

Review

Perspectives of Building-Integrated Wind Turbines (BIWTs)

Mladen Bošnjaković ^{1,*} , Nataša Veljić ¹ and Ivan Hradovi ²¹ Technical Department, University of Slavonski Brod, Trg Ivane Brlić Mažuranić 2, 35000 Slavonski Brod, Croatia; nveljic@unisb.hr² Industrial School, E. Kumičića 55, 35000 Slavonski Brod, Croatia; ihradovi@gmail.com

* Correspondence: mbosnjakovic@unisb.hr

Highlights

What are the main findings?

- BIWTs are still a technological challenge due to their low efficiency in urban environments, their low capacity factor and their high investment and maintenance costs
- The use of new technologies such as computational fluid dynamics (CFD), 3D printing, artificial intelligence, and advanced materials is accelerating the development of more efficient BIWT.

What is the implication of the main finding?

- BIWTs will remain a niche technology in the coming years.
- Technological advances and regulatory incentives could promote their wider application, especially in coastal areas with favorable wind conditions.

Abstract: There is a trend towards urbanization and thus higher energy consumption in buildings, while decarbonization and renewable energy sources (RESs) are becoming top priorities. Building-integrated wind turbines (BIWTs) represent a potential solution, especially in urban areas where space is limited. The aim of this article is to examine the technical, economic, and environmental aspects of the application of BIWTs based on the scientific literature, considering innovations and challenges related to their wider application. The analysis shows that BIWTs have a high capital cost (CapEx) and levelized cost of electricity (LCOE) due to the lower capacity factor, shorter lifetime, and high cost of building integration. However, the application of technologies such as computational fluid dynamics (CFD), additive manufacturing (3D printing), and artificial intelligence (AI) makes it possible to enhance the efficiency of turbines and reduce production and maintenance costs. Esthetically acceptable performance, noise reduction and possible integration with photovoltaic systems further enhance BIWT. In the short term, BIWT will remain a niche market, but policies and legislation mandating greater use of RES in buildings, as well as financial incentives, can significantly boost the growth of BIWT, which is particularly likely in coastal areas with favorable wind conditions. In the long term, BIWT has the potential to make an important contribution to sustainable urban development and the energy transition.



Academic Editor: Pierluigi Siano

Received: 28 February 2025

Revised: 19 March 2025

Accepted: 21 March 2025

Published: 25 March 2025

Citation: Bošnjaković, M.; Veljić, N.; Hradovi, I. Perspectives of Building-Integrated Wind Turbines (BIWTs). *Smart Cities* **2025**, *8*, 55. <https://doi.org/10.3390/smartcities8020055>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: building-integrated wind turbine; urban wind energy; capacity factor; efficiency; LCOE

1. Introduction

There is a trend towards urbanization and thus higher energy consumption in buildings, while decarbonization and sustainable energy sources are becoming top priority. BIWTs are wind turbines that are integrated into the design and structure of buildings, enabling on-site power generation. Unlike conventional wind turbines, BIWTs are installed on roofs, facades, or other architectural elements, transforming urban structures into active energy generators while maintaining esthetic and functional integrity.

With cities accounting for more than 70% of global energy consumption, BIWTs are an answer to the critical challenges of urban energy demand and space constraints. By generating electricity directly at the point of consumption, BIWTs reduce power transmission losses and dependence on the grid, supporting decarbonization goals. Their role is particularly important in densely populated urban areas where rooftop PV systems do not meet the entire energy demand and provide a complementary renewable source.

BIWT systems primarily use vertical-axis wind turbines (VAWTs), which are compact and operate efficiently in turbulent urban wind conditions. These are usually different types of Darrius and Savonius wind turbines, but other types of turbines can also be used. Horizontal-axis wind turbines (HAWTs) are less common due to space constraints, but can be integrated into buildings in special cases, such as the iconic World Trade Center in Bahrain, which has large HAWTs between its towers. Newer designs include microturbines and bladeless designs that blend in well with the architecture.

Ecological, economic, and social reasons speak in favor of the development and application of BIWT. The environmental reasons are the reduction in dependence on fossil fuels, the reduction of CO₂ emissions and cleaner air in cities with less particulate emissions [1]. By generating their own electricity, buildings can reduce the operating costs associated with energy consumption [1]. Many regions offer incentives for the installation of renewable energy systems, including tax breaks, grants, and subsidies to promote green technologies. In addition to the above economic reasons, there is also the possibility of employing labor in jobs related to BIWT. Resilience and energy independence is another reason aimed at providing backup energy sources in regions with unstable energy flows. To a certain extent, esthetic reasons can also be cited, in the sense that BIWTs can improve the attractiveness of modern architecture and promote the commitment of companies or municipalities to “clean energy”.

Governments and institutions are increasingly promoting BIWT through measures such as the US Investment Tax Credit (ITC), feed-in tariffs and net metering. Green building certifications such as LEED award points for the integration of renewable energy sources, while EU directives (Renewable Energy Directives and Energy Performance of Buildings Directives) require the inclusion of renewable energy sources in urban planning. Local spatial planning laws and grants further promote the application of BIWT and position BIWT as one of the essential components of global efforts to reduce climate change. We can say that BIWT is a combination of modern architecture and renewable energy technology that leads the way to transforming cities into self-sufficient, low-carbon ecosystems. The integration of wind turbines into buildings has been developing for decades, driven by energy crises, environmental awareness, and technological innovations. Inspired by the oil crisis in the 1970s, architects and engineers began experimenting with BIWTs, with vertical-axis wind turbines (VAWTs) attracting attention due to their compact design. The World Trade Center in New York City (1970s) briefly tested roof-mounted wind turbines, with the built-in wind turbines proving ineffective in urban wind conditions.

The green building initiatives in the 1990s revived interest in BIWTs. In projects such as the Enercon building (Germany, 1990s), small BIWTs were installed on the roofs. A pioneering project was the installation of a BIWT on the Energy Research Unit (ERU) in

the UK in 1999 as part of an EU-funded initiative led by Imperial College. This project aimed to evaluate optimal designs for the integration of small vertical- and horizontal-axis wind turbines into buildings. The Bahrain World Trade Center (2008) (Figure 1) became a landmark as three HAWTs with a rotor diameter of 29 m and a total capacity of 225 kW were installed between the towers. They generate ~15% of the building's energy needs and produce between 1100 MWh and 1300 MWh per year. The total cost of the wind turbines amounted to approximately 3.5% of the total cost of the project [2,3].

Advances in materials (e.g., lightweight composites) and aerodynamic modeling have improved the efficiency of turbines in turbulent urban environments. As a result, interest in BIWT has increased since 2010. Projects such as London's Strata Tower (2010) (Figure 2) with three 19 kW roof turbines and the 309 m high Pearl River Tower in China (opened in 2013) have become one of the most energy-efficient skyscrapers in the world [4].

This skyscraper has four wind turbines of the Windside type with a vertical axis and a height of 5 m. The wind turbines are installed in air tunnels at heights of 100 and 200 m and produce about 5% of the building's total annual energy requirements. The design also incorporates a variety of energy-efficient technologies, including solar panels and advanced ventilation systems. The Canton Tower, the tallest building in China (Guangzhou, 602 m) and the fourth tallest in the world, was commissioned in 2010 and has two WS-4B turbines at a height of 200 m. The Viikki Environment House office building in Helsinki, Finland (Figure 3), was completed in 2011 and is known for its energy efficiency. It has four WS-030B turbines mounted on the edge of the roof.

The Shanghai Tower (2015) has 270 vertically aligned wind turbines integrated along its spiral-shaped parapet. These smaller turbines harness the turbulent winds of the urban environment at different heights, contributing to the building's sustainability goals. Although the electricity generation is modest compared to large turbines, this project has demonstrated the feasibility of using wind turbines in skyscrapers [2].

