

Article

Optimal Wind Farm Layout in a Complex Terrain by Varying Turbine Hub Heights: Case Study of Yeongdeok, South Korea

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Abstract

In this study, we investigated the optimization of a wind farm layout on complex mountainous terrain in Yeongdeok, South Korea, with varying hub heights. Specifically, the energy performance of mixing two commonly used commercial models with different heights, i.e., Vestas V82 and V162, was evaluated. The impact of site scale in terms of farm area (ranging from 1 to 9 km²) on power generation and wake effects was also determined. The results obtained using WindPRO and the Wind Atlas Analysis and Application Program demonstrated that, with increased wind farm area, the annual energy production increased while wake losses decreased. Compared with the case employing hubs with a uniform height, the mixed-height case showed a decrease in wake losses of up to 1.7% while maintaining comparable AEP. The findings of this study demonstrate that combining turbines of different hub heights provides more energy-efficient layouts, even in complex mountainous terrains. Insights from these findings can be further utilized to expand wind power in complex terrain in other countries.

Keywords: different height wind turbine; optimization; wind farm layout; wake effect; WindPRO

1. Introduction

In response to climate crises, the international community has been accelerating efforts to decrease carbon emissions by increasing the proportion of renewable energy sources. Wind power has played a major role in these efforts [1]. Over the past few decades, wind energy has attracted increasing attention as a sustainable energy source, and its use has continuously grown worldwide, driven by technological maturity and improved cost-effectiveness [2]. According to Ashraf et al. [3], the cumulative installed capacity of the global wind industry exceeded 1 TW by 2023, with onshore wind power accounting for most of the total installed capacity. Figure 1 presents growth of global cumulative installed wind power capacity [3].

To increase wind power generation, a large number of turbines should be installed, mostly in limited areas, to form wind farms. Location is an important factor affecting the success of wind power generation. Unfortunately, many countries, including South Korea, face difficulties because of limited land area; for instance, approximately two-thirds of the land area in Korea is complex mountainous terrain. Further attention should be paid to the installation of wind farms under different conditions.

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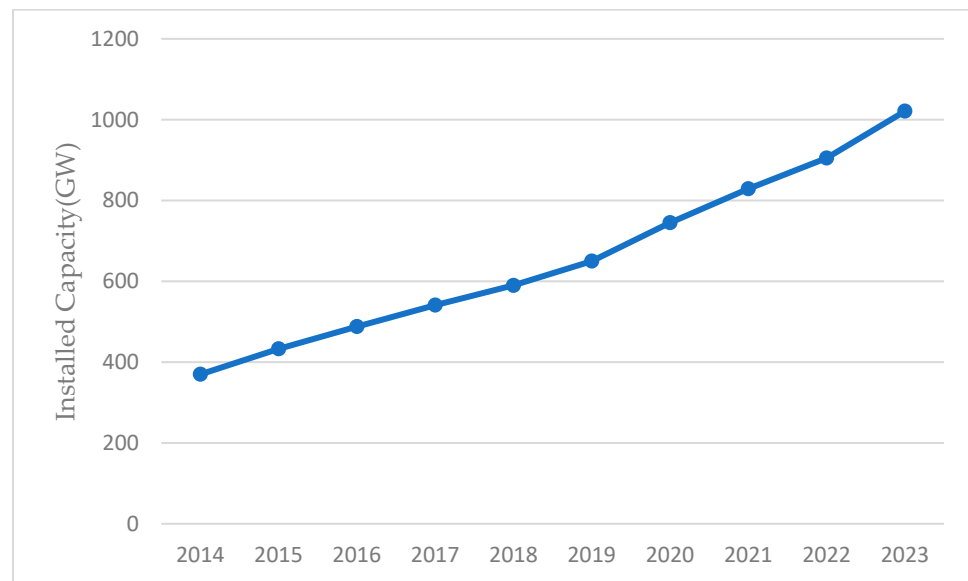


Figure 1. Growth of global cumulative installed wind power capacity for 2001–2023.

In the context of multiple turbines installed densely, wake effects occur because of turbine-to-turbine interactions, which reduce the total energy production of the farm [4]. When an upstream turbine intercepts wind, the wind speed reaching the turbines behind it decreases with the generation of turbulence, which, in turn, decreases their performance. This is referred to as the wake effect. In practice, wake interactions are among the main causes of power loss in wind farms and must be carefully considered for efficient operation [5].

To minimize such wake losses, attention should be paid to determining the most suitable locations for wind turbines instead of improving the turbines themselves. Decision-making for wind turbine positioning is, thus, important for increasing the total energy production of wind farms and decreasing generation costs [6,7]. Extensive research has been conducted to optimize wind turbine layouts. Establishing an optimal layout for mitigating wake effects is critical in the planning and design stages of wind farms [8].

This paper presents a case study of wind power generation on complex mountainous terrain in Yeongdeok, Korea, where the hub heights of wind turbines can be varied to minimize wake loss and maximize power generation. In this case study, we examined how various combinations of turbine heights were influenced by wake effects under actual local wind conditions and topography and sought optimal layout strategies for efficient power generation. Several previous studies have already explored wind farm layouts with mixed or multiple hub heights and have shown that vertical staggering can reduce wake interference and improve energy yield or land-use efficiency. However, most of these works have been conducted on idealized flat terrain or simplified virtual sites, often relying on research-oriented codes and idealized inflow conditions. As a result, the applicability of mixed hub-height strategies to real complex mountainous wind farms, based on long-term measured data and industry-standard design tools, remains insufficiently validated. In this context, this study applies mixed hub-height strategies to an actual onshore wind farm site in Yeongdeok, South Korea, characterized by steep and highly complex terrain. By combining long-term corrected wind data, WAsP flow modeling, and the commercial WindPRO platform, we systematically compared single- and mixed-hub-height layouts under different site-area scenarios. The turbine layout strategies derived through this approach provide actionable insights that extend beyond purely theoretical models and can be directly applied to real-world projects. In particular, this study demonstrates under which conditions mixed layouts using different hub heights can effectively

reduce wake losses while maintaining comparable energy production in mountainous terrains, thereby offering practical guidelines for the design of onshore wind farms in regions like Korea.

2. Literature Review

The wake generated by a wind turbine reduces the inflowing wind speed to downstream turbines, significantly affecting power generation. Various wake models have been developed to predict these effects. The Jensen wake model is the most representative, which assumes that the velocity deficit in the wake cross-section is uniform with a top-hat profile [9]. Later, Katic extended this model to develop the Park–Wake model for the theoretical estimation of wind farm outputs [10]. In this model, constant velocity loss occurs inside the wake, whereas outside the wake, the loss is zero, and the width is predicted to expand linearly.

In recent years, more advanced wake models have been proposed to better represent the near-wake structure and turbulence, particularly under conditions relevant for large wind farms. Several studies have shown that the near-wake region can exhibit a double-Gaussian velocity deficit profile, and corresponding double-Gaussian wake models have been developed and applied to wind farm layout optimization. Hu et al. [11] proposed a double-Gaussian yawed wake model and validated it against both CFD simulations and wind tunnel measurements for single and multiple yawed turbines. Compared with several existing yawed wake models, the double-Gaussian formulation in Hu et al. [11] significantly reduced RMSE and MAE in wake prediction and highlighted the importance of wake superposition methods for multi-turbine arrays. Furthermore, Hu et al. [12] combined CFD-based flow modeling in complex terrain with an improved genetic algorithm and particle swarm optimization (IGA-PSO) framework, explicitly considering different wake and cost models to enhance wind farm layout optimization performance.

These developments indicate that advanced wake formulations and high-fidelity flow simulations can provide more accurate predictions of wake behavior and improve the robustness of layout optimization compared with classical engineering models such as the Jensen (PARK) model. In the present study, however, we employ the widely used Jensen model as implemented in the commercial WindPRO software, with a focus on demonstrating the relative impact of mixed hub-height layouts in complex mountainous terrain. Incorporating double-Gaussian or other high-fidelity wake models, potentially coupled with more advanced optimization frameworks, into the design of mixed hub-height wind farms in complex terrain is left as an important topic for future research.

