Investigation into offshore wind farm repowering optimization in Hong Kong

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Abstract

With the growing prosperity of the offshore wind energy market and the approaching end of the lifetime of the first-generation offshore wind farms, the high decommissioning cost has attracted increasing attention all over the world. To decrease this cost, the spotential repowering strategies are applied into the wind farm optimization and investigated in this study. In the repowering optimization strategy, the wind turbine foundations are not dismantled immediately after their service lifetime, and the lifecycle of them is extended to two generations' service time. The costs of removing the first foundations and installing the second foundations are saved. With the layout optimization method, the wind loss caused by wake effect can be decreased, which improve the energy output of the wind farm in the whole lifetime. Levelised cost of energy (LCoE) is set as the criterion to evaluate the wind farm layout. Both aligned and optimized layouts are analyzed in this study. A case study in Sha Chau Island seawater area in Hong Kong is then discussed. The results reveal that Hong Kong has many advantages to exploit offshore wind power and the repowering optimization layout is practical for cost-saving. According to this study, the LCoE of an offshore wind power farm in Sha Chau Island seawater area could be decreased to 0.9130 HK$/kWh.

Keywords: repowering strategy; offshore wind farm layout optimization; wake effect; multi-population genetic algorithm; levelised cost of energy

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1 INTRODUCTION

The restriction of traditional fossil fuel is an important issue for the whole world [1]. The matter is now becoming even worse because of the declining reservoirs and the severe impact on environment [2]. At the same time, the demand of energy is increasing annually with the raise of global population and develop of economy [3]. Considering all kinds of energies, renewable energy is the relatively promising one because of its inexhaustible characteristic. It is environment-friendly and clean as well, which is an ideal energy source to deal with the pressure from the on-going global warming and pollutions. Therefore, utilizing renewable energy will lead to a sustainable energy development in the future [4].

Wind energy is a representative renewable energy, which is developing fast in the recent years. In the year of 2017, the new globally installation of wind industry was in excess of 52.5 GW, which was mainly contributed by China with 19.7 GW new installations [5]. By the end of the year 2017, the new global total was 539.1 GW, whereas the cumulative market grew more than 11%. Specially, offshore wind resources are stronger, more abundant, and more consistent in terms of their availability [6]. It is reasonable that offshore wind power develops quickly and is the most potential renewable energy resource to coastal regions in the future [7]. By 2017, the number of newly installed offshore wind power was 4.3 GW globally [5].

Offshore wind farms are relatively new. The decommissioning phase, which is also the last phase in a project, has just been given little attention to date [8]. In the year of 2015, seven offshore WTs in the UK and Sweden were decommissioned [9], which also declares that the first generation of offshore WTs arrives their final stage of 20-year service time and an unprecedented

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decommissioning market is emerging [10]. The incalculable high decommissioning costs becomes a new challenge. Saving the decommissioning cost will cut down the total cost to a great extent, which is a commonly seen solution to decrease the levelised cost of energy (LCoE) of a wind farm.

Generally, offshore wind farms, including foundations, must be decommissioned after their life cycle's operation in order to protect marine ecological environment [11]. The high cost of decommissioning an offshore wind farm is an unavoidable problem and is therefore rising more and more attention. DNV GL, a renewable energy and technical advisory, estimated that the cost to decommission offshore wind turbines will be EUR200 000–500 000/MW, which equals to 60~70% of quoted installation costs [12]. Interviews within the Contact Programme suggested that the average decommissioning cost for offshore wind would make up around 2.5% of the total project cost or 2% of operating cost when spread over the lifetime of a project [13]. Removal of foundations may need near 50% of the total decommissioning expenses, because the heavy offshore structures require more complex techniques and specialized equipment [14].

Commonly, the offshore WT has a longer life expectancy of around 25~30 years [15]. The foundations are often overdesigned [16], which means foundations still have the capability to serve when WTs are to be decommissioned. Type and load will influence the specific lifespan of the foundations. For example, some gravity bases can be projected last over 100 years [17]. Under this circumstance, the repowering idea has been proposed recently. Hou *et al.* [18] presented an offshore wind farm repowering strategy, in which other types of WTs chose to replace the original WTs. The repowering strategy is demonstrated to be better than replacing the old WTs with identical ones. However, in that repowering strategy, the layout of wind farm is just aligned. If the repowering optimization is considered, variables like positions and heights of WTs are involved, the LCoE will be further decreased.

Therefore, the repowering strategy is continuously investigated with the wind farm optimization problem. In this study, the idea of repowering strategy is that when the first generation of offshore WTs are decommissioned, their foundations remain to work for the second generation of WTs after some strengthening work, thus the huge decommissioning cost is saved. On the premise of foundations' structural strength, the second generation WTs are supposed to be smaller and some strengthening measures should be adopted. All WTs and foundations are decommissioned at the end of the whole lifecycle, therefore no additional marine ecological problems are caused.

