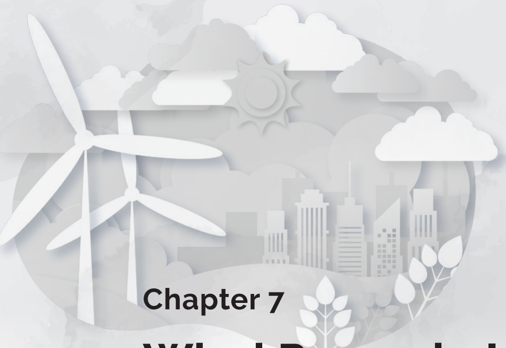

Chapter 7

Wind Power in Indonesia: Potential, Challenges, and Current Technology Overview

Taufal Hidayat

A. Wind Power Technical Potential

Wind power has been used for more than two millennia since humans put sails into the wind and continue to grow until now. According to Global Wind Energy Council (GWEC), 2020 was the best year in history for the global wind industry, with 93 GW of new capacity installed, resulting in a cumulative capacity of 743 GW (Lee & Zhao, 2021). China has the largest wind power generation market globally with a total of 206 GW or equivalent to 36% of the global market, followed by the USA, Germany, and India with a total capacity of 96 GW, 2.4 GW, and 2.2 GW, respectively. The wind turbine has supplied almost 6% of the total electricity demand in the world. Some countries have begun developing wind power as their energy resource in

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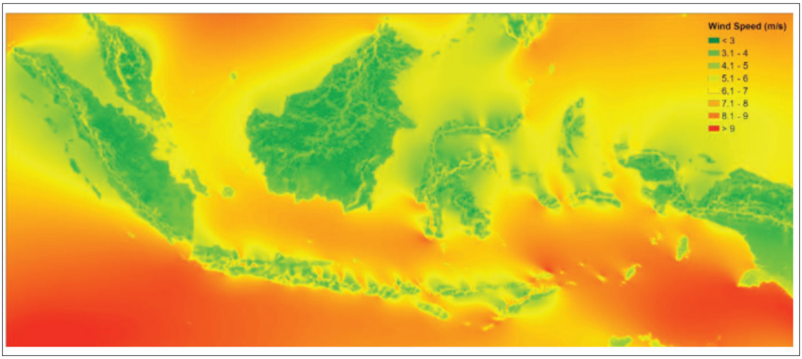
Southeast Asia. Vietnam, Thailand, Malaysia, and Indonesia represent 84% of the total installed renewable energy capacity in the Southeast Asian country. Vietnam has the largest capacity with 24,519 MW (34%), followed by Thailand, Indonesia, Malaysia, and the Philippines with 11,860 MW, 9,861 MW, 8,046 MW, and 6,695 MW.

As mentioned in strategic planning in directorate general of new, renewable, and conservation energy, Ministry of Energy and Mineral Resources, 2020–2024, the mean annual speed in Indonesia is only between 3 m/s–6 m/s, only half compared to the country in the northern and southern hemisphere that have wind speed higher than 8 m/s. That low speed happens due to the location of Indonesia, which is on the equator with warm air and low pressure. Based on that wind speed data, the technical potential of wind power notes in the ministry of ESDM is about 60.6 GW, with the utilization being about 0.15 GW until 2020. This utility is still far from the target in RUEN that in 2020, at least Indonesia is already installing 0.6 GW of wind power.

Based on the data from RUEN, Nusa Tenggara Timur have the most significant wind power potential in Indonesia with about 10.18 GW, followed by East Java with 7.9 GW, West Java with 7.03 GW, Central Java with 5.2 GW, and the South Sulawesi with about 4.19 GW. More detailed research shows that the highest wind speed is in Sukabumi, West Java, with about 7 m/s, and Sangihe Island, with 6.4 m/s. Indonesia's largest wind power plant is the District of Sidenreng Rampang, South Sulawesi, with about 75 MW capacity.

Based on the Institute for Essential Service Reform (IESR) (Puspitarini, 2021), wind power potential in each province in Indonesia with hub heights of 50m and 100 m are shown in Table 7.1. From the table, IESR reports that Indonesia has 25 GW wind potential with 50m Height and 19,8 GW with 100m hub height by using a minimum mean annual wind speed of 7.25 m/s at 50 m and 7.99 m/s at 100 m.