Recently, BIWT systems have been combined with other renewable energy and energy storage technologies in nZEB concepts [6]. Examples include bladeless turbines (e.g., Vortex Bladeless) [7] embedded in building facades.

In general, it can be said that BIWTs are used in different types of buildings, as can be seen in Table 1.



Figure 1. The Bahrain World Trade Center [5].



Figure 2. Strata SE1 is a 147 m tall building (London, UK) [5].



Figure 3. Viikki Environment House. (<https://windside.com/gallery/>, accessed on 15 January 2025).

Table 1. Types of buildings where BIWTs are installed.

Building Type	Description
Tall Skyscrapers	BIWTs are often integrated into tall buildings, e.g., skyscrapers several hundred meters high, in order to make efficient use of wind energy, which increases with height.
Commercial Complexes	Large commercial buildings use BIWT to reduce energy costs and increase sustainability. The turbines can be placed on the roof or integrated into the building envelope.
Educational Institutions	Universities and other schools are increasingly using BIWT for educational purposes and to demonstrate their commitment to renewable energy. The Viikki Environment House in Finland is one such example.
Mixed-Use buildings	BIWTs can be integrated into mixed-use complexes that combine residential, commercial and public spaces. This approach not only increases energy efficiency but also promotes the use of renewable energy.
Rooftop Installations	BIWTs of smaller capacity and size can be installed on the roofs of various buildings, including warehouses and factories, to generate electricity on site without the need to acquire and occupy additional land.
Local government buildings	Local government buildings can incorporate BIWT as part of their sustainability initiatives to provide renewable energy for local needs and activities while exploring “green energy”.

The general progress in the development and application of BIWT, especially in the last 15 years, has been significantly supported and enabled by numerous scientific studies dedicated to this topic. By searching and analyzing the available literature on BIWT, the

authors have identified the most important scientific papers, focusing on those published in the last 5 years. The main findings and contributions of these papers are summarized in Table 2 to provide a better overview and comparison.

Table 2. Significant scientific papers related to BIWT.

Author(s)	Aim	Main Results	Ref.
Christian V. Rodriguez Alberto Ríos, Jaime E. Luyo (2020)	This article critically examines and analyzes recent advances in the field of CFD design of BIWTs.	In terms of CFD modeling, the standard k- ϵ turbulence model has been most commonly used. Simulation of BIWT has evolved from 2D to 3D analyzes that include more details on modeling BIWT and urban environments.	[8]
Mao et al. (2021)	The aim of the research is to estimate the efficiency of a Savonius wind turbine installed on the edges of a tall building using transient 2D CFD methods.	The wind angle has a considerable influence on the power output of a Savonius turbine. The average C_p value of the turbine at a wind angle of 360° is 0.4256, which is 92.5% higher than that of a turbine with a steady flow.	[9]
Calautit, K (2023)	The research objective is to assess the status, challenges and limitations of BIWT and micro or small wind vibration technologies in order to improve their performance, efficiency, reliability and cost-effectiveness.	The authors emphasize how important it is to take advantage of the acceleration of wind speed caused by the shape of the building roof when using wind energy technologies.	[10]
Huang, C.; et al. (2024)	The aim is to evaluate methods for determining the location of wind turbines and assessing resources.	Development of methods to optimize the placement of turbines in port and city scenarios.	[11]
Alam, F. et al. (2023)	The main objective of this study is to analyze the limitations of using wind energy through small wind turbines to generate electricity in built-up areas for residential and commercial purposes.	The design of current small wind turbines needs to be modified to take advantage of the aerodynamic benefits of the local wind profile in built-up areas.	[12]
Zagubień, A. et al. (2022)	The aim of this study was to determine whether the wind zone that characterizes a particular area in open space is reflected in the built-up area that lies within the zone	It has been shown that the planning of small wind turbines in urban areas requires data on the annual measurement of wind characteristics at the location and height of each planned turbine.	[13]
Zhang et al. (2023)	This article analyzes the feasibility of using small wind turbines for private households in New Zealand cities with regard to their construction and operation.	It has been shown that small wind turbines for households have considerable potential for generating electricity and bring economic benefits in the long term.	[14]
Kwok, KCS (2023)	This article analyzes a perspective for wind energy research based on the aerodynamics of buildings and cities.	An overview of current developments in wind energy systems in the built environment is given.	[15]
Ding, TJ (2022)	This overview aims to capture the fact that recent advances in wind energy systems can bring tangible benefits to the entire renewable energy industry.	This study provides readers with a knowledge platform to explore possible methods of utilizing urban wind profiles with minimal vibration, noise and space requirements.	[16]
Anh Dinh Lee et al. (2025)	In this study, the effects of novel cylindrical deflector systems on the aerodynamic performance of the Savonius turbine are investigated numerically.	The analysis has shown that the existing natural obstacle shapes can be effectively used as deflectors to improve the aerodynamic performance of the Savonius wind turbine.	[17]

Table 2. *Cont.*

Author(s)	Aim	Main Results	Ref.
Ruiz, Claudio Alanis et al. (2021)	The aim of the work is to investigate the aerodynamic advantages of ventilation openings in buildings and the possibilities of their use for wind energy utilization.	A CFD analysis of the dimensions of the openings in the building was carried out in order to make the best possible use of wind energy.	[18]
Dongxu Li et al. (2021)	The aim of the work is to investigate the aerodynamic performance of the BA-VAWT with different diffuser parameters by numerical simulation.	The results show that diffusers have a major influence on the aerodynamic performance of the BA-VAWT. The trapezoidal diffuser is the most efficient with a power coefficient of 1.56 and an optimum tip speed ratio of 4.62.	[19]
Shuaibin Zhang (2022)	The aim of the study is to understand the wind resources of a neighborhood, the operation of small rooftop turbines and their impact on wind conditions in the neighborhood.	We note that the flow over the urban area shows a clear acceleration due to the displacement effect of the urban area and the turbulence intensity increases drastically.	[20]
Garcia, O et al. (2019)	The study examines ROSEO-BIWT, a new building-integrated wind turbine (BIWT) intended for installation on the edge of buildings.	According to the results, an increase in wind speed by a factor of three would lead to an increase in working hours at rated power due to the edge effect and concentration plumes, which means more than 2000 h per year.	[21]

This paper analyzes the development and application of BIWTs with a particular focus on their role in sustainable development and the transition to decentralized energy sources. It examines the technical, economic, environmental and safety aspects of the application of BIWTs, as well as the factors affecting their competitiveness in the market and the barriers to their wider application. It also identifies possible directions for the further development of this technology as well as short- and long-term opportunities for the use of BIWTs.

There is a lot of literature on BIWT, but most of it only deals with certain aspects of the subject. There are very few scientific studies that provide a comprehensive picture of BIWT, and there are virtually no forecasts of short- and long-term BIWT installations. This research aims to fill this gap. So, this study can serve as an excellent basis for young scientists to continue their research in this field and contribute to the scientific community.

2. Materials and Methods

The aim of this study is to investigate the status of the application of BIWT and the prospects for further application of wind turbines in urban areas based on the latest available data (last 5 years) from the literature. The introductory section discusses the context of the topicality of the issue and then examines the historical application of the BIWT. Then, the specifics related to wind energy in urban areas were analyzed and explained, resulting in certain limitations for the use of wind turbines. In this context, an overview is given of the possible locations of wind turbines on the buildings and the potential types of wind turbines that could be used. Based on these facts and the factors arising from the current economic, environmental (climate change) and political situation in the world, factors influencing the further application of BIWT can be identified and considered. Economic viability is the most important factor influencing the application of BIWT, followed by safety of application. Therefore, these elements were analyzed in more detail. The potential impacts on humans, animals and the environment were also analyzed. As the maintenance of BIWT in urban areas has some specificities, a brief overview of this topic is given, as well as the question “What is at the end of life of BIWT”?

