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Editorial

Recent Development and Future Perspective of Wind Power Generation

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1. Introduction

The expansion of wind energy has progressed rapidly in recent years. Since 2014, the installed capacity has almost tripled globally. In 2023, the installed capacity exceeded 1 TW for the first time [1]. There are various reasons for the growing popularity of wind energy, including the need to transition to renewable energy sources, advances in wind turbine technology, and increasing investment. The continued success of wind energy depends on factors such as available wind resources, land, wind turbine design, political and economic conditions, environmental impact, and social acceptance. Here, the most recent developments and future perspectives of wind power generation in the scientific literature are briefly reviewed. Five decisive topics for the future development of onshore and offshore wind energy are described and discussed.

2. Wind Potential Assessment

The opportunities for operating wind turbines depend on wind potential. It is divided hierarchically into sub-potentials: the resource potential, the geographical potential, the technical potential, and the economic potential [2]. Each of these potentials varies spatially and temporally. Improvements in the literature compared to the status quo are needed to ensure an accurate assessment of wind potential. These include better validation of wind resource assessments, the application of sensitivity analysis to input data, the inclusion of social and political factors, the appropriate consideration of wind turbine design, the consideration of large-scale kinetic energy extraction, the application of dynamic approaches, the development of holistic frameworks, and the production of a complete balance sheet [3].

The Special Issue 'Recent Development and Future Perspective of Wind Power Generation' comprises articles that consider some of these shortcomings. Amsharuk and Łaska [4] apply a hybrid model including multi-criteria decision-making and a semi-automatic spatial analysis method for wind farm site selection in Poland. They also consider economic, social, and environmental criteria and constraints. Bogdanović and Ivošević [5] assess the offshore wind energy potential in Montenegro related to wind farm structure (floating, fixed, and jacket).

Statistical wind speed distributions are required to estimate technical potential. The two-parameter Weibull distribution is often used as a wind speed distribution [6]. However, current studies reveal that higher-parameter distributions (e.g., Kappa, Wakeby) and bimodal distributions (e.g., bimodal Weibull distribution) may be more suitable [6]. Lencastre et al. [7] investigate the accuracy of the Weibull distribution compared with other low-parameter distributions. They find better goodness-of-fits for the Gaussian, Nakagami, and Rice distributions for short wind speed time series.

Besides the wind speed distribution, power curves are needed to assess the technical potential [8]. However, applying the traditional theoretical power curve approach yields uncertainties [9]. Thus, Ferreira et al. [9] introduce a new nonparametric method for a more accurate wind speed–wind power relationship.

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3. Wind Power Forecasting

The wind speed volatility introduces issues in power system operations [10,11]. Wind speed and power forecasting assist in assessing the uncertainties. Physical, statistical, and hybrid methods are used for wind power forecasting in studies. Furthermore, time horizons, input features, and error measurements vary [12].

There is a need for improvement in wind power forecasting. Progress is achieved by applying hybrid methods for large wind farms, improving the removal of noise in the raw data, developing suitable methods for offshore wind regimes, and developing a base model that works well when benchmarking other forecasting methods [12]. Artificial intelligence should be more often considered for wind speed forecasting as it copes well with the complex non-linear behavior of wind speed [13].

4. Wind Power Under Climate Change

In addition to short-term fluctuations in wind speed, it also varies on long time scales [14]. Long-term trends and inter-annual variability characterize wind resources in many global regions [15]. Global warming will also lead to changes in spatio-temporal wind speed patterns [16]. Climate models simulate decreasing and increasing wind resources, depending on the geographical area [17]. In the mid-latitudes of the Northern Hemisphere, wind speed is likely to decline due to lower baroclinicity resulting from polar air temperature amplification [18]. In contrast, wind speed may increase in regions close to the equator as the warming of the land surface exceeds the warming of the ocean surface [18]. Studies dealing with wind resources under climate change may be improved by using realistic shared socioeconomic pathways, applying multi-model ensembles, and investigating periods of more than 30 years [19].

