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Review

Recent Development in the Design of Wind Deflectors for Vertical Axis Wind Turbine: A Review

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Abstract: Developments in the design of wind turbines with augmentation are advancing around the globe with the goal of generating electricity close to the user in built-up areas. This is certain to help lessen the power generation load as well as distribution and transmission network costs by reducing the distance between the user and the power source. The main objectives driving the development and advancement of vertical-axis wind turbines are increasing the power coefficient and the torque coefficient by optimizing the upstream wind striking on the rotor blades. Unlike horizontal-axis wind turbines, vertical axis turbines generate not only positive torque but also negative torque during operation. The negative torque generated by the returning blade is a key issue for vertical-axis wind turbines (VAWTs) that is counterproductive. Installation of wind deflectors for flow augmentation helps to reduce the negative torque generated by the returning blades as well as enhance the positive torque by creating a diversion in the upstream wind towards the forwarding blade during operation. This paper reviews various designs, experiments, and CFD simulations of wind deflectors reported to date. Optimization techniques for VAWTs incorporating wind deflectors are discussed in detail. The main focus of the review was on the installation position and orientation of the deflectors and their potential contribution to increasing the power coefficient. Topics for future study are suggested in the conclusion section of the paper.

Keywords: wind deflector; VAWT; wind turbine optimization; flow augmentation; small wind energy; aerodynamic-enhancement

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1. Introduction

Increasing concerns about environmental pollution and degradation, climate change, global warming, and sustainable socio-economic development are among the reasons for the advancement and development of renewable energy systems [1,2]. Renewable energy demand is likely to increase four- to five-fold with population growth, as predicted in the World Energy Council (WEC) Scenarios to the year 2050. Renewable energy generation will continue its expansion in the future energy mix of the year 2050, as predictions indicate it will show the highest growth rate among other sources [3]. Wind energy is the most promising source amongst all renewable energy sources and is considered as a major investment sector by WEC to meet future electricity demand [3]. To ensure compatibility between the targeted goal and wind energy development, the availability of databases on energy exploration, generation and consumption are equally important. The statistical analysis of these databases helps policymakers to assess the feasibility of renewable energy generation targets for the year 2050 and engage in relevant planning [4].

For attractive increases in wind farm income, it is important to evaluate wind speed, wind direction, and wind turbine performance [2]. Analysis of wind turbine data for accurate predictions also contributes to wind farm income. The common method for such an analysis is to install a supervisory control and data acquisition system (SCADA) in the wind turbine [5]. The data on wind speed, direction, and generated power are analyzed to understand the relationship between generated power and available wind power, and then to make predictions. Whether making long- or short-term or ultra-short-term wind power predictions, it is equally important to consider the deterioration of offshore wind turbines, as this significantly affects power output and predicted results (it can be up to 8% deviation from the rated power) [6]. Moreover, considering the degraded conditions of an offshore wind turbine can improve the accuracy of predicted results, thereby reducing the RMSE between the predicted and real-time power output by up to 1% [6]. The predicted outcomes help the management team manage power generation on the wind farm, its distribution, and storage at the grid. For battery maintenance on the wind farm, the aging of wind turbines can be studied thoroughly. The battery aging of each machine can be obtained by analyzing the history of each turbine [7]. Wind turbine performance enhancement methods are summarised in Table 1, including their pros and cons.

Table 1. Summary of performance enhancement methods for the wind turbine.

Author(s)	Method	Pros	Limitations
Delgado I. et al. [5]	Prediction: Long Short-Term Memory (LSTM) based prediction	Applicable in real-life scenarios	Short-term prediction about turbine's power generation and wind speed and direction
Li S. et al. [6]	Prediction: Health Condition Assessment based on Modified Fuzzy Comprehension Evaluation (MFCE)	Improved indication of marine environmental deterioration on the wind turbine	Limited to onshore wind turbines only
Astolfi D. et al. [7]	Prediction: Wind Turbine's Aging Impact Analysis	The performance of the wind turbine can be analyzed at a certain age	Machine and location-dependent
Yuan Z. et al. [8]	Wake-Field: Numerical Simulation	A fast and accurate method to design the optimized array of VAWTs by simulating the wake-field	The method is theoretically feasible; however, experimental validation is limited
S. Tang et al. [9]	Pitch Controller: Loop Transfer Recovery (LTR) based Pitch Controller Optimization	Turbine rotor rotation and tower motion controller (due to aerodynamic forces), Improved performance for tower load alleviation and power fluctuation mitigation	Suitable for HAWT only, Output power stabilization needs to be investigated under different wind conditions
O. Benavides et al. [10]	Aerofoil: Optimization by CFD analysis on low Reynolds number aerofoil	Compared to the unmodified version of the aerofoil, the aerofoil with a tubercle at the leading edge has a lower maximum lift coefficient and lower stall angle	Not suitable for large scale HAWT, instead it performs better for small VAWT in small winds
M. Abdelsalam et al. [11]	Hybrid VAWT Rotors	The improved self-starting ability of Savonius rotor due to additional Darrieus blades	Variation in radius ratio has a significant influence on performance, Structural complexity

Table 1. *Cont.*

Author(s)	Method	Pros	Limitations
Zadeh M.N., et al. [12]	Blade Optimization	Compared to the basic helical Savonius, the optimized Bach model performs better in the high velocity and turbulent environment	Lack of experimental validation
Wang et al. [13]	Blade optimization (based on the combined method of Surrogate model and numerical simulation)	Optimized blade of HAWT can capture more kinetic energy, power coefficient increased by 4.3%	The structural load on the HAWT blade is also increased, Not applicable for VAWT
Aniruddha et al. [14]	Flow Augmentation	A pool of airfoils to design the diffuser as an augmentor for wind turbines	The thurst coefficient and tip clearance effect of the turbine in the diffuser are yet to be studied
M. Mohammadi et al. [15]	Flow Augmentation	The performance of the Savonius turbine is increased by adding a nozzle in front of the advancing blade	The nozzle is fixed and hence can not follow the wind direction
Dighe et al. [16]	Flow Augmentation	Among different shapes of the Duct for DWT, the S1223 airfoil-shaped duct attains better coefficient of performance	Increased structural complexity

Flow augmentation is the most effective technique to improve VAWT efficiency. The rotor geometry and the airflow patterns around the rotors are changed to achieve higher efficiency. One way to do this is to install the stators around the rotor, such as in the Savonius turbine, and a performance gain of 30% can be achieved, as reported by [17]. However, experimental results do not confirm this gain, and 3D CFD simulations and wind tunnel testing of this technique show that the air flows above the rotor instead of converging towards it through the stator vane [18].

Installing the deflector as a flow augmenter reduces the pressure exerted on returning blades, improving the positive net torque and delivering a 20% to 50% increment in power performance [19]. Furthermore, installing the deflector as a flow augmenter does not add structural complexity to the rotor, while offering the maximum power coefficient improvement compared to other augmenters [19]. The simplest form of a wind deflector is a flat plate deflector placed upstream of the VAWT rotor. When installing a deflector, it is important to know the correct orientation and position. The literature has shown that wrong orientations of the deflector will lead to an adverse effect on turbine performance, and the result will be even worse than that of a turbine without a deflector [20]. Similarly, the height and length of the flat plate deflector will also vary according to the rotor height of a VAWT. In general, a larger length of deflector will increase the performance as the area to deflect the wind is also increased. Placing the turbine rotor in a deflector near the wake region yields a smaller increase in performance, whereas a significant increase in performance is obtained when the turbine is placed outside the near-wake region of the deflector [21]. It becomes crucial to understand these characteristics of the deflector. Therefore, this review is aimed at providing the reader with a clear understanding that will aid in the selection of the type of deflector and its design parameters when developing a VAWT.

