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Review

Wind Turbines for Decarbonization and Energy Transition of Buildings and Urban Areas: A Review

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Abstract

The recent tendencies of drastic variations of environmental conditions, inundations, severe winds, and gusts besides heavy and unexpected long-duration rains showed the world an image of what could happen if emissions and global warming are not adequately controlled. Implementing new energy solutions as fast as possible is essential to cope with climate change, one of the biggest threats to our survival. These alarming signs intensified research and development efforts to replace fossil-based activities with renewable, eco-friendly energy resources to ensure reduced emissions and global warming effects. Wind energy stands out as one of the favorable renewable energy sources for decarbonization and energy transition of buildings and urban areas. The installation of small and medium-sized windmills in urban areas and on roofs of buildings attends the recommendations for sustainable energy transition, and the UN Sustainable Development Goals, SDG 7, which ensures equity and justice to affordable and reliable clean energy. Installation of windmills of small and medium capacities in urban areas and buildings roofs faces significant challenges, including noise, mechanical vibration, efficiency, and mechanical security necessary for healthy ambient and social acceptance by the population. This review provides a general evaluation of the design and performance of moderate capacity horizontal and vertical axis wind turbines, geometry optimization, current installations on rooftops of buildings and urban districts, studies on horizontal axis and vertical axis wind turbines for rooftops of buildings and metropolitan areas, vibration, noise, and aerodynamic induced mechanical forces, end of life of wind turbine and blades waste recycling and reusing methods. Finally, the review provides conclusions based on the findings from the review and future research and development prospects.

Keywords

Decarbonization of buildings and urban districts; wind turbines; end-of-life of wind turbine; recycling blade material; vibration and noise; aerodynamic induced forces

1. Introduction

The continuously increasing global warming and its disastrous effects all around the world alerted society, scientists, and scientific associations pro ambient about the eminent risks facing the planet if no severe action is taken to stop activities provoking global warming. The world decided to reverse the situation by replacing fossil-based energy activities with others that use renewable energy. As a result, many investments were destined to install wind and solar energy projects and develop other technologies and applications for sectors known as big energy consumers in the building industry, among others.

Wind energy global potential is high [1], and 20% of the global total wind power potential was estimated to be about 123 petawatt-hours (PWh) annually, which is more than the total current global consumption of electricity. In 2023, the global wind industry installed a record 117 GW of new capacity, a 50% increase from the previous year. It generated 7.8% of the world's electricity in 2023, more than double the share in 2015 (3.5%). Most wind energy farms are installed to provide electricity for centralized grids, usually onshore (units of 3-4 MW) and offshore (units of 8-12 MW). Wind turbines have some disadvantages including the fact that the wind is unreliable in many areas, the wind turbines cause noise pollution, and can impact local wildlife [2]. At the end of its life, the turbine blades present big deposition problems currently under investigation. Also, ideal wind sites are often in remote locations, hence needing transmission lines and a distribution grid for consumption localities, which increases costs and electric losses.

The recent efforts to decarbonize the electricity sector and applications require the implementation of renewable energy sources and decentralized applications, when possible, to attend to the recommendations for sustainable energy transition. Installing small windmills in urban areas and on roofs of buildings follow these recommendations and provide local access without extensive transmission lines besides avoiding electric losses. Considering these new tendencies, the projects of new windmills of small and moderate capacities must be reevaluated regarding noise, mechanical vibration, efficiency and security. The objective of the present study is to provide a review covering small and intermediate wind turbines up to 250 kW of power used in the energy supply of villages, hybrid systems, distributed control and roofs/facades of buildings and their contribution to energy transition and reduction of emissions of greenhouse gases. The review provides a general evaluation of the design and performance of horizontal and vertical axis wind turbines, design models of horizontal and vertical axis wind turbines, geometry optimization of wind turbines, wind turbines for rooftops of buildings and urban districts, aspects of wind turbines in urban environments, wind turbine types, the wind resource in urban areas, studies of small to moderate scale horizontal and vertical axis wind turbines for rooftops of buildings and the metropolitan regions, vibration, noise, and aerodynamic induced mechanical forces, impact on building structure, measurements, and analysis, mitigation strategies, end-of-life wind turbines blades including deterioration of wind turbine components by corrosion, blades waste policy and strategy and blades waste recycling and reusing methods. Finally, the review provides conclusions based on the findings from the review and future research and developments.

The review provides an extensive coverage of small and medium wind turbines both vertical and horizontal axis wind turbines destined to applications on buildings roofs and urban areas focusing on aerodynamic modeling and optimization of rotors and blade geometry, vibration, noise, and aerodynamic induced mechanical forces and end-of-life wind turbines blades. This information is helpful for professionals involved in the research and development of wind turbines. The review also shows how installations of wind turbines in urban areas and roofs of buildings can decentralize energy production and utilization, reducing losses and emissions besides attending the objectives of the United Nations Organization (SDG 7) concerning access to clean energy and in conformity with energy transition basic lines.

2. Design and Performance of Moderate Wind Turbines

2.1 General Aspects of Moderate Wind Turbines

Moderate capacity wind turbines can be used for local off-grid and on-grid energy generation, in urban and rural areas. The most adequate wind turbine type, geometry and dimensions depend on the applications and the environment. In this section, the physical aspects, modeling methods and the performance of different types of small and moderate wind turbines are discussed.

According to [3], the horizontal axis wind turbine (HAWT) has a blade rotation axis parallel to the ground. In contrast, the vertical axis wind turbine (VAWT) has a blade rotation axis perpendicular to the ground. Despite the greater efficiency of HAWTs, they must face the wind direction to work efficiently, while VAWTs can capture winds coming from any direction. HAWTs work with lift forces over the blades to generate the rotation movement. On the other hand, there are different VAWTs: the Darrieus VAWTs use lift forces to create the rotation movement, and the Savonius VAWTs use drag forces to create the rotation movement. The Darrieus VAWTs can have curved or straight blades (H-type). Also, there is the Gorlov VAWT, with helical curved blades, that uses the lift forces to generate the rotation movement [4, 5]. Figure 1 shows a diagram of the classification of wind turbines.

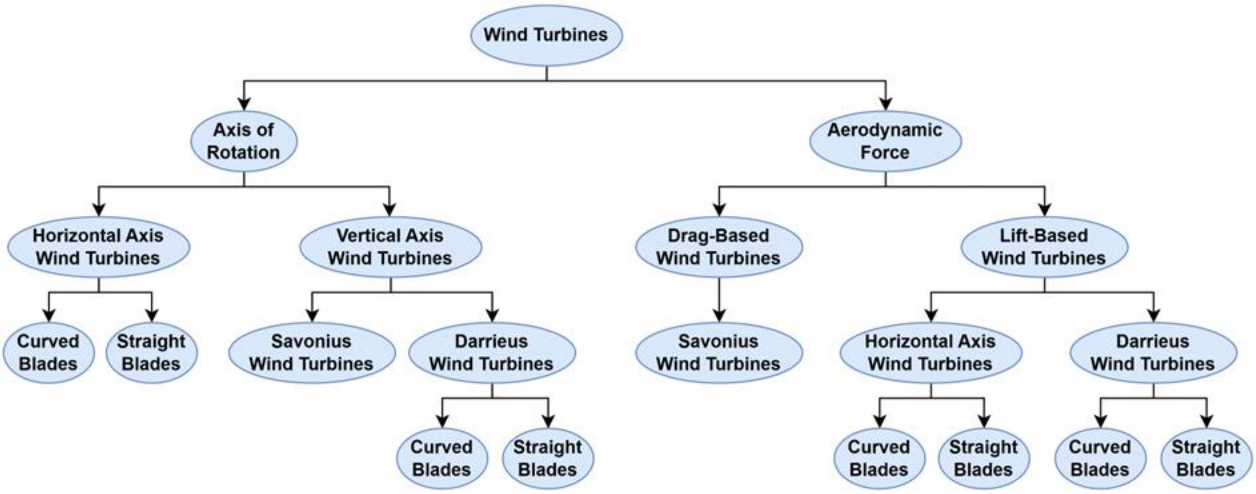

Figure 1 Classification of wind turbines.

Sefidgar et al. [6] conducted a study on cross-flow wind turbines (CFWT), similar to the Savonius VAWT. According to the authors, the maximum theoretical efficiency of a CFWT is between 12 and 15%, while the efficiency of a VAWT is about 35%. For HAWTs, the maximum efficiency can reach 45%. Table 1 shows the standard classification system for wind turbines and the rating of wind turbines [7].

Table 1 Standard classification system for wind turbines [7], permission for use authorized by International Journal of Energy and Environment.

Scale	Diameter of swept area	Power rating
Micro	Less than 3 m	50 W-2 kW
Small	3-12 m	2 kW-40 kW
Medium	12-45 m	40 kW-999 kW
Large	46 m and larger	More than 1.0 MW

2.2 Summary of Computational Methods of Analysis

Goudarzi [8] describes CFD as a powerful tool to estimate the aerodynamic performance and the flow behavior around the wind turbine components. Some examples of CFD software are ANSYS Fluent, COMSOL, and Open Foam. There are three main steps in a CFD analysis: preprocessing, solver, and post-processing. In the preprocessing step, the geometry, mesh, and boundary conditions are defined. In the solving step, the appropriate turbulence models are selected, and Navier-Stokes (N-S) equations associated with preprocessing definitions are solved. In the post-processing step, the forces and torque acting in the wind turbine are obtained, and the flow characteristics can be visualized.

According to [9], CFD is a widely used tool that produces accurate results. However, a CFD analysis requires high computational cost and processing times.

An alternative of less computational cost is the Blade Element Momentum (BEM) theory, which is most frequently used in the industry and scientific research due to its mid-fidelity and faster results. Through the BEM theory, a HAWT's geometry can be optimized for maximum power generation, and the aerodynamic forces and torque acting on the blades can be derived. Dehouck et al. [10] describe the BEM as an extension of the Rankine-Froude's theory [11], in which the wind turbine rotor is replaced by a circular thin disk (actuator disk) under the pressure difference that reduces the flow velocity. The BEM theory assumes that the flow is bi-dimensional, homogeneous, incompressible, steady, uniform and axial (no rotational component). The fluid stream is divided along the blade span into a finite number of annular and coaxial tubes. The aerodynamic forces are assumed uniform over the disk and can be calculated on each blade element based on the local flow conditions.

Another method of analysis of wind turbines is the cascade model. It presents relatively accurate results, with a low computational cost. Golmirzaee and Wood [12] performed a HAWT analysis through a cascade flow model. A cascade consists of an infinite number of identical airfoils, separated by an equal distance. According to the results reported by the authors, this assumption was found to be conservative: the lift/drag ratios of cascade elements were generally more significant than that of the corresponding airfoils.

Wood [13] described a generic free-wake vortex modeling for HAWTs. The tip vortices were represented by straight segments and the blades were modeled as lines of constant bound vorticity. According to Currin and Long [14], free vortex wake models give a more accurate and detailed description of the aerodynamic wake than BEM. The computational cost of free wake models' codes is higher than that of BEM models and lower than that of CFD models.

An alternative to CFD analysis for Darrieus VAWTs is the Double-Multiple Stream Tube (DMST) model. According to Ayati et al. [15], in a DMST model, the rotor is divided into its front part (upstream or upwind zone) and its rear part (downstream or downwind zone). Each part corresponds to a half-cycle. The flow passing through the rotor is discretized into a set of stream tubes, crossing two actuator disks. In the first crossing, the flow enters the rotor core, and in the second crossing, the flow leaves the rotor core. Each stream tube is defined by an azimuthal angle. Combining the described approach with the momentum theory and aerodynamic load analysis, predictions for the Darrieus VAWT performance can be made through the DMST model. The actuator disk approach of the DMST and BEM models are similar. The DMST model was applied to estimate the available power generated from the wind with a Darrieus VAWT. The DMST model can be implemented in a low computational cost algorithm [16, 17].

Table 2 summarizes the wind turbine analysis methods, types of wind turbine, advantages and disadvantages.

Table 2 Summary of the wind turbine analysis methods.