The main barriers to a wider application of BIWT have been analyzed and identified, as well as encouraging factors for their wider application. New technologies that can promote and contribute to a wider application of BIWT are also analyzed.

Key words were defined for each of the content units mentioned, on the basis of which a search was carried out in various scientific document databases in order to obtain answers to the questions posed. First, scientific databases such as Web of Science and Scopus were searched. Part of the information came from articles published in journals of academic publishers such as Elsevier, MDPI, Taylor and Francis, articles from IEEE, articles from international conferences, and specialized literature. A range of information was found in reports and studies from the International Renewable Energy Agency and NREL. Some of the references were found based on references from other works used in this study. The relevant articles are selected on the basis of the abstract and their relevance to the topic of the study. The next step is to review the selected articles. The data found in the literature sources were sorted and analyzed, and on their basis, through the method of synthesis and deduction, appropriate conclusions were drawn regarding the evaluation of the perspective of the application of BIWT in the short and long term.

3. Results

The analysis of local wind conditions is a crucial first step in the planning of building-integrated wind turbines, as it has a direct impact on their cost efficiency, application safety and environmental impact. Wind conditions in cities vary greatly, especially at lower elevations, due to the “urban canyon effect” where buildings create turbulence and reduce wind speed (Figure 4). Detailed annual wind mapping helps to identify locations with frequent and stronger winds, which is crucial for sustainable energy production [11,13].

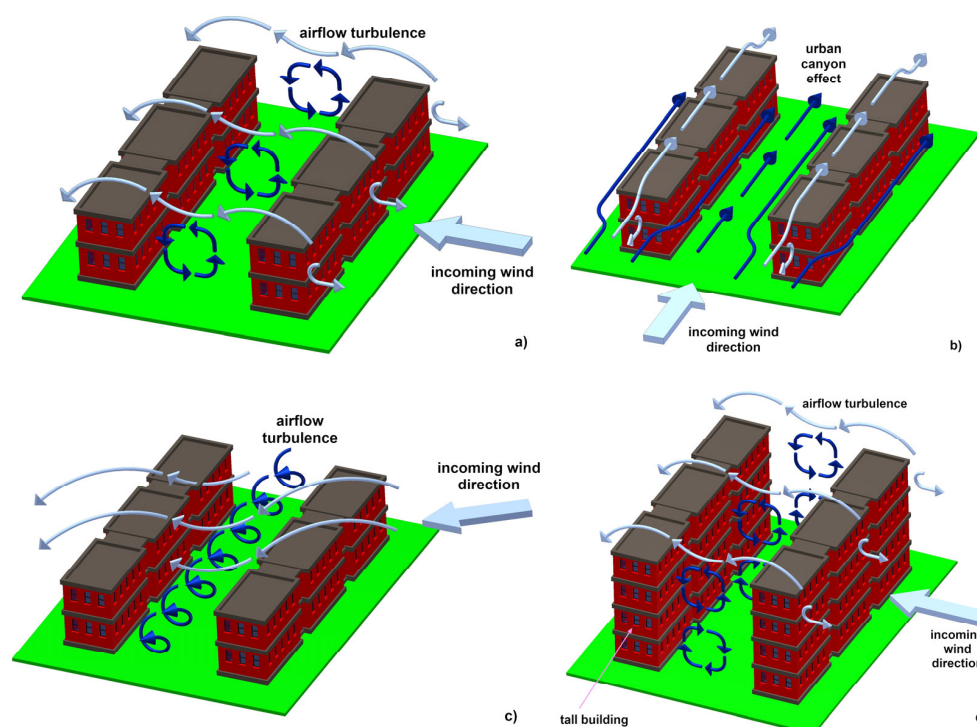


Figure 4. Direction and shape of the airflow in an urban environment depending on the incoming wind direction a) cross-flow of wind on buildings b) longitudinal flow of wind on buildings c) flow of wind at an angle on a building d) cross-flow on tall buildings).

Accurate wind data enables the calculation of annual energy production (AEP) and annual capacity utilization, important indicators for assessing return on investment (ROI) [21].

Annual wind data are also important for forecasting extreme weather conditions (e.g., wind gusts, storms) to ensure the structural integrity of the BIWT during planning. It should also be borne in mind that higher wind speeds and strong turbulence can increase the noise generated by the rotor blades, which must not exceed the city's noise regulations. Finally, the visual impact of the BIWT on the cityscape has an impact on public acceptance, which is crucial for the approval of the project [22].

To determine the distribution of wind speeds around and on tall buildings and to find the optimum position of the BIWT, it makes sense to use computational fluid dynamics (CFD) [8].

The optimum position of the wind turbine depends on the prevailing direction and the average wind speed at the site [9]. For existing buildings with an architecture that is not planned for the integration of wind turbines (e.g., asymmetrical design, sharp edges), determining the optimum position can be complex.

However, by carefully planning the site and designing the building with rounded edges close to the space intended for the wind turbine, favorable airflow conditions around the turbine can be achieved. The sloped edges at right angles to the top of tall buildings obstruct the airflow and result in zones of turbulent flow. Although sloping edges can cause local acceleration of the wind due to the large velocity gradient along the vertical axis, they are not suitable for the installation of larger wind turbines with large blade diameters.

3.1. Distribution and Placement of BIWT Depending on the Installed Capacity

The installed capacity of a BIWP system depends on several factors, including the size and height of the building, the wind conditions in the city and the chosen system design (horizontal axis—HAWT or vertical axis—VAWT). Considering the different classifications of wind turbines according to their installed power that can be found in the literature, the authors present in Table 3 their own classification adapted to the latest trends in increasing the power of wind turbines. This classification is based on the work of Zhiguo Zhang et al. [14] and refers to the installed capacity of a single turbine.

Table 3. Classification of wind turbines according to power rating.

Class	Subclass	Rotor Diameter (m)		Swept Area (m ²)		Power Rating (kW)	
		From	To	From	To	From	To
Small-scale	Micro	0.50	1.25	0.2	1.2	0.01	0.40
	Mini	1.25	3	1.2	7.1	0.40	2.5
	Medium	3	16	7	200	2.5	50
Commercial	Small	16	25	200	490	50	100
	Medium	25	50	490	1962	100	1000
	Large	50	310	1962	75,400	1000	20,000

However, the definition according to the standard of the International Electrotechnical Commission (IEC) 61400-2 [23] was taken into account, according to which small-scale wind turbines are defined as turbines with a rotor swept area of less than 200 m² and a rated power is below 50 kW.

Micro systems: They are ideal for use in residential buildings or smaller commercial premises with low energy requirements. These systems require little space and can be easily integrated into urban environments.

Mini systems: They are suitable for residential buildings, schools, or smaller commercial facilities. They make a significant contribution to covering energy requirements with

simple installation and maintenance. They can also significantly reduce energy costs for small consumers.

Medium systems: These are used in taller buildings or industrial facilities with good wind orientation. These systems can supply larger amounts of energy and are, therefore, suitable for buildings with higher energy requirements.

Commercial turbines: Rare but feasible in megastructures with optimized aerodynamic design, such as the Bahrain World Trade Center (3×225 kW). It is important to note that there are no BIWTs in the large commercial wind farm category, but this category includes offshore or onshore wind farms that are part of large wind farms.

For small-scale wind turbines (up to 10 m in height and less than 7 m in diameter), there are no specific regulations for the installation and use of BIWTs in most countries. For example, local authorities in the UK, Ireland, Spain, Italy, and Sweden only have legal recommendations for distances, noise levels, and shadow flicker. In Portugal and the Netherlands, there are non-binding guidelines that only regulate noise levels. In Australia, the regulation of BIWT applications is still in its infancy. There are still no laws and guidelines for planning permission, the installation of BIWT, insurance, or grid connection [12].