Source: Hesty et al. (2021)

Figure 7.1 Indonesia's Global Wind Speed at 50 m Height-Resolution 5 km

Table 7.1 Indonesia Wind Power Technical Potential

Province	**Technical potential**	
	at 50 m hub height (MW)	**at 100 m hub height (MW)**
Aceh	1,104.5	1,211.1
Bali	71.5	20.9
Banten	0.0	0.0
Bengkulu	0.0	0.0
DI Yogyakarta	0.0	0.0
DKI Jakarta	0.0	0.0
Jambi	0.0	0.0
Jawa Barat	780.3	418.6
Jawa Tengah	444.4	185.3
Jawa Timur	488.2	205.3
Kalimantan Barat	0.0	0.0
Kalimantan Selatan	120.4	86.7
Kalimantan Tengah	0.0	0.0
Kalimantan Timur	0.0	0.0
Kalimantan Utara	0.0	0.0
Kepulauan Bangka Belitung	0.0	0.0
Kepulauan Riau	36.2	0.0

Province	Technical potential	
	at 50 m hub height (MW)	at 100 m hub height (MW)
Lampung	70.4	0.0
Nusa Tenggara Barat	183.8	34.5
Papua	1,085.2	161.4
Papua Barat	0.0	0.0
Riau	0.0	0.0
Sumatra Barat	11.9	0.0
Sumatra Selatan	15.9	0.0
Sumatra Utara	246.2	38.4
Nusa Tenggara Timur	4,933.0	5,943.8
Sulawesi Utara	0.0	0.0
Sulawesi Tengah	15.2	0.0
Sulawesi Selatan	8,732.7	6,525.0
Sulawesi Tenggara	2.1	0.0
Gorontalo	65.1	9.7
Sulawesi Barat	107.2	0.0
Maluku	6,391.7	4,857.6
Maluku Utara	20.9	0.0
Total	24,926.8	19,698.4

Source: Puspitarini (2021)

B. Wind Power Problem

Although the potential of wind power as a renewable energy source in Indonesia is growing steadily, there are some problems following the installation and development of wind power.

1. Noise

Wind farms can cause mechanical and electrical noise. Some reports and research studies show that the wind farm can produce noise at sound pressure levels that cause negative emotion, insomnia, and various symptoms.(Mar et al., 2020; Mittal et al., 2017; Yamani et al., 2018) According to ISO, the allowable noise level in residential areas is 45 dB, and for an industrial area up to 50 dB (ISO, 1996).

In certain circumstances, wind turbines can cause electromagnetic interference with television signal reception or microwave transmission for communication. The height of the wind turbine is determined by analyzing wind turbulence and wind strength data. Aerodynamic noise is a function of many factors such as propeller design, rotational speed, wind speed, and inflow turbulence.

Moreover, aerodynamic noise is also the main problem caused by the wind farm. Some scientists argue that the wind kinetic energy of large-scale wind farms can affect local and global climate change. Therefore, it is essential to limit the speed of the wind turbine rotor to below 70 m/s.

2. Ecological Problem

Wind farms also potentially affect the animal population, mainly bird and bat populations. Some studies reveal that wind farms can disrupt bird and bat migration. Moreover, the construction of wind farms also potentially affects soil quality and the surrounding land.

3. Visual Impact

The wind farm requires a large installation area, which is impossible to hide. The minimum distance of a wind farm is five times the rotor diameter, which means that for a standard 2 MW wind turbine with a 40 m blade diameter, the required area is 40 km^2 for one turbine. The critical area can disturb the view and reduce the agricultural land.

C. Wind Power Challenges in Indonesia

The prospect of wind power development is relatively high despite several obstacles. In Indonesia, there are several obstacles or challenges, such as:

1. Low Wind Velocity

As a tropical country, Indonesia has a low annual wind speed between 3 m/s–6 m/s. The minimum wind speed required to spin the blade of a wind turbine is 5 m/s, so as the mean annual wind speed in Indonesia, the wind energy potential in Indonesia is low. Referring to the report from IESR (Puspitarini, 2021), compared to solar photovoltaic with 7,714.6 GW potential, wind power has only 194 GW potential for both onshore and offshore. Therefore, it requires further research to optimize the wind energy potential, especially regarding the type of blade that can spin at lower wind speed.