As an application of the proposed method of the offshore wind farm repowering method, potential offshore wind farms in Hong Kong are discussed. Hong Kong is a coastal region full of offshore wind energy, with the potential of 1.13×10^{10} kWh annual power generation, which accounts for 25.54% of the total annual consumption of electricity in the year 2014 [19, 20]. However, the energy used in Hong Kong now is either produced using fuel inputs, or imported from China mainland, only excluding a very small portion of electricity generated from wind energy since early 2006, but still with no energy supplement from any offshore wind farm yet [21]. Thus, Hong Kong is having a good opportunity to develop its offshore wind energy industry now.

To find a better layout solution for Hong Kong, a wind farm optimization process is applied in this paper. The results from both the conventional strategy and repowering strategy are compared. In the repowering optimization process, not only types but also positions of WTs are considered. The submarine cable is also considered in this study but not as a variable. Namely, cables also will serve for two generations' period, so the second generation WTs remain the same positions as the first generation WTs.

In view of all above mentioned situations, this study aims at studying the repowering strategy of offshore wind farm from the very beginning phase of optimizing the positions of WTs. As an application of this study, an economical offshore wind farm layout for Hong Kong is then proposed. In Section 2, calculation models applied in this study are demonstrated. In Section 3, the method of optimizing wind farm layout is demonstrated. In Section 4, a case study for Hong Kong is conducted to show the effectiveness of the layout optimization process based on the repowering strategy. Finally, in Section 5, summaries of this study are drawn.

2 CALCULATION MODELS

2.1 Wind farm model

The calculation tool adopted in this study is the MATLAB software. Positions of WTs are expressed by coordinates. Relative positions of two WTs and wind velocities are firstly expressed by vectors. The diagram of wind farm model is shown in Figure 1.

In the Figure 1, X axis and Y axis represent the coordinate axes of the wind farm. The red points represent any two WTs i and j in the wind farm. (x_i, y_i) and (x_j, y_j) are the position coordinates of WTs. $\overrightarrow{X_r}$ is the vector from i to j, and it can be calculated by $\overrightarrow{X_r} = (x_j - x_i, y_j - y_i)$. $\vec{u}$ is the wind velocity vector. $\overrightarrow{u_0}$ is the unit vector of $\vec{u}$, calculated from $\overrightarrow{u_0} = \frac{\vec{u}}{\|\vec{u}\|}$. d_{vertical} is a vertical distance to judge the relative position of two WTs, whereas d_{normal} is to judge whether a WT is under the effect of wakes. d_{normal} and d_{vertical} are obtained from the following formula:

$$d_{\text{normal}} = \vec{X}_r \cdot \vec{u}_0 \quad (1)$$

$$d_{\text{vertical}} = \vec{X}_r \times \vec{u}_0 \quad (2)$$

2.2 Wake model

Wake is a principle factor that affects the energy yield of wind farms. In large wind farms, wakes may cause 10~20% power losses of the total energy output [22, 23]. When designing the

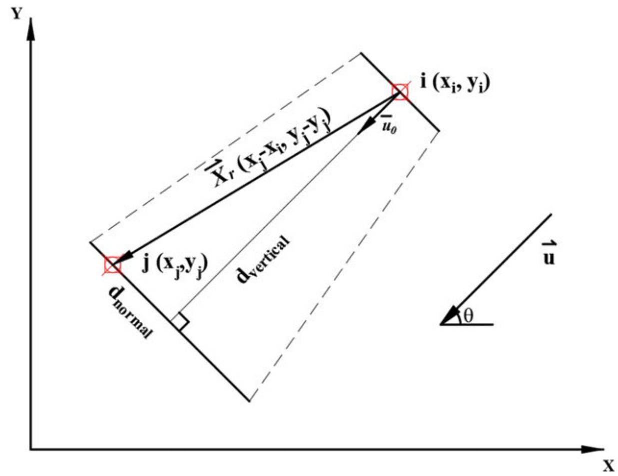

Figure 1. *Distance between turbines along wind direction.*

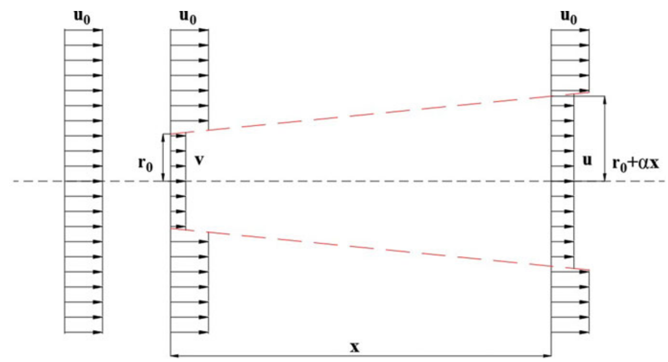

Figure 2. *Jensen wake model.*

layout of a wind farm, much power losses can be avoided by taking wake effect into account.