There are three ways to integrate wind turbines into the urban environment:

- (a) Retrofitting wind turbines on existing buildings. The term building-mounted wind turbines (BMWTs) is also used in the literature.
- (b) The complete integration of wind turbines into new buildings together with the architectural form.
- (c) The installation of free-standing wind turbines on vacant urban land.

Categories (a) and (b) are commonly referred to as building integrated wind turbines (BIWT). Category (c) is not considered further in this paper, as the installation of a free-standing wind turbine on a vacant urban site is not a form of building-integrated wind turbine. The geometry of the building plays an important role in choosing the optimal location for building-integrated wind turbines (BIWTs). Buildings can be aerodynamically designed to increase wind speed at certain locations. Placing turbines in these locations makes them more efficient, and such systems are sometimes referred to as building-augmented wind turbines (BAWTs). Figure 5 illustrates typical BIWT placement options. Relatively large (commercial) BIWTs can be placed on a roof, between two adjacent buildings, or in a larger opening in a building (Figure 5a). Small BIWTs can be installed as a row of turbines on the roof or along the height of the building (Figure 5b).

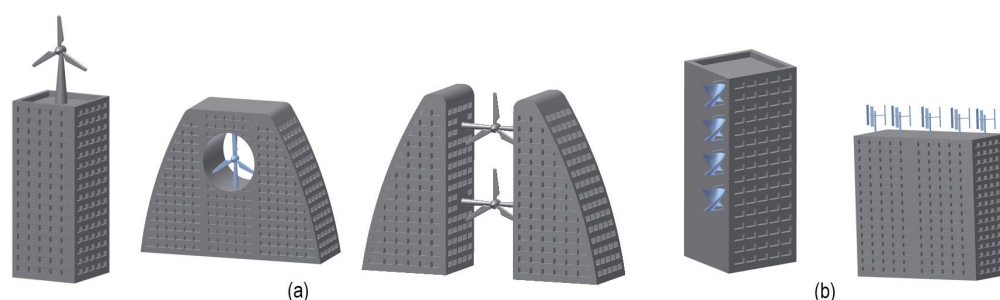


Figure 5. Common locations of BIWTs: (a) locations of commercial turbines and (b) locations of small-scale wind turbines.

The performance of small Savonius wind turbines attached to the vertical edge of a tall building (Figure 5b) was analyzed by Mao et al. using the computational fluid dynamics (CFD) method [2]. It was found that the edge-mounted Savonius turbine achieved a higher power coefficient than the turbine operating in steady flows. The average power coefficient

(C_p) of the turbine at a wind angle of 360 degrees was 92.5% higher than that of the turbine operating in steady flows. They also found that the average power of the turbine decreases as the distance between the turbine and the building increases.

This research shows how important the correct positioning of wind turbines is to maximize their efficiency. Optimizing the building design, such as aerodynamically shaped edges, can also further improve the airflow conditions around the turbine, increasing its efficiency and energy production.

3.2. Economic Profitability

Analyzing the local wind conditions in an urban environment is crucial for determining the optimal location of the BIWT, which has a direct impact on the efficiency of the system and its viability. In the case of a planned new building, the shape of the building can be designed to optimize the location of the turbine and the wind flow conditions on it. The height of the building has a significant impact on the profitability of the BIWT system. Tall buildings offer an advantage due to the higher wind speed at greater heights where the impact of urban obstructions such as other buildings and trees is less. Research shows that wind speed increases with height according to the logarithmic law, which increases the energy potential of the wind. For example, at a height of 100 m, the wind speed can be 20–30% higher than at a height of 10 m, which significantly improves the performance of the turbine [24].

Tall buildings can reduce the negative effects of turbulence, especially if they are aerodynamically shaped. For example, some skyscrapers use a special design of the façade to direct the wind towards the turbines, as is the case with the Pearl River Tower in China. However, the lack of aerodynamic optimization can lead to excessive vibration and noise, which shortens the lifespan of BIWTs, which is already shorter compared to large commercial wind turbines.

Increased building height allows for greater potential for energy generation but also increases initial costs due to the need for additional structural reinforcements and the difficulty of installation in hard-to-reach parts of the building. Studies on the integration of wind turbines in high-rise buildings show that the economic benefits only materialize if the wind resources are good and the system is properly designed. If these conditions are not met, high maintenance costs, low efficiency, a low capacity factor (5–30%), and a shorter lifetime (15–30 years) make such projects economically unviable. Incentive or subsidy programs for investment costs can play an important role in improving economic viability. Table 4, which is based on National Renewable Energy Laboratory (NREL) research results from 2024 [25], shows that CapEx and LCOE for BIWT are much higher compared to large commercial wind turbines, while the capacity factor and specific annual energy production (MWh/MW) are lower. The OpEx (operating costs) are roughly the same as for onshore wind turbines. OpEx are expenses incurred by a company in the normal course of business and include rent, maintenance and repairs, inventory costs, property management, insurance, etc. Capital expenditures (CapEx) are funds that a company uses to acquire, modernize and maintain physical assets such as land, facilities, buildings, technology or equipment. In addition to the cost of the asset itself, CapEx also includes Balance of System (BOS) costs. BOS includes items such as support structures, converters, cables, substations, monitoring and control systems, and the like. BOS costs for BIWTs are significant as they deal with site-specific engineering, regulatory hurdles and infrastructure integration unique to urban environments. BIWTs require a customized infrastructure to be integrated into buildings, including special foundations and structural reinforcements. Special electrical components such as converters and transformers are often required for connection to the building's energy system or to the power grid. BOS investment costs also include the cost

of permits, metering equipment and compliance with municipal grid standards, as well as noise, vibration, and building esthetics requirements. Unlike turbines, which benefit from economies of scale and innovation, the cost of BOS is less flexible and often dominates the budget of a BIWT project. Balance of System (BOS) costs can account for 41.2–54.6% of total capital costs, depending on project size, with turbine costs making up the remainder.

Table 4. Comparison of the LCOE for different categories of wind turbines [25].

Parameter	Units	Land-Based	Offshore		Distributed (Single Turbine)		
		Utility Scale	Fixed Bottom	Floating	Residential	Commercial	Large
Wind turbine rating	MW	3.3	12	12	0.020	0.10	1.5
Capital expenditures (CapEx)	\$/kW	1968	5411	7349	8665	6800	3362
Operational expenditures (OpEx)	\$/kW/yr	43	135	108	41	41	41
Net annual energy production	MWh/MW/yr	4104	4295	3346	2580	2846	3326
Levelized cost of energy (LCOE)	\$/MWh	42	117	181	240	174	80

From the above, it is clear that BIWTs have a longer payback period compared to larger commercial turbines (LCOE and payback are correlated due to the same influencing factors).

The biggest influence on high LCOE is a low capacity factor, followed by a shorter lifetime of the wind turbine. Locations where the capacity factor is good (coastal areas and islands with good wind) have significantly lower LCOE.

The economic viability of BIWT systems depends on a number of complex factors that vary by country and region. In addition to local wind conditions, LCOE is influenced by labor costs, equipment costs, and energy market conditions. The application of new technologies such as artificial intelligence (AI) with machine learning, deep learning and neural networks, as well as computational fluid dynamics (CFD) enables the precise mapping of urban wind flows. These methods are used to identify locations with optimal potential for deployment, which forms the basis for wider commercialization of these systems [26]. Increased commercial deployment, together with a range of development innovations, can lead to lower capital expenditure (CapEx) and system costs (BOS), further reducing LCOE. Financial incentives play a key role in accelerating the uptake of BIWT, including the following:

- Feed-in tariffs (FiTs) to encourage the sale of energy to the grid;
- Production Tax Credits (PTCs) to reduce operating costs;
- Investment Tax Credits (ITCs) to support initial investment.