2. High Investment Cost.

The initial investment for a new wind farm is high. In 2017, the initial investment for the wind farm was around USD 0.02/kWh (Lee & Zhao, 2021). The primary investment comes from the area and turbine cost. Therefore, further research is vital to reduce the cost of wind farm energy.

D. Wind Power Technology

Various researches have been developed to increase performance and mitigate the problem possibly caused by wind power resources. Some related research can be adopted to answer the challenge of implementing wind turbines in Indonesia. In this chapter, three prominent technologies are detailed in terms of some research done by the researcher. The researchers can implement the technologies to improve the performance of wind power and mitigate the problem caused by the implementation of wind power resources.

1. Wind Turbine Design

As mentioned in the previous chapter, low wind speed is one challenge to wind power resources in Indonesia. The average wind speed in Indonesia is around 3–6 m/s, which is not suitable for all types of blades. The wind turbine will spin at the wind speed called cut-in speed. For standard wind blades (HAWT), the cut-in speed is 6 m/s which means that the wind turbine will not spin and start to produce power below that speed. Scientists have developed some new blades designed to reduce the minimum wind speed. For example, the implantation of the vertical axis wind turbine can reduce the minimum wind speed to only 2 m/s, which is more suitable to implement in Indonesia. To discuss the recent technology related to blade design, the classification of wind turbines should be detailed first. The wind turbine design can be classified in the following ways.

As seen in Figure 7.2., wind turbines can be classified into two main parts: horizontal axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). VAWT is a popular type of wind turbine utilized in many wind farms globally. The blades of this wind farm have a vertical direction or are perpendicular to the land, while in HAWT, the edges are parallel with the ground. The comparison of both types of wind turbines is explained in detail in Table 7.2.

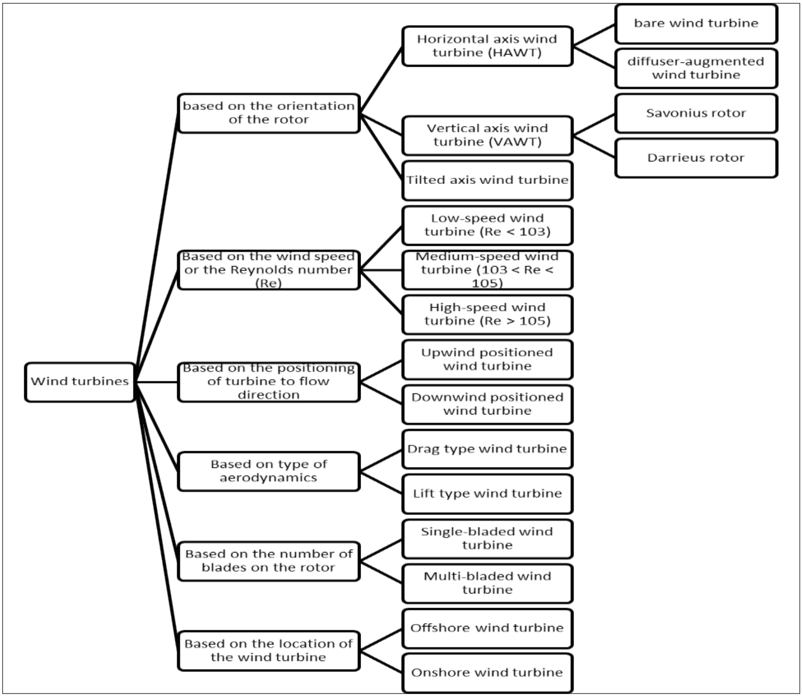


Figure 7.2 Wind Turbine Classification

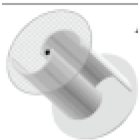
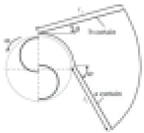
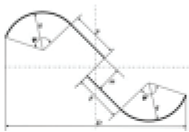
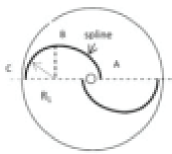
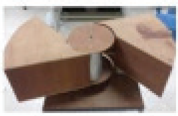
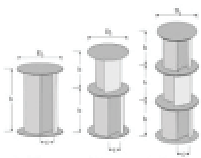
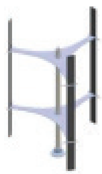
Table 7.2 The Comparison of HAWT and VAWT