In recent years, various techniques for deflector installation and modified designs have been reported [22]. Many of these designs have been reported with validated simulations and have contributed to turbine blade wind flow improvements. There is a limit to the reliability of the proposed designs and techniques for deflectors, as very few have been tested using real-time experimentation. It is, therefore, necessary to assess the reliability of these designs and vital to categorize which ones have been experimentally tested. The current study sought to review the available wind turbine deflector designs that have been reported to date. In the first aspect, we reviewed the updated literature to better understand the modified designs and installation techniques for wind deflectors. Thereafter, efforts have were made to classify the best-suited wind deflector designs into different categories.

The paper is organized as follows. Section 1 contains the introduction and background of the study; Section 2 reviews the relevant theories and prior literature; Section 3 presents the search strategy and adopted methodology for the current review; Section 4 reports the results of the study from the bibliometric analysis of the review; Section 5 discusses the main findings and future research aspects; and finally, Section 6 concludes the paper.

2. Prior Literature

Most wind energy is harnessed by employing large horizontal axis wind turbines (HAWT) in areas of high wind density, mostly in rural and off-shore sites where abundant wind velocity is observed throughout the year [23,24]. Offshore wind farms are the main source of global wind energy generation, contributing up to 50% of the capacity factor. Offshore wind power is harvested by either bottom fixed or floating wind turbines that share a cumulative contribution of 0.3% to total global electrical generation (current global capacity of 23 GW) [25]. On the other hand, urban areas are marked by comparatively high turbulence, fluctuation, and variability in the wind direction and speed [1]. These drastic changes are experienced due to large buildings and other urban structures, rendering large HAWTs unsuitable for power generation under such conditions [26]. HAWTs are also known for noise generation which creates a disturbance in their surroundings [27,28]. Obstacles to the installation of HAWTs also include visual as well as environmental impacts on their surroundings (such as to animal behavior, including birds). Conversely, a vertical axis wind turbine (VAWT) is the most popular and effective device for electrical power generation from the kinetic energy of wind in urban built-up environments. These turbines are cross-flow, drag-driven wind turbines, and their power generation coefficient varies from 4% to 24% as reported in the literature [1,23,29,30]. The VAWTs are easy to manufacture and install, cheaper in price, produce less noise pollution, and can run in omni-directional winds. These advantages make them more attractive than HAWTs for harnessing wind energy, but on the downside, VAWTs can not produce appreciable power when compared to HAWTs on a large scale. Hence, vertical turbines are more suitable and cost-effective when considering small-scale power generation and self-starting at low wind speeds [25,29]. From a general perspective, the most common types of vertical axis wind turbines are the Savonius wind turbine and Darrieus wind turbine, further classifications are shown in Figure 1. The Savonius turbine is drag-based and has the self-start ability, while the Darrieus turbine is lift-based and has higher efficiency than the Savonius but is not able to self-start [31]. Improving the performance of both types of turbines has remained a crucial challenge for researchers and engineers in recent years [32]. One of the methods to improve the performance (Cp value) and self- starting ability is flow augmentation, where the wind turbine design is optimized in a way that the upstream wind is appropriately blocked while ensuring maximum positive torque and minimum negative torque achieved [31]. Nevertheless, when an array of VAWTs is installed, then the main focus of optimization shifts to reducing the wake created by upstream turbines. The most common methods for wake improvement and array optimization are the vortex particle and finite vortex methods, or a combination of both [8].

The paramount challenge in urban wind energy systems is to increase the performance of VAWTs [33]. VAWT performance can be increased by several methods, as summarized in Table 1. The electrical power generation coefficient of the vertical axis wind turbines is up to 24%; however, a 30% efficiency increase can be achieved by optimizing the existing VAWT designs [1]. Initiatives have been taken by many researchers to improve power generation efficiency; these attempts incorporate modifications in the blade geometry design or the configuration of VAWT devices [34]. Nevertheless, blade geometry modification is one of the techniques to consider when designing a VAWT, such techniques are summarised in Table 2. Wind turbine designers have optimized cost savings and simplified the structural complexity by designing smaller rotors to generate high power. Power generation capacity can also be increased by optimizing the blade geometry or structure, which can result in increased torque. For instance, a 35% increase in static torque can be achieved by replacing the blades of the Savonius turbine with hinged flaps [35]. On the downside, hinged blades then increase the complexity of the structure of the turbine rotor. The main concern of the low power coefficient in VAWTs is the negative torque generated by the returning blades. In this regard, flow augmentation techniques reduce the negative torque and improve the positive torque by converging the wind streamflow from a large area to a smaller, resulting in a greater mass flow rate directed towards the advancing blade [19]. The flow augmenters can be deflectors, guide vanes, ducts, diffusers, or stator shrouds installed upwind of the VAWT or in the downstream wind [31]. To ensure the optimal performance of the above-mentioned VAWT configurations, various techniques can be used prior to turbine installation [36]. These techniques are summarized in Table 2.

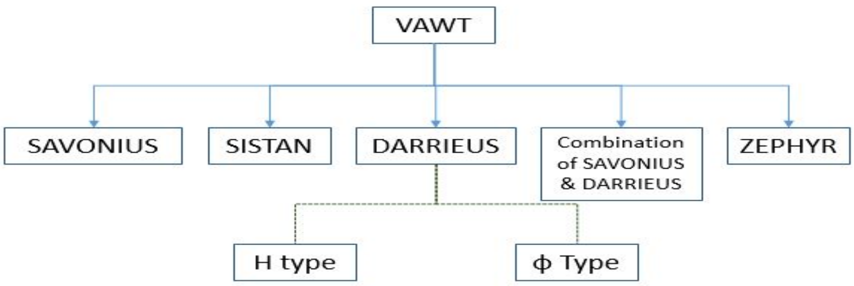

Figure 1. Classification of vertical axis wind turbines [22].

Table 2. Summary of techniques to design efficient vertical axis wind turbine.

Technique	Method(s)	Description
Calculation of Aerodynamic Load	Belade element momentum (BEM) [37]	This method is useful to calculate aerodynamic drag, assuming an order of 10–20 rotor sections to be independent and calculated separately
	Actuator disc [37]	This method has more accuracy but relatively higher complexity compared to BEM; the turbine rotor is assumed to be a permeable disc that is subjected to surface forces when flow passes through it
	Vortex method [38]	This is useful when considering the parts where vorticity is observed, rather than calculating aerodynamic characteristics at all the grid nodes on the blade
	Impulsive method [38]	It is based on the relationship between the time average of aerodynamic forces on blades and the impulse loss of the airflow across the rotor swept area
	Dynamic analysis [39]	This method can be useful to calculate aerodynamic load as well as to estimate the vibratory stress on the blade with great accuracy

Table 2. *Cont.*

Technique	Method(s)	Description
Efficiency	Computational fluid dynamics (CFD) [18]	CFD simulations are very useful to determine the power coefficient of the turbine; the correct utilization of fluid models can ensure good agreement between experimental and simulated results
	Exergy analysis [40]	It can be based on different operating conditions, design parameters, and geometries, and help to identify the area of improvement
	Buckingham Pi theorem [41]	A relation based on which power coefficient can be obtained for a given tip speed ratio
Airflow Analysis	Particle image velocimetry (PIV) [42]	Flow is visualized by dye injection while the PIV combined with an imaging technique measures the distribution of velocity around the blade
	CFD [43]	CFD simulations capture vortex shedding flow structure over the blade in close agreement with experimental data
Vibration and Fatigue Analysis	Operating wind turbine analysis [44]	The aerodynamic load affects the aero-elastic and structural behavior of the wind turbine. Therefore, it is important to analyze the fatigue life of an operational wind turbine
Analysis of Weathering Effects	Wind tunnel tests [45,46]	Weathering effect on a wind turbine is analysed in terms of attachments (such as ice) on the blades

