

# *A Review of Wind Farm Operation Optimisation Considering Atmospheric Stability*

**Jinyu Tao**

*Tara Anglican School for Girls, Sydney, Australia  
clairetao.792@outlook.com*

**Abstract.** Atmospheric stability is a critical meteorological factor affecting flow characteristics, wake development, and power generation performance in wind farms. This paper provides a review of current research on wind farm engineering optimisation under the influence of atmospheric stability. It systematically collates quantitative characterisation methods for atmospheric stability and analyses the patterns of influence of different stable stratifications on wind speed profiles, turbulence intensity, wind turbine wakes, and energy output. Existing engineering optimisation strategies and research progress are summarised across four aspects: wind farm layout and siting, wind turbine blade design improvement, wind turbine control and regulatory systems, and operation and maintenance optimisation. On this basis, a comprehensive wind farm optimisation framework integrating multi-module and multi-objective development is introduced, elaborating on its design objectives, core components, implementation schemes, and application prospects. Finally, the limitations of current research are highlighted, and future development directions, such as high-precision stability forecasting, automatic application across all operating conditions, and integrated optimisation of offshore wind farms, are discussed. This paper provides a reference for improving the operational efficiency and safety of wind farms under complex atmospheric conditions.

**Keywords:** Atmospheric Stability, Wind Farm, Engineering Optimisation, Wake Loss, Wind Profile, Integrated Optimisation Framework

## **1. Introduction**

With the fast development around the world, the demand for global sustainability has continued to increase. In the 21<sup>st</sup> century, people's construction of wind farms has rapidly increased, not only enlarging the scale of onshore wind farms but also advancing the design of offshore wind farms. Both onshore and offshore wind farms are playing a crucial role in large-scale energy generation due to their significant ability to generate energy. From the WWEA Annual Report 2025, global wind capacity exceeds 1,345 gigawatts, 169 gigawatts added, which was 35% more than in 2024, wind power generates more than 11% of world demand [1]. Wind energy has generally become one of the most popular and reliable sources of energy in modern society, supporting people's daily lives and driving the economy.

However, due to climate diversity and the hard predictability of the atmosphere, optimising the performance of wind farms remains a complex challenge, which also creates improvement space in the engineering design area. To solve this problem, the fundamental atmospheric stability, the advanced engineering optimisation and the integrated framework solutions need to be considered.

Within a wind power generator system, atmospheric stability plays a critical role in shaping wind speed profiles, turbulence intensity, and wake behaviour. An unstable atmosphere will decrease these, which directly influence energy capture. However, many conventional wind power models make assumptions about natural atmospheric conditions that may not accurately reflect the real-world situation, thereby limiting future prediction accuracy.

In addition to the effect of atmospheric stability the design of wind power generator must take into account environmental effects such as surface roughness, terrain, and, in offshore cases, wave dynamics and humidity. These need to be considered in the design of wind power generators, which further influence wind flow characteristics and turbine performance. Engineering design plays a fundamental and significant role in determining how efficiently wind energy is captured and then transferred to the power that is ready to be used. Design factors such as turbine height, blade length, blade rotation angle, and wind farm framework all directly affect the overall efficiency and reliability of the energy generation system.

At present, research on the optimisation of wind farms under different atmospheric stability conditions has made certain progress, but multi-objective collaborative optimisation, dynamic adaptive regulation, and the construction of integrated frameworks still need to be deepened and improved. Based on this, this paper systematically reviews quantitative characterisation methods of atmospheric stability, elaborates on its effects on wind profiles, turbulence, wakes, and energy output patterns, summarises engineering optimisation strategies from multiple aspects, including layout optimisation, operational control, wake suppression, and operation and maintenance scheduling, and introduces a comprehensive optimisation framework integrating multiple modules.

Finally, the paper discusses the limitations of existing research and future development directions, providing theoretical reference and technical support for enhancing the efficient, safe, and stable operation of wind farms under complex meteorological conditions.

