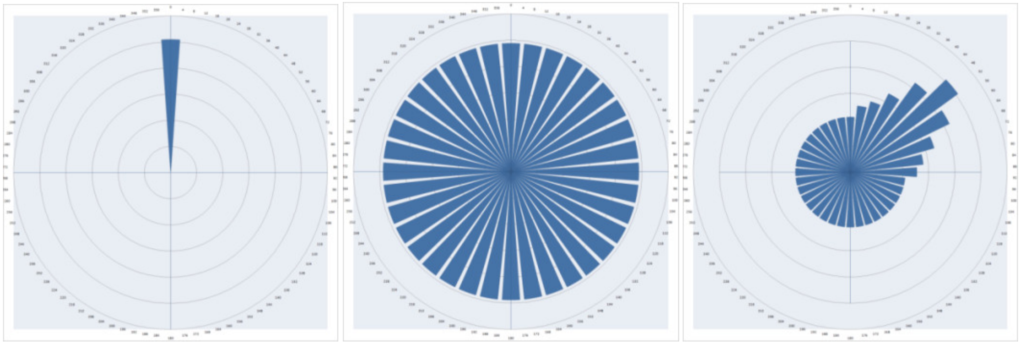
For the sake of optimal solution rather than precise and reliable production prediction, WindMax prefers the standard wake model to some more complex ones. In this scene, the Jensen-Katic wake model [7] is used to determine the wake loss with respect to 360 degree directions while maintain computing efficiency. The merged wakes are considered in WindMax by the sum of kinetic energy deficits of all turbines with full and/or partial wakes.

3. Case studies

Some case studies have been conducted to test different optimization algorithms. In 1994, Mosetti et al. constructed three ideal case studies to test layout optimization and solved it with genetic algorithm (GA) [3]. The same cases were used in many following studies which mainly aimed at developing various optimization methods, such as improved GA by Grady et al. [4], particle swarm optimization [8], extended pattern search [9], and so on.

In above cases, the wind farm with area of 2000m*2000m was divided into 10*10 square cells, the width of which is equal to 5 rotor diameters for operation safety, and only the center of which can be placed with wind turbine. The hub height of the turbines is 60m, rotor diameter 40m, 0.88 of thrust coefficient which is considered constant throughout the process.

Three wind cases with different complexities were studied: (a) a sole north wind direction with a wind speed 12m/s; (b) 36-direction evenly distributed wind with a speed 12m/s; (c) 36-direction distributed wind with varied probability of the speeds 8, 12, and 17m/s. The wind roses for three cases are shown in figure 4 and wind speed & direction distribution for case (c) is shown in figure 5.



case (a) case (b) case (c)

Fig. 4 : Wind rose for three wind cases

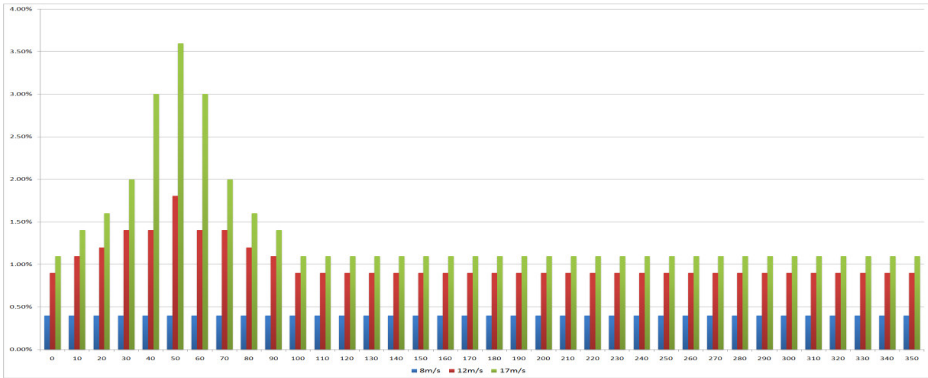
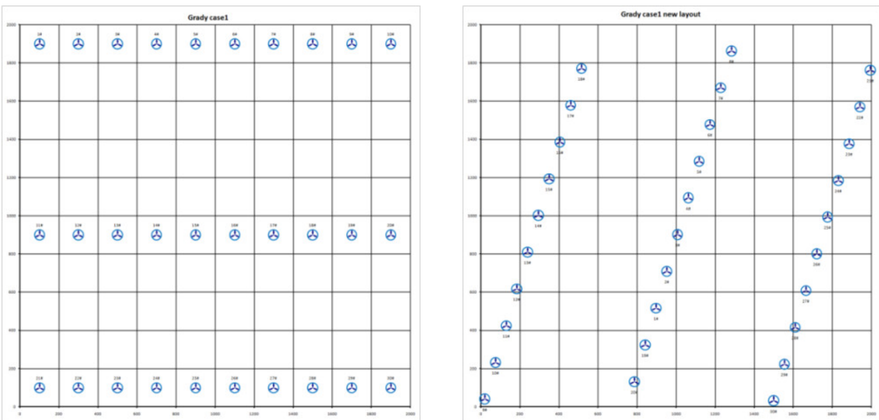