Wind-farm layout optimization (WFLO) is a complex problem that aims to minimize wake losses and maximize power generation profits. Global optimization methods are widely used to solve this problem. Among them, the genetic algorithm (GA) is one of the most representative. Mosetti et al. [13] conducted a pioneering study that optimized the positions of wind turbines using the GA and Jensen models. Since then, several studies have reported performance improvements by optimization with GA to decrease the levelized cost of electricity (LCOE) or increase the amount of power generated by wind farms [13]. Recently, PSO has been widely used for complex layout problems owing to its high computational efficiency and rapid convergence. Yeghikian et al. [14] utilized PSO to determine the optimal layouts for wind farms in Iran and analyzed the wake effects. In addition, the random search algorithm was introduced to explore the solution space more broadly, thereby overcoming the local optimum limitations of traditional methods. Feng and Shen [7] employed a random search to solve large-scale layout problems and achieved maximum power generation. Furthermore, various optimization algorithms, such as Monte Carlo simulations and evolution strategies, have been applied to designing wind farm layouts. Recent studies have also investigated hybrid algorithms and progressive

optimization methodologies that combine the strengths of different approaches. Table 1 summarizes representative studies on wind farm layout optimization.

Table 1. Review of the literature on optimal wind farm layouts.

Author	Optimization Algorithm	Wake Model	Year	Optimization Target
Mosetti et al. [13]	Genetic algorithm	Jensen	1994	Min. LCOE
Grady et al. [15]	Genetic algorithm	Jensen	2005	Min. LCOE
Emami and Noghreh [16]	Genetic algorithm	Jensen	2010	Min. LCOE
Chen et al. [17]	Genetic algorithm	Jensen	2013	Min. LCOE
Parada et al. [18]	Genetic algorithm	Gaussian	2017	Max. power
Bin Ali et al. [19]	Genetic algorithm	Jensen	2022	Maximizing energy production
Huang et al. [20]	Genetic algorithm	Jensen	2024	Minimizing total wake loss
Chen et al. [21]	Multi-objective genetic algorithm	Jensen	2015	Min. LCOE
Gao et al. [22]	Multi-swarm genetic algorithm	Jensen Gaussian	2016	Max. power
Gao et al. [23]	Multi-swarm genetic algorithm	Jensen	2015	Max. power
Yeghikian et al. [14]	Particle swarm optimization	Jensen	2021	Maximizing power generation and minimizing electricity generation costs based on the Mossetti cost function
Jaadi et al. [24]	Particle swarm optimization	Jensen	2023	Maximizing farm output energy and minimizing wake effects
Wan et al. [25]	Gaussian particle swarm algorithm	Jensen	2012	Max. power
Marmidis et al. [26]	Monte Carlo simulation	Jensen	2008	Min. LCOE
Feng and Shen [7]	Random search algorithm	Jensen	2015	Max. power
Kirchner-Bossi and Porté-Agel [27]	Evolutionary strategy	Gaussian	2018	Max. power

Deploying turbines with different hub heights within the same wind farm is attracting growing interest as a strategy to reduce wake loss.

Some studies have demonstrated that mixed heights can reduce wake interference and improve land-use efficiency in virtual flat terrains or simplified topographies. For example, Chen et al. [28] introduced two hub heights to a small-scale wind farm optimization study using the GA. By fixing the wind speed and direction over a limited 2×2 km site, they compared single- and mixed-height layouts. They found that combining turbines of different heights improved both the energy yield and revenue compared with uniform height configurations [28]. This was the first case to demonstrate the feasibility of designing a wind farm using height difference. However, their study was based on a small virtual wind farm with fixed wind speed and direction over a 2×2 km flat site and did not consider complex terrain effects or long-term measured wind conditions. Stanley et al. (2019) applied the FLORIS Gaussian wake model and different analytical optimization techniques to optimize layouts involving two hub height combinations [29]. Their

results demonstrated that, when the shear exponent of the wind speed was low, employing two different hub heights significantly reduced the LCOE compared with single-height layouts. This demonstrates that mixed-height strategies can enhance economic performance in low-shear environments. However, their analysis was conducted under idealized inflow conditions on a simplified terrain. Chatterjee and Peet [30] conducted an LES-based simulation of a multiscale wind farm in which large, medium, and small turbines were mixed. It has been reported that the larger the difference in height (and scale) between turbines, the smaller the wake interference, and the larger the total amount of power generation; however, the addition of a medium-sized turbine may cause complex vortex interference and some power generation loss [30]. Therefore, the turbine combination should be carefully designed even when using a height difference, because the wake interaction varies depending on turbine height and size configuration.

In recent years, field case studies applying a height-mixed arrangement to wind farms have emerged. Yeghikian et al. [14] investigated the optimal layout of the Manjil wind farm in Iran using the Jensen wake model and PSO. They demonstrated that the mixed hub height reduced wake effects and improved total power generation. Similarly, El Jaadi et al. [31] studied a wind farm in Morocco and optimized its layout by varying hub height. By replacing the original single-height arrangement with a mixed-height configuration, they reported an increase in total energy output and a decrease in wake losses. This is one of the first successful applications of commercially available turbines at multiple hub heights for enhancing the efficiency of an existing wind farm, offering a practical alternative for minimizing wake losses at sites with limited land availability. While this work represents an important step toward practical applications of mixed hub heights, it focused on a specific existing wind farm and did not systematically compare different site-area scenarios or assess the sensitivity of mixed hub-height benefits to complex mountainous terrain characteristics.

Overall, these previous studies demonstrate that mixed or multiple hub heights can be beneficial, but they also reveal an important gap: most of the existing work is based on idealized flat terrains, simplified inflow conditions, or single specific sites, and does not systematically address strongly complex mountainous terrain under realistic long-term wind conditions. In particular, there is still limited quantitative understanding of how mixed hub-height strategies perform relative to single-height layouts when terrain-induced elevation differences, spatial constraints, and wake interactions are considered together in real projects.

This study is novel in the following ways. First, although several previous works have investigated wind farm layouts with mixed or multiple hub heights, most of them have been conducted on idealized flat terrain or virtual case studies and have not explicitly addressed real complex mountainous sites. In contrast, in this study, we adopted an empirical approach by analyzing actual complex mountainous terrain sites in South Korea, in which turbines of varying hub heights are mixed within each wind farm. Second, the practical applicability of the research results was increased by applying industry-verified modeling techniques using WindPRO, a commercial software package.

The turbine layout strategies derived through this approach provide actionable insights that extend beyond theoretical models and can be directly applied to real-world projects. In particular, this study demonstrated that mixed layouts using different hub heights could reduce wake losses and improve power generation efficiency in mountainous terrains, thereby suggesting a new direction for the design of wind farms with complex topographies.

3. Materials and Methods

3.1. Overview of the Study Site

This study focused on the mountainous terrain located in Yeongdeok, which is in the center of the eastern coast of South Korea. The Yeongdeok Wind Farm is situated in complex mountainous terrain characterized by high elevation and steep topographic variations, while also benefiting from consistent wind conditions from the nearby coastline. This site represents the typical geography of Korea, where more than 70% of the land consists of mountainous terrain. Therefore, this study is significant because it considers the complex topographic conditions of an actual site rather than relying on idealized terrain assumptions. The following section addresses the collection of necessary data, such as long-term meteorological observation data and high-resolution topographic data, for assessing the wind resource characteristics of the area.

3.2. Meteorological Data Collection and Wind Condition Analysis

To analyze wind conditions, regional meteorological observation data and simulated datasets were combined. First, high-resolution annual wind data obtained from the EMD-WRF South Korea mesoscale model were used along with 20 years (2003–2022) of observational data collected from the Yeongdeok region through the Korea Meteorological Administration (KMA) automated weather stations (AWS).

In the measure–correlate–predict (MCP) framework, the KMA Yeongdeok AWS station was used as the long-term reference station, and the overlapping period between the AWS observations and the EMD-WRF model output was used as the concurrent short-term dataset. Based on the correlation between these two datasets, the measure–correlate–predict (MCP) technique was applied to correct and extend the short-term simulated data into long-term wind records. The MCP analysis was carried out using the Regression method implemented in WindPRO, which constructs direction-specific regression models for wind speed. In the MCP Regression setup, the wind direction was divided into 12 sectors, and the Regression method was selected after comparing its performance with the Simple Speed Scaling, Matrix, and Neural Network options, based on statistical indicators such as mean bias error, root mean square error, correlation coefficient, and Kolmogorov–Smirnov (KS) statistics.