Analysis Method	**Types of Wind Turbines**	**Advantages**	**Disadvantages**	**Authors**
CFD	HAWT, Darrieus VAWT, Savonius VAWT	Complex geometries. High accuracy.	High computational cost and processing times.	Goudarzi [8], Bouhelal et al. [18], Rezaeiha et al. [19], Beri and Yao [20].
BEM	HAWT	Low computational cost and processing times. Reasonable to accurate results.	Limitations due to simplifying assumptions. Limited ranges of analysis (such as wind velocity).	Dehouck et al. [10], Bouhelal et al. [18], Bufares and Elmnefi [21]
Cascades	HAWT, Darrieus VAWT	Low computational cost and processing times. Reasonable to accurate results.	Limitations due to simplifying assumptions.	Golmirzaee & Wood [12], Shyam et al. [22]
Vortex	HAWT, Darrieus VAWT.	accurate and detailed description of the aerodynamic wake compared to BEM.	Higher computational cost than BEM.	Wood [13], Currin & Long [14], Shi et al. [23]
DMST	Darrieus VAWT	Low computational cost and processing times. Reasonable to accurate results.	Limitations due to simplifying assumptions.	Ayati et al. [15], Ramkissoon et al. [16], Saber et al. [17]. Beri and Yao [20]

3. Wind Turbines for Rooftops of Buildings and Urban Districts

In this section, the application of different types of wind turbines in urban districts, such as on the rooftops of buildings, is reviewed. Also, the wind resource characteristics in an urban environment are addressed.

3.1 Wind Turbines in Urban Environments

Before discussing technical aspects of wind turbines in urban environments, the social acceptance of wind energy projects in cities is an important non-technical aspect that must be addressed in this work. Khorsand et al. [24] evaluated the influence of the region, community involvement and practices on social acceptance of wind energy projects among residents surveyed from cities in four OECD and three non-OECD countries. Their results indicated interurban variations among the generally high levels of acceptance of wind energy projects reported. The acceptance level was even higher among city residents in developing countries with lower domestic CO_2 emissions.

According to Bošnjaković [25], wind turbines installed on buildings, sports facilities, roads and other places present relatively low efficiency, long payback period, noise problems and are criticized for the threat that blades potentially represents on the environment.

One of the potential environmental problems wind turbines can cause is bird collisions, especially in urban areas. According to Blary et al. [26], the average number of collisions is 8, 7 and 3 birds per wind turbine per year in Canada. The authors describe the development of automatic detection systems that detect approaching birds and trigger wind turbines to slow down their rotational speed. Increasing the contrast between wind turbines and their environment may effectively detect low rotation velocities by birds, and a complete wind turbine shutdown is an option.

Another aspect of wind turbines placed near urban and residential areas is the depreciation of residential properties. According to Brunner et al. [27], in the United States, homes located within 1 mile of a commercial wind turbine experience a decline of 11% in value following the announcement of a new commercial wind energy project, in relation to homes located 3 to 5 miles away. However, there has been a recovery in property values, and the impact of the wind energy project is almost insignificant after 9 years of the project announcement.

Another critical aspect of the use of wind turbines is the CO_2 emission reduction. According to [28], wind energy produces around 11 g of CO_2 per kWh of electricity generated, coal produces around 980 g CO_2/kWh and natural gas produces around 465 g CO_2/kWh. However, these numbers may vary according to the source.

On the technical aspects, the different types of wind turbines have specific advantages and disadvantages related to their application in urban environments. However, it is essential to state the general aspects and differences between the main types of wind turbines.

According to Alam and Jin [29], wind turbines are generally classified into three groups: small, intermediate, and large. Small wind turbines usually have less than 10 kW of power and are used for built-up residential, commercial, farming, and remote applications. Intermediate wind turbines have 10 to 250 kW of power, used in the energy supply of villages, hybrid systems and distribute power. Wind turbines over 250 kW are considered significant and used for commercial power generation. Small-scale wind turbines, which typically operate with an average wind velocity of 5.5 m/s and produce less than 20,000 kWh/year, can be divided in three sub-categories [29]:

(a) Micro wind turbines: produce about 1,000 kWh/year, with 1.5 m or less rotor diameter. In distant locations, they are used for lower power purposes, such as simple illumination and battery charging.

(b) Mini wind turbines: produce 1,000 to 2,000 kWh/year, with 1.5 to 2.6 m rotor diameter.

(c) Domestic scale wind turbines: produce 2,000 to 20,000 kWh/year, with 2.7 to 9.0 m rotor diameter. They are used for various applications, including residential households, farms and small businesses.

Figure 2 shows different types of wind turbines adequate for the range of power of interest to the present study.

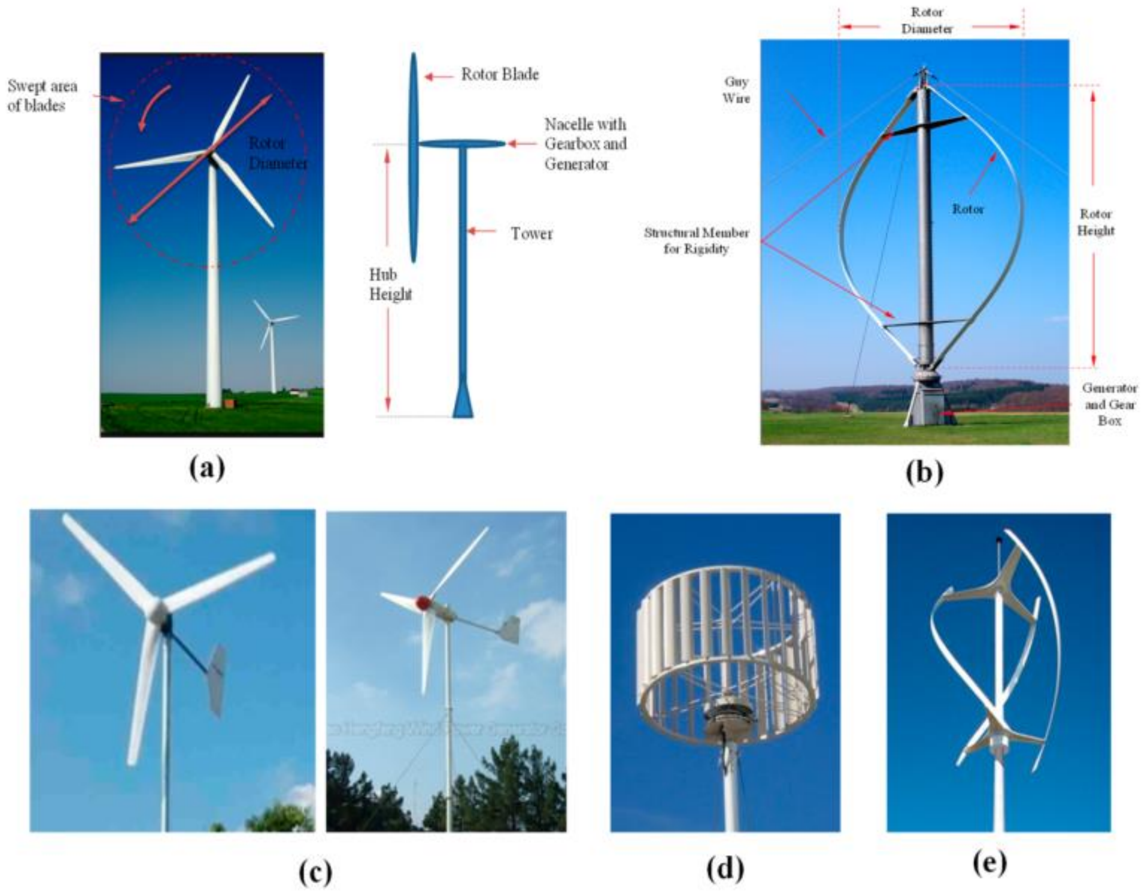

Figure 2 (a) HAWT, (b) VAWT, (c) Domestic (small scale) HAWTs, (d) Domestic (small scale) VAWT (Savonius type), (e) Domestic (small scale) VAWT (Darrius type), [29], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

It is essential to assess the wind potential of each urban area in which wind turbines are planned to be placed. According to Zagubień & Wolniewicz [30] the wind zones that characterize the wind potential of an open area have no significant influence on the wind conditions of a built-up region inside the same open area. The installation of small wind turbines in urban areas requires a minimum of annual wind measurements in the exact place in which the wind turbine will be placed.

The prediction of the wind behavior in urban environments is a challenge, since the wind flow tends to be complex due to the urban roughness elements (mainly buildings). The free stream velocity is typically experienced above 300 m in urban areas [31].

According to Gil-García et al. [32], small-scale wind power offers new opportunities for decentralized energy generation, reducing the dependency on the grid, which presents transmission losses. There are several locations in the urban environment that can place a wind turbine. High-rise buildings are especially promising due to the elevated heights, in which the wind speed is higher and the turbulent wind conditions are lower. Figure 3 shows different types of urban wind energy collection systems. Table 3 shows the specific advantages and disadvantages of urban wind turbines. In a Spanish case study in Cadiz, more than 68,000 kWh can be produced yearly with an investment recovery time of less than 6 years.

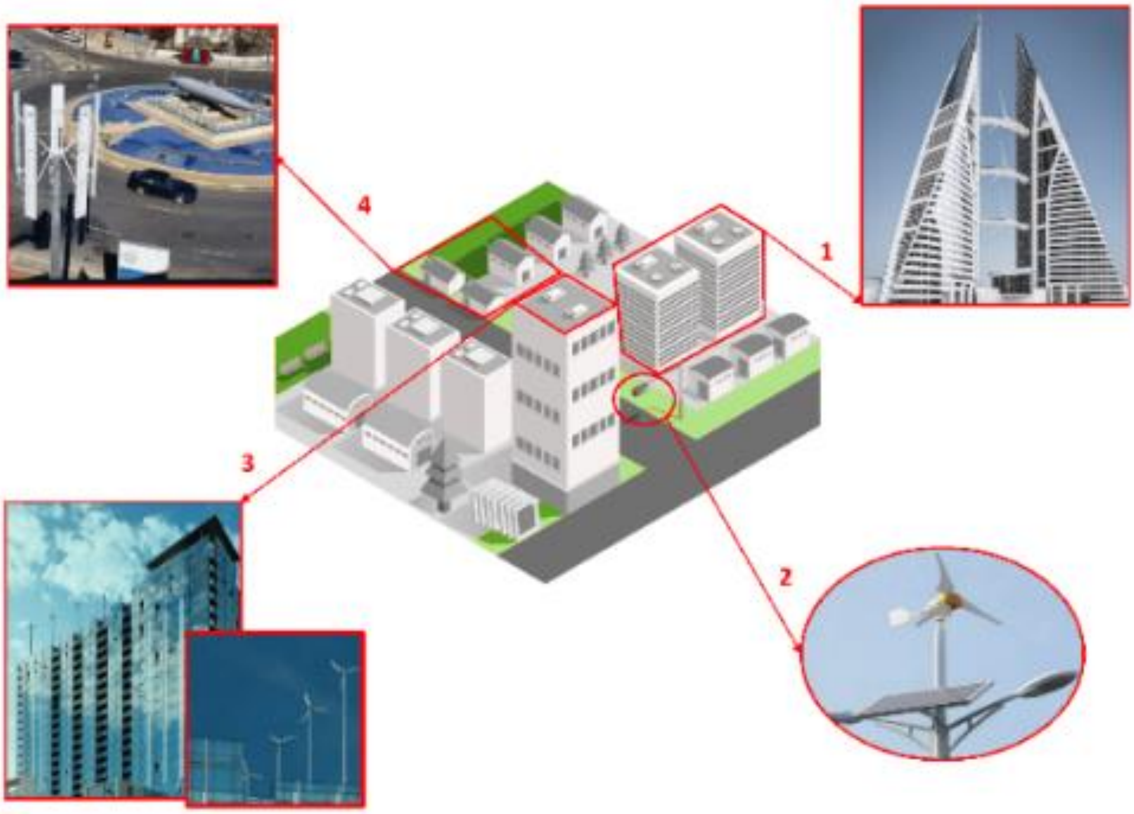

Figure 3 Types of urban wind energy collection systems: (1) Integrated; (2) Freestanding; (3) On the roofs of buildings; (4) Near buildings [32], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

Table 3 Advantages and disadvantages of urban wind turbines, reproduced from [32], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

Turbine Type	Advantages	Disadvantages
HAWTs	● Economic ● Efficient ● Commercial variety ● Proven technology in high-power wind farms	● Dependent on wind direction ● Does not cope well with buffeting

Lift VAWTs	● At a given wind speed, it is equal in efficiency to HAWT ● Independent of wind direction and turbulence ● Less vibration ● Shocks and little noise	● More sensitive to turbulence than drag-based VAWTs
Drag VAWTs	● Proven product ● Less acoustic emission ● Independent of wind direction and turbulence ● Less vibration ● Potential benefit from turbulence	● Not efficient ● Comparatively uneconomic

Ledo et al. [33] studied the flow patterns over different types of residential roofs: flat roofs, pitched roofs, and pyramid roofs. For the pitched roofs, CFD simulations showed that the most extensive areas of recirculation and reverse flow occur when the wind flows at 90° to the central line of the roof. When the wind direction is parallel to the central line of the roof, no significant separation is observed. For pyramid roofs, the extent of the separation regions is much smaller and limited to the space directly behind the roof. For the flat roof, the separation is even more minor. According to the authors, anywhere above a flat roof is a suitable site for installing a wind turbine. For pitched and pyramidal roofs, only the corner position is recommended as a mounting position.