Fig. 5 : wind speed & direction distribution for case (c)

Grady's optimization results were used to compare with WindMax's solutions. In Grady's study, the numbers of installed turbines for three wind cases are 30, 39 and 39 respectively, while the numbers of turbines by WindMax are 30, 40 and 40 correspondingly.

3.1 Case (a)

The layout conclusions by Grady and WindMax are shown in figure 6, and the calculated production and the park efficiency are shown in table 1.



Grady layout **WindMax layout**

Fig. 6 : layout conclusion comparison for case (a)

Case (a)		
	Grady layout	WindMax layout
Number of turbines	30	30
Mean wind speed before wake(m/s)	12	
Mean wind speed after wake(m/s)	11.48	12
Annual energy production (MWh)	115369	136236
Park efficiency(%)	84.68	100

Tab.1: calculation results for case (a)

In case (a), even with minimum distance of 5D, WindMax reaches a zero wake loss layout. For the given sole 0° wind direction, the effective distance between wind turbines is less than 2D from the perspective of wind blowing, as shown in figure 7. Moreover, the park efficiency varies greatly with wind direction and the peak value stay close to worst wake loss, as shown in figure 8, which means optimization sensitivity to wind direction.

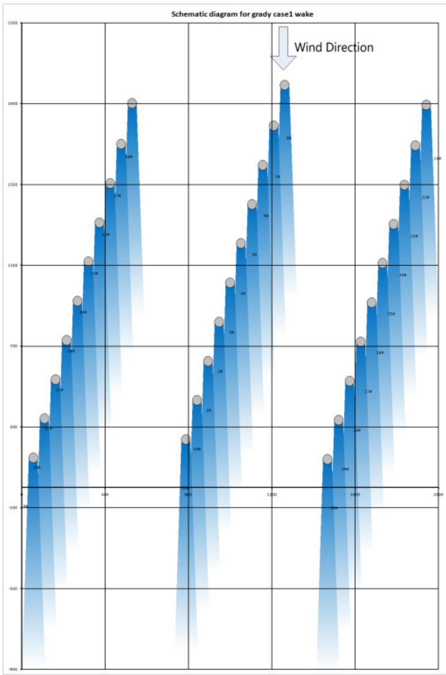


Fig. 7： explanatory wake effect graph for case (a)

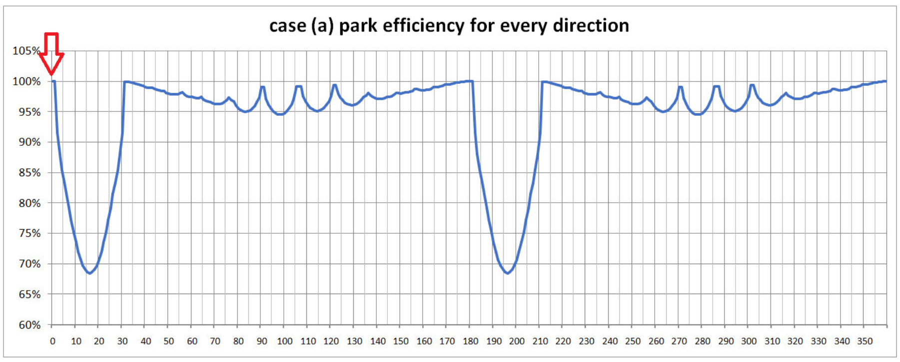
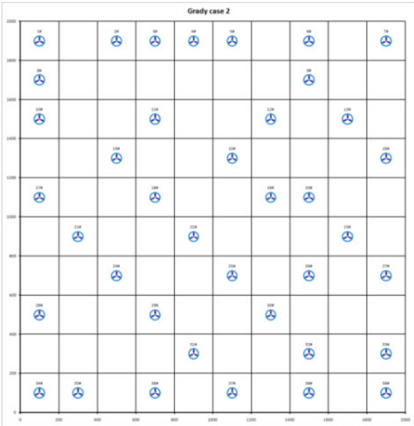
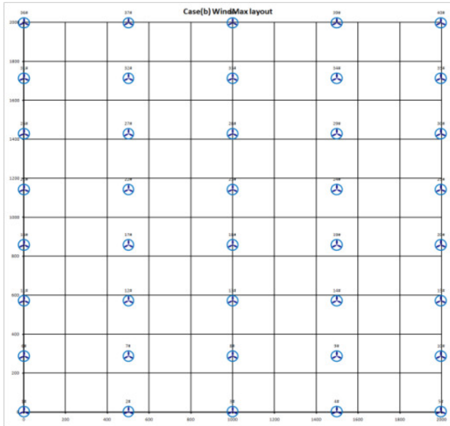