The resulting long-term wind dataset was used to derive the wind speed distribution (Weibull distribution) and direction frequency (wind rose), allowing for a detailed understanding of the annual wind speed patterns and prevailing wind directions at the study site. This information was subsequently applied to wind resource assessment and power generation forecasting. Using long-term corrected wind data, seasonal and annual wind speed patterns in the study area were more accurately identified, enabling a realistic evaluation of the wind farm's potential energy production and wake effects. Figure 2 presents the Weibull distribution (mean value = 6.6 m/s, Weibull A = 7.5 m/s, k = 1.78) and wind rose derived from the analysis of the wind direction in the Yeongdeok area at 75 m.

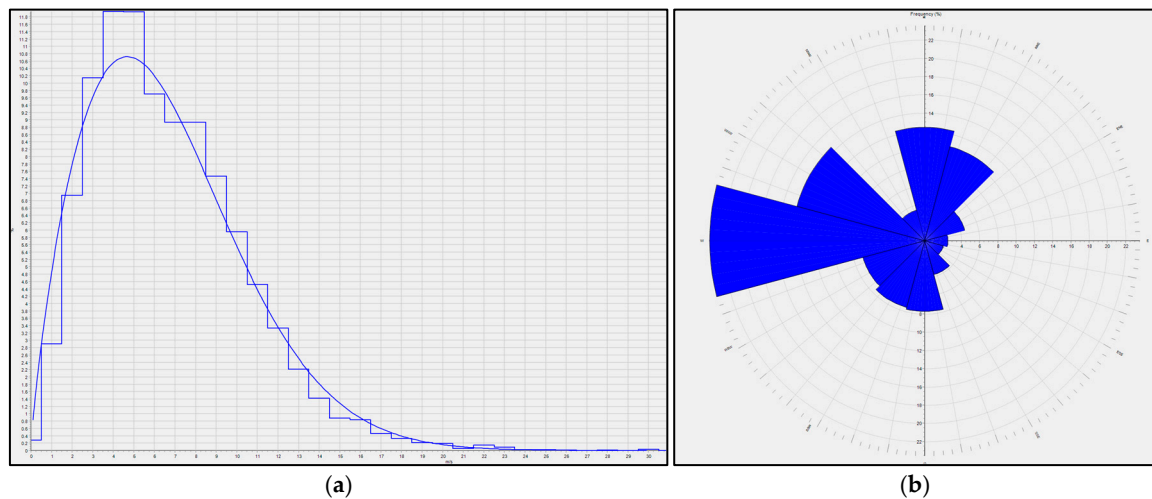


Figure 2. Wind resource data for Yeongdeok at 75 m: (a) Weibull distribution; (b) wind rose.

3.3. Wind Resource Assessment and WAsP Modeling

In this study, we used the Wind Atlas Analysis and Application Program (WAsP), which is one of the most widely used software tools for wind resource assessment, to quantify wind resources at the wind farm site. WAsP is based on a linear flow model that considers the topographical characteristics of the target site, such as elevation, surface roughness, obstacles, and forest density, to generate wind resource maps and estimate the expected power output of wind turbines. In this study, the long-term wind data obtained in the previous section were used as inputs for the WAsP model. A detailed wind resource map of the study site was constructed by integrating the topographic elevation and surface roughness information from the surrounding area. Topographic data were obtained from the Copernicus digital elevation model (DEM) provided by the European Space Agency. Specifically, the GLO-90 DEM with a spatial resolution of 90 m was used to represent the elevational profile of the study region. To account for the attenuation of wind speed due to surface roughness, the Copernicus Global Land Cover Layer (CGLS-LC100, 100 m resolution) was referenced to assign surface roughness lengths according to land-use types. Figure 3 shows a 3D resource map of the Yeongdeok Wind Farm.

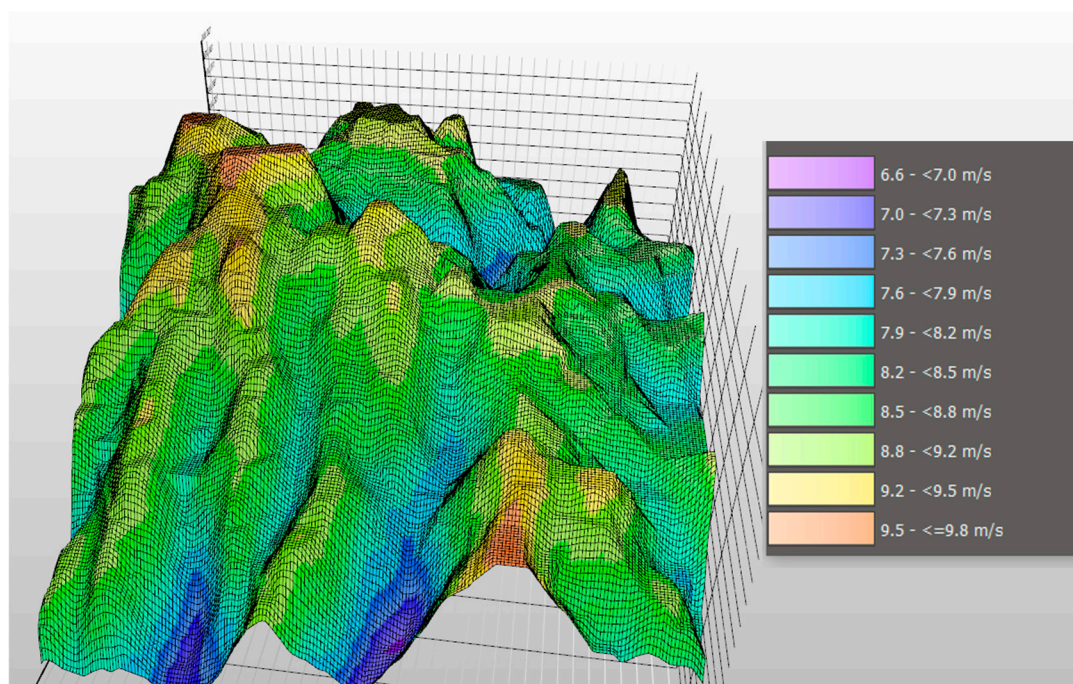


Figure 3. Three-dimensional resource map of Yeongdeok Wind Farm (wind speed).

3.4. Turbine Layout Optimization Simulation Using WindPRO

WindPRO was used to evaluate wind farm design and wake effects in complex terrain. WindPRO is one of the most widely used commercial wind farm design tools and provides a comprehensive set of functions ranging from wind resource analysis and power production estimation to layout optimization and environmental impact assessment. In this study, turbine placement optimization was performed using WindPRO with previously collected and analyzed wind resource data as input, and annual energy production (AEP) accounting for wake effects was calculated. An optimization algorithm was then applied to automatically search for optimal turbine layouts, and the wake losses and total annual energy production were evaluated for each candidate configuration. WindPRO employs WAsP as its computational engine and uses a commercial engineering wake model to simulate wake interactions among multiple turbines. The resulting outputs were used to assess the efficiency of each layout, enabling a quantitative analysis of power generation efficiency and wake effects across different deployment scenarios and the identification of optimal turbine placement strategies.

Wind farm layout optimization was carried out using the PARK optimizer implemented in WindPRO, with the objective of maximizing net annual energy production (AEP) after wake losses, as calculated by the Jensen wake model. A uniform minimum spacing constraint of two rotor diameters (2D) was applied between all turbines, regardless of the prevailing wind direction. Turbine candidate locations were evaluated on a 10 m resolution grid within the buildable area defined by the project boundary and exclusion zones. During the full optimization process, up to 200 candidate layouts (“points before stop in full optimize”) were evaluated prior to termination. For each candidate layout, net AEP was computed using the long-term wind climate obtained from the MCP analysis. The optimizer iteratively adjusted turbine positions on the 10 m grid while enforcing spacing and boundary constraints, and the layout yielding the highest net AEP among all feasible solutions was selected for further analysis.