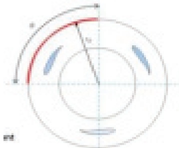
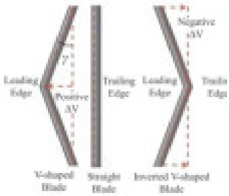
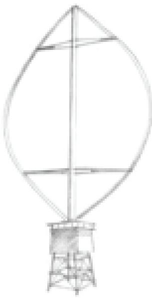
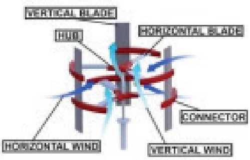
Characteristics	HAWT	VAWT
Rotor orientation	Horizontal	Vertical
Weight	Heavier	Lighter
Wind direction	Specific wind direction	All win direction
Wind speed range	6–25 m/s	2–65 m/s
Environmental impact	Higher chance of bird collision	Lower case of bird collision
Noise level	Higher	Lower
Starting function	Self-starting with high starting torque	Not-self-starting with lower starting torque
Cost and construction	Higher	Lower
Power produced	Higher	Lower

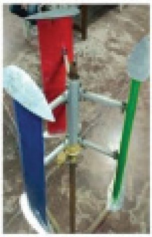
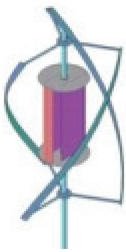
HAWT and VAWT have pros and cons, so the implementation of both should consider the installation area's requirements and conditions. The standard VAWT should be more suitable for Indonesia with low wind speed due to the low cut-in rate, but the energy produced is also lower. Therefore, the researcher should elaborate more research on improving VAWT to increase the energy produced by the wind turbine. Based on the literature review, VAWT can be classified into two categories: Savonius-Rotor and Darrieus rotor. Numerous researchers have also modified each of these types to increase performance. The detailed configuration of this type of VAWT is detailed in Table 7.3.

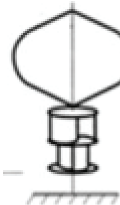
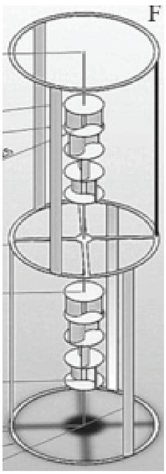
Darrieus rotors have excellent aerodynamic overall performance. However, typically they are not self-starting simultaneously as the Savonius rotors are self-starting but have low aerodynamic overall performance. The Savonius rotors will feature with drag forces. A mixture of them or in different hybrid Savonius-Darrieus rotors will assist in resolving the self-starting venture for the Darrieus rotor and the low aerodynamic overall performance of the Savonius rotor.

Table 7.3 The Modification of VAWT

Type	Modification	Model	Benefit	Drawback
Savonius VAWT	Conventional (Menet & Rezende, 2013)		Low starting torque; Low angular velocity,	Drag device; Low efficiency
	Conventional with curtain (Altan & Atilgan, 2010)		Increasing power coefficient	Fixed wind direction; Drag device; Low efficiency
	Without shaft (Kamoji et al., 2009)		Higher maximum power coefficient	Negative torque coefficient; Drag device; Low efficiency
	Elliptical blade (Sanusi et al., 2016)		Higher maximum power coefficient	Drop-in performance in the use of endplates linking shaft
	Double wind tunnels (Promdee & Photong, 2016)		Higher voltage	Limited wind angle range
	Multiple stages with twisted blade (Saha et al., 2008)		A higher power coefficient compares to two blades	Consume More material
Darrieus VAWT	Three straight-bladed Darrieus rotors with upper and lower surface connectors (Raciti Castelli et al., 2011)		Exceed Betz limit 3 times during one rotor revolution.	Lower average power coefficient