Rezaeiha et al. [34] also described different types of urban wind systems. They assessed the urban wind energy potential for the Netherlands, by considering the installation of 18,156 small wind turbines on the roofs of 1,513 existing high-rise buildings in 12 cities. The predicted annual energy production was 150.1 GWh, which is a considerable amount.

Park et al. [35] proposed an innovative building-integrated wind turbine (BIWT) system using the building skin. The system combines a guide vane to collect the incoming wind and increase its velocity at the rotor. The authors applied a series of CFD analyses to determine the optimal configuration of the proposed system. Figure 4 shows a schematic diagram of the proposed system [35]. For a Savonius VAWT with 0.793-m length, 0.30-m diameter, and 8 blades, the maximum Cp was 0.381, which can be considered high. According to the authors' estimation, the proposed system can supply about 6.3% of the needed electricity in the building.

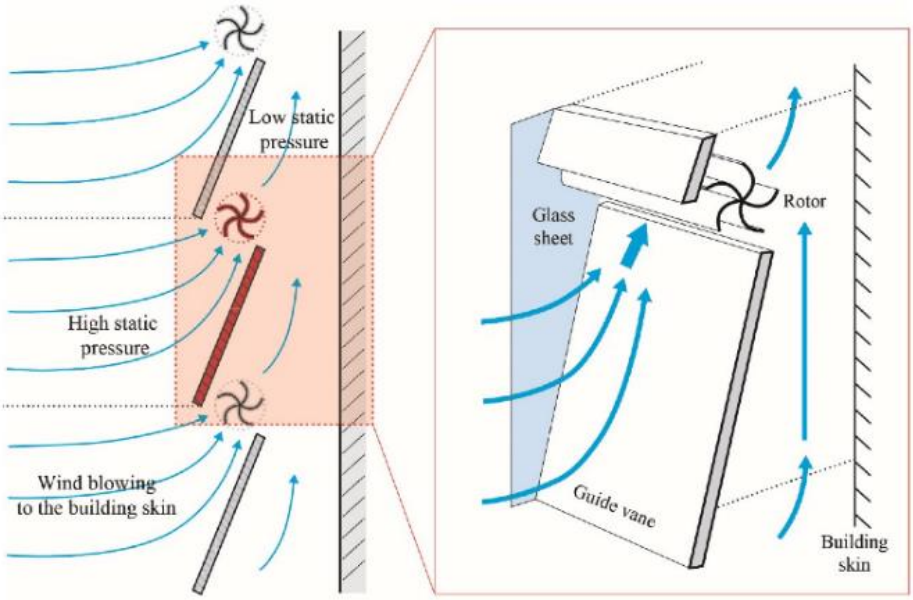

Figure 4 Proposed system [35], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

Filipowicz et al. [36] presented an overview and data on the wind turbines integrated into the Center of Energy AGH Building in Krakow, Poland. Two wind turbines are installed in the building: a HAWT on the top, and a VAWT at the bottom. The basic parameters of both wind turbines are shown in Table 4. Preliminary results showed that VAWTs are not a good solution as a facade wind turbine, and it is better to install VAWTs on a roof edge. Also, the noise was about 2 dB, which is negligible.

Table 4 Basic parameters of the wind turbines of the Center of Energy Building, adapted from [36], permission for use authorized by the Institute of Physics, IOP.

	HAWT	VAWT
Type	Ventus Energia, Swind New 1500	Hipar, Ecorote 600
Wind speed of start-up [m/s]	2.3	1.2
Power [kW]	1.5	0.65
Nominal wind speed [m/s]	10	12
Wind speed of break on [m/s]	-	25
Size	Diameter 2.2 m	Diameter 1.0 m, Height 1.5 m
Changing blade angle	Yes, in the range of +/- 40 degrees	No
Changing blade position of the turbine nacelle	Yes, in the range of +/- 10 degrees	-
Number of blades	3	4

Banu and Bhadani [37] assessed the feasibility of wind energy in Surat, India. The authors applied Rayleigh and Weibull distributions based on annual wind velocity data. The power availability on the site has been calculated as 42.6 W/m^2. Several commercial wind turbines for residences were evaluated against site power availability, including horizontal and vertical axes. Table 5 shows the wind turbine models and characteristics. The highest annual energy generation was 8 MWh, for the VisionAIR3 wind turbine.

Table 5 Commercial wind turbines considered in the study (adapted from [37], permission for use authorized by Oxford University Press).

Wind turbine	Company/ manufacturer	Rated Power (kW)	Cut-in Speed (m/s)	Cut-out Speed (m/s)	Furling Speed (m/s)	Rotor Diameter (m)	Axis/Number of blades
Pass at 1.4 kW	FORTIS Wind Turbine Systems, Netherlands	1.4	2.5	16	60	3.12	Horizontal/3
Skywind	SkyWind NG, Germany	1	4	20	20	1.5	Horizontal/2
E-3	RyseEnergy, UK	1.9	2	11	60	3.8	Horizontal/3
VisionAIR3	V-AIR wind technologies, France	1.5	3	12	50	2.7	Vertical/3
UE15 plus	Unitron, India	1.8	2.7	10.5	55	3.4	Horizontal/3
AVATAR-1	Avangrade Innovations, India	1.4	1.9	-	60	3	Horizontal/3
9 Blade Wind Turbine	Revayu Energy, India	1.8	1	12	50	1.25	Horizontal/9

In the review work of Kwok and Hu [38], the authors presented the potential application of Artificial Intelligence (AI) and Machine Learning (ML) in the context of urban wind energy generation to predict wind-induced crosswind responses, pressure patterns on buildings and interferences effects of adjacent buildings. According to Reja et al. [39], in metropolitan settings, the traditional method of assessment of wind resources is hampered by the inability to collect data in a turbulent environment. For this reason, in the future, AI, ML, deep learning and multiple neural networks will dominate this industry, to provide precise forecasts and minimize the operational time and costs of the systems.

3.2 Application of Horizontal Axis Wind Turbines for Buildings´ Rooftops and Urban Areas

Zhang et al. [40] applied a CFD analysis for small HAWTs on the rooftops of buildings, to assess the wind resources of an urban district and the effects of the operation of small HAWTs on the block wind environment. The wind turbines were modeled by the actuator disk model and the metropolitan district was represented by 16 cube shaped buildings. The authors concluded that the flow speed increases due to the crowding out effect of the metro district, and the turbulence intensity is enhanced. The impacts of the wind turbines on the rooftops of buildings on the environment are mainly restricted to the rooftops and almost negligible in the blocks.

Dar et al. [41] performed wind tunnel experiments to investigate the influence of minor modifications of the roof edge shapes on the power performance and wake of a HAWT over a cube-shaped building. Minor modifications in the roof edge shapes can significantly affect both power performance and the wake of a turbine sited on top of the building.

Krasniqi et al. [42] studied the amount of pollution reduced by using 300-Watts HAWT (S-300) in the rooftop of a building in Prishtina, Kosovo, in 2019. The average wind speed in 2019 was 1.44 m/s, and the energy produced in the same year was 189.008 kWh. Table 6 shows the results of reduced pollution. For a single small HAWT, the results seem to be modest. However, with the use of several small wind turbines placed in high wind velocity areas, an excellent pollution reduction can be achieved.

Table 6 Amount of pollution reduced, in kg/year [42], permission for use authorized by International Energy Journal.

Year	Dust	SO_2	NO_x	CO_2
2019	0.082345	0.957965	1.301098	441.9573

Su & Janajreh [43] assessed the wind energy potential at Masdar City, United Arab Emirates, and combined the Weilbull wind probability density distribution with the power generation and capacity factors of two different HAWTs under different heights: the large Nordtank 500/41 and the small 3.5 kW Windspot. At a height of 50 m, the annual energy production results were 330.62 MWh for the Nordtank 500/41 and 50 MWh for the 3.5 kW Windspot. However, considering the wind turbine efficiency and the return on investment, results favored the deployment of the 3.5 kW Windspot.

Mârza et al. [44] performed a case study for a Skystream 3.7 HAWT installed in Pianu, Romania, with simulations and experimental results. The wind turbine has a rated power of 2.4 kW, with a rotor diameter of 3.72 m, swept blades, and a tower height of 10.2 m. During the monitoring period of experimental measurements (1st of July to July 31, 2014), the average energy production of the wind turbine was 1.62 kWh/day, for an average wind speed of 2.44 m/s. The peak production was 4.58 kWh in a day, when it was recorded an average wind speed of 3.86 m/s. According to the authors, the results represent a decrease of 90% in the CO_2 emissions per kWh produced compared to the energy provided by the national system.

Rehman et al. [45] investigated using small HAWTs for off-grid loads in the eastern region of Saudi Arabia. They focused on the influence of hub height on annual energy production. The most efficient HAWTs were the Fortis Passat (1.4 kW), Fortis Montana (5.8 kW), Fortis Alize (10 kW), and CF20 (20 kW). The highest percentual increase in the annual energy production was achieved by increasing the hub height from 15 to 20 m. The subsequent highest percentual increase in annual energy production was achieved by increasing the hub height from 20 to 30 m. Figure 5 shows the energy yield from 2006 to 2009 for the studied wind turbine models, at different hub heights (10, 15, 20, 30 and 40 m).

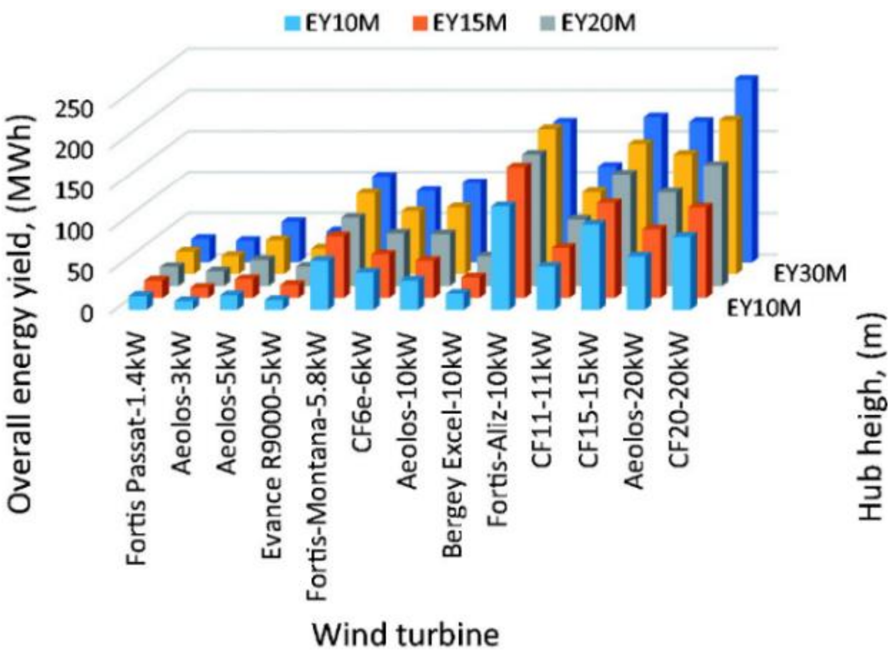

Figure 5 Overall energy yield from 2006 to 2009, for different wind turbines and hub heights [45], permission for use authorized by Sage Journals.

In the work of Gebrelibanos [46], small HAWTs were analyzed to be installed in the building of the Energy Technology Department of the Royal Institute of Technology, Sweden. Since most Nordic countries experience heavy snowing during winter times, ice fragments can fall from the wind turbine, and this was one of the safety issues addressed. For that reason, a safe distance between the HAWT and the public was considered. The selected wind turbine was the Aircon 10 kW, with a hub height of 24 m. Based on the wind velocities distribution throughout the year, the HAWT's annual energy production was estimated at 23,163.85 kWh. Since the energy consumption in the building is 1,259,800 kWh per year, the wind turbine can supply 1.84% of the building consumption, with a payback period of 14 years.

As one example of BIWT, the Bahrain World Trade Center, Figure 6 [47], built in 2008, consists of two 240 m high-rise buildings. Between them, there are 3 250-kW HAWTs, with 29 m diameter. The buildings are shaped to form a funnel, to make the wind flow in the desirable direction. These wind turbines generate 11 to 15% of the electrical power required for this building (11,000 to 13,000 MWh/year [48]). This was one of the first major architectural projects that successfully integrated wind generation into a high-rise building.

Figure 6 Bahrain World Trade Center, Bahrain ([47], permission for use authorized by Unsplash).