According to a study by Alam and Jin [12], the market for small wind turbines is expected to grow by over 9% annually between 2022 and 2030, indicating a growing interest in this technology. However, further development depends on the synergy between technological advances, regulatory incentives, and the reduction in production costs.

3.3. Security of Application

An important aspect of any energy system is the safety of its application. Below is analysis of the security of the BIWT system. General safety measures and strategies to protect the environment are defined in the EHS Guidelines [27]. The EHS Guidelines for wind energy contain information on environmental, health and safety aspects of onshore

and offshore wind turbines. They should be applied to wind turbines from the initial feasibility studies and environmental impact assessment and continue to apply throughout the construction and operational phases. The applicability of the EHS Guidelines should be tailored to the hazards and risks identified for each project, based on the results of an environmental assessment that takes into account site-specific variables such as the host country context, urban area, and other project factors.

3.3.1. Structural Integrity

Every building must meet all legal planning and construction requirements in order to obtain planning permission. The integration of BIWT into a building requires additional testing, including an analysis of the impact on structural integrity, environmental safety and compliance with local noise and vibration regulations. European standards (e.g., EN 1991: Eurocode 1), for example, define the maximum permissible vibrations for buildings, which may require adjustments to the design of BIWTs.

The safety of BIWTs is an important priority due to their close interaction with people and the surrounding infrastructure. Turbines must withstand dynamic loads (turbulence and gusts of wind) and extreme conditions such as earthquakes. The interaction between the turbine and the building vortices can lead to harmonic resonances between the turbine and the building vortices, which increases the load on lightweight building materials (e.g., steel beams or glass facades) and affects structural stability over time. The use of vibration isolators and dampers can help to reduce the transmission of vibrations from the turbine to the building structure. This includes the use of specially designed supports that absorb vibrations before they are transmitted to the building [5,28]. Poorly designed turbines run the risk of mechanical fatigue or even component detachment, posing a danger to occupants and pedestrians below the building. If the turbines are exposed to turbulent winds over a longer period of time, the load on the turbine components (e.g., rotor blades, bearings) can increase, which increases the probability of mechanical failures [5].

Regular inspections and preventive maintenance are key to detecting wear, loose connections, or cracks at an early stage. The use of IoT sensors to continuously monitor vibration, temperature and noise enables a quick response to anomalies. Implementing BIWT requires a multidisciplinary approach—from building code compliance to advanced engineering solutions for vibration management. Without systematic support, these systems can become a critical point of risk in urban environments.

3.3.2. Fracture and Detachment of the Blade

One of the main safety issues associated with BIWT is the risk of blade fracture. While cases of flying blades are more common in large, free-standing HAWTs, they have not yet been reported in urban areas. The consequences in urban areas can be severe due to the proximity of people and property. VAWT blades are subjected to alternating tensile and compressive loads during rotation, especially in turbulent, windy urban environments. This cyclic loading accelerates material fatigue, especially at the blade joints. Rapid changes in the angle of attack of the wind during rotation cause unstable aerodynamic loads that lead to torsional oscillations and stress concentrations. Straight or curved VAWT blades (e.g., Darrieus or H-rotor designs) are subject to uneven centrifugal forces and bending moments during rotation, which increases the risk of fracture at the support struts. Prolonged exposure to turbulent wind (e.g., wind shear, gusts) leads to material fatigue, especially in light turbine structures with higher power [29–31]. Blade fractures may be primarily due to fatigue damage, stress concentration and complex operating conditions.

The failure of bolts in hubs of HAWT blades, for example, is related to the alternating loads caused by the rotation of the blades and the stress concentration at the root of

the thread [19]. Composite blades often suffer structural collapse due to a combination of bending and torsion, exacerbated by failure of bonded joints and delamination [18]. Blades made of composite materials (common in VAWTs) are susceptible to ultraviolet (UV) radiation, moisture penetration and cracking of the resin matrix, weakening structural integrity over time. Therefore, they face degradation issues such as trailing edge cracking and shear-induced delamination [18,32]. For this reason, there are methods that can detect and warn of possible blade and/or other turbine component failure at an early stage. These methods include acoustic emission (AE) signal detection, dynamic vibration analysis, changes in aerodynamic noise patterns [18,21,22], and blade-embedded fiber Bragg grating (FBG) sensors to detect local stress anomalies and early cracks. Machine learning algorithms increase the classification accuracy for damage types. Changes in aerodynamic noise patterns correlate with damage to the blade surface [21]. By using drone-based inspection: in combination with deep learning, surface defects such as erosion or cracks can be detected, which improves the efficiency of the inspection [23] and makes the use of BIWT safe.

3.3.3. Lightning Strikes

When wind turbines are mounted on the roofs of taller buildings, they are exposed to an increased risk of lightning strikes, which can cause damage to the turbine itself as well as potential hazards to the building and its occupants. To reduce the risk of lightning strikes, it is necessary to design and implement surge protection systems and high-quality earthing that ensure a safe path for the dissipation of lightning energy into the ground.

3.3.4. Dangers During Installation and Maintenance

The integration of wind turbines into tall buildings presents unique logistical and safety challenges, particularly during installation and maintenance. These challenges stem from the vertical complexity of skyscrapers, the turbulent wind conditions in urban environments, and the need for specialized equipment to access elevated structures.

The installation of BIWTs on tall buildings often requires the use of specialized machinery, including cranes that can reach extreme heights. The Bahrain World Trade Center (2008), for example, required large cranes to place three HAWTs between its twin towers. The logistical complexity of such installations is due to the limited space in cities, where narrow streets and adjacent buildings restrict the maneuverability of the cranes. In densely populated cities such as Shanghai, modular cranes or helicopter elevators may be required, significantly increasing capital expenditure (CapEx).

However, it should be noted that tall buildings create turbulent airflow due to the “urban canyon effect”, which increases dynamic loads during lifting, which can destabilize the cranes or temporarily stress the building frames. The installation teams must also take this into account.

BIWTs must be inspected regularly to ensure their mechanical integrity, especially in corrosive urban environments where pollution (or salinity) accelerates wear. Maintenance work such as lubricating bearings, replacing rotor blades, or repairing generators often requires technicians to work at heights of more than 100 m. The 270 vertical-axis turbines of the Shanghai Tower, for example, which are installed along the spiral-shaped parapet, require access to the platform by lowering or hanging.

When maintaining BIWTs, components such as bolts, blade parts, or tools pose a significant risk to pedestrians and the infrastructure below. Therefore, BIWTs require safety measures (e.g., a safety net around the building) to catch debris during repairs [33].

3.4. Impact on People and the Environment

3.4.1. Noise

Turbines can generate low-frequency noise and vibrations that can spread through the building structure. This is particularly problematic in residential or office spaces, where noise pollution can affect people's concentration, comfort and health. The noise generated by BIWTs can pose a health risk to occupants, especially if it disrupts sleep or contributes to stress. Prolonged exposure to noise has been linked to various health problems [34]. Vertical-axis wind turbines (VAWTs) are often preferred for BIWT due to lower noise levels, but uncertified models can still exceed permissible noise levels. De Santoli et al. [35] qualitatively assessed the noise impact from a 3.7 kW micro wind turbine. The noise emissions were estimated at 45–50 dB(A).

3.4.2. Flickering Shadow Effect from Turbine Blades

BIWTs can have a flickering shadow effect, although much smaller compared to larger wind turbines due to their smaller blade size, casting a moving shadow on nearby buildings. Shadow flicker is most pronounced when the turbine blades are directly between the sun and the windows of nearby buildings. The frequency and intensity of flickering depends on the position of the sun, which varies during the day and through the seasons. The potential for shadow flicker decreases with increasing distance from the turbine, typically within a radius of about ten rotor diameters. To address the problems associated with shadow flicker, various mitigation strategies are implemented such as an automatic shutdown system when shadow flicker is likely to disturb nearby residents [36].