## 2. Information analyst

### 2.1. Atmosphere stability

#### 2.1.1. Basic concepts of atmosphere stability

Atmospheric stability is an important physical property that determines the degree of turbulent mixing and the strength of vertical motion within the atmospheric boundary layer. It is normally classified into three categories: stable, neutral, and unstable stratification.

In the unstable conditions, the strong thermal convection will increase the turbulence, leading to rapid wake dissipation and more uniform wind profiles. In contrast, under stable conditions, the vertical mixing will be constructed by the stable atmospheric boundary layer, leading to weak turbulence and long-distance wakes. Meanwhile, under neutral conditions, it represents a balanced state with most mechanical turbulence

The different categories of the atmospheric boundary layer can be determined by the different forms of clouds, as the formation of clouds is closely related to the stability or instability in the atmosphere.

When the atmosphere is in the unstable state, the centre of the cloud has a warmer temperature than its surroundings, so the cloud will rise and expand; when the atmosphere is in the stable state, the centre of the cloud has a cooler temperature than its surroundings, so the cloud will sink and compress; when the atmosphere is in the neutral state, the centre of the cloud has the same temperature as its surroundings, so the cloud wall has no change.

Atmospheric stability significantly influences the wind speed distribution, turbulence characteristics, and wake behaviour within the wind farms. Therefore, it directly affects the power output and overall performance. Quantifying the influence of atmospheric stability is highly hopeful for assessing the wind resources and efficient wind farm optimisation.

### 2.1.2. Quantitative characterisation methods

Common quantitative parameters and methods to determine atmospheric stability include the Richardson number, Monin-Obukhov length, and Pasquill-Gifford stability classification.

The Richardson number (Ri) is a dimensionless number that quantifies the ratio of buoyancy forces to shear (inertial) forces in a stratified fluid. The Richardson number has two common forms: the gradient Richardson number and the Bulk Richardson number.

The gradient Richardson number (Ri) uses wind speed and the temperature gradient to determine whether turbulence has been suppressed or enhanced, and then further determines the atmospheric stability as shown in Table 1.

Table 1. Different range of richardson number in different atmospheric stability and their characteristics

Atmospheric Stability	Richardson Number (Ri)	Characteristic
Unstable	$Ri < 0$	Strong turbulence, strong vertical mixing
Neutral	$Ri \sim 0$	Mainly mechanical turbulence, normal vertical mixing
Stable	$Ri > 0$	Weak turbulence, suppressed vertical mixing

While the Bulk Richardson number (Bulk Ri) does not use gradients, it only uses the differences in wind speed and temperature between two heights.

The Monin-Obukhov length (L) is the height at which turbulence is generated more by buoyancy than by windshear. This is the core parameter that determines the stability of the atmosphere, which considers both the influence of heat (temperature) and mechanical (wind) effects as shown in Table 2.

Table 2. Different range of monin-obukhov length in different atmospheric stability and their characteristics

Atmospheric Stability	Monin-Obukhov Length (L)	Characteristic
Unstable	$L < 0$	Enhanced turbulence, strong convective mixing
Neutral	$L \sim \infty$	Negligible thermal effect, mechanical turbulence only
Stable	$L > 0$	Weak turbulence, suppressed vertical mixing

The Pasquill-Gifford stability classification is a systematic method that uses wind speed, solar radiation, and other relevant parameters to range the stability class.

In addition, atmospheric stability can be estimated from the wind profile exponent, derived from wind speed at different heights. These parameters can be classified into different atmospheric

stabilities, providing the basic evaluation information to improve the wind farms' design.

### **2.1.3. Influence mechanism of atmospheric stability on wind farm performance**

Atmospheric stability is one of the most important meteorological variables impacting the development of the wind profile and turbulence, as well as the wind from the wake effect. The wind will perform differently under different stability conditions, leading to different energy input. Improving the technique of predicting atmospheric stability can improve the wind energy generation system and further enhance global stability.