3.5. Wind Turbine Models and Hub Height Configurations

In this study, two types of wind turbines with different specifications were selected as target models. The Vestas V-82 model (with a rated capacity of 1.65 MW) was used as the medium-sized turbine, and the V-162 model (with a rated capacity of 6.2 MW) was used as the large-sized turbine. Table 2 shows the technical specifications of the system [32,33]. Both are commercially available models suitable for installation in mountainous terrains in South Korea. Two hub-height options were included in the experiment for each turbine model. The V-82 model was evaluated with hub heights of 59 and 80 m, whereas the V-162 model was analyzed with hub heights of 119 and 169 m. This configuration was designed to introduce heterogeneity in the turbine height within the same wind farm in order to mitigate inter-turbine wake interference. The turbine characteristics for the two turbines are presented in Figures 4 and 5. The specifications were prepared based on the windPRO database (EMD International A/S). The medium-scale turbine (V-82) installed at lower hub heights was more sensitive to near-surface boundary layer effects, whereas the large-scale turbine (V-162) could harness stronger wind resources at higher altitudes. The complementary characteristics of these turbines enable a synergistic effect when they are deployed together. Accordingly, we analyzed the effects of mixed hub-height configurations on reducing wake losses and improving energy output in comparison with conventional single-height layouts within a wind farm.

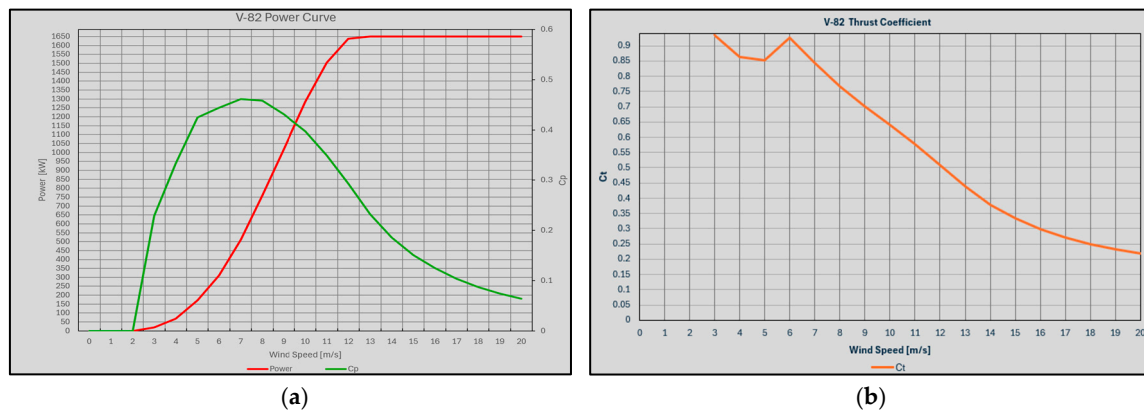


Figure 4. V-82 turbine characteristics: (a) power curve; (b) thrust coefficient.

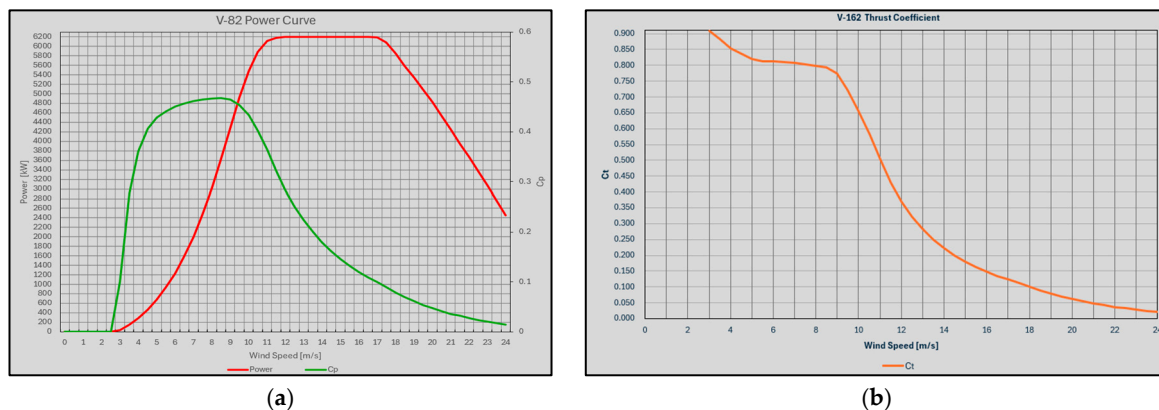


Figure 5. V-162 turbine characteristics: (a) power curve; (b) thrust coefficient.

Table 2. Technical specifications of target wind turbines [32,33].

	V-82	V-162
Rated power (kW)	1650	6200
Rotor diameter (m)	82	162
Maximum hub height (m)	80	169
Minimum hub height (m)	59	119
Swept area (m ²)	5281	20,612
Cut in wind speed (m/s)	3.5	3
Rated wind speed (m/s)	13	12
Cut off wind speed (m/s)	20	24

3.6. Evaluation of Wind Farm Area Variation and Mixed-Layout Strategy

As turbine layout optimization is closely related to the available site area, in this study, we evaluated the performance of layout strategies for varying site sizes. The available area within the Yeongdeok site was gradually expanded from 1×1 km to 3×3 km, and the turbine layout was optimized for each area condition. For each site area, an optimized layout configuration was derived, and key performance indicators, such as wake loss, AEP, and capacity factors, were compared and analyzed between layouts using mixed hub height configurations. This approach allowed us to examine whether the mixed layout strategy combining turbines of different hub heights was more effective at smaller sites where the turbine spacing was constrained. It has been found that the advantages of mixed deployment are relatively reduced in scenarios where the site area is sufficiently large to secure a sufficient distance between the turbines. By conducting a performance evaluation based on these area changes, we investigated the effectiveness of mixed turbine height optimization

strategies at limited sites and established guidelines for deploying wind farms of various sizes.

3.7. Jensen (PARK) Wake Loss Model

To simulate the wake-up effect between the wind turbines, the Jensen wake-up model (PARK model) was used in the WindPRO simulation, which is the oldest theoretical model for calculating the velocity deceleration of the flow behind a turbine. The relationship between the axial induction coefficient and trailing velocity reduction was derived by applying mass conservation and the Betz limit [11]. Figure 6 shows a schematic of the Jensen wake model [34], in which the wake was assumed to expand linearly downstream of the turbine, and the airflow passing through the rotor was represented as a conical flow region. The wake cone radius r can be calculated using the following equation:

$$r_x = r_0 + ax \quad (1)$$

where r_0 is the rotor radius of the turbine and a is the wake expansion (decay) constant.

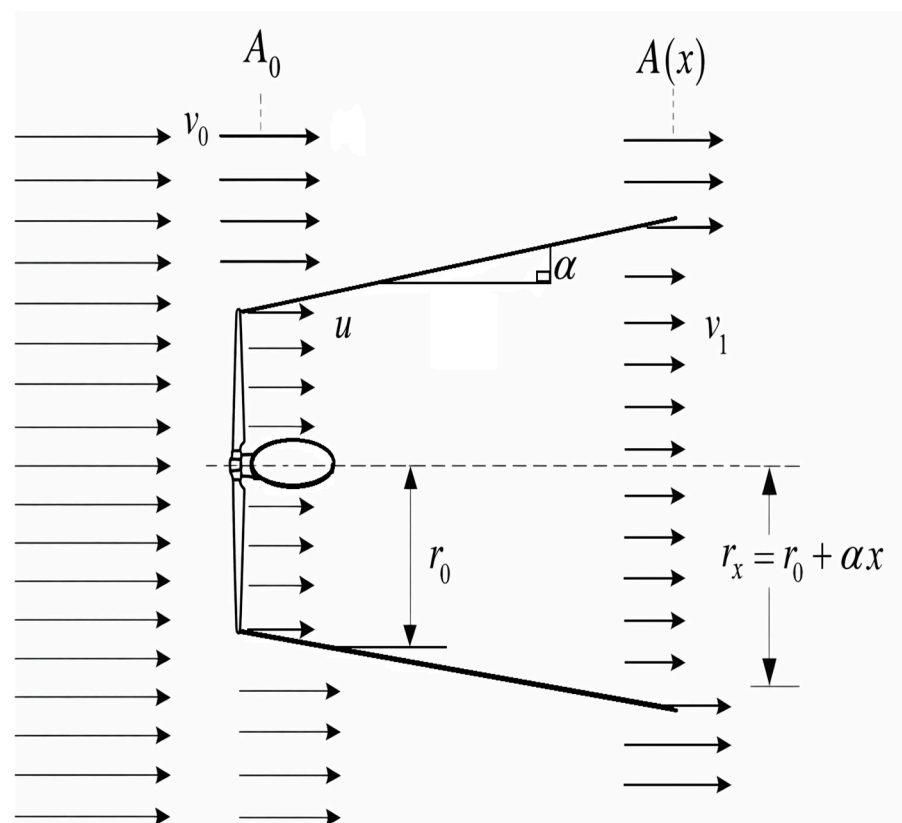


Figure 6. N. O. Jensen wake model.