Strata SE1 is a 148 m high residential building in London, UK, Figure 7 [49]. There are 3 19.5-kW HAWTs in the openings at the building. The HAWTs were designed to generate 8% of the building's energy consumption. While there are no official records of the actual power generation in the building, there are several unofficial accounts of these wind turbines rarely being in operation, due to the complaints of the building's residents about the noise [50].

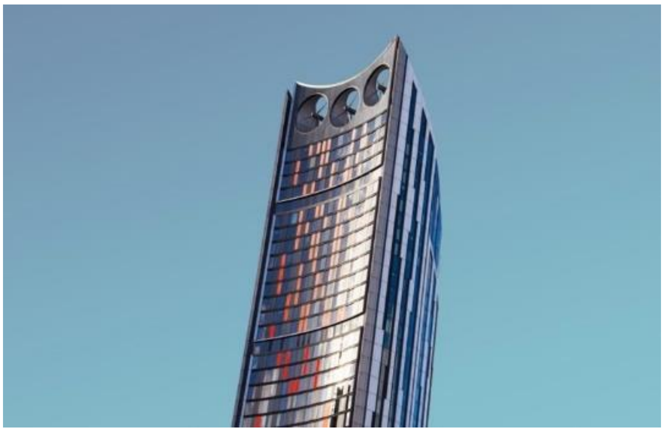

Figure 7 Strata SE1, London, UK [49], modified, permission for use authorized by Unsplash.

An example of HAWTs installed on a low-rise building is the 81-m Twelve West building in Portland, USA, with 4 small HAWTs placed on the roof, Figure 8 [51]. The annual energy production of the 4 wind turbines combined is about 5,500 kWh. There are no records of complaints from residents about the wind turbines. However, they produce only 1% of the building's energy consumption, with an expected payback of about 40 years, which makes the project relatively unsuccessful [50].

Figure 8 Twelve West building, Portland, USA [51], permission for use authorized by Wikimedia Commons.

3.3 Installation of Vertical Axis Wind Turbines for Buildings´ Rooftops and Urban Areas

Considering the urban application of wind turbines, VAWTs have significant advantages over HAWTs, including the possibility of capturing winds from any direction [32]. Another benefit of VAWTs is that the generator and the gearbox can be installed on ground level, which facilitates the installation and maintenance of buildings [52].

Despite the self-starting inability of Darrieus VAWTs, the work of Batista et al. [53] describes the design of an innovative airfoil, named EN0005, which gives the self-starting ability for Darrieus VAWTs applied to urban areas. The DMST model was used to Darrieus VAWTs with a height of 4.6 m, a radius of 2 m, 5 blades and a chord of 0.3 m, at 12 m/s wind velocity. Results were compared with NACA 0012 and NACA 0018 airfoils. Results showed that the performance of the EN0005 airfoil was superior to the other airfoils.

Shiraz et al. [54] applied 3D RANS CFD analyses and meteorological data to assess the energy production of a Darrieus VAWT placed on the roof of a building located in a high building density (HBD) area and in a low building density (LBD) area. The Darrieus VAWT was reproduced from the work of Samson and Paraschivoiu [55]. Results showed that the energy production in high-density urban environments is significantly reduced due to the wind behavior. In the best scenario, the annual energy generation was 1,632 kWh. The estimated energy productions for winter months in the best control points of buildings in LBD and HBD areas were 480 kWh and 178 kWh, respectively. A HBD site leads to a low energy production, even if the wind turbine is placed in a high altitude. According to the authors, no wind turbine should be placed in HBD sites, as the energy production is much lower.

Naik et al. [56] performed a case study of a combined use of a VAWT with a photovoltaic system in 2050 Homes Development in Nottingham, England, a cluster of 27 houses. Preliminary results showed that two Quite Revolution (QR6) helical blade VAWTs can bring the 27 terrace homes from the 2050 Homes scheme into zero energy class performance. Turhan & Saleh [57] designed a three-bladed IceWind VAWT, with arc angle of 112° and an aspect ratio of 0.38 and simulated the integration of 40 small IceWind turbines to a building in the Airport of Istanbul, Turkey. Results showed that the energy consumption of the building is 175.45 kWh/m² per year, and the energy consumption of the building with 40 IceWind VAWTs is 157.3 kWh/m² per year, representing a 9.3% reduction.

Mansi et al. [58] described the design of a Savonius VAWT for residential areas. Such turbines are needed in regions with dense population, such as Gaza Strip, in which energy self-sufficient buildings are desirable due to the severe electricity shortage in the local grid. The authors stated that two main factors were considered in the Savonius VAWT's design: first the safety factor, and second the ability to generate electricity at low wind velocities. The target power was 5 kW, a considerable amount of power to supply a typical household. An efficiency value of 0.12 was applied for the power calculation. A Savonius wind turbine prototype was developed, and the dimensions of the blades were 3.4 m in length and 0.62 m in width. It was installed 35 m above sea level. The estimated output power values were 48 W for a wind speed of 4 m/s, 210 W for a wind speed of 6 m/s and 780 W for a wind speed of 8 m/s. The Savonius VAWT has a lower efficiency, and safety was selected as trade-off power efficiency. A combination of the Savonius VAWT with HAWT rotors was proposed to generate extra electricity.

Ali et al. [59] investigated the performance of a straight bladed VAWT in Tabuk region, Saudi Arabia, through experimental results and CFD analysis. The rooftop wind turbine test evaluated the power output and the Cp under noncontact natural wind velocities. In contrast, the CFD analysis was performed to assess the resistance of the shear stress and pressure. The VAWT prototype has a radius of 0.36 m, three blades with a height of 1 m, a constant chord equal to 0.3 m, and an NACA 0018 airfoil. According to the authors, the VAWT reached its rated power and maximum Cp at a wind velocity of 9 m/s. At this wind velocity, the output power was 146.09 W, and the Cp was 0.45, at a TSR of 1.94 and angular velocity of 450 rpm. CFD results showed that the wind turbine can resist high wind velocities.

Among the results reported by [59], the high angular velocity of the rotor, equal to 450 rpm for a wind speed of 9 m/s, draws attention. Also, the equivalent Cp of 0.45 can be considered high for a VAWT.

Yadav et al. [60] studied the feasibility of implementing VAWTs on United Arab Emirates highways. According to the authors, VAWTs can harness unused kinetic energy from cars. In the simulated cases, the helical VAWT achieved 1,041 kWh of annual yield (single VAWT). The blade height was equal to 2.5 m, and the VAWT diameter was equal to 1.6 m. Considering the suggestion of installing one VAWT each 2 km, the total number of turbines would be 478, generating 497,598 kWh annually.

The Pearl River Tower in Guangzhou, China, is an example of a high-rise building integrated with VAWT, Figure 9 [61]. The 310-m building has four openings located at two different heights, which are 104 m and 205.4 m. Each opening houses a Savonius VAWT. The openings were aerodynamically shaped to increase the wind velocity by 90%, increasing the power outputs of the VAWTs. Due to the different heights and locations of the openings and the wakes created by nearby buildings, the power generation varied among the 4 VAWTs. The bottom left VAWT viewed from the south is expected to show the lowest annual energy production of 487.76 kWh. In contrast, the upper left VAWT is expected to show the highest annual energy production, estimated at 3,613.29 kWh [50].

Figure 9 Pearl River Tower, Guangzhou, China [61], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

Another example of an integrated VAWT building is the Greenway Garage in Chicago, USA, which has multiple small lateral VAWTs [50].

3.4 Comments

The flow over urban areas is disturbed due to the obstacles the wind faces. Under such conditions, the performance of a VAWT is usually better than the performance of a HAWT. Also, VAWTs can capture winds coming from any direction, perform well under low wind velocities, produce less noise than HAWTs and their structure is more suitable for buildings. For those reasons, VAWTs are usually more ideal for urban environments than HAWTs. Most of the reviewed works on using small wind turbines in urban environments describe the application of VAWTs in urban and residential areas.

Much of the performance data for wind turbines operating in urban environments comes from estimates and computer simulations. It is necessary to implement more viable ways to measure the actual performance parameters of these wind turbines, as limited information on their power generation performance is available. AI can be used to predict more precisely the disturbed urban wind behavior, which is essential for wind turbine projects. Also, in many cases, there is a need to assess more deeply the positive and negative environmental impacts of the operation of wind turbines in urban areas, such as the amount of greenhouse gases produced compared with non-renewable energy sources.

The percentages of wind energy generated in BIWTs in relation to the buildings' consumptions are under 15%, and still can be considered low. In the example of the Twelve West building in Portland, USA, the wind energy generation was only 1% of the building's energy consumption.

Hence, it is necessary to increase the efficiency of wind turbines in urban environments. This can be done, for example, with alternative geometries for the blades.

4. Vibration, Noise, and Aerodynamic Induced Mechanical Forces

In recent days, when the world's energy production is under stress and seeking alternative ways to support the growing demand, rooftop wind turbines have come to play an important solution in urban environments. At the same time, rooftop wind turbines are potential players in district decarbonization by providing a localized and renewable source of energy that contributes to the overall reduction of carbon emissions. However, there are many challenges associated with the integration of rooftop wind turbines in urban areas, such as vibration, noise, and aerodynamic-induced mechanical forces. As large wind turbines, the sources of vibration and noise have some similarities; however, they differ significantly due to variations in size, design, and operational characteristics.

The Strata SE1 in London, UK, is an example of the challenges associated with the integration of wind turbines in buildings. According to Škvorc & Kozmar [50], there are several unofficial accounts of these wind turbines rarely being in operation, due to the complaints of the building's residents about the noise. The chair of Southwark's planning committee has confirmed that the wind turbines on the building were shut off due to the high levels of noise and vibrations [62]. On the other hand, no significant complaints about the wind turbines of Bahrain World Trade Center in Bahrain were found.

Even for small wind turbines, the knowledge about controlling these phenomena can significantly improve the structural integrity of buildings, the comfort and well-being of occupants, and the overall effectiveness of the turbines. Uncontrolled vibrations are starting points for mechanical failures while wearing down the wind turbine components and building structures – Awada et al. [63]. Noise footprint can be very annoying, reducing the quality of life for nearby residents while generating public reluctance to rooftop wind turbines (Teneler & Hassoy, [64]; Onakpoya et al., [65]; Michaud et al. [66]; Karadag and Kuruçay [67]). The continuous movement associated with the aerodynamic forces on blades, nacelle, and tower can contribute to material stresses while jeopardizing the wind turbines' energy output. Many are the issues associated with the use of rooftop wind turbines, and they must be addressed to guarantee the safety, reliability, and public acceptance of such machines into urban renewable energy systems [33].

This subsection explores the sources, impacts, and mitigation strategies for these issues, providing a comprehensive overview of the current state of research and practical applications. Based on experience and a dense literature survey on the subject, critical aspects of vibration, noise, and aerodynamic-induced mechanical forces that impact the operation and integration of these urban turbines are scrutinized herein.

We have seen so far that while the design of urban wind turbines is very important, the intentional design of buildings incorporating rooftop wind turbines is also crucial [68]. There are many challenges related to energy production in urban environments, as previously seen, starting with the complexity of airflow in such areas due to the volumetric distribution of different obstacles (buildings) as well as the proximity of such machines to final users. As discussed by Micallef & Bussel [69], studies specifically targeted for urban wind turbines are still limited nowadays.

As the wind turbines come close to humans, vibrations are transmitted to the structure on which they are mounted. At the same time, for an urban environment, a major concern with wind turbines is the generated noise [70]. It is known that on the rooftops, the flow is turbulent with high-speed fluctuations and change of direction under the boundary layer effect caused by buildings, obstacles, and a lower rotor altitude [71]. To minimize the rooftop turbulence, the wind turbines would have to be mounted on towers high above the roof, which jeopardizes the tower's costs while adding complexity and reducing safety [72].

4.1 Sources of Vibration and Noise on Rooftop Wind Turbines

The nature of the interaction of airflow with buildings and with the wind turbine itself creates a complex, dynamic, and unsteady fluid domain, which is the source of vibration and noise. Structural control and vibration issues in wind turbines are reviewed by Xie and Aly [73].

Figure 10 summarizes the main vibration and noise sources from a small-scale rooftop wind turbine. These sources will be scrutinized in sequence, shedding light on the most important aspects related to their impacts on real-life applications.

Figure 10 Vibration and noise sources in a rooftop wind turbine.

As seen in Figure 10, the sources of vibration and noise on rooftop wind turbines share some commonalities with ground-mounted wind turbines (large scale). However, they present unique challenges and characteristics due to their proximity to buildings and smaller size, which influence the primary sources of vibration and noise. Overall, the main sources of vibration and noise from a rooftop wind turbine are related to structural vibrations, mechanical components, and aerodynamic forces [74-76].