Fig. 8： park efficiency versus wind direction for case (a)

3.2 Case (b)

The layout and the calculated results are shown in figure 9 and table 2 respectively:





Grady layout **WindMax layout**

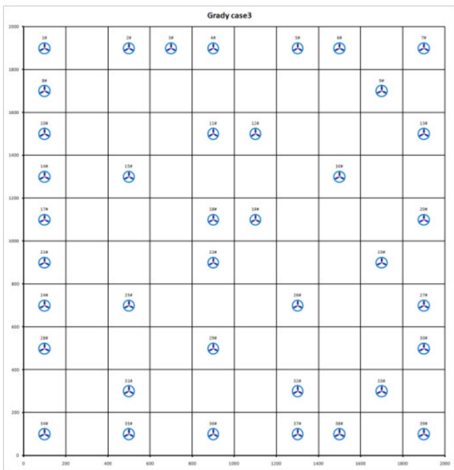
Fig. 9 : layout conclusion comparison for case (b)

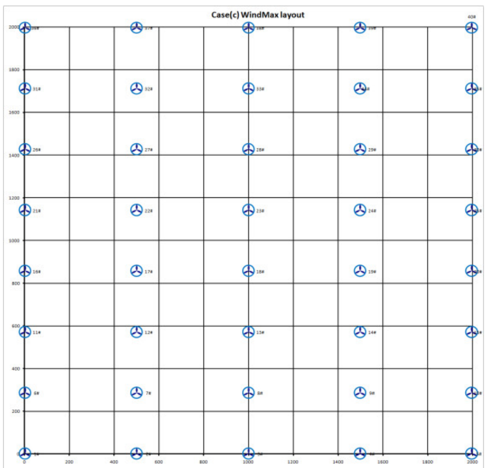
Case (b)		
	Grady layout	WindMax layout
Number of turbines	39	40
Mean wind speed before wake(m/s)	12	
Mean wind speed after wake(m/s)	11.23	11.35
Annual energy production (MWh)	147121	159348
Park efficiency(%)	83.06	87.72

Tab.2: calculation results for case (b)

3.3 Case (c)

The layout and the calculated results are shown in figure 10 and table 3 respectively:





Grady layout **WindMax layout**

Fig. 10 : layout conclusion comparison for case (c)

Case (c)		
	Grady layout	WindMax layout
Number of turbines	39	40
Mean wind speed before wake(m/s)	13.89	
Mean wind speed after wake(m/s)	13.02	13.17
Annual energy production (MWh)	165755	173406
Park efficiency(%)	93.24	95.1

Tab.3: calculation results for case (c)

It should be noticed that case (b) and case (c) share the same layout by WindMax. In fact, the shape of wind farm area, which limits the admissible solution space, has perceptible impact on WindMax output.

4. Offshore wind farm study

Beside the case studies, a factual offshore project was used to test WindMax. The Danish offshore wind farm Horns Rev 1 was chosen for its well studied nature. The mesoscale model wind data from DX wind was used as input, whose wind rose is shown in following figure compared with WAsP Tab format wind rose.

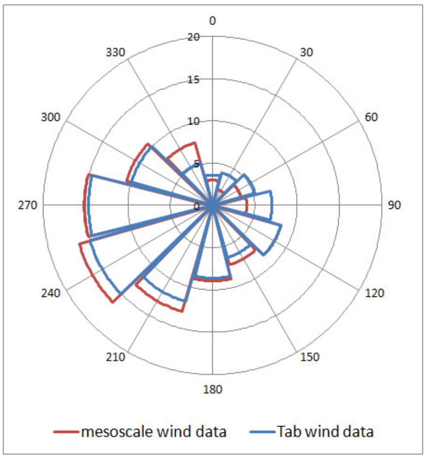


Fig. 11 : mesoscale wind rose compared wtih Tab wind rose in 12 sectors

It can be seen from above figure that mesoscale data has a high correlation with Tab data, which justified the use of mesoscale data for optimization and comparison to considerable extent. The park efficiencies were calculated by WAsP with 36 direction sectors and by WindMax by 360 degrees at 0.035 wake decay constant.

There are two layouts by WindMax, the first one is with the exactly same wind farm range, and the second is with the equal area but different wind farm range shape, as shown in figure 12(b) and (c).