3. Methodology

In this review process, a search strategy was followed to identify the research papers that were relevant to the scope of the study. In the search strategy, the Scopus database was used to search relevant literature based on "wind deflector", "wind turbine optimization", "wind turbine design", "Vertical axis wind turbine AND Wind performance" keywords. All the records spanned from the Scopus database inception up till the year 2021 and included research reports, journal articles, and review papers published in English. All extracted records were from the fields of engineering, science, and mathematics and were not limited to any specific region. The search was then narrowed to subject areas including engineering, energy, physics and astronomy, computer science, material science, mathematics, and multidisciplinary. A total of 830 records were extracted from the database, and that was reduced to 824 after removing duplicates. The year-wise distribution of the searched articles is presented in Figure 2. The increment in the research can be seen as having peaked from the year 2012 and onwards, where the number of research articles published each year ranged from 70 to 80 for the above-mentioned keywords, except in the years 2018 and 2019. These searched articles were from different sources; of the total of extracted articles, 360 were journal papers, accounting for the largest share. The distribution of these published research articles in the major sources, i.e., journals and conference proceedings, is presented in Figure 3. However, not all of the searched sources are represented in Figure 3, as many sources contained only one record in this field for the years searched. Therefore those sources that had at least 10 or more records were considered major sources and thus are presented in Figure 3. Figure 3 provides a clear picture of the major sources for relevant research outcomes in this field. The major sources in this regard were the Journal of Physics: Conference series and Renewable Energy, which accounted for the largest number of records, at 35 and 31, respectively. Nevertheless, other journals such as Wind Energy, Energies, Energy, and Energy Procedia could also be searched for relevant literature in this field. The search and review process followed the PRISMA framework (Moher et al., 2009), as shown in Figure 4. All extracted records were screened to check their eligibility for assessment, and from the screening, we identified 53 articles eligible for qualitative assessment. In order to maintain the quality of the review process, all the documents were inspected thoroughly for the duplication of content. The abstract of each article was reviewed in depth to ensure the relevance and quality of the research work. Exclusions and inclusions of shortlisted articles were decided on the basis of several reasons, as shown in Figure 4. After a careful evaluation, a total of 27 out of 53 research studies were included for the quality assessment. In the quality assessment stage, three studies were identified that did not fit the scope and merits of our conceptualization. Therefore, in the final stage, a total of 24 studies were included for data extraction.

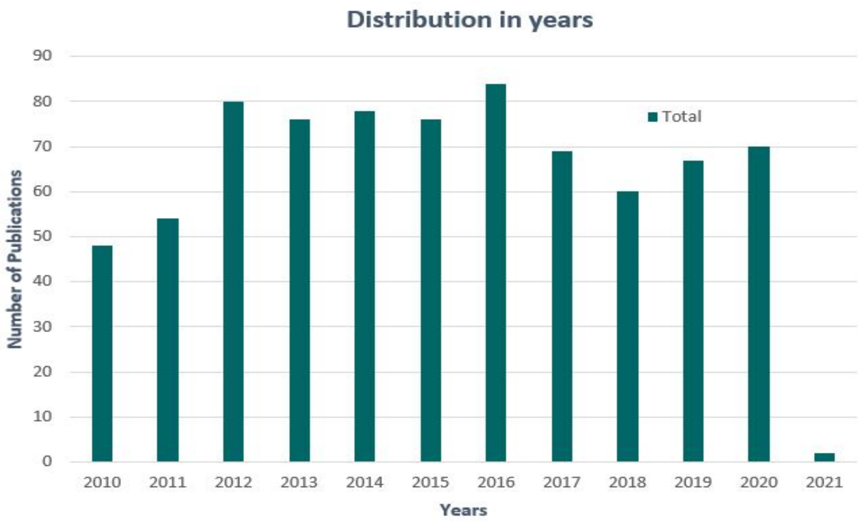

Figure 2. Article distribution in years extracted from 2010 to 2021.

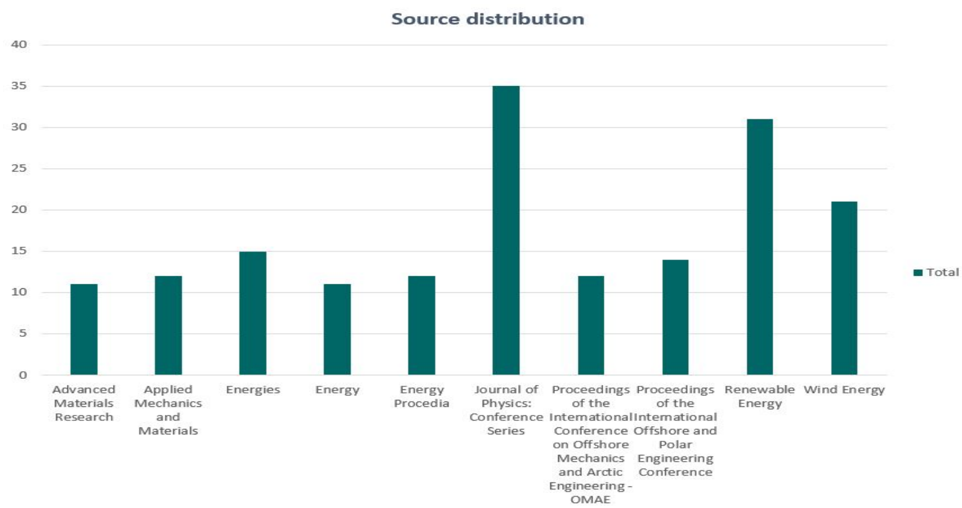

Figure 3. The number of articles extracted from different sources.

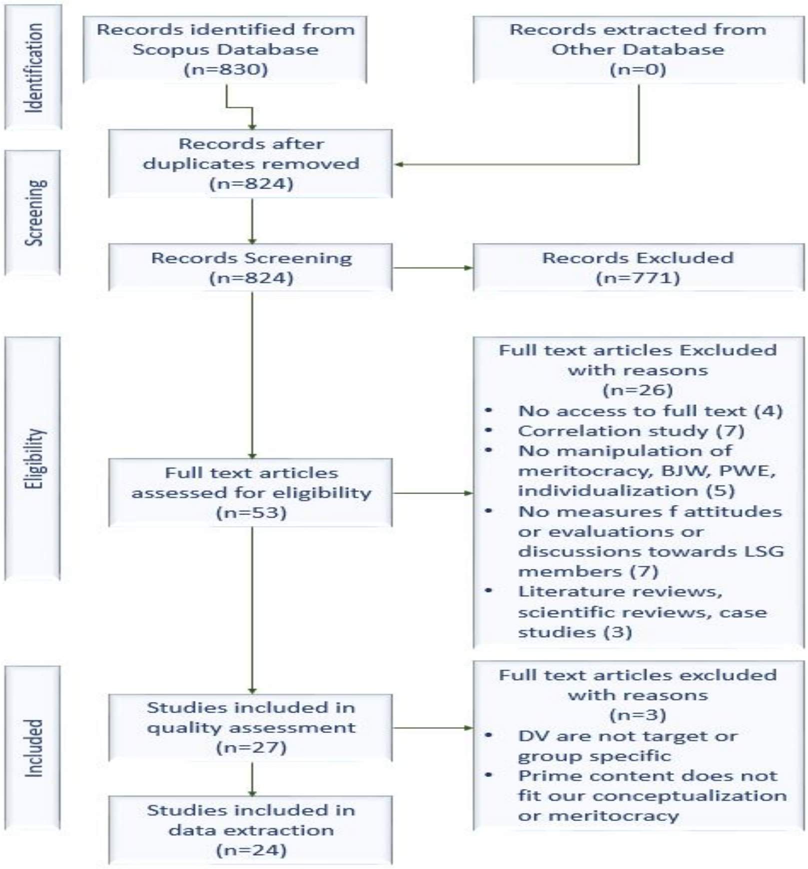

Figure 4. PRISMA framework for reviewing the articles.

4. Results

This review process focused on small-scale wind turbine performance enhancement techniques, with attention to flow augmentation in the upstream wind of the rotor. Different techniques that can increase turbine performance to a remarkable level have been reported in the literature. The outcome of our analysis of the reviewed literature is discussed in the following sections.