Many scholars have conducted research on wake models to cut down the computational cost and improve the accuracy [24]. Many wake models were presented for wake calculation [25]. However, only Jensen wake model is applied in the most wind farm layout design work now [26–30].

Jensen wake model is simple, and it also has relatively high accuracy. Compared to the other models, it needs the least computation cost [31]. Jensen wake model assumes that wakes expanded linearly behind the upstream WT, as shown in Figure 2 [25].

u_0 is the upcoming wind velocity; r_0 is the radius of the upstream WT; x is the downwind distance; and u is the wind velocity of the downstream WT. The wake models for single WT and multiple WTs are shown in equations (3) and (4), respectively.

$$u = u_0\left[1 - \frac{2ar_0^2}{(r_0 + \alpha x)^2}\right] \tag{3}$$

$$u_i = u_0\left[1 - \sqrt{\sum_{i=1}^{N}\left(1 - \frac{u}{u_0}\right)^2}\right] \tag{4}$$

On the other hand, one apparent problem is that the distribution of wind speed downstream a WT blade is not a linear problem. The linear assumption of Jensen wake model is far from reality. Therefore, in this paper, a two-dimensional (2-D) wake model which is a further development of Jensen wake model is applied, as shown in Figure 3. In the 2-D wake model, the partial wake effect is taken into consideration. Similar modifications on Jensen wake model have also been made by many

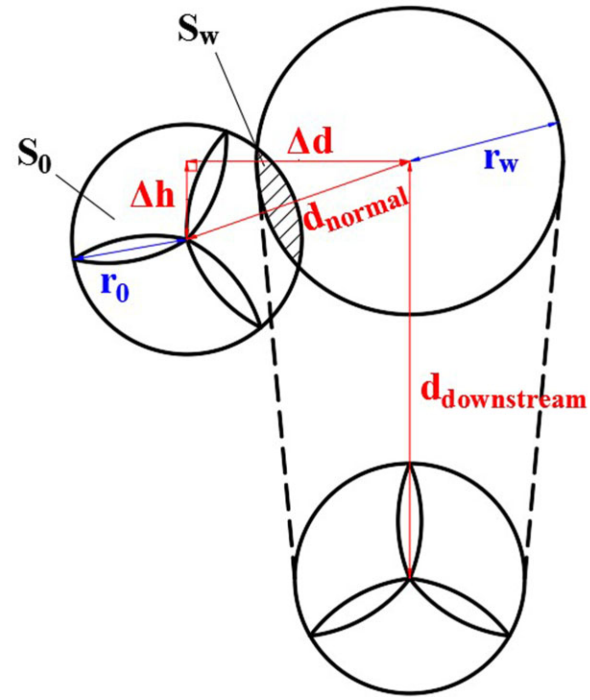

Figure 3. 2-D *wake model.*

other scholars, like Hou *et al.* [18], Amaral and Castro [32], Wang *et al.* [33] and Chowdhury *et al.* [34]

In formulae, r_0 is the radius of the WT blade; r_w is the assuming wake radius; s_0 is the swept area of WT; s_w is the wake-influenced area. d_{normal} is obtained from formula (9). Δh is the hub height difference and Δd is WTs' horizontal distance that perpendicular to the wind direction.

$$d_{normal} = \sqrt{\Delta h^2 + \Delta d^2} \tag{5}$$

Thus, the wake formula for single WT is modified as equation (10).

$$\begin{cases} u = u_0, & r_w + r_0 < d_{\text{normal}} \\ u = u_0\left[1 - \dfrac{2ar_0^2}{(r_0 + \alpha \cdot d_{\text{downstream}})^2}\right] \cdot \dfrac{S_w}{S_0}, & r_w - r_0 \le d_{\text{normal}} \le r_0 + r_w \\ u = u_0\left[1 - \dfrac{2ar_0^2}{(r_0 + \alpha \cdot d_{\text{downstream}})^2}\right], & d_{normal} < r_w - r_0 \end{cases} \quad (6)$$

2.3 Cost estimation

The total cost of conventional strategy is shown in equation (7). In that strategy, after one generation's service time, both WTs and foundations are dismantled directly. While in repowering strategy, two generations of WTs' service time is considered. The cost estimation formula is shown as equation (8).

$$Total\_Cost_{CS} = Cost_{WT} + Cost_f + Cost_i + Cost_d \quad (7)$$

$$Total\_Cost_{RS} = Cost_{WT1} + Cost_{f1} + Cost_{i1} + Cost_m + Cost_{WT2} + Cost_{i2} + Cost_{d2} \quad (8)$$

In formulae, $Cost_{WT}$ is WT cost and consulted from $Cost_{WT} = A_P + B_P \cdot P_{\text{rated}}$ [35]; $Cost_f$ is the foundation cost, which is assumed to be proportional to WT's rated power; $Cost_i$ is the installation cost, which is set to be 80% of the corresponding $Cost_{WT}$; $Cost_d$ is the decommissioning cost, which is assumed to be 60% of $Cost_i$; and $Cost_m$ is the maintaining cost, which is assumed to be 10% of $Cost_i$.