Type	Modification	Model	Benefit	Drawback
	Straight-bladed Darrieus rotor with upstream deflector. (Stout et al., 2017)		Higher maximum power coefficient	Specific wind direction; Specific deflector angle
	Three V-shape blade Darrieus rotor (Su et al., 2020)		higher maximum power coefficient	energy loss on the blade tip region
	Darrieus Phi rotor (eggbeater/curved rotor) (Islam et al., 2013)		Cost-effective	Rotor height limitation; Uneven wind velocity on the rotor blades
	Cross axis helical Darrieus rotor (Muzammil et al., 2017)		Collect wind energy from horizontal and vertical Directions. Suitable for low wind speed areas	Not suitable for high wind speed areas. Suitable for small-scale wind turbines
	Helical twist Darrieus rotor (Patel & Sapariya, 2017)		Lower noise	Lower max. power coefficient

Type	Modification	Model	Benefit	Drawback
	Straight blade Darrieus with wing tip devices (Mishra et al., 2020)		Aerodynamic efficiency; Decrease the induced drag.	Trailing vortices weaker; increase the total drag.
	J-shaped straight Darrieus (Zamani et al., 2016)		Improves self-starting ability; Less turbulence and noise.	Change the optimum TSR
	Darrieus Phi rotor (Hilewit et al., 2019)		Higher max power coefficient; Higher TSR range Lesser cost	Reduce blade wake interactions
Hybrid Savonius - Daerrius	Two-bladed Savonius with three-bladed straight Darrieus (Nemati, 2020)		Low TSR; It can function at low wind speed.	Complex geometry.
	Two-bladed Savonius with three-bladed helical Darrieus (Pallotta et al., 2020)		Less starting speed; Self-starting	Lower energy produced compared to Darrieus rotor

Type	Modification	Model	Benefit	Drawback
	Double stages two-bladed Savonius with egg beater Darrieus (Wakui et al., 2005)		Self-starting.	Lower output power compares to the Darrieus rotor
	Double stages two-bladed Savonius with two, three, and four-bladed straight bladed Darrieus (Ahmedov, 2016)		Better efficiency; Self-starting.	Lower power coefficient
	Three-bladed Savonius and thirteen-bladed Darius (Belmili et al., 2017)		Self-starting; Better performance compared to Darrieus rotor	Complex geometry; Costly
	Combined Bach-type and H Darrieus rotor (Hosseini & Goudarzi, 2019)		Self-starting	Complex model and higher cost

2. Optimization in Wind Power Generation

a. Optimization Algorithm

Wind Farm Layout Optimization (WFLO) usually refers to placing a wind turbine (WT) inside a particular area to maximize or minimize the objective function while meeting various constraints and considerations. However, the optimization process in WFLO is not an easy task due to the complexity of the problem, so it cannot be solved by using classical analytical optimization techniques. Researchers have developed many optimization methods to solve the problem, including heuristic, meta-heuristic, and other evolutionary algorithms—the primary method described in Table 7.4.

Table 7.4 Optimization Method Algorithm

Algorithm	Reference
Genetic Algorithm (GA)	Abdulrahman & Wood (2017); Emami & Noghreh (2010); Gao et al., (2020); Grady et al., (2005); Parada et al., (2017); L. Wang et al., (2015)
Greedy Algorithm	Chen et al., (2016); Ozturk & Norman, (2004); Chen et al., (2013); Changshui et al., (2011)
Particle Swarm Optimization (PSO)	Asaah et al., (2021); Chowdhury et al., (2013); Pso et al., (2021); Wang, S. M. G., (2014)
Ant Colony Algorithm (ACO)	Eroĝlu & Seçkiner, (2012)
Random Search Algorithm (RS)	Feng & Shen, (2015)
Evolutionary algorithm (EA)	(Gonzalez et al., 2010; Kusiak & Song, 2010; Li et al., 2017; Mora et al., 2007; Pso et al., 2021; Y. Wang et al., 2018)

b. Objective Function

Several objective functions can be defined in WFLO programming, some works of literature use a single objective, and others use multi-objective. The most widely used metrics are the wind farm Annual Energy Production (AEP), the instantaneous power conversion, and the Cost of Energy (CoE).

Power Conversion and Annual Energy Production

Four metrics equivalents to the AEP and the instantaneous power conversion were found in the literature, such as (1) the wind speed reaching each WT in the wind farm (to be maximized); (2) the wind speed deficit at each WT (to be minimized); (3) the wind farm capacity factor (to be maximized); and (4) the wind farm efficiency (to be maximized), defined as the ratio of the wind farm power conversion to the ideal wind farm power conversion (if no wake and turbulence effects are taken into account).