As shown in Figure 6, the N.O. Jensen model in a simple single-wake model assumes a linear wake cone expansion.

The dimensionless scalar a is defined as follows:

$$a = \frac{1}{2 \ln \left(\frac{z}{z_0} \right)} \quad (2)$$

where z is the hub height of the upstream turbine and z_0 is the surface roughness constant, which varies depending on the local terrain characteristics of the local terrain. The scalar a takes different values depending on the local topography and wind climate conditions. When the turbine is not affected by any upstream flow disturbance, an a value

of 0.04 is generally appropriate, whereas $a = 0.075$ is typically used when upstream wake effects are present.

In this study, $a = 0.075$ was applied according to site-specific conditions. The wind velocity within the wake decreases with increasing distance from a turbine. In the Jensen model, the wake is assumed to exhibit a top-hat profile, suggesting that the velocity deficit within the wake region is uniform. The wind speed V_1 at a downstream distance of x behind the turbine was calculated using the following relationship:

$$V_1 = V_0 + V_0 (\sqrt{1 - C_T} - 1) \left(\frac{r_0}{r}\right)^2 \quad (3)$$

where V_0 is the free-stream wind velocity (undisturbed wind speed approaching the turbine), and C_T is the thrust coefficient of the turbine, which typically ranges around 0.8 under the rated operating conditions for each turbine model. As shown in the above equation, the velocity deficit caused by the turbine wake effect decreases rapidly with increasing downstream distance x .

If the number of wind turbines at a wind farm or at a neighboring wind farm increases, the wake effect increases in severity [34]. When a wind turbine is exposed to several overlapping wakes, the resulting wind speed V_i at that position can be determined by equating the total kinetic energy loss of the mixed wakes to the sum of the individual kinetic energy losses induced by each upstream wake. v_{ik} is the wind speed at the i -th turbine location influenced by the wake of the k -th upstream turbine.

$$V_i = V_0 \left[1 - \sqrt{\sum_{k=1}^{N_t} \left(1 - \frac{v_{ik}}{v_0} \right)^2} \right] \quad (4)$$

4. Results

4.1. V-82-Based Wind Farm Layout Optimization

Wind farm layout optimization was performed for three sites of different sizes, 1×1 km, 1.5×1.5 km, and 2×2 km, using Vestas V-82 turbines with hub heights of 59 and 80 m. The variations in wake loss, energy production, and capacity factors (CFs) were analyzed and compared across different site configurations. The results of the proposed framework are summarized in Tables 3–5 and in Figures 7–9, which present the optimized layout results for each wind farm configuration and compare cases composed exclusively of shorter-hub turbines with those composed exclusively of taller-hub turbines. Each case label follows the notation format: V-82 [hub height] m, [number of turbines].

Table 3. Optimization results for a wind farm consisting of V-82 turbines with the lowest and highest hub heights within a 1×1 km area.

Optimization Result (1×1 km)			
Turbine model, its number	V-82 80 m, 0	V-82 80 m, 19	V-82 80 m, 24
Turbine model, its number	V-82 59 m, 24	V-82 59 m, 5	V-82 59 m, 0
Result (PARK; MWh/yr)	139,391.1	146,541.7	147,370.0
Gross Free WTGS (MWh/yr)	164,018.6	169,758.0	171,298.5
Wake Loss (%)	15.0	13.7	14.0
Capacity Factor (%)	36.1	38.0	38.2
WTG distance, min.	2.0	2.0	2.0
WTG distance, max.	2.8	2.7	3.0

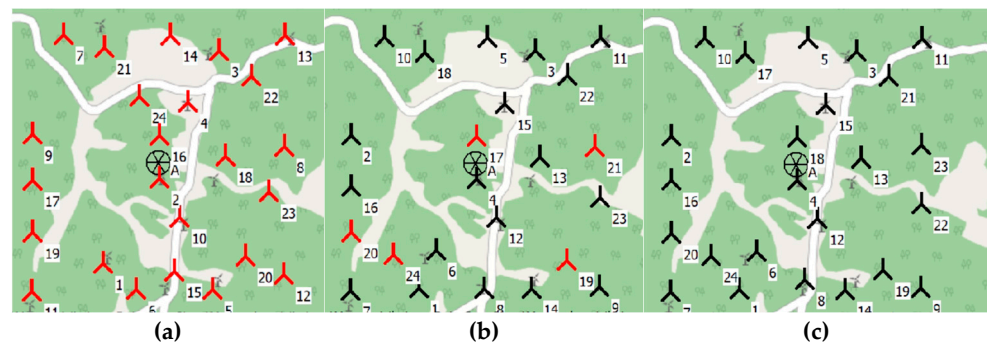


Figure 7. Comparison of optimized turbine layouts for different hub heights (1 × 1 km area): (a) V-82 80 m—0 and 59 m—24; (b) V-82 80 m—19 and 59 m—5; and (c) V-82 80 m—24 and 59 m—0.

Table 4. Optimization results for a wind farm consisting of V-82 turbines with the lowest and highest hub heights within a 1.5 × 1.5 km area.

Optimization Result (1.5 × 1.5 km)			
Turbine model, its number	V-82 80 m, 0	V-82 80 m, 19	V-82 80 m, 24
Turbine model, its number	V-82 59 m, 24	V-82 59 m, 5	V-82 59 m, 0
Result (PARK; MWh/yr)	150,930.3	156,334.0	158,127.1
Gross Free WTGS (MWh/yr)	167,415.4	172,055.2	174,340.8
Wake Loss (%)	9.8	9.1	9.5
Capacity Factor (%)	39.1	40.5	40.8
WTG distance, min.	2.0	2.0	2.0
WTG distance, max.	4.5	4.6	4.5

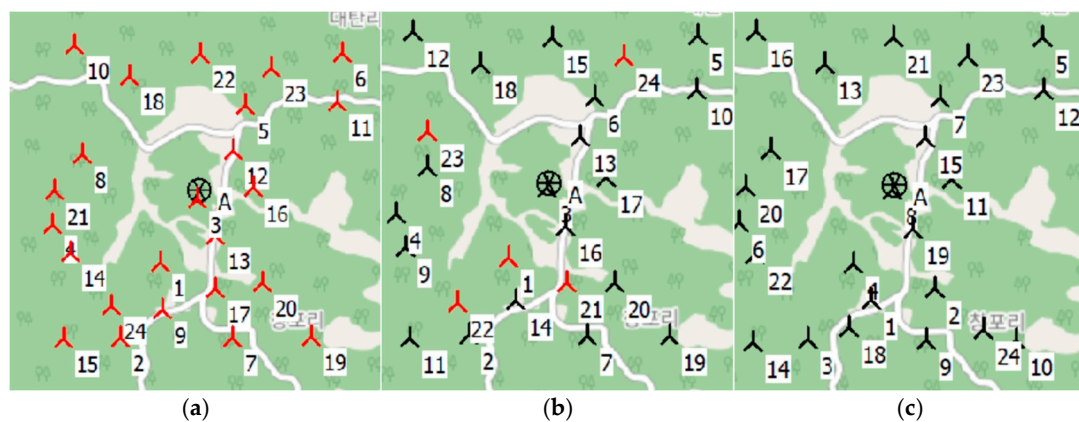


Figure 8. Comparison of optimized turbine layouts for different hub heights (1.5 × 1.5 km area): (a) V-82 80 m—0 and 59 m—24; (b) V-82 80 m—19 and 59 m—5; and (c) V-82 80 m—24 and 59 m—0.

Table 5. Optimization results for the wind farm consisting of V-82 turbines with the lowest and highest hub heights within a 2 × 2 km area.