3 OPTIMIZATION OF WIND FARM LAYOUT

3.1 Optimization process

When adopt the repowering strategy, both the aligned and the optimized layouts are analyzed. The process of optimization is shown in Figure 4.

LCoE is decided by total energy and total cost, as shown in equation (9), and the lowest LCoE is the objective of this optimization process.

$$\text{LCoE} = \frac{\text{Total\_cost}}{\text{Total\_energy}} \quad (9)$$

Total cost can be estimated as introduced in Section 3.3. Total energy in the repowering strategy considers two generations' energy yields, which have close relationship with wind frequency and wind losses. Wind frequency should be obtained from the real wind data. The total wind velocity loss is a more complicated result of multiple wake effects.

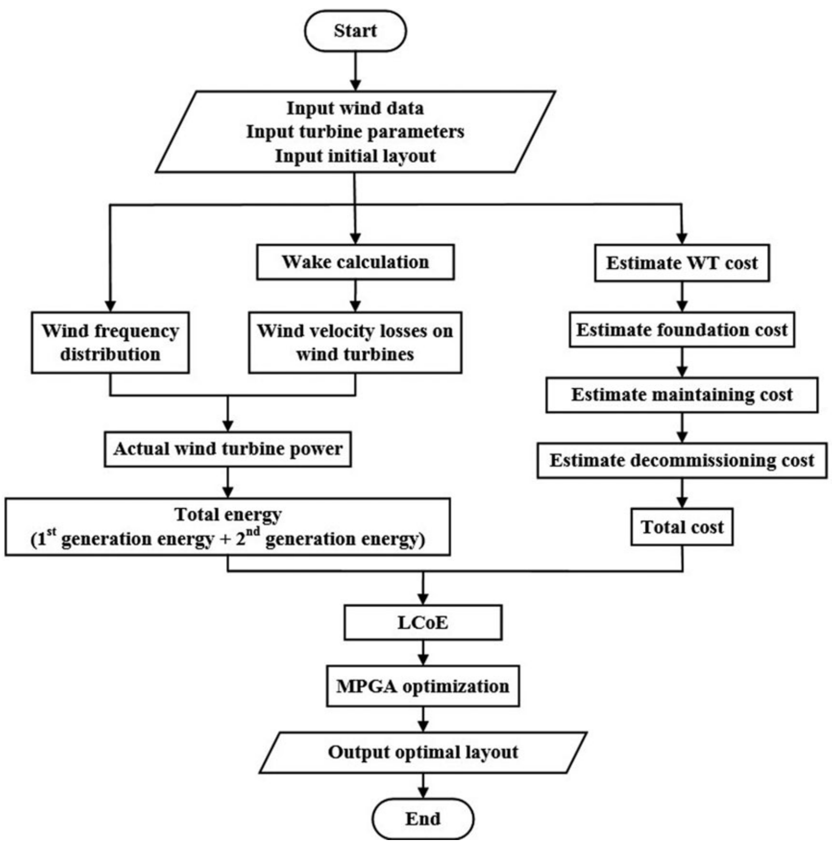

Figure 4. *Flow chart of the optimization process.*

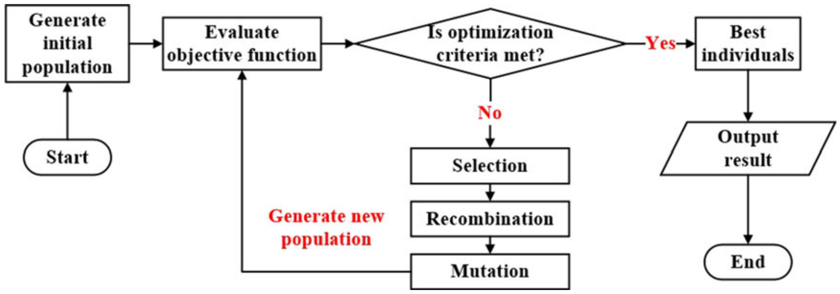

Figure 5. *Procedure of the MPGA.*

3.2 Multi-population genetic algorithm

The optimization algorithm applied in this study is MPGA. The effectiveness of using MPGA to obtain the optimal layout of offshore wind farms has been verified by Gao *et al.* [19], [36] and Sun *et al.* [37].

The widely known process of MPGA is demonstrated in Figure 5. The first step is to determine the function of objective and set an optimization criterion. Secondly, the initial population is generated randomly. Thirdly, the population is applied into the objective function. The next step is to judge whether the criterion of the optimization is met. If the answer is *yes*, the best individuals are obtained. However, if the answer is *no*, a new population will be generated by selection, recombination and mutation, and then returns into the circulation at the third step, and continues until the optimization criterion is met.