### **2.1.4. Effects on wind profile and turbulence**

When the profile is the wind speed changing by the energy generators' height as a result of 'The impact of stable atmospheric boundary layers on wind-turbine wakes within offshore wind farms' for offshore wind farms, the wind speed generally increases with downstream distance increasing from the coast [2]. This is due to the line having more buildings, a higher temperature, and its terrain being rougher. The faster wind speed will cause stronger turbulence and change the wind profile's shape. The faster the wind speed, the stronger the air mixing and the closer the profile will be to the ideal neutral situation.

### **2.1.5. Effects on the wind farm wake effect**

The result from the past thesis, 'The impact of stable atmospheric boundary layers on wind-turbine wakes within offshore wind farms', shows that the wake effect in the stably stratified situation is twice as strong as in the unstably stratified ABL, which directly shows how different atmospheric boundary layers affect wind farms' wake effect [2].

When the atmospheric boundary layer is stable, the turbulence is weak, and the vertical mixing is suppressed and leads to slow wake recovery and long wake tails, which could result in significant power loss for downstream turbines.

When the atmospheric boundary layer is unstable, the turbulent mixing accelerates wake dissipation, and the wake extension is shorter than the wake interference, resulting in less power loss.

When the atmospheric boundary layer is neutral, the turbulent mixing rate and power loss are normal.

## **2.2. Engineering optimisation**

Atmospheric stability has become the fundamental factor in wind farm engineering optimisation, significantly changing the flow characteristics, power generation efficiency, and equipment durability. Many scholars have conducted targeted and in-depth studies to increase the wind farm's functions under different atmospheric stratification conditions.

However, different regions have different terrains and climate types. These are key factors affecting atmospheric stability, and any optimisation plan has its own unique characteristics and limitations, which cannot be generalised.

### 2.2.1. Wind farm layout optimisation

Optimising the layout of the wind farm can minimise the loss of interaction and related electricity, making it one of the most effective and sustainable methods.

From the passage written by 'A multi-objective framework for wind farm layout optimization considering land area and performance uniformity', which is an analysis of a new type of turbine, Vestas V80-2MW, used for the Mungil region in northern Iran [3]. Based on several single and multi-objective optimisations, and through much experimental data and theoretical proofs, the cumulative velocity defect weaker crisis model is proved to be better than the traditional trailing overlay method because of its stronger physical stability. Also, the great refinement can improve the optimisation performance, converging when the unit size reaches the two rotor diameters.

Also from the study 'Multi-Criteria Optimization of Wind Turbines in an Offshore Wind Farm with Monopile Foundation Considering Structural Integrity and Energy Generation', the adjusting spacing from 250 metres to 282 metres and hop height from 148 metres to 155 metres can reduce wake interference by 25% and monopile fatigue loads by 18%, while lowering the levelised cost of electricity by up to 15% [4]. The staggered layout is often preferred for farms with dominant wind directions, while well-matched or circular arrangements suit sites with multiple prevailing directions.

With the continuous improvement and development of programming technology, an increasing number of program algorithms can be utilised to strengthen the layout optimisation of the wind farms and development in energy systems, thereby improving generator power and reducing energy loss.

From the report 'Wind farm layout optimization through multi-strategy differential evolution-based reinforcement learning algorithm', a rate enforcement learning-based multi-strategy differential evolution algorithm is developed to solve the wind farm layout optimisation problem. The Genetic Algorithm (GA), Differential Evolution (DE), and Reinforcement Learning (RL) have been analysed to improve energy generators' predicting ability, better suit the different atmospheric stability [5].

In response to different climate types and surrounding environments, each region has different generator upgrade plans; the two plans above are just for reference.

### 2.2.2. Wind turbine design improvements

The number and arrangement of wind turbine blades have a significant impact on the efficiency and speed of the turbine. Poor performance is often due to low efficiency caused by too few blades, but having too many blades increases their weight and manufacturing costs. Therefore, selecting the appropriate number of blades is important, with the three-blade wind turbine currently being the most widely promoted. The core solution for minimising blade mass is to find the most suitable production materials. Such materials need to have certain properties, including corrosion resistance, durability, stiffness, and stability, as well as being low-density, fatigue-resistant, and environmentally friendly. Additionally, for offshore wind farms, the material also needs to be rust-resistant; recommended materials include carbon fibre or glass fibre composites.