4.1. Bibliometric Analysis

After finalizing the selection of research articles for data extraction from the PRISMA framework, a bibliometric analysis was carried out on the final selected papers. The analysis focused on the co-occurrence of terms in the abstracts and title fields of the selected papers, as presented in Figure 5. The papers contained information on the wind flow in unstructured fields such as buildings, air exhaust, sunroofs, etc. [47–50], where the main focus was to obtain efficient flow. The most common application was in wind turbines, with the aim of optimizing power output by increasing the airflow. Most of the aerodynamic optimization techniques in VAWTs were based on two-dimensional airfoil theory [51]. The scope of this literature review encompassed the study and review of applications of wind deflectors. Therefore, apart from wind deflectors, only one of the latest techniques for the use of ducts for airflow optimization can be seen in Figure 5.

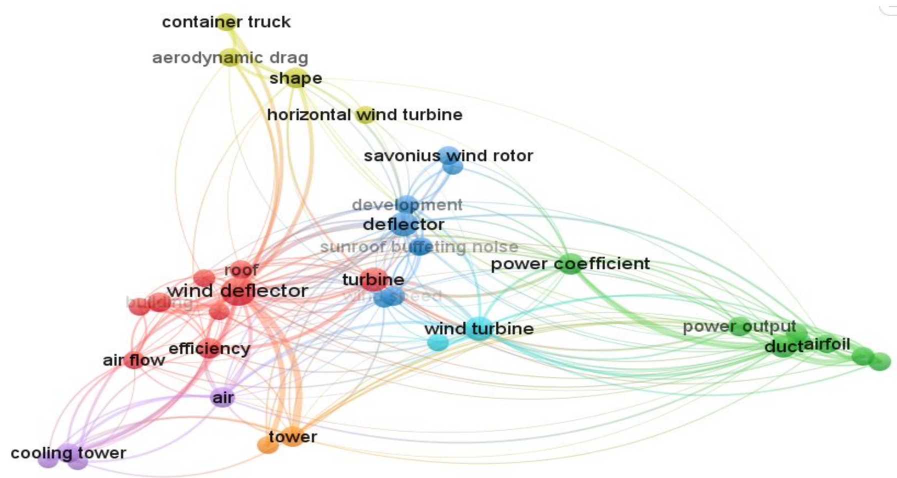

Figure 5. Bibliometric analysis of selected papers for data extraction.

Wind deflectors have a variety of applications in air exhausts, natural draft wet cooling towers, and most importantly, in drag-driven wind turbines. In drag-driven wind turbines such as the Savonius turbine, the deflector behaves as an obstacle to the incoming wind on the returning blade and hence improves the static torque [52]. The research on wind deflectors in turbines has mainly focused on the design of deflectors, flat plates, and airfoil-shaped deflectors, installation positions, fixed and adjustable deflectors, the installation of active deflectors, and selection of material for manufacturing [53–55].

The bibliometric analysis of the literature helped in classifying the fields based on their occurrence and relation to other fields. Wind deflectors possess a variety of applications in different fields, given the relationships shown in Figure 5. Thus, deflectors can be classified on the basis of on their applications, such as in wind turbines, cooling towers, sunroof buffering, and vehicles and containers.

4.2. Small-Scale Wind Energy Generation

Wind energy on a larger scale is harvested by installing large horizontal-axis wind turbines. However, small wind machines such as VAWTs still play an important role in wind energy generation as standalone off-grid systems or sharing the generation task in distributed energy systems [56]. Small-scale wind power generation is not as popular as large-scale wind power; searching for "small winds" in the database of MDPI found 59 research articles, only, compared to 900 for "wind power" or "wind energy" for the same period from 2010 to 2019. Lack of interest towards small wind systems for decades resulted in highly counterproductive VAWTs, lower efficiency, and hence, high costs per kilowatt [57,58]. The development of smart grids and distributed energy systems is spurring renewed interest in small energy again. One recent development in small-scale wind power generation was the introduction of a committee dedicated to for small wind energy generation by the European Academy of Wind Energy (EAWE) [59]. Small-scale wind energy generation also incorporates wind hybrid systems, which can supply 67% of oil replacement energy [60]. Wind hybrid systems may integrate VAWTs as their main source of energy and have battery storage and oil generator backup as secondary sources [61]. Combining solar and wind as a hybrid source offer much higher value in resource droughts (resource droughts are when cumulative generation is lower than the arbitrary threshold). A study carried out in Poland [62] calculated a resource drought probability of 11.5% for solar, 12.6% for wind, and 6.5% when they were joined in a hybrid arrangement. Such a low value for the probability of resource drought highly encourages the installation of hybrid wind systems and hence enhances small wind installation. Moreover, it was important for small wind energy owners to evaluate machine history and forecast generation, in order to facilitate energy storage and optimize the source [63,64]. Forecasts for small wind systems can be up to 2 days ahead (up to 48 h), whereas for large wind farms, this input of 2 days is very rare. These techniques can lower per-kilowatt prices for small-scale wind generation, which could be a basis for its popularity in the near future. More work and research on large-scale wind generation has resulted in a surprising decrease in prices during the past 15 years [58,65]. Likewise, if the research in small wind energy continues, engineers will find it more attractive to harness energy from small wind sources.

Small wind turbines are more flexible than large ones; they are also easily installed and occupy limited space. The power generation from wind depends upon the aerodynamics of the blade's geometry and the velocity profile of upstream wind. A wind turbine with rotor radius "R" and upstream wind speed "v" can generate wind power "P_w" by the following equation [66]:

$$P_w = \frac{1}{2}\rho v^2 \pi R^2, \tag{1}$$

where "ρ" stands for the density of air. However, the rotor power "P_r" is the power harnessed by the wind turbine rotor when placed in a free wind speed that contains the wind power "P_w". Rotor power is also known as power coefficient "C_p" and depends upon the aerodynamic efficiency of the rotor. Then Equation (1) becomes:

$$P_r = P_w C_p(\lambda) = \frac{1}{2}\rho v^2 \pi R^2 C_p(\lambda), \tag{2}$$

where "λ" shows tip speed ratio and can be computed as:

$$\lambda = \frac{\omega_r R}{v}, \tag{3}$$

Torque power is defined from the rotor power as:

$$P_r = T_r \omega_r \text{ or } T_r = \frac{1}{2}\rho v^2 \pi R^3 \frac{C_p(\lambda)}{\lambda}, \tag{4}$$

4.3. Applications of Wind Deflectors in Wind Turbines

Wind deflectors in small wind turbines are installed to improve the static torque generated by the rotor; however, in large wind turbines, their applications improve the ventilation to enhance the thermal performance of the stator generator [67]. Installing deflectors for stator ventilation in a 3 MW turbine improves the cooling system, which effectively decreases the temperature of the stator teeth and windings. Conversely, in small wind turbines, rising temperatures in the windings and stator teeth can be cooled by the atmospheric wind, such that no special ventilation or liquefied cooling systems are required. Small wind turbines largely incorporate applications of flow augmentation systems for overall performance improvements. According to the Betz limit, the maximum efficiency a wind turbine can achieve is 59.3% [68]. However, the power generated by a turbine depends on the cube of the wind velocity. This velocity can be increased by installing a wind deflector, as the small increase in velocity can lead to a significant increase in efficiency, even exceeding the Betz Limit [69]. Wind deflectors installed in the upstream field of Savonius-type wind turbines have been reported to double the turbines' original performance [29]. The wind deflector-based optimization of a wind turbine depends upon several variables such as shape, angle, and location of the deflectors. The optimization process includes three basic steps: model setup (i.e., for preparing geometry and generating the mesh), optimizer setup (i.e., for optimizing the variables such as location and angle), and simulator setup (i.e., for simulating the flow to calculate the power coefficient). Hence, techniques to optimize and increase the coefficient of performance could spur interest in the development of small wind power generation [56].

4.3.1. Airfoil-Shaped Wind Deflectors

Instead of low efficiency, Savonius turbines and other VAWTs could have more favorable benefits in terms of lower cost, self-starting ability, and simplicity of design [52,70–72].