In this study, the population is the coordinates of WTs. LCoE is the objective, while the criterion is the minimum LCoE keeps for five hundred of generations. If the criterion is met, the optimal positions of WTs (i.e. the best individuals) is obtained; while if not, the new population should be generated and go into the circulation until the criterion is met.

4 A CASE STUDY IN HONG KONG

The presented optimization method for offshore wind farm is then applied to Hong Kong. The optimal results tend to provide useful references for Hong Kong's offshore wind industry development.

4.1 Site selection of the offshore wind farm

In Hong Kong, there are four potential sea areas that are proper to develop offshore wind farms [19]. Sha Chau Island sea area (as shown in Figure 6) has huge sea area and good potential of offshore wind energy to build offshore wind farms, which is therefore selected here. The size of the chosen offshore area is 3740 m×5828 m.

The first-hand data wind velocity is the 10-year hourly wind speed data obtained from the Royal Observatory, Hong Kong. The location of the anemometer tower is 22°20′45″ N, 113°53′

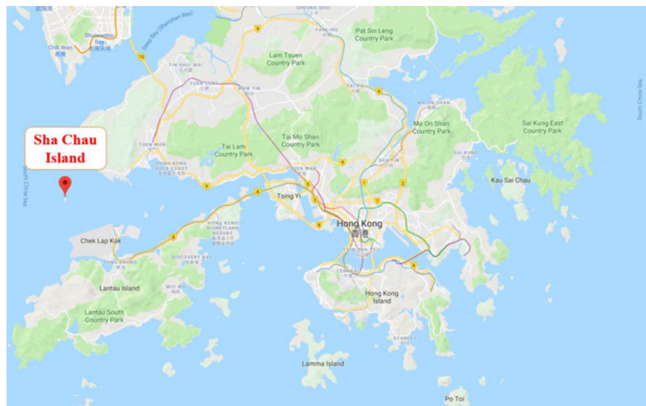

Figure 6. *The location of Sha Chau Island [38].*

28″ E. The elevation of the anemometer is 31 m above the mean sea level, whereas the elevation of the station is 21 m above the mean sea level. Then the wind rose diagram is obtained, as shown in Figure 7.

4.2 Wind speed variation

Wind speed changes in the direction of altitude, therefore, the anemometer height and hub heights of WTs are also considered. The wind power law is used, of which the equation is shown as follows:

$$v = v_0 \cdot \left(\frac{z}{\delta}\right)^{\alpha} \tag{10}$$

v is the wind speed at the height of z; v_0 is the incoming wind speed measured at the reference height of δ, whereas α is the coefficient of the wind speed power law, which can be referred to [39]. For the wind blows over a distance from smooth terrain to rough terrain, the following equation should be used:

$$\frac{V_2}{V_1} = \left(\frac{z_2}{\delta_2}\right)^{\alpha_2} \cdot \left(\frac{\delta_1}{z_1}\right)^{\alpha_1} \tag{11}$$