AEP can be modeled as cited from Lackner & Elkinton, 2007; Manwell & Mcgowan, 2014:

$$AEP = 8766 \sum_{m=1}^{N} \int_{0}^{360} \int_{0}^{U_{max}} \left[\frac{1}{2}\rho A U^{3} C_{p}(U,\rho)\right] p_{\theta}(\theta, m) \left[\left(\frac{k(\theta,m)}{c_{eff(\theta,m)}}\right)\left(\frac{U}{c_{eff}(\theta,m)}\right)^{k(\theta,m)-1} e^{-\left(\frac{U}{c_{eff}(\theta,m)}\right)^{k(\theta,m)}}\right] dU\, d\theta \tag{7.1}$$

Cost of energy (CoE) and Levelized Cost of Energy (LCoE)

The cost of the energy (CoE) wind farm is the cost divided by the total power production, as shown in Eq. 7.2:

$$CoE = \frac{Cost}{AEP} \tag{7.2}$$

The wind turbine cost is a function of the number of wind turbines that can be modeled in Eq. 7.3 (Mosetti et al., 1994)

$$Cost = N_{wt}\left(\frac{2}{3} + \frac{1}{3} e^{-0.00174 N_{wt}^{2}}\right) \tag{7.3}$$

Two equivalent definitions to the CoE that were identified in the literature are (1) the Levelized Cost of Energy (LCoE) and (2) the Levelized Production Costs (LPC). In addition, different definitions of Financial Balance (FB) (or economic profits) were identified in the literature. The main difference between FB models resides in which costs are considered. Some works did not implement any performance metric, as their objective was to treat a specific issue of the WFLO problem (e.g., review assignments, derivation of mathematical approximations, etc.). LPC can be formulated as:

$$LPC = \frac{C_{INV}}{a\, E_a} + \frac{C_{O\&M}}{E_a} \tag{7.4}$$

$$E_a = A_f \left[\sum_{i=1}^{N} \left(E_{WT,i} - E_{Loss,wake,i} - E_{Loss,col,i} \right) - E_{Loss,trans} \right] \tag{7.5}$$

Sales Revenue, Profit, and Financial Balance (FB)

The formula is given as cited from Réthoré et al. (2014):

$$FB = WB - C_D - C_{O\&M} - (C_F + C_G)\left(1 + \frac{r_c - r_i}{n_L}\right)^{T(n_L)} \tag{7.6}$$

Where Wp is the sales revenue of the expected electrical energy conversion over the wind farm operational lifetime, C_D is the accumulated cost of components degradation, $C_{O\&M}$ is the cost of overall operation and maintenance, C_F and C_G represent variable investment costs of foundations and electrical infrastructure, r_c [%] is the interest rate, r_i [%] is the inflation rate, n_L is the number of times interests of loans have to be paid in a year, and T is the wind farm expected operational time in years

Net Present Value (NPV)

The Net Present Value (NPV) is a widely used financial metric in discounted cash flow analysis. It is a standard method implementing the idea of the time value of money to appraise long-term projects, such as wind farms. The NPV is similar in definition to the FB. It is the sum of present values of individual cash flows over finite periods

Formulation of NPV can be given as cited from Gonz & Pay (2012):

$$NPV = \sum_{k=1}^{T} \frac{N_K}{(1 + r_i)^k} - C_{INV} + V_R \tag{7.7}$$

Where N_k represents the net income (or profit, which is the value of the energy sales revenue minus all variable costs such as O&M costs) produced by the wind farm during the *k*th year, r_i represents the equivalent discount rate or interest rate [%], which is an indicator of the opportunity cost of capital goods (e.g., the higher the discount rate, the lower the present value of the future cash flows), C_{INV} represents all the current capital investments during the expected operational lifetime. V_R represents any present residual income/outcome after the project's lifetime.