About the mechanical components, it is known that smaller wind turbines for urban use are simpler than the large ones. While large wind turbines have complex designs for hub and rotor to support large forces and torques, also including mechanisms for pitch control, its smaller counterpart is designed for lighter loads and simpler operations with standard bearing systems suitable for lower loads and stresses. Some rooftop wind turbines could present simpler gearboxes to increase the rotational speed from the rotor to the generator [77-79]. However, it's more common to find a direct-drive system connected to the generator to reduce complexity and maintenance. The generators are also of low capacity, often designed for a constant speed operation producing kilowatts of electricity rather than megawatts in large WT. If control systems are present, they are simpler and focused on essential functions. Condition monitoring (CM) techniques, if present, have fewer and less sophisticated sensors for remote monitoring of performance and maintenance alerts. Generally, rooftop wind turbines are smaller, simpler, and designed for lower power output with a focus on integration with building structures and minimizing their vibrations [80-82]. Nevertheless, mechanical imbalances and component misalignment are the primary sources of vibration in smaller wind turbines. These can occur due to manufacturing defects, wear and tear over time, or the accumulation of dirt and debris on the blades [83-85]. Misalignment of key mechanical components such as the generator, shaft, or bearings can cause vibration, which can further propagate through the turbine structure.

Regarding the assessment of vibration in components like gearbox (if present), generator, and bearings for rooftop wind turbines, the literature work envisages a large growth in condition monitoring (CM) techniques [86-91], among others. The CM techniques will be discussed in more detail in the Measurements and Analysis subsection. Now, it is important to note that due to their variable speed and loads in combination with harsh operating environments, especially rooftop wind turbines experience substantial failures [92].

As discussed by Cai et al. [89], gearbox and, to a lesser extent, generator failures continue to be a major problem for large wind turbines, while there is an absence of much work on the assessment of condition monitoring for bearings in small turbines, especially in remote locations. As wind turbines come to urban areas, it is easier and cheaper to launch predictive maintenance approaches such as SHM (Structural Health Monitoring) [90]. Hamdan et al. [93] reviewed the possibilities of using Structural Health Monitoring (SHM) of VAWT wind turbine blades used in urban areas for local climatic conditions in Malaysia. Such measures can increase costs but provide useful insight into the turbine's structural performance in situ.

On the other hand, vibration also occurs due to the aerodynamic loads associated with the blade, nacelle, and tower's airstream interactions. Again, a large number of research results on these issues are available to large wind turbines (on-shore and off-shore applications) [94, 95], among others. Recently, Ou et al. [90] used a Windspot 3.5 kW WT model that was tested in both healthy and damaged states under varying environmental conditions imposed by means of a climatic chamber, constituting a benchmark study on a small-scale WT blade. As mentioned by the authors, the main challenge in the design of these tests lies in experimentally producing the desired system conditions and the most dangerous and failure scenarios.

While large wind turbines have significant blade lengths and high-altitude installations facing more substantial and complex aerodynamic forces, which can be handled with pitch control systems, rooftop wind turbines have much shorter blades, resulting in lower lift and drag forces. In contrast, rooftop wind turbines operate in environments with more turbulent and less predictable wind conditions experiencing lower but more variable aerodynamic loads [96-98].

Even for a small wind turbine structure, many degrees of freedom are present, such as the tower bending in the longitudinal and lateral directions. The nacelle and rotor can translate and rotate in tilt and roll, respectively. Also, bending of the blades can occur in both flat wise and edgewise directions [99, 100], which is an aero-elastic optimization for small wind turbine blades. Perhaps the most interesting and well-researched solution to improve the performance of urban wind turbines is the shrouded rotor concept [101-106].

It is known that the tower vibration originates from the coupled wind–rotor–tower system, mechanical transmission twist vibration, and rotor rotation [107], resulting from external loads such as wind turbulence, wind shear, gravity, tower shadow, mass, and aerodynamic imbalances and wake effects [63].

Moreover, structural resonance may happen when the frequency of the combination of tower and roof falls within the operating frequency range of the turbines [72]. This phenomenon can lead to amplified vibrations, causing increased stress and potential damage to both the turbine and building structure. Addressing this issue involves careful design and analysis to ensure that the natural frequencies of the tower and roof do not coincide with the turbine's operating frequencies. This may require structural modifications, vibration-damping techniques, or adjustments to the turbine's operational parameters to prevent resonance and maintain the integrity of the installation [63, 108, 109].

Besides structural vibrations, the aerodynamic noise from the blades is of primary concern. This noise is generated by the interaction of the turbine blades with the air as they rotate. The primary components of aerodynamic noise include blade tip noise and trailing edge noise. Blade tip noise is produced when the tips of the blades move rapidly through the air, creating vortices and turbulence. Trailing edge noise, on the other hand, is generated by the airflow over the trailing edge of the blades. As discussed by Volkmer *&* Kaufmann [110], although several flow-induced noise mechanisms contribute to the overall noise, trailing edge noise is typically dominant - similar to large wind turbines and may be audible to off-axis listeners as the amplitude-modulated (i.e. time varying) noise as pointed out by Perkins et al*.* [111].

Also, for small turbines an additional sound mechanism may occur: working at relatively low Reynolds numbers, laminar flow separation can cause significant noise [112, 113]. The area of laminar flow on the blade surfaces may become substantial since the laminar-turbulent transition point is shifted from the leading towards the trailing edge. Then, the chordwise adverse pressure gradient can provoke the separation of the laminar boundary layer. When the separated boundary layer becomes turbulent and reattaches to the blade surface, a laminar separation bubble may occur [114].

Finally, structural noise is a result of vibrations caused by the turbine's operation being transmitted through the mounting structure into the building. According to Mollasalehi et al*.* [74], Small wind turbines generate noise from the tower, with most vibration energy occurring in the very low-frequency band (10 Hz). This type of noise can be particularly problematic as the vibrations can travel through the walls and floors of the building, creating a humming or droning sound that can be disruptive to occupants [115]. The design and installation of the turbine's mounting system play a crucial role in mitigating structural noise. Poorly designed or improperly installed mounts can amplify these vibrations, making the noise more pronounced [75, 116, 117].

4.2 Aerodynamic-Induced Mechanical Forces

The continuous interaction of the airstream with the rooftop wind turbines causes the appearance of aerodynamic-induced mechanical forces at the blades, nacelle, and towers. These mechanical forces generate structural stress and fatigue [118, 119]. The structural integrity of the rooftop wind turbine could be jeopardized due to these dynamic loads that can cause wear and tear on the other mechanical components. Continuous exposure to these forces can weaken the structure, leading to potential failures, damage to the building, and the need for frequent maintenance or replacements.

As previously mentioned, due to the geometric complexity of the urban environment, often these rooftop wind turbines are subjected to wind speed and direction variability that can lead to inconsistent energy production, increased mechanical stress, and more pronounced vibration and noise issues [34, 54, 120, 121]. Another consequence is that, in some cases, due to the need for frequent adjustments in rotor and blade positions, the mechanical parts suffer more wear and tear. In cases where the wind turbine has a control system, this high variability of airstream challenges efficiency and poses risks to structural integrity, necessitating robust design and regular maintenance to ensure reliable and safe operation in urban environments. The problem associated with this issue is caused by higher costs, which generally impact its viability and application in urban areas.

In this harsh environment, the blade design of rooftop wind turbines plays a crucial role in efficiency and performance, particularly in managing aerodynamic forces. Optimized blade designs aim to maximize energy capture while minimizing noise and vibration [122, 123]. To achieve such objectives, the blade design for rooftop wind turbines is a challenge because it must enhance energy production while also mitigating structural stress by minimizing turbulent flow interactions. Additionally, features like serrated trailing edges, winglets, or even non-conventional designs can further reduce aerodynamic noise.

Building effects significantly influence wind flow and turbulence patterns around rooftop wind turbines, posing both challenges and opportunities for their operation. Buildings can create complex wind environments characterized by turbulent flows, wind shear, and vortices due to their shapes, heights, and orientations [124-128].

Building-populated areas can create locally sheltered regions and wind channels that either enhance or diminish wind speeds, depending on their proximity and layout. As discussed by Peng et al. [126], the maximum available wind power due to the acceleration effect of the optimized roof shapes reached three times that in an area without buildings. These results evidently suggest that the rooftops of buildings possess great potential for wind power production [129].

Proper placement and orientation of rooftop turbines are crucial to harnessing favorable wind flows and minimizing turbulence. Innovative turbine designs and aerodynamic enhancements can help mitigate these effects by improving the turbine's ability to operate effectively in complex urban wind environments, thereby maximizing energy production and reducing operational challenges.

4.3 Impact on Building Structure

Vibrations generated by the turbine's rotating blades or mechanical components can resonate through the building's framework, causing vibrations that may be felt or heard indoors [115, 130]. This transmission can be particularly disruptive in residential or office environments, affecting daily activities and overall quality of life. Effective mitigation strategies such as using vibration isolation mounts, damping materials, or isolating the turbine from the building structure are crucial to minimize these effects. A mechanical device on the top of the turbine tower support, called a decoupler, helps mitigate vibrations transmitted to the supporting structure, limiting stress generation and acoustic comfort for inhabitants [76].

Noise pollution from sources such as rooftop wind turbines can have significant impacts on both occupants and their surroundings. In residential and office settings, excessive noise can disrupt daily activities, impair concentration, and disturb sleep patterns, decreasing productivity and overall well-being. Wind turbine noise is associated with increased noise annoyance, but not with stress effects and sleep bio-physiological variables [131]. Exposure to wind turbine noise up to 46 dBA is not associated with health-related endpoints like migraines, tinnitus, dizziness, sleep disturbance, sleep disorders, quality of life, and perceived stress [66].

Even in an urban area, this noise pollution could impact domestic animal’s life and natural habitats. Effective mitigation measures, including advanced turbine design, soundproofing technologies, and strategic placement, are essential to minimize noise pollution and ensure sustainable integration of wind energy systems while preserving the comfort and health of surrounding communities. According to [132], a multifaceted approach, including accurate local noise surveys, noise modeling, vibration assessment, and site-specific wind data, is necessary for efficient building-integrated wind turbines.

Structural integrity concerns arise when integrating rooftop wind turbines into building structures. These turbines can impose significant stresses on buildings, potentially leading to structural damage such as cracks, deformations, or even structural failure if not properly supported or if the building lacks the necessary structural capacity. Proper assessment of the building's structural adequacy, reinforcement where necessary and adherence to safety standards, are crucial to mitigate these risks. Regular inspections and maintenance help ensure the continued safety and longevity of the building and the integrated wind energy system. Predictions of wind energy potential in urban areas are challenging due to the large number of parameters involved and the need for a large-scale assessment at city or country scales [34].

4.4 Measurements and Analysis

Regarding the mechanical components, especially for large wind turbines, condition monitoring (CM) techniques have been incorporated in wind turbines (May, 2016). The main CM techniques, along with the signal processing methods used for diagnosis and their applications in wind power, are discussed by Koukoura et al. [133]. However, vibration control in turbines varies significantly between large and small-scale systems due to differences in design, operational environments, and purposes. In large-scale turbines, the sheer mass and size lead to different natural frequencies and vibration modes compared to their smaller counterparts. According to Zuo & Hao [108], Vibration mitigation in wind turbines is challenging due to complex dynamic behaviors, limited space in towers and blades, and limited conventional control devices. Larger turbines exhibit more structural complexity, requiring advanced modeling and analysis techniques to understand and mitigate vibrations effectively. Additionally, large-scale turbines often use high-grade materials with superior fatigue resistance and are installed in environments with stringent regulatory requirements. In contrast, small-scale turbines have simpler structures, making them easier to model and analyze. They often use more cost-effective materials and are installed in more varied environments with less regulatory oversight. Also, small-scale turbines experience less pronounced aerodynamic forces because of their smaller blades and lower tip speeds. Their smaller components make mechanical imbalances easier to control, and they generally face lower operational loads. Bukala et al. [134] present an evolutionary computing methodology for small wind turbines supporting structures by a comprehensive methodology for small wind turbines supporting structures, combining genetic algorithms, finite-element structural analyses, and economic evaluation.

The vibration control techniques applied to large-scale turbines benefit from advanced monitoring systems that use real-time data to detect and address vibration issues. The use of active control systems, such as active mass dampers, is often employed to manage vibrations dynamically. Also, maintenance schedules are crucial for identifying and mitigating potential problems. According to Feng Xie et al. [73], viscous dampers have the best efficacy among passive control systems for vibration control in wind turbines. The foundation design for large-scale turbines is typically heavy and complex to minimize vibrations transmitted to the environment. In contrast, small-scale turbines rely more on basic monitoring systems and passive control methods, such as damping materials and tuned mass dampers. Their maintenance procedures are more straightforward and less frequent, and their foundation designs are lighter and more straightforward.