3.4.3. Impact on Biodiversity and Birds

BIWTs and commercial large-scale onshore and offshore wind farms contribute to meeting renewable energy targets, but BIWTs have much lower negative impacts on biodiversity and habitat fragmentation, as well as less noise and vibration, due to their design and integration into existing urban landscapes. Compared to large wind farms, BIWTs have a lower collision risk for bird and bat populations as the blades are smaller (lower blade speeds) and the urban area is not on the bird migration routes [26]. Urban bats and birds (e.g., jays, house sparrows) may be at risk of collision with the turbine blades if the turbines are located near green spaces or bird habitats.

3.5. Maintenance of BIWT

The maintenance of building-integrated wind turbines (BIWTs) is associated with various challenges and costs that can affect their overall economic viability.

One of the biggest challenges is accessing the turbines for routine maintenance and inspection, especially when they are installed at high altitudes or in hard-to-reach locations. This requires specialized equipment and safety measures, which increases logistical complexity and costs.

BIWTs are often custom-built, which complicates standardized maintenance protocols that require specially trained technicians, and consequently leads to higher operating costs [37]. Maintenance schedules vary depending on turbine design and environmental conditions as follows:

- Routine inspections are carried out every 6–12 months to check lubrication, tightening of screws and wear of parts;
- Predictive maintenance is based on built-in IoT devices (e.g., acoustic sensors), which enables real-time condition monitoring;
- Major overhauls are usually performed every 10–15 years to replace components for moving parts like gearboxes.

Maintenance costs include the cost of regular maintenance, the cost of spare parts, the cost of logistical support, and downtime costs [38].

Depending on the size and complexity of the system, the cost of routine maintenance can vary widely, ranging from a few thousand to tens of thousands of dollars per year. The cost of replacement parts for repairs can be significant, especially for large components such as turbine blades and reducers (15–20% of the cost of a new turbine) [39]. Downtime costs refer to maintenance or repair periods during which the BIWT is not producing electricity, resulting in loss of revenue. BIWTs typically have annual maintenance costs of 1.5% to 3% of the original turbine investment, depending on age and design [40].

3.6. The End of Lifetime

The discrepancy between the lifespan of BIWT systems (typically 20–25 years) and buildings (50–100+ years) raises critical questions about sustainability, maintenance and circular economy. The options available at the end of life of BIWTs are discussed below.

3.6.1. Lifetime Extension

In fact, there are no direct studies on BIWT life extension, so research for onshore and offshore turbines can be used to some extent as a basis for the methodology. In some cases, it is possible to extend the life of BIWTs through thorough inspections and regular maintenance. This includes assessing the structural integrity and performance of turbine components to ensure that BIWTs can continue to operate safely for several more years [26].

3.6.2. Repowering

Electricity refurbishment involves replacing old turbines with newer, more efficient models. This approach enables higher energy production without taking up additional space and is considered a sustainable solution. End-of-life turbines are often replaced with new generation turbines (e.g., bladeless designs, AI-optimized VAWTs) that perform better in turbulent urban wind conditions.

3.6.3. Dismantling and Recycling

If neither an extension of the useful life nor repowering is possible, the BIWT should be decommissioned and dismantled. During dismantling, the turbine and its components must be safely removed from the building. Many parts, such as metals, can be easily recycled or reused, reducing the amount of waste and promoting a circular economy. Dismantling requires careful planning in accordance with local regulations and safety measures.

The decision whether to expand, revitalize or dismantle the BIWT also depends on economic factors. When maintenance costs begin to exceed the financial gains from electricity generation, the options of decommissioning or repowering should be considered. The availability of incentives or support for such projects has an impact on the decision [26].

4. Discussion

4.1. Barriers to Greater Implementation of BIWT

The main obstacle for a wider application of BIWT is the complicated installation of the turbines, the low energy efficiency due to the unpredictable and turbulent wind in urban environments and the low capacity factor, i.e., the low annual electricity production. Insurance premiums for buildings equipped with BIWTs are 15–20% higher than for conventional buildings due to the risks associated with operation and debris liability which also increases the LCOE.

4.1.1. Unpredictable Wind Patterns and Turbulence

Buildings disrupt the laminar flow of the wind and generate turbulent winds that differ significantly from outdoor conditions. The main problems include “dead zones” where wind speeds drop sharply due to vortices or air currents, variations in wind speeds and directions that fluctuate greatly near buildings (which reduces turbine efficiency), and interference from wind shear: the natural increase in wind speed with height is hindered by buildings, reducing the perceived benefit of tall buildings [41].

4.1.2. The Specific Annual Energy Yield in Urban Environments

The specific annual energy yield, expressed in kWh/m² rotor area, depends on a number of factors that together strongly influence the efficiency and cost-effectiveness of BIWT applications. Wind speed is the most important factor influencing the energy yield of BIWT installations. Studies show large differences in specific annual yield for individual sites as follows [42]:

- At locations with an average annual wind speed of around 3.7 m/s, the specific annual energy yield reaches up to 118 kWh/m² rotor area;
- At locations with an average wind speed of around 2.4 m/s, the specific annual energy yield is significantly lower and amounts to 14 to 20 kWh/m².

This large difference clearly shows how decisive the choice of location is for BIWT systems.

The frequency of wind direction changes has a considerable influence on the turbine's energy yield. While horizontal-axis turbines with a tilt system can follow the prevailing wind direction, their efficiency, like that of diffuser turbines, decreases in conditions where the wind changes direction frequently and turbulence is present. In such conditions, especially in urban areas, VAWTs (Savonius and Darrieus type) have an advantage because their energy production depends primarily on the speed and not the direction of the wind. The height at which the turbine is installed has a significant impact on energy production. For example, at the same site in a suburb, a slight increase in the height of the turbine installation from 9.2 m to 11.3 m resulted in a more than two-fold increase in specific annual energy production from 8.9 to 20 kWh/m² [42].

The shape of the building can significantly influence the wind speed at the installation site of the wind turbine and thus the specific annual energy production. When planning new buildings, this can be significantly influenced by the planner. When renovating existing buildings, however, the shape of the building can only be influenced to a very limited extent.

Economic profitability is closely related to the average annual energy yield and usually requires at least 2000 operating hours per year at rated capacity, which can rarely be achieved in urban environments with lower average wind speeds [8]. A good energy yield can be achieved in coastal areas with more constant and stronger winds, where conditions are more favorable for power generation.

4.1.3. Structural Barriers

Building-integrated wind turbines (BIWTs) face significant structural barriers that prevent widespread adoption in urban environments. These challenges arise from technical, material and regulatory complexities. Integration into buildings requires careful consideration of load-bearing capacity, particularly for older buildings that were not originally designed for the installation of wind turbines [43]. The aerodynamic forces generated by turbulent urban wind patterns result in dynamic loads that require reinforced structures to prevent structural fatigue. The operation of turbines generates low-frequency vibrations that can propagate through the building structures. Sustained vibrations from wind tur-

bines can lead to fatigue damage in building structural components and requires advanced damping systems [43,44]. Modern materials must have a balance of strength, weight and durability to withstand cyclic loading from wind gusts and vibrations. Innovations in composite materials and modular designs are critical to reduce weight while maintaining structural integrity.

Existing building codes often lack BIWT-specific guidelines, forcing engineers to adapt standards developed for traditional rooftop solar or free-standing wind turbines [45]. For example, electrical safety protocols for ground-mounted systems do not align with BIWT requirements, making compliance difficult. Certification procedures for mechanical strength require adapted criteria to take into account the dual function of construction material and energy generators.