At the same time, a reasonable blade shape is also very important for the power generation process. Through 'A multi-faceted review of wind turbine optimization techniques: Metaheuristics and related issues', and by designing the blade's geometric shape as well as the distribution of chord length, twist angle, and thickness according to aerodynamics, the ideal shape of the blade is often

the outer surface of the blade, and the pitch angle of the blade ( $\beta$ ) at different wind speeds will also change [6]. ( $C_p$  is the power coefficient, and  $\lambda$  is the tip speed ratio.), as shown in Figure 1.

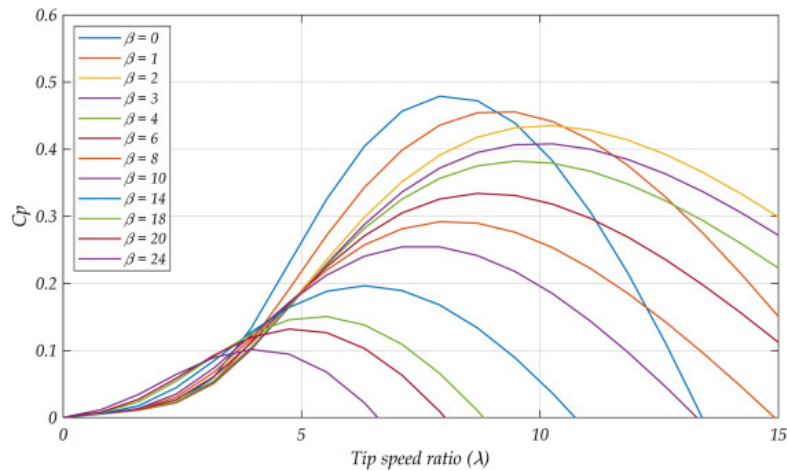


Figure 1. The relationship between the tip speed ratio and the power coefficient [6]

### 2.2.3. Monitoring technologies and intelligent control systems

The best way to enhance monitoring technologies and intelligent control systems is to improve the research and practice of mechanical automation. Currently, we have many emerging automation technologies, such as infrared sensors, which can identify dangers around wind power stations and protect the service life of generators. Another example is the introduction of artificial intelligence, which improves the accuracy of identifying different environmental characteristics. In the reference 'Overview of Agricultural Machinery Automation Technology for Sustainable Agriculture', scholars studied various sustainable mechanical technology improvement schemes, including positioning technology, perception technology, and control and execution technology [7]. This is not only applicable to agricultural machinery but also to the use of mechanical equipment in major wind power stations and other venues.

### 2.2.4. Structural protection measures

Rather than wind-form layout, turbulent design, monitoring techniques, and intelligent control system optimisation, the physical protection measures are still very important. The physical protection measures can protect it from external threats, such as vandalism or unauthorised access. Such protective measures include physical barriers, alarm systems, surveillance cameras, and access control systems, which can primarily serve as a comprehensive deterrent against potential attacks.

## 2.3. Integrated framework

### 2.3.1. Framework design objectives and principles

The goal of the framework design is primarily to unify atmospheric stability, wind farm performance, and engineering optimisation. It aims to achieve multi-objective optimisation, increase power generation, reduce loads, minimise wake losses, and lower operational costs. Its principles are mainly real-time capability, synergy, and practicality. It can dynamically adjust according to atmospheric stability, and while satisfying the coordination of layout, control, wake, and operation

and maintenance, it remains applicable to actual wind farms. This is the core of improving wind farm performance.

For example, as mentioned in literature 'An optimization framework for wind farm layout design using CFD-based Kriging model', researchers through the study of Kriging models, and by comparing their results with a conventional staggered layout along the dominant wind direction, found that the optimised wind farms produced a higher total annual energy production and had a more uniform distribution among the wind turbines [8]. They indicated that the optimisation framework consistently attempts to keep downstream turbines away from the wakes of upstream turbines, aligned along the dominant wind direction. This proposal provides a more accurate and more flexible alternative.