Some recent works point towards monitoring techniques for vibration in small-scale rooftop wind turbines, although still not very common from the commercial point of view. Tatsis et al. [135] established a numerical benchmark for condition assessment of a small-scale wind turbine blade using a finite element model and artificial damage scenarios. Wang et al. [130] carried out a dynamic study of a rooftop vertical axis wind turbine tower based on an automated vibration data processing algorithm. A computerized algorithm based on stochastic subspace identification (SSI) with a fast-clustering procedure can process ambient vibration data for mode identification in rooftop vertical axis wind turbines.

Several techniques are employed to measure and analyze vibrations in large and small-scale wind turbines. Experimental methods are widely used due to their direct measurement capabilities. Accelerometers are commonly attached to various parts of the turbine, such as the blades, nacelle, tower, and mounting structure, to measure acceleration and thus infer vibration levels [90]. Laser Doppler Vibrometry (LDV) provides a non-contact method of measuring the velocity and displacement of vibrating surfaces, making it particularly useful for assessing vibrations in rotating components like blades. Strain gauges, which measure the deformation of turbine components under vibration forces, are often placed in critical areas to gather data on the mechanical stresses involved. Additionally, microphones can capture airborne noise generated by vibrations, providing an indirect measurement of vibration levels. At the same time, seismometers measure ground vibrations to assess the impact on the building structure hosting the rooftop turbine. Civera and Surace [82] presented a literature review of the last 20 years of using non-destructive techniques for structural health monitoring of wind turbines. Non-destructive techniques have advanced significantly in condition and structural health monitoring of wind turbines over the last 20 years, offering practical solutions for both mechanical and civil engineering fields.

Analytical techniques complement experimental methods by providing deeper insights into the nature of vibrations. Frequency analysis, which involves the use of Fast Fourier Transform (FFT) techniques, helps in identifying the dominant frequencies in vibration signals and their sources.

Modal analysis, both experimental and numerical, aids in understanding the natural frequencies, mode shapes, and damping characteristics of the turbine components, which are critical for predicting their dynamic behavior under operational conditions.

Numerical techniques offer powerful tools for simulating and analyzing the vibration behavior of wind turbines. Finite Element Analysis (FEA) models the turbine and its components to simulate their response to various loading conditions, predicting natural frequencies, mode shapes, and dynamic responses [90, 130, 136, 137]. Computational Fluid Dynamics (CFD) simulations provide insights into the aerodynamic forces acting on the turbine blades, which are essential for understanding aerodynamic-induced vibrations [97, 124, 128, 138, 139]. Multi-body dynamics (MBD) simulations model the interaction between different turbine components, considering their dynamic behavior and contact forces, thereby offering a comprehensive view of the vibration response of the entire turbine system [140, 141].

Hybrid techniques, which combine elements of both experimental and numerical approaches, provide a more holistic assessment. Operational Modal Analysis (OMA) involves measuring the operational vibrations of the turbine while it is running to identify modal parameters, combining experimental data with analytical models for accurate assessments. Data fusion techniques, which integrate data from various sensors and measurement methods, offer a more comprehensive understanding of the vibration characteristics, enabling better diagnosis and mitigation of potential issues [80, 130, 142, 143].

By leveraging these diverse techniques, engineers can accurately assess the vibration behavior of small-scale wind turbines, identify potential issues, and develop effective mitigation strategies. This comprehensive approach is essential for ensuring the reliable and efficient operation of rooftop wind turbines, thereby contributing to their successful integration into urban renewable energy systems.

4.5 Social Impact and Community Acceptance

The social impact and community acceptance of rooftop wind turbines are influenced by various factors, including visual impact, health and safety concerns, community involvement, and economic considerations. While there is a steady increase in academic publications and industry reports [24, 144] the field of small rooftop wind turbines has fewer studies compared to more established renewable technologies. Urban-specific wind energy research is often part of broader studies on distributed energy systems or microgrids. As urbanization continues and cities aim to achieve carbon neutrality, research into small-scale urban wind energy will likely accelerate. Investments in green energy infrastructure, advances in wind turbine technology, and growing interest in decentralized energy systems are expected to drive further exploration of this area in the coming years.

As highlighted by Khorsand et al. [24], increased community involvement and fair distribution of earnings and costs positively affect social acceptance of wind energy projects. The work of Yuan et al. [145] demonstrates that residents in Shandong Province, China, show general support for wind power development. Still, support drops when small-scale wind turbines are installed or electricity prices increase. Higher acceptance levels of wind turbines are found in areas with participatory decision-making, turbine ownership by citizens, and electricity consumption in the region [146].

As seen in a few published works on this subject, the answer to the social impact and community acceptance of the acceptability of rooftop wind turbines is not straightforward. Factors influencing social acceptance of rooftop wind turbines include project characteristics, perception of cost and benefit distribution, public participation, and impacts on landscapes, property values, health, and biodiversity [147].

As reported by Ellis and Ferraro [147], social acceptance cannot be sufficiently addressed through simple 'fixes' such as one-off consultation events or community benefit packages. There is complexity, going from structural issues related to trust in state institutions up to cultural influences and citizen relationships with the energy system. Also, the transition to a low-carbon economy is challenging a wide range of aspects of society, and the tensions arising from the social acceptance of wind are just one of these.

Rooftop wind turbines are increasingly used in urban environments to harness renewable energy. However, the noise generated by these turbines can be a significant concern, especially in densely populated areas. Noise levels from wind turbines can vary significantly. For instance, a study on a 200 kWp wind turbine generator installed on a rooftop reported a high noise level of 94.67 dBA at a distance of 1 meter from the base, which was reduced to 77.76 dBA after modifications to reduce vibration [148]. Another study measured A-weighted sound levels at 125 feet distance for individual wind turbines with power ratings between 20-120 kW, finding levels typically in the range of 65-75 dB under moderate to high power output conditions [149].

4.6 Mitigation Strategies

Mitigation strategies for noise and vibration in rooftop wind turbines focus on minimizing their impact on building occupants and surroundings. Effective measures include using vibration isolation mounts and damping materials to reduce the transmission of vibrations from the turbine into the building structure. Implementing advanced turbine design features such as aerodynamic blade profiles and noise-reducing technologies like serrated trailing edges or winglets help mitigate aerodynamic noise at the source. Strategic placement of turbines and proper orientation can minimize turbulence and optimize wind flow patterns, thereby reducing noise generation. Regular maintenance and inspections are essential to identify and address potential noise and vibration issues early. Overall, a holistic approach combining engineering solutions, soundproofing techniques, and operational considerations ensures that rooftop wind turbines operate quietly and harmoniously within urban environments, enhancing their acceptance and sustainability.

Vibration isolation techniques are crucial for minimizing the transmission of vibrations from rooftop wind turbines into building structures and surrounding environments. These techniques typically involve using specialized mounts and damping materials that absorb and dissipate vibration energy before it can propagate through the building. Standard methods include employing resilient mounts or isolators that decouple the turbine from the building structure, thereby reducing direct contact and vibration transmission paths. Additionally, installing vibration-absorbing pads or materials under the turbine's base can further attenuate vibrations. Effective vibration isolation not only enhances occupant comfort by reducing noise and structural vibrations but also helps protect the building's integrity by mitigating potential damage from prolonged exposure to dynamic forces. Proper selection, installation, and maintenance of vibration isolation systems are essential to ensure the long-term performance and sustainability of rooftop wind turbines in urban settings.

Aerodynamic optimization of turbine blades is essential for maximizing the efficiency and performance of rooftop wind turbines. This process involves designing blades with optimal aerodynamic profiles that minimize drag and turbulence while maximizing lift and energy captured from the wind. Techniques such as airfoil shaping, twist distribution along the blade length, and incorporating features like serrated trailing edges or winglets are employed to enhance aerodynamic performance. By reducing aerodynamic losses and improving energy conversion, optimized turbine blades enable turbines to operate effectively in varying wind conditions typical of urban environments. This not only increases energy output but also reduces noise and vibration, contributing to the turbines' acceptance and integration into urban settings while enhancing overall sustainability.

Structural reinforcement of buildings is crucial when integrating rooftop wind turbines to ensure safety, durability, and performance. This process involves assessing the existing building structure to determine its capacity to support the additional loads and dynamic forces imposed by the turbine. Reinforcement measures may include strengthening key structural elements such as beams, columns, and foundations to accommodate the weight and operational stresses of the turbine. Proper reinforcement not only mitigates risks of structural damage such as cracks or deformations but also enhances the building's resilience to wind-induced loads and vibrations. Engineers employ advanced techniques and materials to bolster structural integrity, ensuring the building can safely and effectively host rooftop wind turbines over their operational lifespan. Regular inspections and maintenance further ensure continued safety and optimal performance of the building and integrated wind energy system.

Noise control measures for rooftop wind turbines are essential to mitigate their impact on building occupants and surrounding environments. These measures focus on reducing both aerodynamic and mechanical sources of noise. Aerodynamically, turbines can be designed with optimized blade profiles, serrated trailing edges, or other aerodynamic features to minimize turbulence and noise generation. Mechanically, using vibration isolation mounts and damping materials helps absorb and dissipate vibrations before they can propagate into the building structure, thereby reducing noise transmission. Strategic placement of turbines and careful orientation can further minimize noise by optimizing wind flow patterns and reducing turbulence. Regular maintenance and monitoring are crucial to identify and address noise issues promptly. By implementing these comprehensive noise control measures, rooftop wind turbines can operate quietly and harmoniously within urban environments, enhancing their acceptance and sustainability while preserving the comfort and well-being of occupants.

4.7 Practical Applications

Urban installations of rooftop wind turbines have taught valuable lessons for future deployments. Understanding the complex and variable wind environments in urban settings is crucial. Turbines surrounded by buildings experience turbulent wind patterns affecting performance. Optimal placement, height, and orientation are essential to maximize energy capture while minimizing noise and vibrations that may disturb occupants.

Structural compatibility is critical. Integrating turbines with existing buildings requires assessing structural capacity and possibly reinforcing them to withstand additional loads and dynamic forces. Noise and vibration management strategies are vital for community acceptance. Advanced turbine design and isolation techniques reduce noise transmission and optimize performance. Regulatory compliance, community engagement, and maintenance are essential. Engaging stakeholders early, adhering to regulations, and ensuring proactive maintenance enhance project viability and sustainability. Continuous technological innovation drives turbine efficiency and integration in urban environments. Applying these lessons ensures future rooftop wind turbine installations are efficient, accepted, and sustainable contributors to urban energy needs.

5. End-of-Life of Wind Turbine Blades

In this section, the end-of-life of wind turbines is discussed. Giving a destination to the blades and other non-recyclable components of a wind turbine after its end-of-life is a challenge. However, there are several proposed solutions, including recycling and circular economy practices.

5.1 Deterioration of Wind Turbine Components by Corrosion

Corrosion is among the main modes of deterioration of wind turbine components. Al-Moubaraki [150] stated that the corrosion process is influenced by environmental factors, such as humidity, temperature, wind velocity, and atmospheric pollutants. According to the author, it is also essential to differentiate between corrosion occurring without mechanical stress and corrosion coupled with mechanical stress. Some types of corrosion without mechanical stress are selective, uniform, dew point, crevice, pitting, scaling, deposition and microbiologically influenced corrosion. Some types of corrosion with mechanical stress are erosion, stress corrosion cracking, cavitation, fretting corrosion fatigue and strain-induced corrosion. There are several methods for corrosion detection, as shown in Figure 11, [151]. The corrosion protection methods can be divided into two categories: active and passive methods. The active corrosion protection techniques are corrosion allowance, influencing the corrosion medium, appropriate constructive design, selection of corrosion resistant materials and cathode corrosion protection. Passive corrosion protection strategies encompass using linings and protective coatings, to segregate the material from the corrosive surroundings.