These structural barriers highlight the need for interdisciplinary research in aerodynamics, materials science and regulatory frameworks to enable safe and efficient BIWT deployments.

4.2. Opportunities for Greater Application of BIWT

The deployment of BIWTs can be accelerated by taking advantage of technological, economic, political and market opportunities. Below is an analysis of key opportunities, supported by historical context and future trends.

4.2.1. Progress and Innovation in Technologies

Innovations such as the Power Augment Guiding Vanes (PAGV) multiply wind speed by improving turbine efficiency, making BIWTs viable even in urban areas with little wind. The ROSEO BIWT system, for example, uses curved blades to concentrate horizontal and vertical wind flows at the edges of buildings. Experimental tests in the wind tunnel have shown that the wind speed at the entrance of the turbine quadruples when PAGV is combined with the effect of edge acceleration of buildings [21,46]. This enabled the Savonius rotor to achieve a capacity factor of 25–30% even in urban areas with an average wind speed of only 3 m/s [30].

At an average wind speed of 3 m/s, the PAGVs enabled 2000 annual operating hours at rated power (17.9 m/s), making the BIWT economically viable.

Advances in the design of VAWTs reduce noise and vibration emissions, which are a major obstacle in densely populated urban environments. The use of rubber silencers and low-speed designs has reduced operating noise to <45 dB [46].

The integration of BIWT with solar panels and energy storage (hybrid energy systems) increases reliability and reduces dependence on the electricity grid (one example is the double façade system).

4.2.2. Possibilities to Reduce Costs

The application of BIWT in urban environments requires a cost reduction strategy, with research highlighting simplified assessment tools and economies of scale as key factors.

In a study by Gonzalez-Arceo et al. [30], reanalysis data were calibrated with anemometer measurements using quantile mapping to predict wind speed and direction over a 10-year period. This method reduced the reliance on expensive CFD simulations while maintaining the accuracy of energy yield estimates. The calibrated data improved predictions of annual energy production by matching wind speeds from the reanalysis with site-specific measurements, providing a cost-effective alternative to complex modeling. Methods such as laser radar wind towers and Weibull probability models for estimating wind resources were also investigated. These approaches have provided reliable turbulence and wind speed profiles even without high-resolution CFD, especially in complex urban environments [47].

Economies of scale are another element influencing costs. Mass production of modular turbines (e.g., rooftop VAWTs) can reduce unit costs, especially when retrofitting existing buildings. The use of IoT sensors and condition monitoring can reduce maintenance costs but also increase the reliability of the system.

4.2.3. Policy and Legal Support

National carbon neutrality targets (e.g., the EU 2050 target [48]) will promote the application of BIWT as an essential element for the decarbonization of the urban environment. Some governments (e.g., China and the EU) are introducing green building laws, setting the stage for increased use of BIWT in new construction projects, especially public facilities. Tax breaks, subsidies or incentive prices for the integration of renewable energy in buildings should also encourage investors to use BIWT. Dynamic zoning laws and subsidies for hybrid renewable systems (e.g., EU Horizon 2020 grants) accelerate the adoption of BIWT. Investments in green bonds and ESG (Environmental, Social, Governance) favor buildings equipped with BIWT.

4.2.4. Urbanization and Smart City Trends

In the coming period, the trend will be towards further global urbanization with the construction of tall skyscrapers to save space. Skyscrapers with aerodynamic design (e.g., the World Trade Center in Bahrain) make use of the effects of wind tunnels and show the potential of BIWTs in urban centers. BIWTs could fit well into decentralized microgrids and contribute to the goals of a smart city in terms of energy resilience [49,50].

4.2.5. Market Demand and Achievement of Green Transition Goals

Building companies are increasingly turning to BIWT to achieve the environmental and social goals of decarbonizing the economy and attracting environmentally conscious tenants. Growing consumer awareness and demand for sustainable infrastructure is increasing the attractiveness of the BIWT market [51].

4.2.6. Esthetic and Architectural Integration

Innovative designs such as turbines embedded in façades, parapets or cavities (e.g., the Pearl River Tower) combine functionality with esthetics, which can be a marketing advantage for projects aiming for sustainability [52]. When designed as part of the architecture, they can be visually appealing and contribute to the esthetics of the surroundings.

4.2.7. Energy Independence for Rural Areas

In conjunction with other renewable energy sources and energy storage systems, BIWTs can power remote regions that are not connected to the grid by providing decentralized access to energy. In certain windy coastal regions, such as Kutubdia Island in Bangladesh, BIWTs are more cost-effective than rooftop PV systems. In such locations, the systems typically include micro wind turbines and battery storage, which could be part of a decentralized energy solution in combination with other renewable energy sources [53]. In summary, BIWTs could evolve from a niche application to a mainstream program if the current limitations are addressed through research, development, and collaboration, especially in larger cities and climate-sensitive regions with sufficient wind energy potential. At the same time, the application of artificial intelligence and CFD simulations can optimize turbine placement and operation to increase energy yield.

4.3. Emerging Technologies with the Potential to Encourage Greater Use of BIWT

The field of BIWT is developing rapidly with innovations that address key challenges such as low turbine efficiency in turbulent urban winds, noise and lack of space. Several

technologies under development or already implemented are expected to significantly improve the performance and application of BIWT. Some of them are provided below.

4.3.1. Bladeless Vibration Turbines and Vortex Turbines (Vortex Bladeless)

Bladeless vibration turbines use vortex-induced vibrations (VIVs) to generate electricity without rotating blades. This technology utilizes aerodynamic phenomena and material innovations for energy conversion. When the wind flows around a vertical, cylindrical mast, it generates alternating vortices (von-Kármán vortex street) [54]. These vortices induce resonant vibrations in the mast at frequencies corresponding to its natural structural resonance (1–2 Hz). The vibrations drive a linear generator at the base of the mast, which uses neodymium magnets and copper coils to convert mechanical movements into electrical energy [55]. In laboratory tests, early prototypes achieved an efficiency of 30–40% when converting mechanical energy into electrical energy [7]. The turbine operates efficiently at wind speeds as low as 1.8–4 m/s, compared to 4.5+ m/s for conventional turbines [7,55].

These turbines have no moving parts such as gears and reduce maintenance costs by $\approx 50\%$ compared to conventional systems. The 3 m high prototypes produce 100–150 W at a noise level <40 dB [56]. The minimal risk of collisions with birds and a 70% smaller footprint than turbines with comparable blades ensure urban compatibility [57].

Power density in field trials is $0.5\text{--}1.2$ W/m² (compared to $3\text{--}5$ W/m² for small HAWTs), but scalability studies suggest a threefold improvement with optimized coil configurations (e.g., 3000 coils per set) [7]. Extreme wind resistance maintains structural integrity at wind speeds of 30–35 m/s ($\approx 108\text{--}126$ km/h) [55]. Current energy production is 30–50% below that of turbines with blades of the same size [57]. Turbine spacing <5 mast diameters hinder vortex shedding in large turbines and reduce performance by 15–25% [57].

This technology has potential for decentralized urban energy systems, but requires material optimizations (e.g., graphene-reinforced composites) to close the efficiency gap to conventional wind solutions [7,57]. Another new technology is piezoelectric wind turbines. These are flexible materials that convert wind-induced vibrations into electrical energy. They can be easily integrated into building façades.

4.3.2. Aerodynamic Optimization Guided by Artificial Intelligence

With the help of machine learning algorithms, artificial intelligence can analyze wind patterns near buildings and suggest the optimal placement of turbines. It can also analyze and suggest the optimal design of the blades and the shape of the building. A “wind-adapted” architecture, for example, increases the wind speed at the turbine locations. One example of this is the Birmingham Blade, a turbine specially developed for urban wind turbines. The turbine has curved blades that rotate around a vertical axis and, according to the developers, is up to seven times more efficient than previous turbine designs in the city [58,59].