### 2.3.2. Core components of the integrated framework

For this study, the core component of the integrated framework mainly consists of four interrelated modules.

The first module is atmospheric stability identification and prediction, which will use real meteorological data when profiles and key parameters such as the Richardson number, Monin-Obukhov length, and Pasquill-Gifford stability classification are used to classify the atmospheric boundary layers and predict future stratification conditions.

The second module is wind farm performance evaluation, which calculates wind speed distribution, turbulence characteristics, wake recovery power output, and structural load based on stability input.

The third module is multi-objective optimisation which integrates layout adjustment, intelligent control, wake suppressing and maintenance scheduling to achieve optimal performance.

The first module is feedback from the real practice, which collects the actual operation data from the wind farm control system using the optimisation strategies to update and improve the module parameters.

Putting these four modules together can achieve the whole process control from environmental perception to strategy optimisation, and actual feedback, providing a systematic solution to improve the wind farm efficiency under stability.

### 2.3.3. Framework implementation approach

The feasibility of the framework can be evaluated from four perspectives.

The first is data. By evaluating measurement data of wind speed and meteorological forecast data, as well as wind turbine performance and characteristics, the optimal wind turbine model can be selected for different climate types and terrains to achieve maximised power output.

The second is models. Through different wind profile models, wake models, load models, and stability discriminant models, the optimal wind turbine type can be selected from multiple angles.

The third is algorithms. By combining more diverse intelligent optimisation algorithms and predictive control model algorithms, improvements can be better achieved through comparison, realising the optimal performance of the wind turbine.

The fourth is application; better integration of wind turbine host control and wind farm monitoring systems is a decisive factor in realising the rational operation of a framework.

### 2.3.4. Application status and feasibility

Currently, many studies have integrated stability into wake control and layout optimisation, proving their feasibility, and there are successful cases of adaptive control in actual wind farms. This can not only increase power generation but also reduce wind turbine loads and minimise wake losses.

For instance, in 'Wind farm layout optimisation with multi-type wind turbines for minimising levelized cost of energy', scholars have used the widely used Jensen model, which assumes linear wake expansion and a uniform velocity deficit [9].

However, due to the complexity of the actual terrain, as well as issues related to offshore adaptability, implementation costs, and the real-time identification accuracy of stability, the practical feasibility of some solutions still requires further improvement and assessment [10].

## 3. Conclusion and future research directions

This paper provides a review focused on the impact of atmospheric stability on wind farm operational performance and related optimisation strategies. Results indicate that atmospheric stability influences wind farm power generation, load levels, and operational efficiency by altering wind profiles, turbulence intensity, and wake development characteristics. A stable atmosphere leads to slow wake recovery and increased power losses, whereas an unstable atmosphere facilitates wake dissipation, thereby enhancing wind energy capture and output.

Existing optimisation measures primarily focus on wind farm layout optimisation, turbine operational control, wake loss suppression, and structural protection measures optimisation, with well-established technical improvement methodologies already in place. Such as the CFD-based Kriging model, the optimised wind power system generates more electricity annually and has a more even distribution of wind turbines. On this basis, a multi-objective integrated optimisation framework has emerged as a key development direction for enhancing overall wind farm performance. This framework enables the integration of atmospheric stability prediction, performance assessment, collaborative optimisation, and real-time feedback, demonstrating strong implementation ability.

However, due to persistent issues such as insufficient precision in stability judgement, limited adaptability to complex terrain, and the significant difficulty of multi-objective collaborative optimisation (for example, in theoretical research we often assume ideal atmospheric stability, which is not the case in reality), many theoretical schemes and practical data issues still require improvement. Future research could further explore high-precision stability prediction, full-condition automated application, and dedicated frameworks for offshore wind farms, providing more reliable theoretical and technical support for the efficient, safe, and stable operation of wind farms.

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