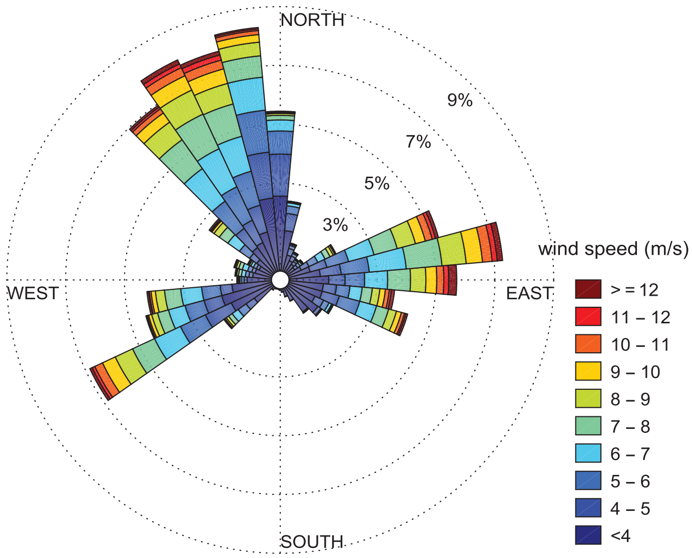

Figure 7. *Wind rose diagram of Sha Chau.*

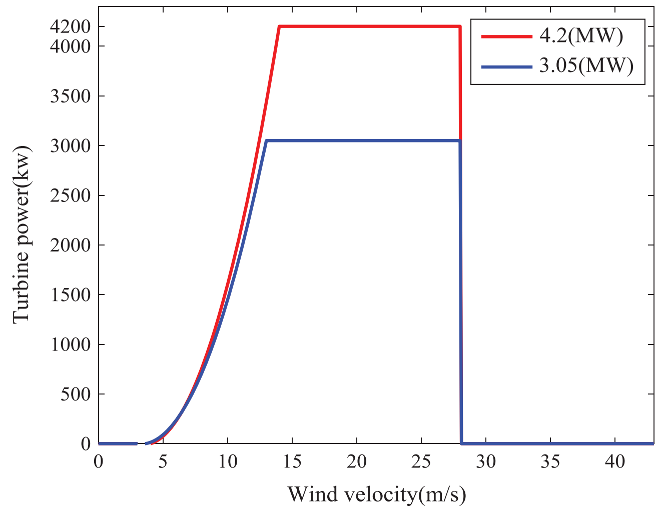

Figure 8. *Wind turbine power curves.*

Table 1. *The parameters of wind turbines [40]*

Parameters	E-126 EP4	E-101
Rated power (MW)	4.2	3.05
Diameter of rotor (m)	127	101
Height of hub (m)	135	99
Rated wind speed (m/s)	14	13
Cut-in wind speed (m/s)	3	3
Cut-out wind speed (m/s)	28	28

4.3 Wind turbines

Two different WTs are considered in this paper, which are E-126 EP4 and E-101 from ENERCON [40]. The parameters of WTs are shown in Table 1.

For the sake of generality, a polynomial power curve is adopted for modeling the power curve in this study. The equation of the power curve is referred to [41]. The power curves of the selected WTs are shown in Figure 8.

4.4 Results

In this section, both aligned layout and optimized layout are analyzed to evaluate the efficiency of the repowering strategy.

4.4.1 Results of aligned layouts

In aligned layout, 54 WTs are arranged, with 9 columns and 6 rows. The layout and annual average electricity outputs of WT are shown in Figure 9. The blue dots represent WTs, the red numbers are the annual average electricity outputs.

More detailed results are listed in Table 2. There are three strategies in comparison. A1 is the conventional strategy, in which the foundations of 4.2 MW WTs are installed in the beginning phase and dismantled in the end of the 20-year service time. A2 adopts the repowering strategy. To be specific, when the first generation 4.2 MW WTs run out of their service time, the WTs are dismantled while the foundations are reserved to support the second generation of the same type WTs for 20 years. A3 is similar to A2, the only difference is that the rated power of the second generation WTs is 3.05 MW.

It is obvious that repowering strategies can reduce much cost. Benefitting from the lowest total cost, the LCoE of A3 reaches 0.9395 HK$/kWh.

4.4.2. Results of optimized layouts

The positions of WTs' and average powers of the optimization method are shown in Figure 10.

The total service time is also in consideration of 40 years. The analyses about the optimal layouts are demonstrated in Table 3. Similarly, there are three strategies in comparison, O1, O2 and O3. O1 is the conventional strategy of 4.2 MW WTs for 2 normal 20-year service periods. O2 is also conventional strategy, but 3.05 MW WTs are applied for the second generation of service time. O3 is the repowering strategy for a 40-year service time, however, types of WT are optimized in the second generation.

From results, the energy yields of optimal layout wind farm are much more than aligned ones. LCoE also decreases a lot, which verifies the effectiveness of the optimization method.

4.5 Discussions

The energy yield comparisons are listed in Table 4. The optimized layout improves energy yield distinctly. For 4.2 MW WTs, the energy yield of optimized layout within 40 years is 5.01×10^4 GWh, which is 2.67% more than aligned layout at 4.88×10^4 GWh. More obvious circumstance happens for 3.05 MW WTs, the increment is 18.54%.