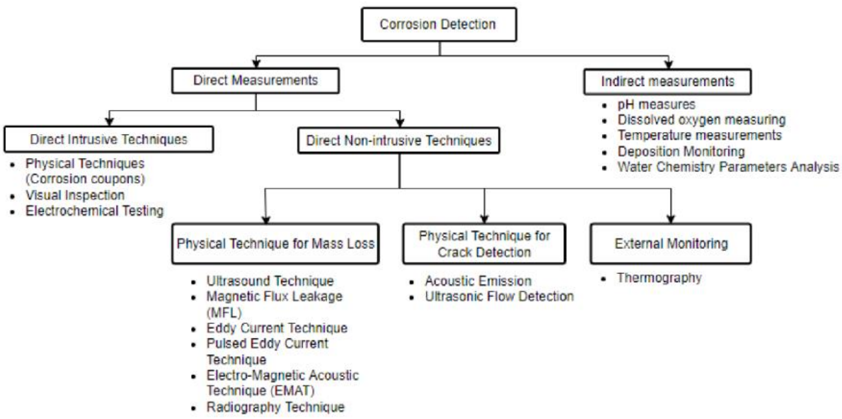

Figure 11 Methods of corrosion detection [151], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

5.2 Wind Turbine Blades Waste Policy and Strategies

According to Majewski et al. [152], with a lifetime of 20 to 25 years for a wind turbine, the cumulative composite waste from the blades to be recycled will be in the tens of thousands of tons worldwide by 2050. There are three common pathways for the wind turbine blades waste: direct deposit in a landfill, incineration and recycling. Only 30% of the fiber-reinforced plastic material from wind turbine blades can be reused to form new composite materials, with most going to the cement industry as filler material. There are legislations for the end-of-life management of wind turbine blades that can be used as models. While in the United States the disposal of wind turbine blades in landfills is the most attractive option, due to the amount of land available and the low cost, many European countries have banned or reduced wind turbine blade landfilling, due to environmental problems, which made the recycling and reuse processes of wind turbines blades be considered. Countries such as Germany, Austria, the Netherlands and Finland do not allow composites being incinerated as well.

Beauson et al. [153] describe the decisions to be made towards the end-of-life of wind turbine blades, considering the cost, technical feasibility, legislation and environmental impacts. Figure 12 shows the value chain of the end-of-life wind turbine blades. Figure 13 shows the decision points of Figure 12 and related questions.

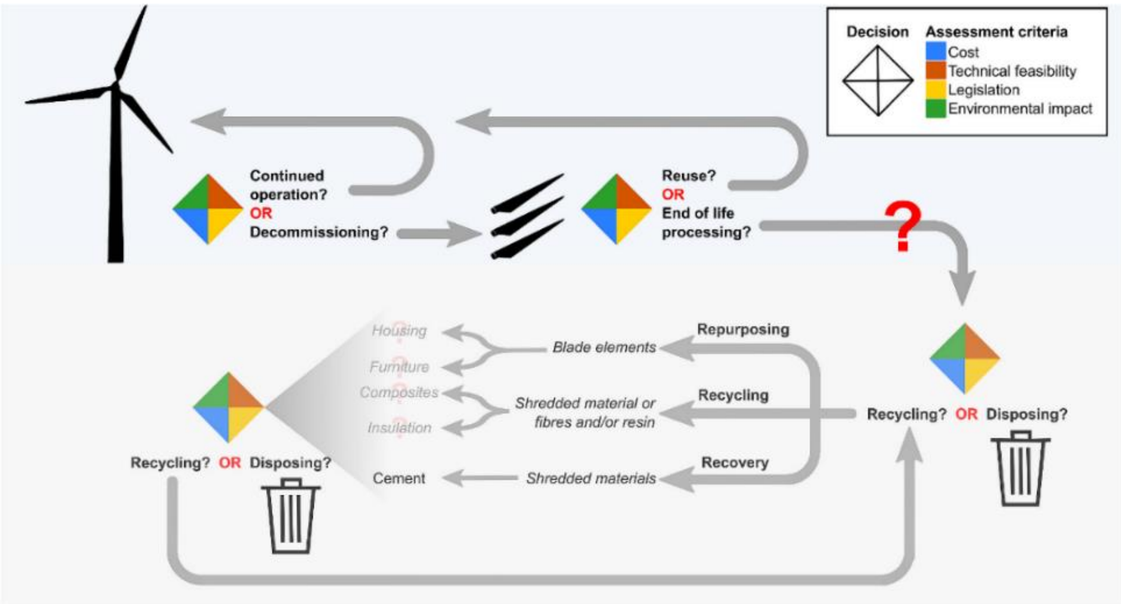

Figure 12 Value chain of end-of-life wind turbine blades [153], permission for use authorized by Elsevier.

Decisions	Economic	Technical feasibility	Legislation	Environmental impacts
Decommissioning OR continued operations?	Is it profitable to continue operating the turbine?	What is the damage state of the wind turbine blades?	Can the turbine continue its operations where it is installed?	What are the environmental impacts of continuing the operations vs decommissioning?
Reuse OR end-of-life processing?	Can the blade be sold as spare parts?	What is the damage state of the wind turbine blades?	Are there legislation preventing reuse (second hand market)?	What are the potential environmental impacts of extending the lifetime of the blade by reusing it?
Recycling OR disposing?	What is the landfill tax? What is the value of the materials in the wind turbine blades and the recycled ones?	Is it possible to recover materials with properties and quality valuable to any applications?	Are there legislation preventing landfill? Are there legislation on the use of recycled wind turbine blade materials for targeted applications?	What are the potential environmental benefits and impacts of recycling the blades *vs.* disposing them?

Figure 13 Decision points of Figure 12 [153], permission for use authorized by Elsevier.

Considering the end of life of wind turbines, the authors pointed to research, industry, and policy needs. Research needs are: methods to assess the general state of the blades to facilitate reuse and repurpose applications; ways to predict the availability time of wind turbine blades; design solutions to enable the end-of-life processing of blades; methods to design blades for recycling and recycling processes; formulation of standards on the use of recycled wind turbine blade materials; assessment of different wind turbine designs and recycling options, to identify the environmentally preferable alternatives. Industry needs are: standards on decommissioning; consideration of the end of life in the design of wind turbine blades; refinement of the estimations on wind turbine blade waste, to be applied on business models. Policy needs are: tracing the end-of-life wind turbine blades to facilitate the estimations of the waste amounts and locations for policy development; harmonized regulations on composite waste across different countries and regions of the world; standard on the use of recovered materials from end-of-life wind turbine blades; guidelines for recycling solutions, based on economic, social and environmental impacts.

According to Zhang et al. [154], the development of end-of-life wind turbine blades waste recycling sector depends on the following aspects:

- Standardization and certification, which ensure the quality, consistency and safety of recycled blades, making them suitable for civil engineering applications.
- Efficient transport systems that may involve specialized equipment and logistics planning, as well as optimized transport routes and modes.
- Establishing a recycling supply chain for wind farms to efficiently and economically cut and transport end-of-life wind turbine blade waste to recycling facilities.
- Economic feasibility analysis, to assess the costs and revenues associated with the collection, transport, processing and material recycling. This also involves the exploration of business models, and the identification of market demand for recycled end-of-life wind turbine blades.

Zhang et al. [154] also point to the hierarchical valorization aspects that can be explored for recycled end-of-life wind turbine blades in civil engineering:

- Material processing and modification.

- Material characteristics and quality control.
- Development of new construction products, such as concrete, mortar, road materials (such as asphalt) etc.
- Compatibility with existing manufacturing processes.

In the review work of Jansen and Skelton [155], the best available wind turbine blade waste treatment technologies in Europe are outlined. However, the authors stated a lack of practical experience in applying secondary materials to new products. Their work also describes the GENVIND innovation consortium, which was a Danish project that sought to evaluate different recycling technologies for composite waste and demonstrate how composite waste can be reused, especially in secondary applications, such as architectural structures, consumer goods and industrial filler material, using the circular economy principles.

5.3 Wind Turbine Material Waste Statistics and Forecasts

Tazi et al. [156] quantified the end-of-life wind turbine material wastes in the Champagne-Ardenne (CA) region in France, from 2002 to 2016, considering the French wind turbine's economic lifetime of 15 years. CA wind turbines represent over 20% of all French onshore wind turbines. For the highest maintenance scenario, their results showed that more than 1,614,216 tons of end-of-life wind turbine materials would be generated between 2002 to 2016, distributed as follows: 556,3830.5 tons of steel and iron materials; 25,602 tons of aluminum; 7,480 tons of copper; 49,290 tons of polymer materials (plastics); 268 tons of lacquers and adhesives; 23,233 tons of glass and composite; 948,389 tons of concrete. Considering the wind turbine population in France (disregarding the concrete foundation), 73% of the wind turbine is recyclable and 10% of the total material goes for incineration.

In the present, China has the largest installed wind power capacity globally. According to Yang et al. [157], based on the current installations and future projections of wind turbines, 7.7 to 23.1 million tons of blade waste will be generated in China by 2050. Tyurkay et al. [158] estimate that the projected growth in onshore and offshore wind energy in Europe in 20 years would generate 3 million tons of end-of-life wind turbine blades fiber-reinforced plastics, of which the responsibility is not currently allocated in the industry and, therefore, the supply chain is not prepared for this amount of waste.

In the review work of Delaney et al. [159], data and forecasts regarding end-of-life wind turbine blade materials are presented, with upper and lower bounds for the mass-to-capacity models (10 t/MW and 15 t/MW) and different wind turbine lifespans (15, 20 and 30 years). Figure 14 shows the total end-of-life blade material for each decommissioning interval, and Figure 15 shows the global annual end-of-life wind turbine blade material quantities.

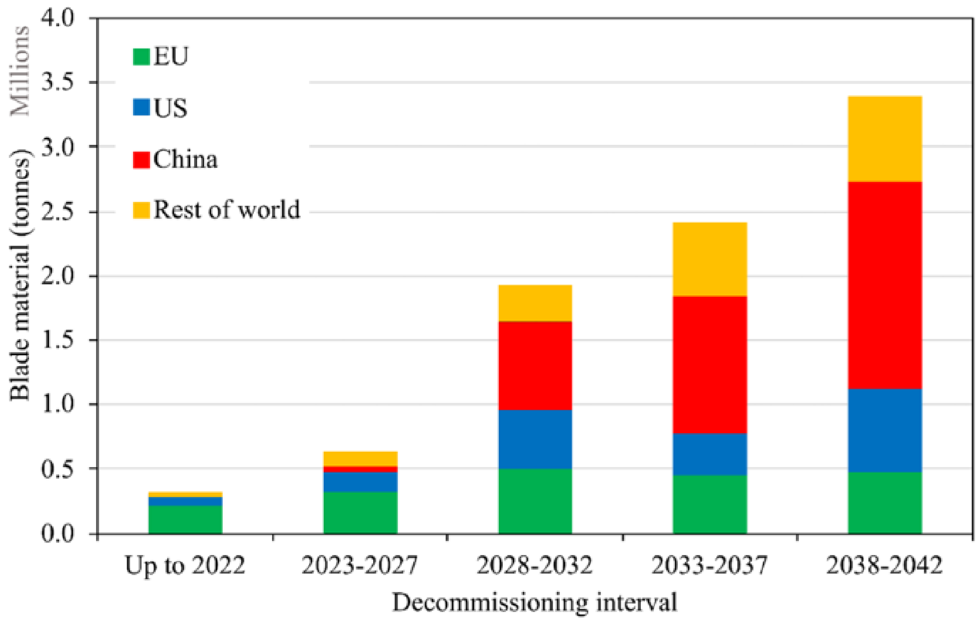

Figure 14 Total end-of-life blade material quantities for each decommissioning interval based on a 20-year service life and a fixed 10 t/MW scenario [159], modified, permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

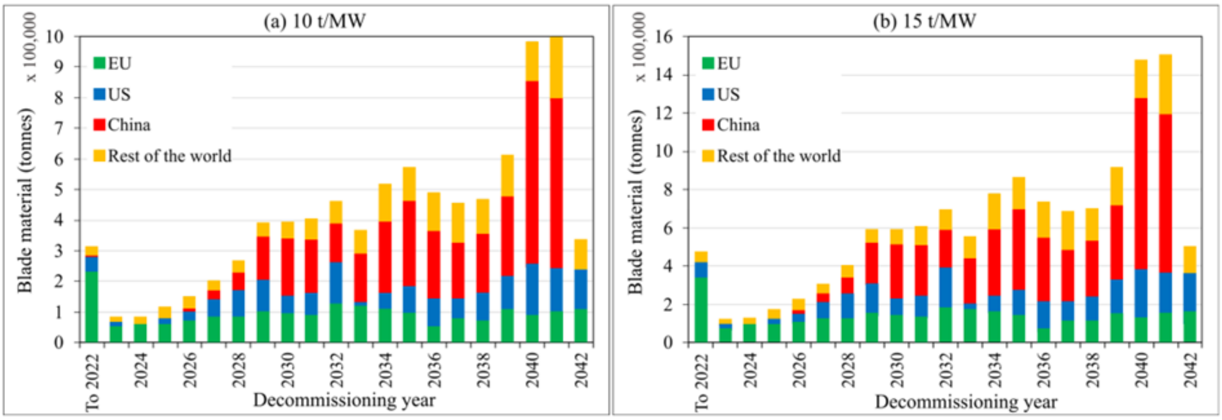

Figure 15 (a) Based on 10 t/MW model; (b) Based on 15 t/MW model [159], modified, permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

5.4 Waste Recycling and Reusing Methods for Wind Turbine Blades

Approximately 94% of a wind turbine's mass is recyclable, but the waste polymer composite blades are mostly landfilled [160]. Wind turbine blades and nacelles are typically made of composite materials, representing more than 90% of the blades' materials. Most blades consist of polymer composites reinforced with glass fiber, and some are reinforced with carbon fiber [161]. On the other hand, the generator, tower and other components are manufactured from metals.