Optimization Result (2 × 2 km)			
Turbine model, its number	V-82 80 m, 0	V-82 80 m, 19	V-82 80 m, 24
Turbine model, its number	V-82 59 m, 24	V-82 59 m, 5	V-82 59 m, 0
Result (PARK; MWh/yr)	153,190.6	158,144.6	158,485.9
Gross free WTGS (MWh/yr)	137,871.5	142,330.1	173,747.4
Wake loss (%)	8.9	8.1	8.8
Capacity factor (%)	39.7	41.0	41.1
WTG distance, min.	2.2	2.0	2.0
WTG distance, max.	4.0	6.5	4.1

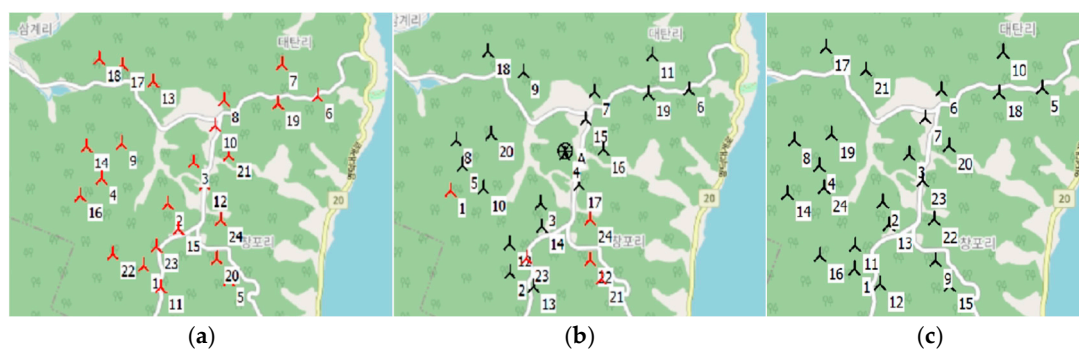


Figure 9. Comparison of optimized turbine layouts for different hub heights (2×2 km area): (a) V-82 80 m—0 and 59 m—24; (b) V-82 80 m—19 and 59 m—5; and (c) V-82 80 m—24 and 59 m—0.

The results according to the optimized wind farm layout showed that energy production increased with site area: for the 1×1 km site, the annual energy production ranged from 139,391.1 to 147,370.0 MWh/y, whereas for the 2×2 km site, the maximum output reached 158,485.9 MWh/y. In addition, wake loss exhibited a clear decreasing trend with increasing site area. Under the 1×1 km condition, an average wake loss exceeding 14% was observed, whereas under the 2×2 km condition, this loss was reduced to approximately 8%. These results indicate that, as the site area increases, the space between the turbines can increase, thereby mitigating the wake interference. A comparison of CFs under different layout conditions also demonstrated an improvement. For the 1×1 km site, the capacity factors ranged between 36.1% and 38.2%, whereas for the 2×2 km site, they increased to 39.7–41.1%.

4.2. V-162-Based Wind Farm Layout Optimization

A wind farm consisting of Vestas V-162 turbines with hub heights of 119 and 169 m was simulated across various areas of the site (2×2 km, 2.5×2.5 km, and 3×3 km). The analysis focused on evaluating wake losses, annual energy production, and CFs in relation to site area expansion and turbine model selection. Using this approach, the effects of increasing site area and varying turbine configurations on the overall performance of a wind farm were quantitatively assessed. Tables 6–8 and Figures 10–12 present the optimized layout results for each configuration, comparing cases composed exclusively of shorter-hub turbines with those composed exclusively of taller-hub turbines. Each case label follows the notation format V-162 [hub height] m [number of turbines]; for example, V-162 169 m 24 refers to a layout configuration consisting of 24 V-162 turbines with a hub height of 169 m.

Table 6. Optimization results for a wind farm consisting of V-162 turbines with the lowest and highest hub heights within a 2×2 km area.

Optimization Result (2×2 km)			
Turbine model, number	V-162 169 m, 0	V-162 169 m, 14	V-162 169 m, 24
Turbine model, number	V-162 119 m, 24	V-162 119 m, 10	V-162 119 m, 0
Result (PARK; MWh/yr)	621,678.8	642,287.0	644,478.8
Gross free WTGS (MWh/y)]	717,008.2	726,489.7	733,623.2
Wake loss (%)	13.3	11.6	12.2
Capacity factor (%)	42.9	44.3	44.5
WTG distance, min.	2.0	2.0	2.0
WTG distance, max.	3.4	3.6	3.2

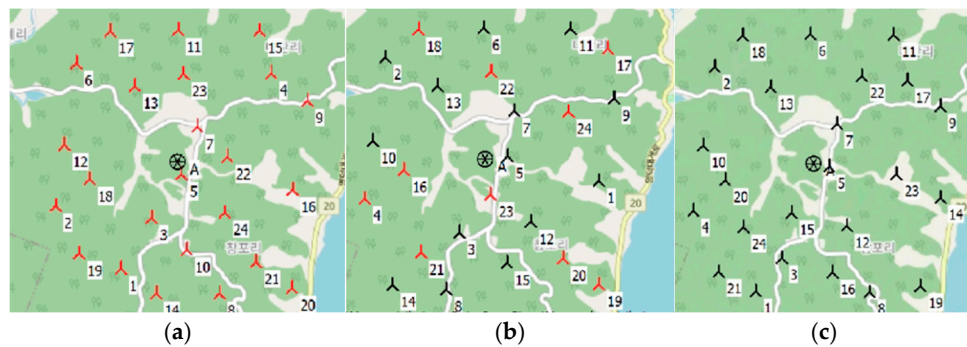


Figure 10. Comparison of optimized turbine layouts for different hub heights (2×2 km area): (a) V-162 169 m—0 and 119 m—24; (b) V-162 169 m—14 and 119 m—10; and (c) V-162 169 m—24 and 119 m—0.

Table 7. Optimization results for a wind farm consisting of V-162 turbines with the lowest and highest hub heights within a 2.5×2.5 km area.

Optimization Result (2.5×2.5 km)			
Turbine model, number	V-162 169 m, 0	V-162 169 m, 18	V-162 169 m, 24
Turbine model, number	V-162 119 m, 24	V-162 119 m, 6	V-162 119 m, 0
Result (PARK; MWh/yr)	630,954.1	653,079.3	654,579.7
Gross free WTGS (MWh/yr)	718,770.2	728,788.0	732,956.1
Wake loss (%)	12.2	10.4	10.7
Capacity factor (%)	43.5	45.1	45.2
WTG distance, min.	2.0	2.0	2.0
WTG distance, max.	3.5	3.7	3.7

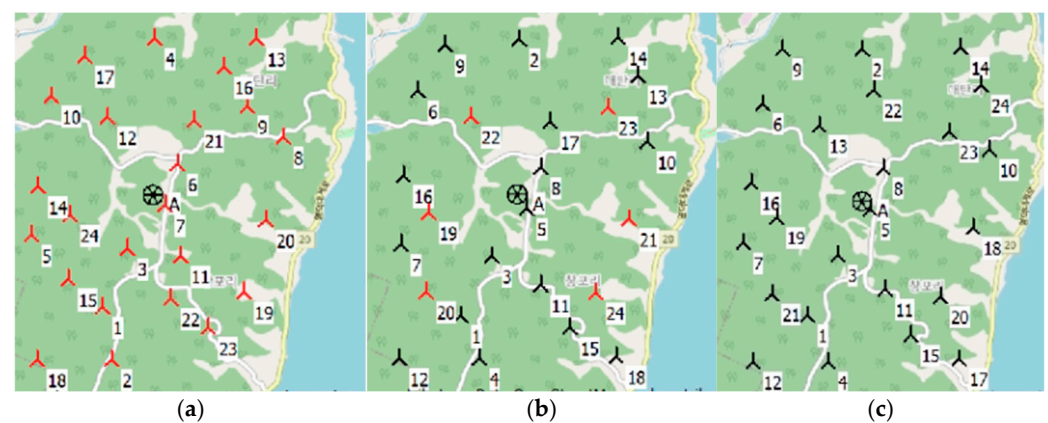


Figure 11. Comparison of optimized turbine layouts for different hub heights (2.5×2.5 km area): (a) V-162 169 m—0 and 119 m—24; (b) V-162 169 m—18 and 119 m—6; and (c) V-162 169 m—24 and 119 m—0.

Table 8. Optimization results for a wind farm consisting of V-162 turbines with the lowest and highest hub heights within a 3×3 km area.