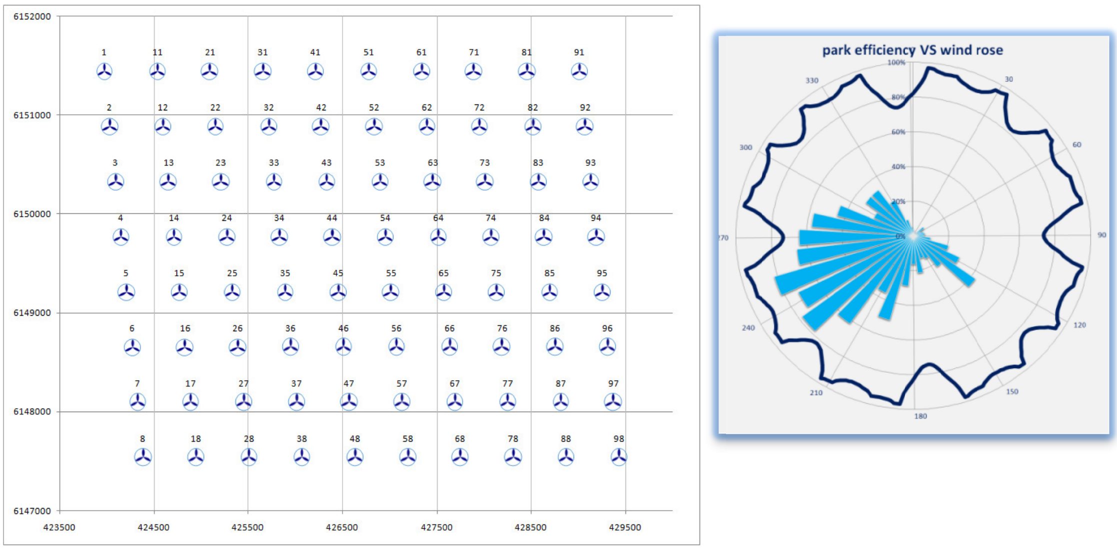


Fig. 12 (a)：Horns Rev 1 original layout   directional park efficiency with wind rose

Fig. 12 (b): WindMax layout1   directional park efficiency with wind rose

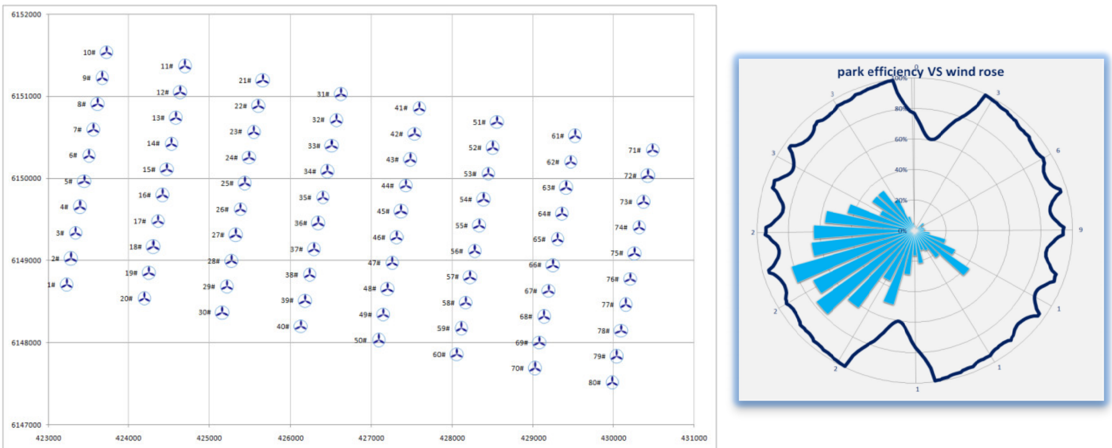


Fig. 12 (c): WindMax layout2   directional park efficiency with wind rose

It can been seen from above graphs, compared to original layout, the WindMax layouts keep dense wind energy sectors away from low park efficiency directions to achieve higher energy yields. The comparison results are shown in table 4.

Park efficiency (%)	Original layout	WindMax layout 1	WindMax layout 2
WAsP	88.16	88.96	90.03
WindMax	88.63	89.22	89.86

Tab.4: layout comparison for Horns Rev 1 offshore wind farm

5. Conclusions

The proposed WindMax optimization strategy transforms the layout optimization problem into geometric parameters optimization, giving out uniform layout solution which is meaningful for offshore wind power engineering application. Three ideal case studies and an actual offshore wind farm study have shown the effectiveness of WindMax in layout optimization, although more case studies, especially the real wind power projects, should be conducted to consolidate the conclusion.

6. References

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