The performance of a Savonius turbine can be improved by installing a wind deflector as the flow augmenter in the upstream wind approaching the rotor blades of the turbine. A wind deflector can be of a very simple form such as a flat plate, or it can also be of an aerodynamic shape [73]. The geometry of the deflector significantly affects the power enhancement of VAWTs [74]. An airfoil-shaped deflector geometry deflects the wind streams from the concave (returning blade) in a more effective way as compared to flat plate deflector geometry. Layeghmand et al., 2020 [75] performed a CFD simulation to evaluate the effects of a deflector with an airfoil geometry, as well as changes in wind deflector angle and position, on the performance parameters of a Savonius turbine. For this purpose, NACA 001 airfoil was used to determine the geometry of the deflector. The simulation was performed in a commercial CFD software application using the $k - \omega$ turbulence model and the Unsteady Reynolds Averaged Navier Stokes (URANS) equation. The CFD setup and the geometric concept of this approach are shown in Figure 6, in which "d" is the diameter of the blade, and "D" is the diameter of the turbine.

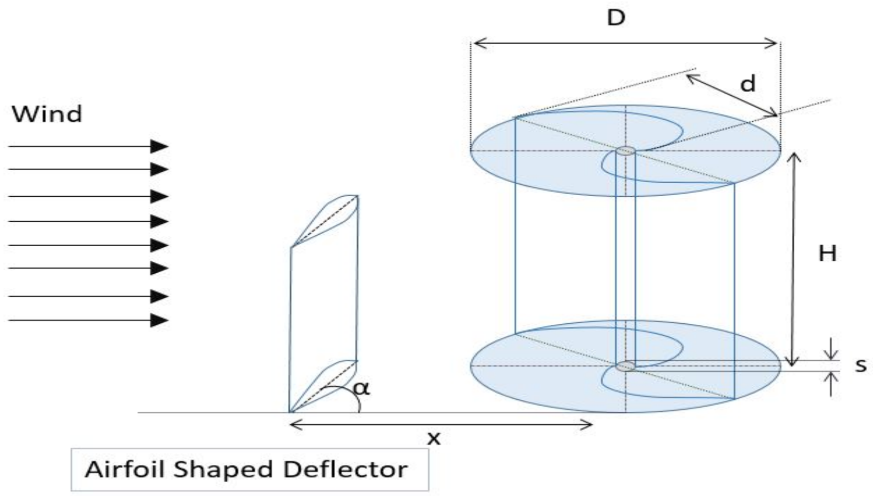

Figure 6. An airfoil-shaped wind deflector in the upstream of a Savonius rotor [75].

An airfoil deflector distributes the cube of wind stream evenly towards the forward blade of the Savonius turbine. There is less separation observed at the tailing edge compared to a flat-plate deflector with the same angle of attack (AOA). However, the AOA significantly affects the position of the separation point on the airfoil, which ultimately affects the performance [76]. The maximum coefficient of performance for the design given in Figure 6 can be increased up to 50% with a tip speed ratio (TSR) of 1.3. The CFD analysis carried out by Layeghmand et al., 2020 for the design shown in Figure 6 concluded that a Savonius turbine achieves its maximum torque and power coefficients at an AOA of 70°. The performance of the turbine can be characterized by the torque coefficient and power coefficient. The power coefficient (C_p) is the ratio of rotational power produced by the rotor (P_r) to the kinetic power available in the wind streams (P_k). Similarly, the torque coefficient (C_t) is the ratio of effective torque generated by the rotor to the total available torque.

$$C_p = \frac{P_r}{P_k}, \tag{5}$$

$$P_r = \tau\, \omega, \tag{6}$$

$$P_k = 0.5\, \rho\, A\, U_\infty{}^3, \tag{7}$$

$$C_t = \frac{\tau}{0.5\, \rho\, A\, U_\infty{}^2\, R}, \tag{8}$$

In the above equations, P_r refers to rotor power, which is a function of the torque (τ) and rotational speed (ω) of the turbine rotor, P_k stands for kinetic power of the wind streams, which is defined as the function of the cube of air velocity (U_∞) and the constants air density (ρ), cross-sectional area (A), and kinetic energy constant 0.5. Equation (4) defines the torque coefficient as the ratio of torque produced by the turbine rotor (τ) to the available torque, where R stands for the radius of the turbine rotor. The tip speed ratio (λ) can be computed by the following Equation (9).

$$\lambda = \frac{\omega\, R}{U_\infty}, \tag{9}$$

4.3.2. Flat-Plate Wind Deflectors

Wind deflectors can be installed to maximize overall performance in two ways: by accelerating the speed of the wind approaching the rotor blades or by reducing the air resistance from the returning blades; however, it can be a combination of both approaches as well. Deflectors are mostly installed upstream of the wind approaching the rotor; the different positions and orientations of deflector installations are shown in Figure 7. Nevertheless, coupled deflectors that include a V-shaped deflector, one upstream deflector and one downstream baffle, or two deflectors upstream of the rotor can also be installed. Furthermore, the performance can also be improved by installing other flow augmentation devices such as windshields, slatted blades, V-shaped deflectors, nozzles, multistage flow, twisted blades, valves, guide boxes, curtain plates, venting slots, concentrators, and guide vanes [19].

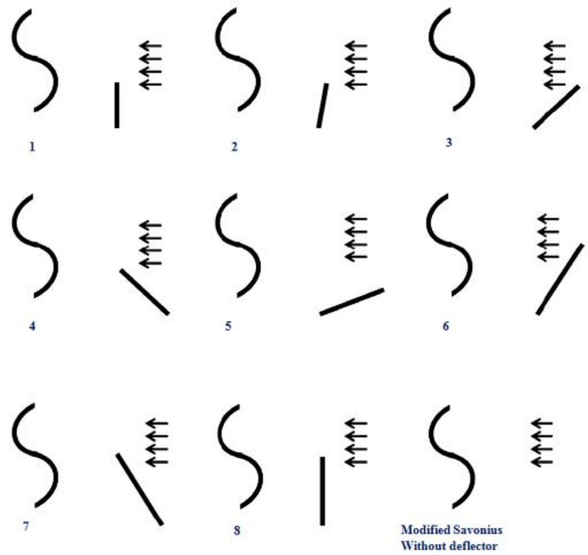

Figure 7. Various installation angles and positions of flat-plate deflectors (adapted from [20]).

Installing a flat-plate deflector can increase the coefficient of power by more than 27%. The performance of two-bladed and three-bladed Savonius wind turbines was investigated with optimally positioned and oriented flat-plate deflectors [77]. The configuration in this study is shown in Figure 8, where the deflector was placed upstream of the wind-approaching rotor to determine the orientation (AOA) and position (distance from the rotor) for achieving the maximum coefficient of power. Wind deflectors also enhance the self-starting performance of the major types of VAWT. The self-starting ability (i.e., coefficient of static torque more than 0) could be achieved at any orientation of deflector for both the turbines (i.e., two-bladed and three-bladed Savonius turbines). However, the deflector was less effective in improving the self-starting performance of the three-bladed Savonius turbine. The optimized position of the deflector was achieved at $\lambda = 0.7$ (the tip speed ratio value of 0.7 corresponding to the highest power coefficient) as X1/R = −1.2383, Y1/R = −0.4539, X2/R = −1.0993 at an angle of 100.83° for the two-bladed Savonius rotor, and X1/R = −1.05632, Y1/R = −0.36912, X2/R = −1.38162 at an angle of 80.52°

for the three-bladed Savonius rotor [77]. The distances X1, X2, and Y1 are presented in Figure 8. The optimized position and orientation of the deflector can lead to an increase in the coefficient of power by 0.068 (increased of 27.3% in performance), and 0.058 (increase of 27.55% in performance) for the two-bladed and three-bladed rotors, respectively, in comparison to similar turbines without deflectors. Thus, if parameters such as increased performance, cost, and complexity are considered for both types of turbines, the two-bladed rotor will be more suitable than the three-bladed type. Nevertheless, the design shown in Figure 8 can be adapted to cover the major drawback of lower efficiency in VAWT turbines, where the increased power coefficient (and hence performance) will compensate for the extra cost incurred.