E. Wind Farm Design Variables and Constraints

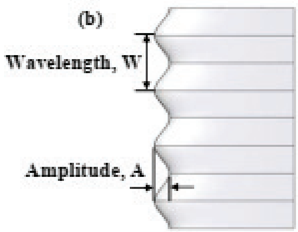
The WFLO problem aims at defining the best value of the following set of variables: (1) WTs emplacement locations; (2) WTs type (e.g., the technology including the control/operation strategy); (3) WTs size (e.g., capacity); (4) number of WTs; (5) WTs hub heights; (6) type of tower, sub-structure, and foundation; and (7) type, size and capacity of auxiliary infrastructure (e.g., auxiliary roads, power collection systems (i.e., transformer number/type/size/capacity and other electric devices), electrical interconnection layout and capacity (i.e., power lines type and length), repeater stations, etc.).

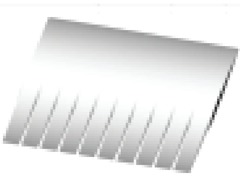
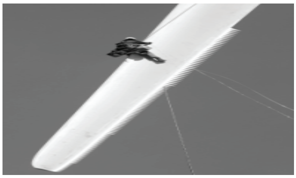
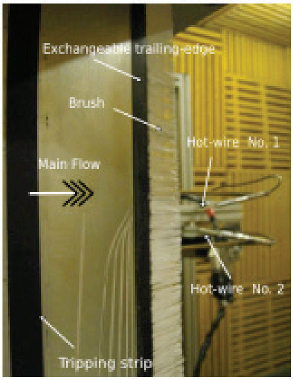
All variables are naturally bounded and constrained by physical factors: (1) the WTs emplacement locations are bounded by the considered wind farm site area and constrained by local terrain aspects, and environmental and climatological characteristics (e.g., land use, restricted areas, geotechnical capacity, setback constraints, obstacles, etc.); (2) the available technology constrains the WTs type; (3) the size and (4) the number of WTs are constrained by the actual power system capacity and the expected demand from the energy consumers. In addition, the theoretical maximum number of WTs can be coarsely calculated as the ratio of the wind farm site area to the individual WT area of $\pi R2$, assuming that two or more WTs cannot be located within an area of $\pi R2$; otherwise, blade collisions would occur. In practice, the maximum number of WTs is much lower due to geometrical and geographical constraints; (5) the minimum and maximum WT heights are constrained by the rotor radius (R), the national aviation regulations, and the available technology, respectively; (6) the type of foundation is a function of the water depth (in the case of offshore wind farms), the bearing capacity of the terrain, the expected loading and the available technology; and (7) the auxiliary infrastructure design, often considered an embedded optimization problem, is constrained by all described variables and the current electric, civil engineering, and communication system capacity.

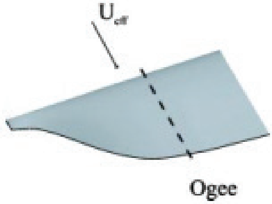
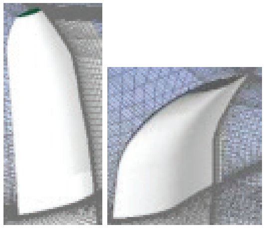
F. Noise Reduction

Noise is the next problem of wind power generation that should be tackled. Numerous experimental and numerical techniques have been developed for noise mitigation by using the knowledge of the noise mechanisms, which offer a perception of the aero-acoustic characteristics of wind turbines. Some techniques and related research that can be implemented to reduce the noise is shown in Table 7.5

Table 7.5 Noise Reduction Techniques for Wind Turbines

Technique	Method	Design
Reduction of influx turbulence noise	Used a sinusoidal leading edge to reduce tonal noise components (Hansen et al., 2010)	
	Bio-inspired leading-edge serrations based on adaptations of the barn owl (Chaitanya et al., 2016)	

Technique	Method	Design
	Sinusoidal leading edge based on adaptations of the barn owl (Chaitanya et al., 2016)	
	Leading-edge slits over serrations for the reduction of aerofoil interaction noise (Paruchuri et al., 2018)	
Reduction of trailing part noise	With trailing edge serration (Oerlemans et al., 2009)	
	Trailing edge brushes over serration (Finez et al., 2010)	
	Porous trailing edge (Geyer et al., 2010)	

Technique	Method	Design
	Ogee type tip shape using acoustic analogy (Geyer et al., 2010)	
Reduction of tip noise	Reference tip and shark tip (Maizi et al., 2018)	

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