Optimization Result (3×3 km)			
Turbine model, number	V-162 169 m, 0	V-162 169 m, 13	V-162 169 m, 24
Turbine model, number	V-162 119 m, 24	V-162 119 m, 11	V-162 119 m, 0
Result (PARK; MWh/yr)	633,197.5	648,910.5	653,923.0
Gross free WTGS (MWh/yr)	716,569.7	726,187.1	733,203.2
Wake loss (%)	11.6	10.6	10.8
Capacity factor (%)	43.7	44.8	45.1

WTG distance, min.	2.0	2.0	2.0
WTG distance, max.	3.6	3.3	3.3

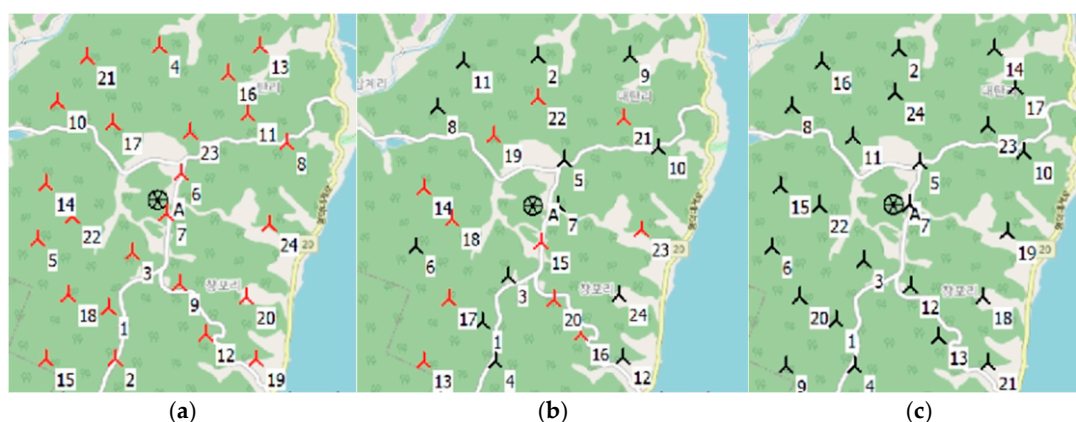


Figure 12. Comparison of optimized turbine layouts for different hub heights (3×3 km area): (a) V-162 169 m—0 and 119 m—24; (b) V-162 169 m—13 and 119 m—11; and (c) V-162 169 m—24 and 119 m—0.

The results based on the optimized layout of the wind farm revealed that energy production increased with site area. For a 2×2 km site, the annual energy production ranged from 621,678.8 to 644,478.8 MWh/y, while for a 2.5×2.5 km site, the maximum output reached 654,579.7 MWh/y. Similarly, wake losses decreased as the site area increased. For the 2×2 km site, wake losses ranged between 11.6% and 13.3%, whereas for the 2.5×2.5 km site, they decreased to 10.4–12.2%. These results indicate that, as the space between the turbines increased with site expansion, wake interference was mitigated, leading to an improved energy yield. The comparison of CFs further supported this trend. For the 2×2 km area, the capacity factor ranged from 42.9% to 44.5%, whereas for the 2.5×2.5 km area, it increased to approximately 45.2%.

All simulations and optimization processes were executed on an AMD Ryzen Threadripper 3990X processor (64 cores, 128 threads, 2.90 GHz) equipped with 256 GB of DDR4 RAM and dual storage devices consisting of a Samsung 970 EVO Plus 1-TB NVMe SSD and Seagate ST1000DM003 1-TB HDD. The GPU-accelerated computations were supported by an NVIDIA TITAN RTX graphics card with 24 GB of VRAM. Each simulation required approximately 75 h to complete.

5. Discussion

In this study, we analyzed the variations in wake loss rate and power generation performance when wind turbines with different hub heights were deployed in a mixed layout within the same site on the complex mountainous terrain of Yeongdeok.

In the mixed-layout cases, a noticeable improvement in efficiency was observed owing to the reduced wake interference, even within the same site area, which can be attributed to the utilization of the natural elevation differences among the turbines caused by mountainous topography. The results demonstrated that both turbine types exhibited a reduction in wake losses when arranged in mixed configurations. For the V-82 turbine, the wake loss rate for the single-height layout using only the highest hub height (80 m) was approximately 14%. When some turbines were replaced with those with lower hub heights (59 m), wake loss decreased to approximately 13.7%. The total AEP in the mixed layout reached approximately 146.5 GWh/yr, which was only 0.8 GWh/yr lower than that with a uniform height layout. That is, while individual low-hub-height turbines generated

slightly less power, the mitigation of wake interference compensated for the overall efficiency loss, allowing the total energy output of the wind farm to remain nearly constant.

A similar trend was observed for the V-162 large-scale turbines. For the uniform layout using only a taller hub height (169 m), the wake loss rate was approximately 12.2%, whereas in the mixed layout alternating with shorter hub heights (119 m), the wake loss decreased to approximately 11.6%. The annual energy production in the mixed configuration was approximately 642.3 GWh/yr, only 2.1 GWh/yr lower than that of the single-height layout. The CF also exhibited negligible differences between the mixed and uniform layouts within 0.1–0.4%, demonstrating that the mixed configuration maintained, or even slightly enhanced, the overall efficiency.

It should be noted that, in all scenarios investigated, the layouts composed exclusively of the larger turbine models with higher hub heights and rated powers yielded the highest AEP. This outcome is physically consistent because the larger turbines capture more energy per unit, and our optimization does not impose explicit constraints on the number of large turbines, the total installed capacity, or structural and permitting limits. Therefore, when AEP alone is considered as the objective, and no additional practical constraints are imposed, an all-large turbine layout is expected to provide the maximum theoretical AEP. However, real onshore wind farm projects in complex mountainous terrain rarely aim to maximize AEP in this unconstrained sense. Site developers typically face severe limitations on usable land area, allowable turbine locations, visual impact, forest clearance, and foundation or grid connection costs. Under such conditions, simply replacing all turbines with the largest possible model is often infeasible or economically suboptimal. In this context, mixed height layouts provide an additional degree of freedom: by combining high and low hub turbines, developers can reduce wake losses and utilize the vertical extent of the boundary layer more effectively, while maintaining nearly the same AEP as all large configurations within a fixed and spatially constrained site. Our results show that, in the densest layouts, mixed height configurations reduced wake losses by approximately 0.3–1.7% while keeping the total AEP within about 0.5–1.5% of the all-large layout. In other words, a portion of the large turbines can be replaced by lower hub units without sacrificing overall farm-level energy yield, provided that the layout is optimized to exploit terrain elevation and vertical separation.

As the area of the complex increased, the effect of additional efficiency provided by hub-height mixing tended to decrease. This is because, with sufficient separation distance between turbines, the wake interference first decreases, and the wake reductions achieved due to height mixing shrink. These findings empirically demonstrate that utilizing hub height variations within complex terrain can effectively mitigate wake losses by reducing turbine-to-turbine interference, even within the same site. In mountainous areas, where the actual effective hub height varies owing to uneven topography, combining high- and low-hub turbines reduces the overlap of wake zones and enables more uniform wind resource utilization compared with that in single-type layouts. The impact of mixed hub height was particularly noticeable when the site area was small. Therefore, mixing turbine heights can effectively secure vertical separation without increasing the horizontal space between turbines. This strategy can reduce the influence of wake, even at a small site. It is also important to note that the Yeongdeok site already exhibits substantial natural elevation differences between turbine locations owing to its complex mountainous topography. As a result, the effective hub height variation caused by the terrain itself is relatively large, even for nominally single-height layouts. In such conditions, the incremental vertical separation obtained by adding a second hub height (e.g., 59 m vs. 80 m, or 119 m vs. 169 m) becomes less dominant compared with the terrain-induced height differences. This partly

explains why the additional AEP gain and wake loss reduction from height mixing remained modest in our results: a significant portion of the potential vertical staggering effect is already provided by the elevation differences in the complex terrain.