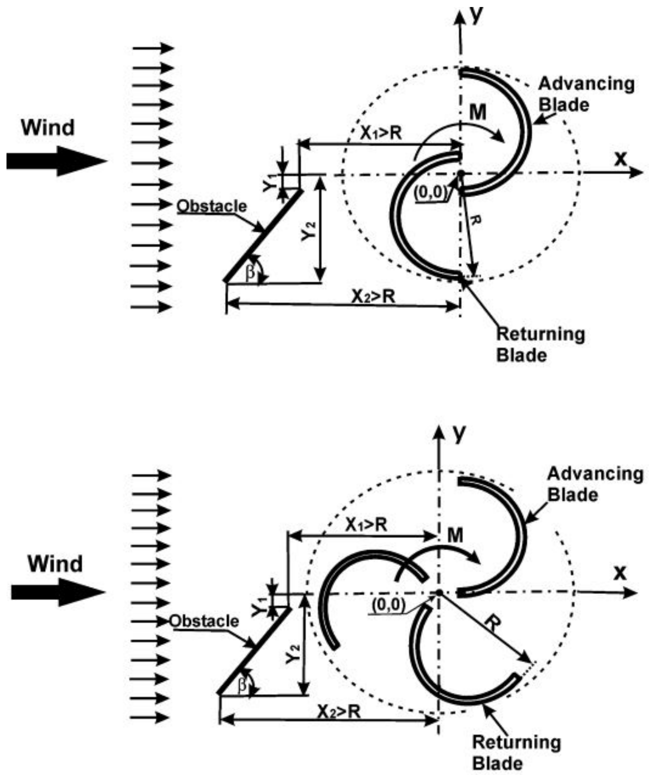

Figure 8. Power coefficient optimization of two-bladed and three-bladed Savonius turbine with flat-plate deflector (adapted from [77]).

A flat-plate wind deflector not only improves the performance of the Savonius turbine but has the ability to improve the performance of VAWT in general. This statement was supported by performing the CFD simulation on a VAWT possessing blade design with airfoil NACA0021, integrated with a flat-plate wind deflector as shown in Figure 9 [78]. The numerical simulations were performed to determine the installation parameters of the flat-plate deflector such as inclination angle, position, and length of the deflector. The computation of performance parameters for the VAWT design shown in Figure 9 was obtained from Equations (5)–(9); however, to determine the angle of attack (α) by the resultant wind stream on the airfoil, the following Equation (10) [79] was used.

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) - \beta, \tag{10}$$

where α is the angle of attack by the wind stream on the airfoil, β is the pitch angle of the blade, and θ is the azimuthal angle.

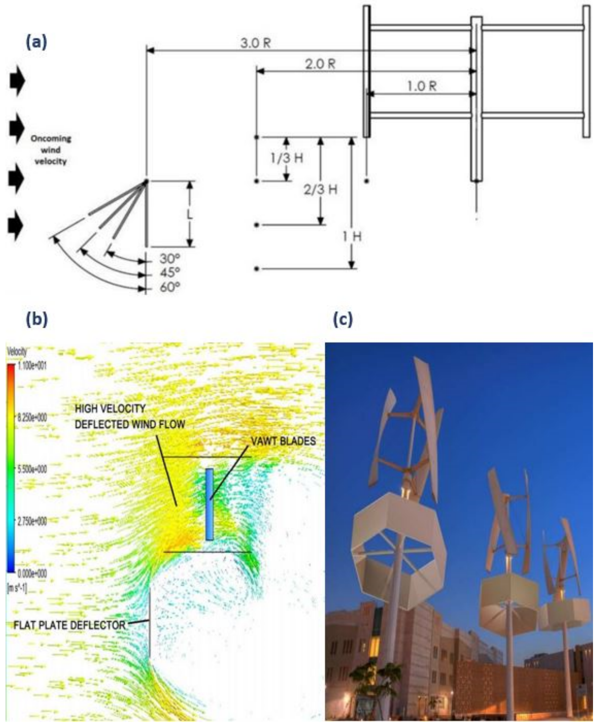

Figure 9. Flat-plate wind deflector in helical vertical axis turbine. (**a**) Design. (**b**) CFD analysis. (**c**) Installed deflector (adapted from [78]).

The helical vertical axis wind turbine is lift-based instead of drag-driven; for such turbines, the important parameters of the deflector may not be exactly the same as in Savonius design. The performance parameters of flat-plate wind deflectors in the Darrieus and helical types of wind turbine are shown in Figure 9a, including the (i) distance (X) from the axis of rotation (horizontal) (ii) distance (Y) between the top edge of the deflector and lower/bottom edge of the turbine blade (vertical), (iii) angle of inclination of the deflector, and (iv) length of the deflector. The performance of the helical turbine and wake and flow interaction are affected by the helix angle of the blade. Apart from wind deflector parameters, the performance can be increased by optimizing the helix angle instead of using a straight-blade helical axis turbine. The turbine performs best when the helix angle is set at 60°; further CFD simulation and experimentation could be carried out to find the most accurate and precise helix angle for better performance [80].

A flat-plate deflector used as the flow augmentation device significantly accelerates the wind speed up to 20% in the region close to the wake, as shown in Figure 9b. The acceleration in the wind speed increases the power coefficient of the VAWT and hence increases overall efficiency. For the maximum accelerated wind speed near the wake, an average torque coefficient gain of 47.10% can be achieved [78]. However, the deflector parameters for the maximum gain from the design in Figure 9 include distance (X) of 2 R (the position of deflector from the rotor shaft in the horizontal direction), distance (Y) of 2/3 H (the distance between the lower tip of the blade and the top edge of deflector), length of the deflector as 1.5 H, and placement of the deflector parallel to the blade with no orientation angle. In the parameters, R refers to the radius of the rotor or the distance from the blade to the rotor shaft, and H refers to the height of the turbine blade.

4.3.3. Compound Structured Wind Deflectors

Compound structures of the deflectors are the third category of deflector proposed; they involve the combination of an airfoil and flat-plate deflectors, two deflectors forming a "V" shape, or deflectors installed between turbine couples.

Similarly to the design shown in Figure 9 reported by [78], they can be modified to install a wind deflector between two vertical-axis turbines, utilizing the accelerated wind speed in the near wake region from both sides of the deflector. An experimental investigation of the improvement of counter-rotating vertical-axis wind turbines incorporating such a configuration of turbines and wind deflector was carried out in [74]. The design configuration and experimental setup are shown in Figure 10; the wind turbine is driven by the lift-generated force VAWT and the deflector is a flat-plate wind deflector, placed normal to the wind streams. The wind deflector accelerates the free stream wind near the wake created, and the counter-rotating turbines are placed in the near wake region to receive this accelerated wind. The maximum power coefficient and the tip speed ratio of the VAWT shown in Figure 10 were computed before the installation of a wind deflector and were observed to be 0.031 and 0.98, respectively. However, after installing a wind deflector, a significant increment in both parameters was observed. The maximum power coefficient was improved three-fold (from 0.031 to 0.101) and the tip speed ratio was increased by 26% (from 0.98 to 1.23) [74].