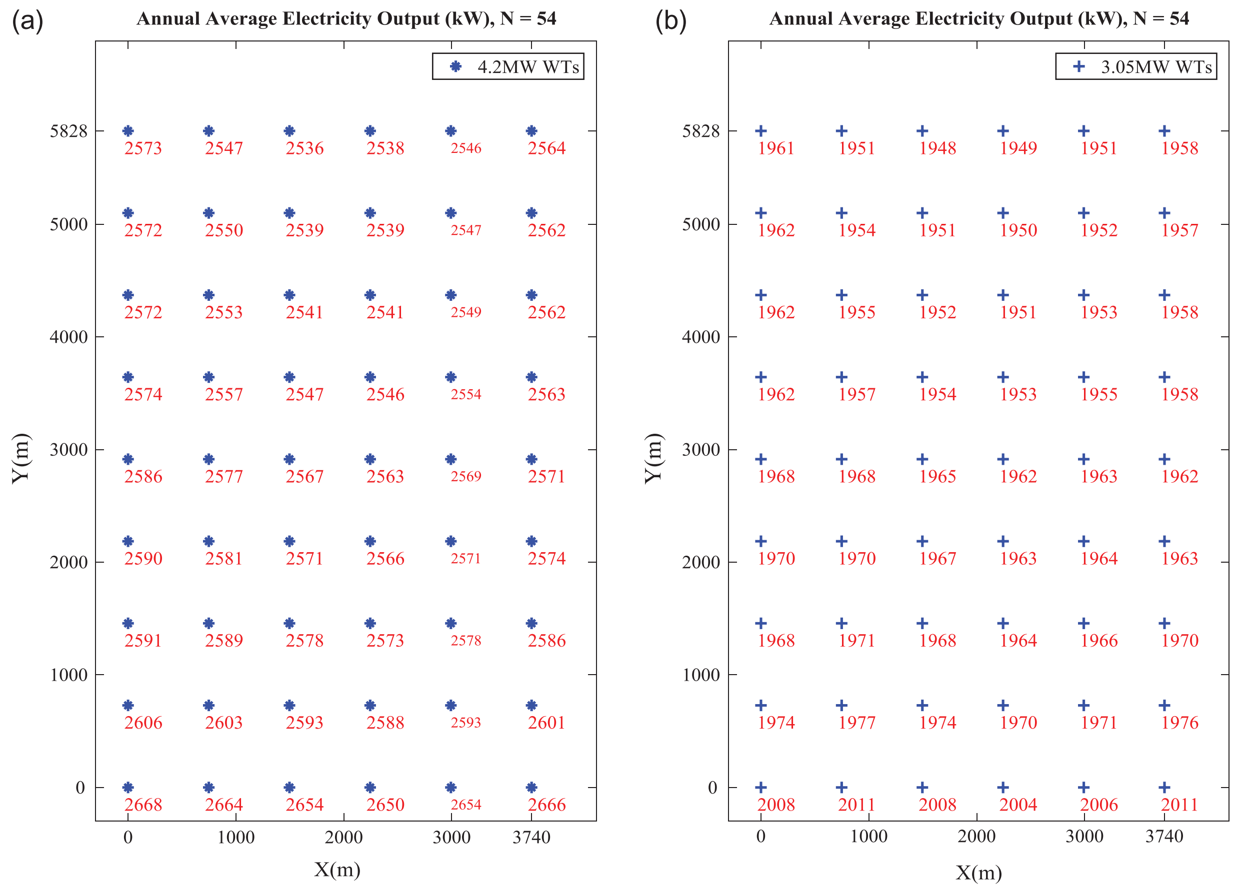

Figure 9. *Aligned layout and wind turbine power: (a) with 4.2 MW WTs; and (b) with 3.05 MW WTs.*

Table 2. *Main results of aligned layouts*

	A1	A2	A3
Number of wind turbine	54	54	54
Service years	20	40	40
Energy yield (GWh)	2.44×10^4	4.88×10^4	4.30×10^4
Total cost (MHK$)	2.83×10^4	4.94×10^4	4.04×10^4
LCoE (HK$/kWh)	1.1598	1.0123	0.9395

Tables 5 and 6 are the LCoE comparisons. In all layouts, it is obvious that repowering strategy can decrease LCoE. Remarkably, if the optimized 1 repowering strategy is adopted, LCoE can be decreased to 0.9130 (HK$/kWh), which is equivalent to decrease 21.28% of A1.

To sum up, A2 produces the most energy and O3 has the lowest LCoE. For the mentioned sea area, if the owner wants to reduce construction difficulties and choose an aligned layout, A2 is the preferred option. However, if the lowest LCoE is the orientation, O3 is the proper solution. Actually, O1 and O2 can also be considered, as their second generation WTs are of the unified types, which makes it easier for construction and management. At the same time the difference of LCoEs among O1, O2 and O3 is not huge and acceptable.

5 SUMMARIES

To reach the minimum levelised cost of energy (LCoE) of offshore wind farms, traditional and repowering strategies are analyzed in this paper. From results, the repowering strategies can significantly decrease LCoE, as when foundations are reused, huge structure cost and construction cost are saved. A case analysis in Sha Chau Island sea area is demonstrated. From this case, the proposed method of offshore wind farm layout optimization is proved to be practical and effective.

Hong Kong is a coastal region with vast offshore wind energy power. Taking the chosen Sha Chau Island offshore area (3 740 m × 5 828 m) as an example, a 226.8 MW offshore wind farm (with 54 4.2 MW WTs) can generate 2.44×10^4 GWh electricity in 20 years. If the repowering strategy is applied, by reusing the WT foundations and replacing the original WTs with the optimized WT combination, the LCoE is expected to reduce to only 0.913 HK$/kWh. So this paper also provides a good reference for Hong Kong's government to develop its offshore wind industry.