Our analysis revealed that both the wake loss rate and energy production were strongly influenced by the turbine layout density; that is, by the available area of the wind farm. According to the optimization results, expanding the site area, thereby increasing the spacing between turbines, led to a significant decrease in wake interference and consequently increased the total power generation. When a wind farm composed solely of V-82 turbines was optimized within a 1×1 km area, the AEP was approximately 146,541.7 MWh/yr. When the site area was expanded to 2×2 km, the output increased to a maximum of 158,144.6 MWh/yr. Correspondingly, the average wake loss rate decreased markedly from 13.7 to 15% to 8.1–8.9%, whereas the CF improved from 36.1 to 38.2% to 39.7–41.1%. Similarly, for the larger V-162 turbines, the annual energy production increased from 642,287 MWh/yr at 2×2 km to 648,910.5 MWh/yr at 3×3 km, with wake losses decreasing from 11.6 to 13.3% to 10.6–11.6%. The capacity factor also increased from 42.9 to 44.5% to 43.7–45.2%, indicating that greater spatial flexibility increased the turbine-level performance across the farm. However, as the site area increased, the marginal benefits of the mixed-hub-height configuration tended to diminish. This was because increased space between the turbines decreased wake interference, thereby limiting the additional advantages gained from hub height diversification. In this study, the performance difference between the mixed- and single-height V-82 turbine layouts was noticeable only under dense arrangements. Beyond 2×2 km, both layouts exhibited nearly identical performance levels.

The same pattern was observed for the V-162 model. Although the mixed configuration reduced wake losses in the 2×2 km area, the difference became marginal in areas of 2.5×2.5 km or larger, where wake losses were already approximately 10%. These results suggest that mixed hub height strategies are most effective under spatially constrained conditions, whereas sufficient horizontal spacing alone can achieve comparable efficiency levels at larger sites.

From a wake-dynamics perspective, these trends can be interpreted as follows. In the densest layouts, turbine spacing in prevailing wind directions is sufficiently small that that wakes from upstream turbines strongly impinge on downstream rotors, producing large velocity deficits and increased turbulence intensity. Under such conditions, introducing a second hub height effectively reduces the geometric overlap between wake cores and downstream rotor disks, particularly along the dominant inflow directions constrained by the mountainous topography. This vertical staggering mitigates the strongest part of the wake deficit and leads to the observed 0.3–1.7% reduction in wake losses for mixed-height configurations compared with single-height layouts. As the site area increases, both horizontal spacing and terrain-induced elevation differences become large enough that wakes have more distance and time to recover before reaching downstream turbines. In this weak-interacting regime, the dominant mechanism for wake mitigation is increased horizontal separation rather than additional vertical offset. Consequently, the incremental benefit of hub-height mixing diminishes, and mixed and single-height layouts converge to nearly identical wake loss rates and AEP when the average wake losses are already around 10%. The mixed-hub-height layouts leverage these combined horizontal and vertical separations, but their advantage becomes marginal once the dominant wakes have sufficiently recovered before reaching downstream turbines.

The generalizability of the present findings beyond the Yeongdeok site should be considered with care. The quantitative benefits of hub-height mixing reported here are specific to the complex mountainous topography, wind climate, and turbine models (V-

82 and V-162) investigated. In particular, the substantial terrain-induced elevation differences among turbine locations already create effective hub-height variation, which tends to reduce the incremental advantage of adding a second hub height. For other sites, the effectiveness of hybrid hub-height layouts will depend on the combination of terrain complexity, wind shear and turbulence characteristics, and rotor size and hub-height options. In flatter terrain with strong vertical wind speed gradients, larger wake loss reductions might be achievable, whereas in low-shear or highly constrained environments, the benefits may be more limited. Moreover, potential cost reductions associated with hub-height mixing are indirect and site-specific; a full techno-economic analysis is required to quantify the economic impact for different turbine mixes and project conditions.

Hub-height selection is also closely linked to cost. Taller towers generally incur higher capital expenditures due to increased material requirements, more stringent structural design, and potentially more demanding transportation and installation logistics, especially in mountainous terrain. Conversely, shorter towers can be less expensive but may suffer from lower energy yield because of reduced wind speeds and stronger shear and turbulence near the ground. As a result, hybrid hub-height configurations may offer a cost–performance compromise, where a portion of taller, more expensive turbines is combined with a portion of shorter, less expensive turbines, rather than deploying only the most expensive high towers across the entire site. In such cases, even a modest net AEP gain on the order of 0.3–1.7% relative to an all-high layout could be economically attractive if it is accompanied by a non-negligible reduction in average tower cost. However, a quantitative assessment of this trade-off requires detailed supplier- and project-specific cost data, which is beyond the scope of the present study.

Although this study focuses on elucidating the performance benefits of mixed-hub-height layouts, several limitations remain and should be addressed in future work.

First, an explicit economic feasibility-based analysis should be incorporated into future optimization frameworks to assess how reductions in wake losses and increases in energy yield are directly transformed into economic gains. In the present study, we deliberately restricted the objective function to technical performance indicators because detailed, project-specific cost data for different tower heights were not available. As a result, the layouts reported here should be interpreted as technically optimal with respect to AEP under the given spatial and terrain constraints, rather than as fully techno-economic optima. It would therefore be particularly interesting in future work to couple the mixed hub-height strategies analyzed here with cost-related metrics, such as levelized cost of energy (LCOE), return on investment, and tower-height-dependent cost functions, in order to evaluate the overall economic feasibility of hub-height mixing and identify under which cost and market conditions the relatively modest AEP gains justify the additional design and logistical complexity.

Second, this study relies on a simplified engineering wake model (the Jensen/PARK model) with linear superposition of wake deficits, including its implicit extension to vertical wake interference between turbines of different hub heights. While such models are widely used in commercial design tools due to their simplicity and computational efficiency, they do not fully capture three-dimensional wake structures, stability-dependent turbulence, or nonlinear wake–wake interactions in complex mountainous terrain. Consequently, the absolute values of wake losses and AEP should be interpreted as approximate estimates, although the relative comparison between single-height and mixed-height layouts is expected to remain qualitatively robust. Future work should validate the predicted wake interaction patterns and performance gains using higher-fidelity approaches, such as RANS/LES CFD or field measurements.

Finally, combining individual turbine hub height optimization with next-generation wake mitigation and control techniques could further deepen our understanding of aerodynamic interactions in complex terrains and contribute to the cost-effective expansion of renewable energy in the future.

6. Conclusions

Wind power has become common worldwide. We should now focus on improving the overall output of wind farms, which consist of multiple wind turbines instead of individual ones. From this perspective, complex mountainous terrain and wake effects are the most important issues that should be considered simultaneously in decision-making. This study focuses on optimizing the layout of multiple wind turbines over complex mountainous terrain by changing turbine heights. Considering the large number of turbines in a wind farm, hub height poses potential for optimization at a huge scale. Furthermore, it is computationally challenging to address wind power generation with the existence of wake effects between turbines during optimization. In this study, we employed WindPRO, a commercially used software in industry, instead of a small conceptual software package, to validate the necessary data and wind power generation.

Some of the key findings are worth mentioning. First, wind turbines (V-82 and V-162) with different hub heights were mixed and arranged at different heights in the same complex to reduce the wake loss of a wind farm located on mountainous terrain. The placement strategy with mixed turbine heights decreased the wake loss by approximately 0.3–1.7% from that of cases with uniform turbine heights. Thus, the AEP and power generation efficiency of the complex were maintained at nearly the same level, despite the inclusion of lower-hub-height turbines. Although the improvement was not large, this study confirmed that, if the height difference between turbines is utilized in farms on complex mountainous terrain, the total power generation can be increased by partially mitigating wake interference. Therefore, it is suggested that mixing hub heights is a realistic strategy that can promote performance improvement, even under limited site conditions.

The findings of this study have several important implications for wind farm design and policy. First, if turbines of different heights are mixed in farms on mountainous terrain, power generation can be increased by utilizing vertical spaces without securing wide horizontal gaps. In other words, wind energy can be collected at various heights, and mutual interference can be reduced by varying turbine heights, even in a topologically complex area. Second, this height-mixing strategy can be used to increase the output of existing wind farms or maximize site-use efficiency when planning new wind farms. If the turbine height configuration is optimized within the same site, the power generation density may be increased without requiring additional sites to be secured. Therefore, development in harmony with environmental considerations, such as minimizing forest damage, may be possible. Finally, policymakers and licensing authorities must flexibly allow and encourage the inclusion of various types of turbines in wind power plant design standards. Previously, turbines of the same type and height were commonly installed. The findings of this study numerically illustrate that a mixed arrangement is technically valid and beneficial. Our findings are expected to contribute to utilizing topographic richness and maximizing the amount of renewable energy generation in particular areas.

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