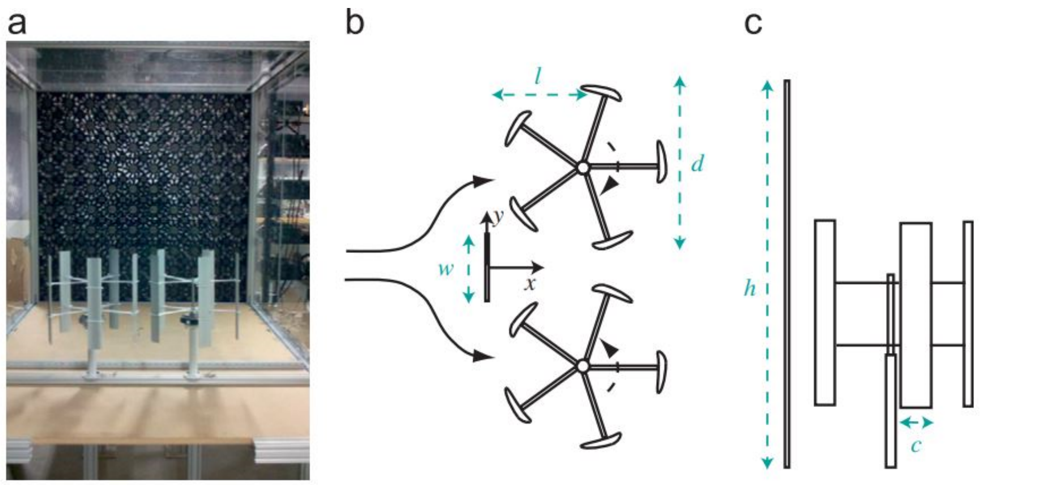

Figure 10. Wind deflector installed between two lift-based vertical axis wind turbines, (**a**) experimental setup in the wind tunnel, (**b**) top view, and (**c**) front view (adapted from [74]).

A similar experimental study was carried out in [81] where the performance of vertical-axis twin turbines was improved by installing a kite-shaped deflector as shown in Figure 11. The modified deflector was in great agreement with the CFD simulation and the experimental results, and contributed greatly to improving performance as compared to the flat-plate deflector. Initially, the VAWT turbine shown in Figure 11 was tested in a wind tunnel without a deflector, and it was observed that the power could be increased for this configuration at medium and high tip-speed ratios [81]. When a wind deflector was installed in the configuration, the performance could be improved at the lower value of the tip-speed ratio. The important parameter to find was the suitable position for the deflector, which had a significant effect on wind turbine performance [1,82]. The twin-turbine configuration presented in Figure 11 was tested with different positions of the wind deflector, and it was concluded that the wind turbine achieved better performance if the deflector was placed closer to the turbine rotor [81]. For the twin-turbine configuration presented in Figure 11, optimum performance could be achieved when the deflector was placed at a distance of 0.7D upstream of the rotor. The observed performance improvement was 26% higher than the performance of a simple flat-plate deflector [74]; this modified kite-shaped wind deflector in twin turbines can increase the performance up to 38.6% [81]. Installing the deflector in twin turbines improved torque generation by eliciting a change in local wind flow, resulting in an accelerated wind speed and larger angle of attack on the rotor blades [82]. Nevertheless, the wind deflector blockage effects contributed significantly to restraining the flow separation and improving the output power generation at the lower value of the tip-speed ratio. The geometry of the wind deflector could be optimized in future studies to obtain the optimum value of the tip-speed ratio for improved power output. Moreover, the study could be carried out to analyze in detail the velocity gradient created by the deflector and the flow instability to improve performance parameters.

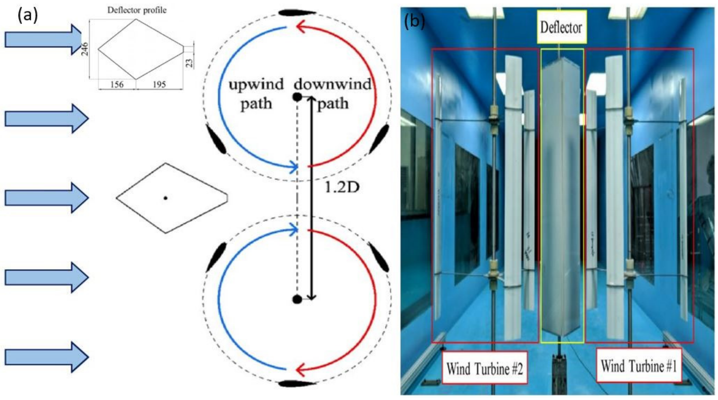

Figure 11. A kite-shaped wind deflector installed upstream of the VAWT. (**a**) Design. (**b**) Experimental test setup (adapted from [81]).

4.4. Application of Wind Deflectors in Cooling Towers

Cooling towers circulate steam water through an air cooling system to condense it and lower its temperature for reuse. Optimizing the efficiency of the cooling rate in cooling towers greatly contributes to the conservation of the water, hence lowering the stress due to water scarcity [83]. The heat is removed by means of natural buoyancy where the hot air near-radiation region in cooling towers is responsible for generating the natural buoyancy. In such conditions, environmental factors such as crosswinds have a significant effect on cooling performance, i.e., natural buoyancy generation.

Improving the cooling rate by generating radiator-friendly environmental conditions can reduce water consumption by up to 10.8% [83]. Installing wind deflectors in cooling towers under crosswind conditions can improve the airflow rate from 5% to 10% and improve the cooling efficiency from 2% to 5% [84]. Du et al., 2018 [85] performed a numerical simulation and experimental investigation to observe the effect of rotating wind deflectors on the cooling rate performance of an air-cooled type cooling tower under different crosswind conditions. This design concept is illustrated in Figure 12. It shows that wind enters the cooling tower uniformly when the environment is in a windless condition. However, under crosswind conditions, the airflow rate on the radiator decreases, thus leading to decreased cooling performance. Wind deflectors are the most suitable method under such conditions to improve the airflow rate and cooling performance. At a crosswind speed of 5 m/s, the wind deflectors can increase the airflow rate up to 61.7% and the heat transfer rate up to 15.1% as compared to cooling towers without wind deflectors at the same crosswind speed.

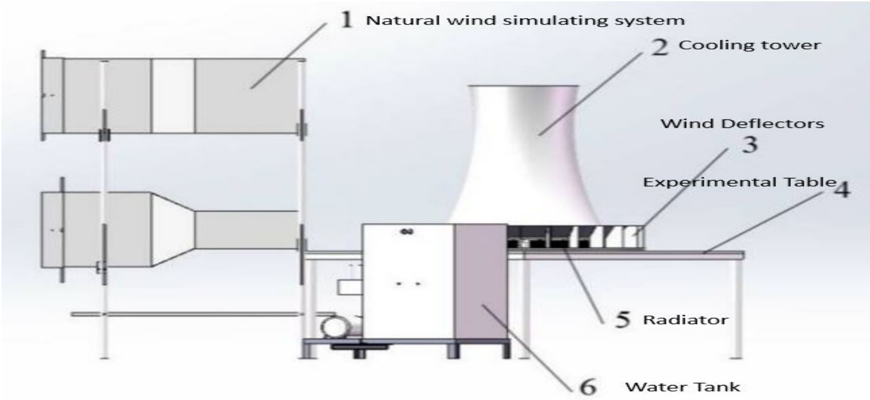

Figure 12. An experimental setup to investigate the effect of deflector in cooling tower [84].

4.5. Applications of Wind Deflectors in Building Structures

The application of wind deflectors in building structures such as building blocks or bridges can involve wind stress created by these structures and their effect on the buildings themselves and their surroundings. The building blocks in urban areas can contribute to the accumulation of aerosols and other air pollutants in the streets and building yards by creating a crosswind effect. The CFD simulation carried out in [55] concluded that wind deflectors can create a diversion to the wind speed to remove the leeward vortex and force the wind streams to flow through the street canyons, which can reduce the accumulation of air pollutants with a channeling effect. The wind deflectors reduce the kinetic energy of the wind into eddies surrounding the buildings in such a way that a diversion for the incoming wind is created, and the wind flows behind the building by reducing the vortex formation at the corners of blocks that contribute to the accumulation of aerosols. However, the construction of wind deflectors is region-dependent, so installation and construction should follow regional characteristics.

Wind deflectors also reduce the vibrations created in urban structures such as bridges. High wind velocity in urban areas creates vibration in bridges; for example, vibrations of 0.8 m amplitude were estimated in the Alconetar Bridge in Spain when the local wind velocity reached as high as 30 m/s for several hours in 2006. The tandem cross-section in the bridge had sharp edges that generated vortex shedding when struck by the wind streams. Adding curve-shaped wind deflectors to the corners of the tandem cross-section reduced the size of the vortices and reduced the associated force on the arch. It was observed that installing wind deflectors on the bridge had the effect of reducing that vortex shedding that was creating vibrations in the bridge. Wind tunnel tests on adding a deflector to the same arch under similar wind conditions showed a reduction in vibration to about one-third of the original [47]. After installing the wind deflectors on the bridge, the amplitude of vibration was reduced to 0.25 m, from its original value of 0.8 m.