The changes in wind resources attributable to climate change are often minor. Pryor et al. [20] found that natural variability because of internal climate modes is generally more relevant than the non-stationarity of wind speed caused by climate change. Consequently, the further development of the wind turbine fleet leads to increasing capacity factors despite a slight decrease in wind resources due to climate change in the mid-latitudes of the Northern Hemisphere [21].

5. Socioeconomic and Environmental Factors of Wind Energy Expansion

Wind energy expansion yields socioeconomic and environmental benefits such as CO_2 emission reductions, fossil fuel substitutions, and job creation [22]. However, wind energy use also has unfavorable socioeconomic and environmental impacts [23], jeopardizing public acceptance of wind energy [24].

A comprehensive review summarizes the recent literature on the impacts of onshore wind energy on the environment [25]. The analyzed abiotic environmental impacts include ecosystem processes, micrometeorology, mitigation strategies, pollution, and soil physics. Furthermore, it investigates biotic impacts on bats, birds, other animals, forests, and vegetation. Noise and visual impacts are also examined. The review detects substantial research gaps and biases. It concludes that adverse impacts should be considered in a broader context of anthropogenic influences. Besides, adequate mitigation strategies can minimize the negative impacts. Sander et al. [25] criticize the unbalanced media debate about the effects on the environment.

The socioeconomic and environmental impacts of offshore wind energy partly differ from those of onshore wind energy. Chomać-Pierzecka [26] investigates the socioeconomic and environmental aspects of offshore wind energy in Poland. The study detects public concerns regarding the effects of the construction and operation of offshore wind farms on ecosystems. The negative public opinions toward offshore wind energy result from potential landscape changes and their negative consequences for coastal tourism.

Floating offshore wind farms operate further away from the coast [27]. However, they also impact marine species and habitats and may pose a risk to mammals, seabirds, fishes, and benthic ecosystems [28].

6. Wind Turbine Design Development

Today, wind power generation is a mature technology [29]. Bošnjaković et al. [30] highlight that future development will include upscaling wind turbines. For instance, in Germany, the mean wind turbine hub height of the onshore wind turbine fleet increased from 79 m to 96 m from 2010 to 2021 [31]. In addition, the rotor diameter increased from 65 to 82 m in the same period [31].

The operation of large wind turbines impacts wake effects within a wind farm [32]. Baruah et al. [33] analyze the wake–rotor and wake-to-wake interactions between two wind turbines in a tandem layout fully and partially aligned with incoming wind. Their work contributes to the understanding of the evolution of wind turbine wakes.

Pucci et al. [34] analyze the performance of a 50 kW ducted wind turbine positioned on top of various hills. The study identifies the geometric characteristics of the diffuser most suitable for power maximization.

Besides upscaling, minor design improvements, including advancements in rotor blade aerodynamics, active control of the rotor blade rotation system, and aerodynamic brakes, will enhance wind turbine efficiency [30]. Furthermore, improvements in system maintenance, early diagnosis of transmission and power-related faults, and blade surface damage will occur to reduce downtimes [30]. In Germany, improved wind turbine technology caused 7.3% higher capacity factors in 2019–2021 compared to 2010–2012 [31].

Besides common horizontal-axis onshore wind power generation, other wind power technologies such as airborne and offshore technologies, smart rotors, and multi-rotors will expand the portfolio of wind energy utilization options [35].

The design of offshore wind turbines is challenging due to the operational requirements and environmental conditions [36]. Nevertheless, in the coming years, newly installed offshore wind turbines will often have rated powers exceeding 15 MW and rotor diameters of 240 m and more [37], leading to an enormous increase in offshore wind energy yields [38]. Furthermore, due to floating offshore wind energy installations, wind resource-rich locations with sea depths of up to 1000 m will be developed [39,40].

7. Conclusions

Wind energy expansion will accelerate further in the coming years and decades. Numerous crucial research questions will be associated with this development. The editorial highlighted much-needed improvements in the scientific research of wind potential assessment, wind power forecasting, wind power development under climate change, socioeconomic and environmental factors of wind energy expansion, and wind turbine design development. Multidisciplinary approaches are becoming increasingly important since research into wind energy utilization covers many areas. The Special Issue 'Recent Development and Future Perspective of Wind Power Generation' provides valuable articles, closing some research gaps.

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