Paulsen and Enevoldsen [161] divide the recycling of end-of-life wind turbine blade waste methods into three main categories: mechanical, thermal and chemical. Figure 16 shows the possible recycling methods.

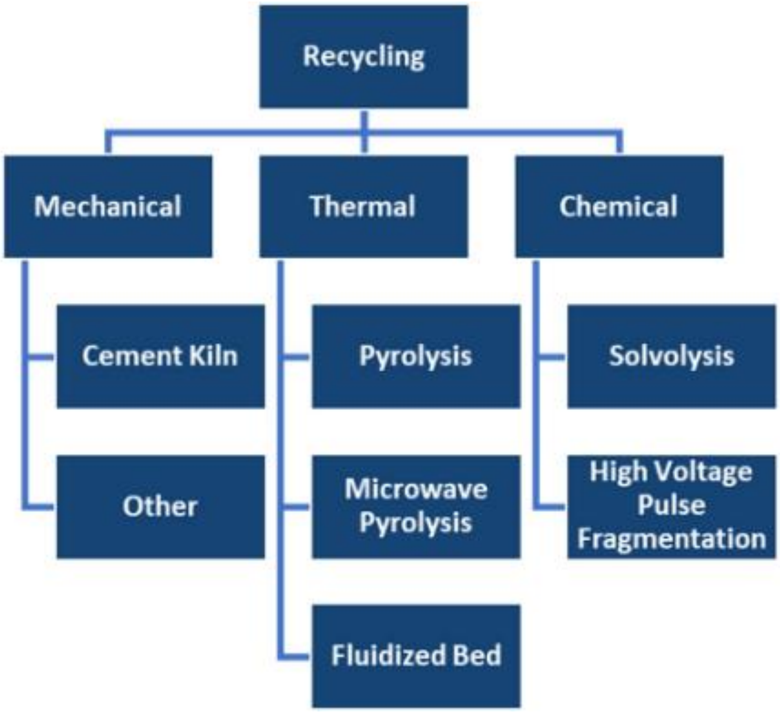

Figure 16 Possible recycling methods for end-of-life wind turbine blade waste [161], permission for use authorized by Multidisciplinary Digital Publishing Institute, MDPI.

In mechanical recycling, mechanical shredders divide the composite material into smaller parts. The residual product can be used for the creation of new products or substituting the raw materials in the production of new material (co-processing). The thermal recycling can be divided into two groups (disregarding the fluidized bed): pyrolysis and microwave pyrolysis. The pyrolysis process heats the composite in the presence of oxygen, while microwave pyrolysis uses microwaves to heat the material. The heat breaks the organic material (resin) into lower-weight molecules. The inorganic materials are left intact for recovery. However, the higher the temperature, the greater the degradation of the fibers, which makes it difficult for residual materials to compete with virgin fiber materials. The most common chemical recycling method is the solvolysis, which uses a solvent to depolymerize the chemical cross-linked bond present in thermoset polymer products. The high voltage pulse fragmentation (HVPF) is also classified as a chemical recycling method [161].

5.4.1 Thermal Recycling

According to Kalkanis et al. [162], the optimal technology for composite recycling is pyrolysis, which leaves the quality of the recycled fibers degraded. In the pyrolysis, the depolymerization occurs at high temperatures between 300°C and 1,000°C in the absence of oxygen, and the polymer breaks down to produce an oil, a gas and a char product, leaving a solid residue. The fibers are then reclaimed. Oil and gas can be used as fuels, representing energy recovery, which benefits the environment [163]. In the Cheng et al. [164] pyrolysis study, when the wind turbine blade waste was pyrolyzed at 420-450°C for 5-6 h, the purity of recycled fiber was above 99% and its tensile strength decreased less than 10%, compared to the original fiber. The concentration of SO_2 in the flue gas had a negligible impact on the quality of the recycled fiber, due to its non-reactivity with SiO_2. Increasing the pyrolysis temperature increased the purity of the recycled fiber and decreased its tensile strength.

Microwave pyrolysis is similar to the conventional pyrolysis. In the microwave pyrolysis, microwaves are used to heat the material. The organic materials are decomposed into low molecular weight substances, while the inorganic materials remain. The microwave pyrolysis occurs in a nitrogen atmosphere chamber between 300°C and 600°C. The advantage of heating with microwaves is that the bulk of the waste material is heated throughout and at the same temperature. Also, polymers usually have low thermal conductivity, which means that microwave pyrolysis can keep the temperature of the process lower than regular pyrolysis. The lower temperatures cause less thermal degradation of the glass fibers, which is another advantage of microwave pyrolysis [161].

5.4.2 Mechanical Recycling

According to Paulsen and Enevoldsen [161], mechanical recycling utilizes mechanical shredders to divide the composite into smaller parts. These parts can be used as fillers, reinforcements or as raw material for new plastic products or cement production. The output of mechanical recycling can be divided into two categories: utilization of materials and co-processing. In the utilization of materials, the residual material, after being processed, is used for the creation of new products. In co-processing, the residual material is used as a substitute for new raw materials to produce new materials. In co-processing, the residual inorganic material can replace new raw organic material, while contributing to incineration and thus reducing the use of fossil fuels, which is beneficial for the environment.

The work of Revilla-Cuesta et al. [165] demonstrates the mechanical and environmental advantages of incorporating raw-crushed wind turbine blades (RCWTB) in concrete. The overall addition of RCWTB up to 6% by volume in concrete can lead to an improvement of 1.5% in the compressive strength in a conventional concrete design, yielding values above 50 MPa in 28 days. This content reduced the carbon footprint per unit of compressive strength by 0.12 $kgCO_2eq/(MPa\cdot m^3)$. Also, 6% of RCWTB improved flexural strength by more than 6 MPa, reducing the carbon footprint per unit of flexural strength by 7.5%.

In the study of Beaumont et al. [166], shredded composite (SC) obtained from the load-carrying beam of a wind turbine blade was used to manufacture composites with a controlled amount of SC. The porosity content was determined to be 1 vol%, indicating high material quality. The measured stiffness and strength of the SC composites were compared to theoretical predictions. The experimental stiffness in the range of 4.0-5.8 GPa were well predicted. In contrast, the experimental strengths in the range of 15-29 MPa were significantly lower than the theoretical predictions in the range of 81-118 MPa. The low failure strength and strain of the composites are due to insufficient bonding between the SC composites and the new polyester matrix. This problem can be solved with the application of a physical or chemical treatment of the SC or the use of an alternative resin such as epoxy to improve the bonding.

5.4.3 Chemical Recycling

The most common chemical recycling process is solvolysis, which is a method that utilizes a solvent composed of catalysts/additives, in combination with temperature and pressure, to depolymerize the chemical cross-linked bond present in thermoset polymer. The solvents may be alcohol, water, and other substances. Solvolysis can occur at high temperatures (higher than 200°C) and pressure or low temperatures (lower than 200°C) and pressure. The high temperatures can represent a problem, since some materials lose their properties. Another problem of solvolysis is that the choice of solvent, temperature, and pressure depends on the construction of the composite material. Finally, solvolysis can be considered more dangerous, compared to mechanical and thermal recycling, as the substances used can harm the environment [161].

5.5 Waste Management and New Materials

Spini and Bettini [167] described a waste management hierarchy, with additional approaches and strategies for end-of-life wind turbine blade waste. The items of the waste management hierarchy are:

- Prevention: based on this approach, blades are designed to have an extended lifespan, to facilitate recycling, or to reduce the amount of material usage.
- Reuse: some blades can be reinstalled in new plants after being decommissioned.
- Repurpose: this approach involves the reutilization of wind turbine blade sections for purposes different than their original one.
- Recycling: mechanical, thermal or chemical methods.
- Recovery: two examples are co-processing in cement kilns to recovery materials and energy, and incineration to reclaim heat or energy.
- Disposal: landfilling or incineration without energy recovery is the lowest in the waste management hierarchy.

According to Dorigato [168], considering the issues related to recycling traditional thermosetting composites, more attention should be paid to recyclable and environmentally friendly composite blade materials. An interesting option for the future is the use of modified thermosetting resins that could be processed like a traditional epoxy resin and recycled like thermoplastics with heat or irradiation. The problem with this solution is the limited number of matrices available on the market and their cost. On the other hand, developing composite blades with natural fibers embedded in biodegradable matrices is another interesting solution due to the lower energy required for blade production and the possibility of disposing of the materials through biodegradation. However, some problems related to this solution are the constancy of the thermo-mechanical properties of the reinforcements and the water absorption of biodegradable matrices. Mishnaevsky [169] stated that wind turbine new generation materials, such as natural fiber composites, wood-based and bamboo composites, were successfully tested and can be well used for small or even medium-sized wind turbine blades. However, their application for large wind turbines is still constrained, due to inferior properties or technological challenges.

5.6 Comments

There is no ideal method for recycling wind turbine blade waste material. The current techniques are divided into three categories: mechanical, thermal and chemical. The pyrolysis is a thermal method that appears to show most advantages. However, there are also negative aspects, such as the material properties degradation. In the short term, the current recycling methods must be improved to absorb future demands from wind energy plants implemented in recent decades. In the long term, solutions that involve the use of materials that are more easily recycled or biodegradable materials seem to be the most suitable for dealing with the problem of end-of-life wind turbine blade waste.

6. Conclusions

In this work, the performance of small and medium-sized wind turbines, particularly HAWTs and VAWTs, was reviewed, focusing on their use in buildings and urban districts. The concluding points, as well as challenges for future research are summarized as follows:

Recent advancements in turbine design and placement strategies have shown that efficiency can be significantly improved, making rooftop/facade wind energy a viable component of urban renewable energy solutions.

On the other hand, the environmental impact of rooftop/facade wind turbines is substantial in the context of district decarbonization. These urban systems can contribute to significant reductions in carbon emissions, thus aiding cities in meeting their sustainability targets. While the potential for noise pollution and aesthetic concerns exists, innovative designs and careful placement can mitigate these issues, making wind turbines more acceptable in urban settings.

Moreover, innovations in turbine design, such as lightweight and durable materials, are enhancing the performance of these urban machines while the costs are decreasing over time.

However, many technical challenges are ahead, such as wind speed variability and the structural integrity of buildings.

Development of advanced materials and innovative designs to enhance performance and reduce the costs of rooftop/facade wind turbines. One key area of focus is advancing turbine design explicitly tailored for urban settings.

Understanding urban wind patterns in greater detail will also be crucial for optimizing turbine placement and maximizing energy output.

Future research includes optimizing the aerodynamics of turbines placed atop buildings to better harness wind resources and minimize disturbances to urban airflow patterns.

Research on noise mitigation involves developing more effective vibration isolation mounts, quieter blade designs, and acoustic materials to reduce the noise footprint of rooftop turbines in urban environments.

Implementing pilot projects and case studies is essential to gather real-world data on the performance, economic feasibility, environmental impact, and public acceptance of rooftop/facade wind turbines.

Abbreviations

AI	Artificial Intelligence
BEM	Blade Element Momentum
BIWT	Building-integrated wind turbine
CA	Champagne-Ardenne
CFD	Computational Fluid Dynamics
CM	Condition Monitoring
Cp	Power Coefficient

DMST	Double-Multiple Stream Tube
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
HAWT	Horizontal Axis Wind Turbines
HBD	High Building Density
HVPF	High Voltage Pulse Fragmentation
LBD	Low Building Density
LDV	Laser Doppler Vibrometry
MBD	Multy-Body Dynamics
ML	Machine Learning
MRF	Multiple Reference Frame
NACA	National Advisory Committee for Aeronautics
N-S	Navier-Stokes
OMA	Operational Modal Analysis
RANS	Reynolds-Averaged Navier-Stokes
RCWTB	Raw-Crushed Wind Turbine Blades
RSM	Response Surface Method
SC	Shredded Composite
SHM	Structural Health Monitoring
SMI	Sliding Mesh Interface
SSI	Stochastic Subspace Identification
TSR	Tip Speed Ratio
VAWT	Vertical-axis Wind Turbines
WT	Wind turbine

Author Contributions

Kamal Ismail: Conceptualization, Writing – review and editing; Fatima Lino: Writing – review and editing; Pedro Baracat: Writing – original draft; Odenir de Almeida: Writing – original draft; Mohamed Teggar: Writing – review and editing; Abdelghani Laouer: Writing – original draft.

Competing Interests

The authors have declared that no competing interests exist.

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