4.6. Applications of Wind Deflectors in Vehicles

The main objective of vehicle performance improvement is to decrease fuel consumption, which is directly associated with the drag created due to the aerodynamic shape of the vehicle. In the case of a container truck, installing additional aerodynamically shaped wind deflectors consequently reduced the drag force on the truck. The wind deflector size and shape can be optimized to install on the cabin of a container truck [86]. The main objective of installing such deflectors is to optimize the shape for achieving a minimum drag coefficient. The parameters to optimize the deflector shape include the length, height, and sketch. The length in particular is the most important parameter, as it can contribute to as much as a 20% reduction in the drag coefficient, whereas the height and sketch account for 10% and 5%, respectively, as compared to the coefficient of drag on the container truck without a wind deflector. An overall drag coefficient reduction of 9.73% can be achieved by installing an optimized wind deflector [86].

Apart from drag reduction, wind deflector applications are also used to reduce the sunroof buffeting noise in vehicles. Automobile customers are attracted to larger sunroof openings that provide comfort and fresh air. However, the openings in the roof of vehicles can create throbbing and hissing noises. Moreover, the buffeting noise is the most annoying noise heard from sunroofs, with a frequency range of 17 Hz to 22 Hz [54]. Installing a simple deflector on the vehicle sunroof improves the interior sound quality [49]. An investigation into installing active wind deflectors [54] concluded that the buffeting noise can be reduced up to 25 dB. An active wind deflector of 460 mm in length was installed on the sunroof of a test vehicle in an open environment and found to be stable under all wind speed conditions and wing yaw angles.

5. Discussion

From the review on wind deflectors for VAWT, it was demonstrated that wind deflectors are a cost-effective and easy to develop method of enhancing the performance of VAWT. Wind deflectors can be broadly classified as flat plates, airfoil shapes, or compound structures. A flat-plate deflector is easy to develop but offers less improvement, whereas the compound structured deflectors offer higher gains but are costly. The augmentation gain of the deflectors is compared in Table 3. The most suitable application of wind deflectors is in the Savonius type of wind turbine, as it has very low self-starting ability among other VAWTs but higher efficiency; therefore, wind deflectors are very effective in improving self-starting ability along with overall performance. Savonius turbines are drag-based, and the number of blades varies from two to four. From the findings of this review, we recommend the two-bladed Savonius turbine with a flat-plate deflector. Three-bladed Savonius rotors with a flat-plate deflector increase the complexity and material costs, while providing only a slight change in flow augmentation. By conrast, in the lift-based VAWT, the flow augmentation gain is much higher if the blade shape is optimized with NACA 0021 airfoil. Building the airfoil-shaped blade is more complex than the Savonius rotor, but the higher flow augmentation gain compensates for the structural complexity. Furthermore, when installing an array of turbines, it would be useful to install counter-rotating twin turbines with a kite-shaped wind deflector. The augmentation gain of the twin turbines with a deflector is much higher than that of a single turbine with a deflector. However, in all of the above cases, the proper position and orientation of the wind deflector are crucial for high flow augmentation. High output power can be achieved when the turbine is placed outside the near wake region of the deflector.

Table 3. Comparison of the types of wind deflectors and VAWTs in terms of performance gain.

Deflector	VAWT Turbine	Result/Augmentation Gain
Flat plate	Savonius 2-Bladed	27.3%
Flat plate	Savonius 3-Bladed	27.55%
Flat Plate	H-Type NACA 0021 blade	47.1%
Airfoil shaped	Savonius	50%
Flat Plate	Straight Blade Twin Turbine	26%
Kite Shaped	Straight Blade Twin Turbine	38.6%

One of the practical applications of wind deflectors is installed at the Education City campus, Doha, Qatar, as illustrated in [78], in which the wind deflector surrounds the pole of a VAWT. The deflector is installed below a straight-blade VAWT and captures the omnidirectional wind and deflects it towards the rotor (i.e., upward), as shown in Figure 9. VAWTs represent applications as stand-alone power generation sources in urban built-up areas, isolated areas that are not connected to the power grid, and remote islands, where adding a wind deflector will ensure an added advantage. The power generated by VAWTs with a wind deflector can be useful for a variety of applications, including powering lighthouses, streetlights during night hours, traffic signals, and powering a home as a stand-alone power generation source in an isolated area. Thus, wind deflectors can play a vital role in rural electrification. Nevertheless, wind deflectors also have applications in building ventilation, sunroof buffering in vehicles, decorative light reflectors, advertisement boards, etc.

Future research on wind deflectors in VAWT could investigate the effect of aerodynamic thrust on the turbine pole. The wind deflector applications and studies reviewed in the literature mostly focused on finding the best deflector positions, orientations, and geometric parameters for deflector installation. In future studies, the aerodynamic shape and geometry of wind deflectors could be improved and tested to find the best tip speed ratio at which the optimum power coefficient can be achieved. Furthermore, given that the velocity gradient created by a wind deflector in the near wake region is still poorly understood, a detailed study could be carried out to improve understanding of flow instability and the velocity gradient and its effect on the torque coefficient and stability (strength) of the rotor shaft and blades. Additionally, modern VAWT turbines such as troposkien-type turbine rotors, flower-shaped VAWT, cycloturbines, and J-shaped wind turbines still have not been tested with deflectors. Adding deflectors to these turbines would decrease their counterproductive effects.

6. Conclusions

Improving the efficiency and reliability of machines has remained a prime objective of the research community. Researchers and engineers in wind energy engineering always seek solutions to fully utilize the natural wind energy approaching the rotor blades to generate the maximum power coefficient. Horizontal-axis wind turbines are generally known for higher energy efficiency, whereas increasing the efficiency (power and torque coefficients) of vertical-axis wind turbines has remained a research challenge for decades. VAWTs are best known for working under variable wind speeds and easy installation; on the downside, poor self-starting performance, low initial torque, and lower power coefficients are their main disadvantages. The efficiency of VAWTs can be increased by adding flow augmentation devices to the turbine rotor; wind deflectors are widely used for this due to their simple design and significant power improvement potential. In the current paper, recent designs and applications of wind deflectors were reviewed, and their installation and coefficient of power improvement capability were discussed. From this review, it was concluded that wind deflectors significantly improve the power coefficient and torque coefficient of VAWTs. Deflectors created a diversion in the upstream wind, thereby blocking the wind from the returning blade of the VAWT rotor and directing it towards the forwarding blade. In this way, the negative torque generated by the returning blade was minimized and the positive torque generated by the forwarding blade was increased, hence increasing the net torque coefficient.

Wind deflectors can be of several designs, from a simple flat plate to an airfoil-shaped model. Installing a flat-plate deflector in the Savonius turbine can increase the power coefficient by 27%. However, the power coefficient can be improved by changing the aerodynamic shape of the deflector, with an airfoil-shaped deflector boosting the power of the same Savonius turbine by up to 50%. Moreover, deflectors in twin turbines have even better performance, increasing the power coefficient up to 38.6%. Nevertheless, large wind deflector structures also have applications in reducing aerosol accumulations near building blocks. Wind deflectors installed on the Alconetar Bridge, Spain decreased the vibration generated by the bridge due to high winds. They can also be useful in crosswind conditions in cooling towers, reducing the buffeting noise from sunroofs in automobiles, and lowering the drag forces on truck containers.

During the last decade, the business revenues generated by VAWTs have been far behind those generated by HAWTs. Innovative solutions and technological improvements are the key drivers that could bring VAWTs into the competitive global trend toward power generation from larger turbine rotors. Offshore wind power and flow augmentation represent the main potential for VAWT applications but are still in the early stages of development. In the future, wind deflector-augmented VAWTs could become one of the popular choices for commercial power generation.

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