Finally, though the repowering strategy provides a good idea to cut down the cost of the offshore wind farm, some more

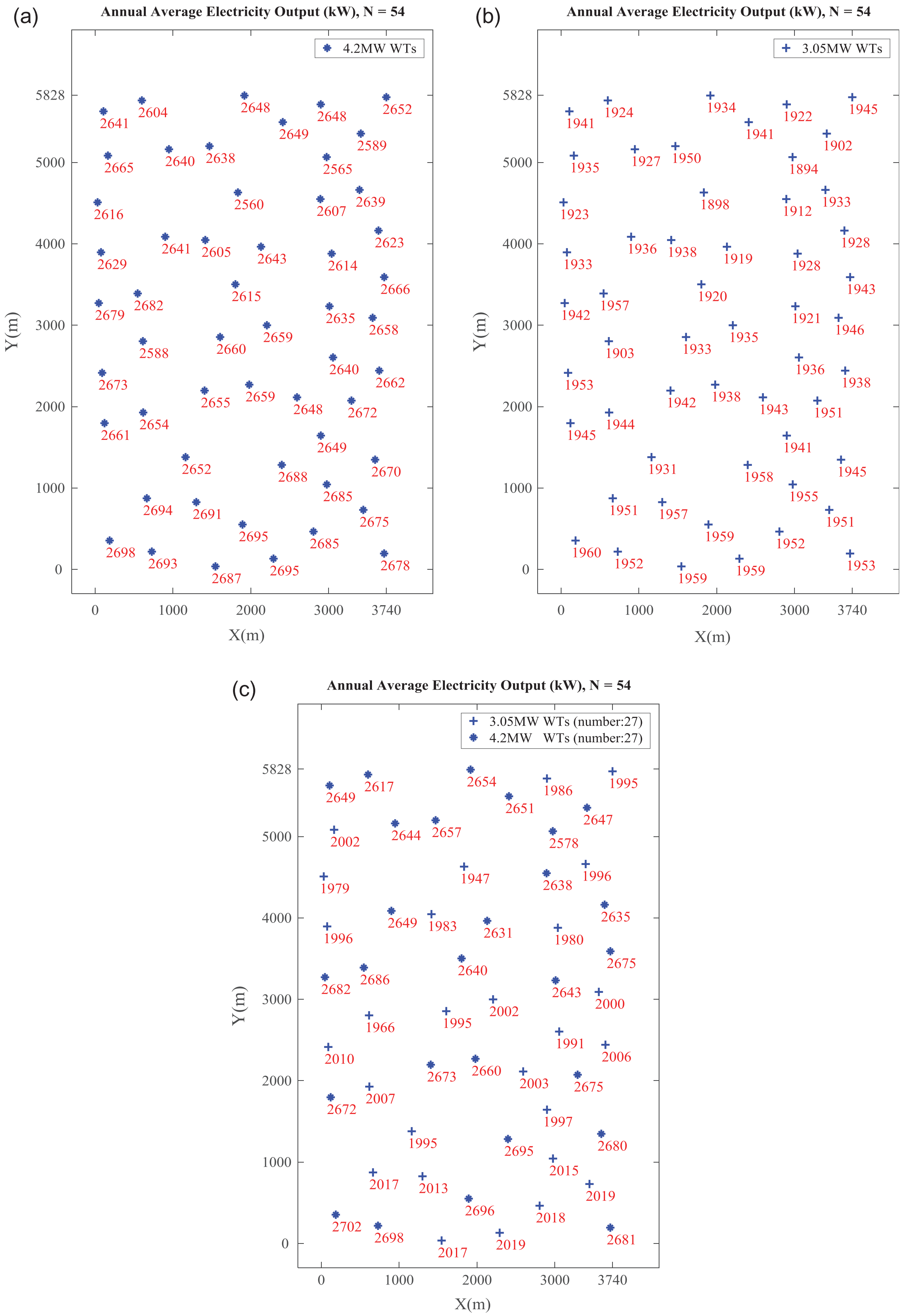

Figure 10. *Optimized layout and wind turbine power: (a) with 4.2 MW WTs; (b) with 3.05 MW WTs; and (c) with 4.2 MW WTs and 3.05 MW WTs.*

Table 3. *Main results of optimized layouts*

	O1	O2	O3
Number of wind turbine	54	54	54
Service years	40	40	40
Energy yield (GWh)	5.01×10^4	4.41×10^4	4.71×10^4
Total cost (MHK$)	4.94×10^4	4.04×10^4	4.30×10^4
LCoE (HK$/kWh)	0.9860	0.9161	0.9130

Table 4. *Energy yield comparisons (40 years)*

	Aligned layout	Optimized layout	Change
4.2 MW (GWh)	$2.44 \times 10^4 \times 2$	5.01×10^4	+2.67%
3.05 MW (GWh)	$1.86 \times 10^4 \times 2$	4.41×10^4	+18.54%

Table 5. *LCoE comparisons of aligned layout*

	A1	A2	A3
LCoE (HK$/kWh)	1.1598	1.0123	0.9395
Change		−12.72%	−18.99%

Table 6. *LCoE comparisons of optimized layout*

	A1	O1	O2	O3
LCoE (HK$/kWh)	1.1598	0.9860	0.9161	0.9130
Change		−14.99%	−21.01%	−21.28%

aspects could be considered in the optimization process. The strategies related to other issues like cable layout, power dispatch and restricted zone etc. will also be considered in the further studies.

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