4.3.3. Advanced Materials and Nanotechnology

Lightweight composite materials improve the performance of building-integrated wind turbines by optimizing structural efficiency and operational safety. Scientific progress focuses on carbon fiber-reinforced polymers (CFRP) and graphene-reinforced composites that address critical challenges in urban wind energy systems. CFRP reduce blade mass by 30–50% compared to conventional glass fiber composites, while maintaining the same strength [60,61]. Hybrid constructions (carbon fiber core + glass fiber outer surfaces) offer a good balance between cost (-50%) and weight (-30%) [60,62].

The addition of 0.01–0.5% by weight of graphene to epoxy resins improves tensile strength by 30%, strength by up to 50%, and temperature resistance by $+30$ °C [63,64].

Lightweight composites allow turbines to operate at wind speeds of 2 to 4 m/s using permanent magnet generators, doubling the potential of urban power generation. Aerodynamic optimization of thinner graphene-reinforced rotor blades increases the coefficient of performance (C_p) by 15–20% due to lower drag and mass-related inertia [61,64].

CFRP/fiberglass hybrid blades save 80% weight compared to pure carbon fiber constructions while retaining 90% strength, enabling larger rotors for low-wind urban locations [60,61]. Epoxy resin composites modified with graphene show 1500% increased durability under cyclic loading compared to unmodified resins. Nano-reinforced interfaces between carbon fibers and matrix material reduce delamination by 60% [64].

It should be noted that the impermeability of graphene reduces salt water corrosion in coastal installations by 70% [63]. UV-resistant thermoplastic coatings with graphene additives retain 95% of their original mechanical properties after 10 years of simulated wear [65].

BIWTs, using these composites, achieve the following:

- A 20–30% lower LCOE compared to conventional systems due to lower maintenance and longer lifetime [63,65]
- A 1.5–2-time higher energy density per covered area in urban wind conditions [62,66]
- Compatibility with circular economy goals through thermoplastic, recyclable composites [65,67].

4.3.4. Small and Modular Turbines

Rows of vertical axis microturbines installed in façades or roofs, such as Aeroma's stationary wind catchers, amplify the air flow by exploiting the aerodynamics of the building.

4.3.5. Magnetic Levitation Bearings

MagLev improves vertical-axis wind turbines (VAWTs) by replacing mechanical bearings with non-contact magnetic systems. These bearings eliminate physical contact between the rotating components and reduce friction in VAWTs by 35% compared to conventional ball bearings [68,69]. As a result, 95–100% of wind energy can be converted into rotational motion instead of heat [70,71].

MagLev VAWTs allow a lower switch-on speed of 1.5–1.8 m/s compared to 4.5 m/s for conventional systems. The next advantage of using MagLev technology is the higher output power of the turbine. At a wind speed of 6.8 m/s, MagLev turbines generate 9.6–20% more power due to the lower rotational resistance²⁶ and because the magnetic levitation technology enables 64% faster turbine rotation at low wind speeds (1.8 m/s) [68].

Eliminating mechanical contact reduces wear, i.e., prevents bearing degradation and extends service life by $\approx 40\%$ in accelerated aging tests [72,73]. MagLev systems do not require lubrication and are corrosion resistant, which reduces maintenance costs by 50%.

Neodymium permanent magnets generate repulsive forces (N-N or S-S polarity) that cause the turbine rotor to levitate. With this setup, axial friction coefficients close to zero are achieved, while structural stability is maintained [72,74]. Field tests have shown that MagLev VAWTs maintain rotation 2–3x longer after the wind stops blowing compared to conventional designs [75]. These improvements make MagLev bearings a key advantage for urban and low-wind environments where conventional turbines underperform due to frictional losses.

4.3.6. Hybrid Systems Consisting of Wind Farms and Building-Integrated PV Systems

Hybrid energy systems combine PV systems on roofs with small wind turbines and realize the synergy of electricity generation from PV systems (during the day) and wind

farms (at night/when the wind blows) [76]. SolarMill® is one such energy device optimized for generating green energy in an urban environment [77]. Wind energy is harnessed with a vertical axis Savonius turbine and solar energy is captured by a PV system. The system is designed to be easily integrated into any type of roof, both grid-connected and off-grid. The most obvious advantage of the hybrid system is the increase in available power per square meter of roof area by combining both energy sources.

4.3.7. Energy Storage in Structural Components

New technologies for integrating energy storage into building materials for wind energy storage focus on innovative electrochemical systems that combine structural functionality with energy storage capabilities. These improvements aim to transform building components into active energy storage units, increasing sustainability and efficiency [69].

For example, the use of modified concrete as a building material and energy storage system has recently been researched. This idea involves the integration of electrodes into concrete: concrete composites are enriched with carbon, polymers, or metals to create conductive matrices for supercapacitors and batteries. Concrete electrodes enriched with carbon, for example, have an improved charge storage capacity while retaining their structural integrity.

Another example is the use of electrolytes in a solid state. Ionically conductive concrete replaces conventional liquid electrolytes and enables the safe transport of ions through its matrix. Additives such as metal salts or conductive polymers improve the ionic conductivity (up to 10^{-3} S/cm in prototypes). These systems fulfill a dual function: they provide mechanical support while storing 5–15 Wh/m² of energy in early prototypes that are scalable for large buildings [69].

Although they are not electrochemical, walls and floors reinforced with phase change materials (PCM) (e.g., kerosene or salt hydrate composites) store thermal energy from wind-generated electricity via heat pumps [78].

An emerging concept such as thermal–electrochemical hybrid systems combines concrete batteries with PCM layers and enables the simultaneous storage of electricity and heat. Initial simulations indicate a 20–30% increase in efficiency compared to single systems.

Current limitations include life (≈ 5000 cycles for concrete batteries vs. 10,000+ for commercial Li-ion batteries) and higher acquisition costs ($\approx$ USD 150/kWh vs. USD 100/kWh for grid batteries) [69]. However, life cycle analyses show the potential to reduce costs by 2030 through material optimization and mass production

4.3.8. Integration of Smart Grid and Internet of Things

Predictive maintenance sensors and IoT networks monitor turbine performance in real time and adjust wind angles to increase turbine efficiency.

4.3.9. Three-Dimensional Printed and Customizable Turbines

Additive manufacturing enables cost-efficient turbine designs that are adapted to specific building geometries or wind profiles. For example, a horizontally oriented wind turbine with an Archimedean conical-spiral design 3D printed using fused filament fabrication achieved a 28.11% higher coefficient of performance (C_p) when combined with a protective shroud that improved efficiency in turbulent urban airflows [79].

This technology enables the production of complex blade shapes with improved strength that cannot be easily realized with conventional methods, which can improve the aerodynamic efficiency of turbines [80].

By using 3D printing to produce parts of complex shapes or entire structures, production and assembly costs can be reduced, making the integration of turbines into buildings a more economical option.

4.4. Perspectives for BIWTs

It is expected that the application of BIWT will increase as the demands for urban sustainability increase. Based on current research and industry trends, it appears as described below.

4.4.1. Short-Term Perspectives (2025–2030)

Based on the issues identified and explained above, the authors estimate that BIWTs are likely to remain niche products in the short term, i.e., in five years' time, used mainly as demonstration installations or as part of special projects that combine esthetics and functionality with energy efficiency. However, as technology advances, the efficiency of BIWTs will increase and turbine noise and costs will decrease. Combining BIWTs with solar panels or other renewable energy sources can ensure a more constant flow of energy, which is highly desirable. The renovation of the building stock promoted by the EU directives and the mandatory use of renewable energy sources in nZEB and ZEB systems should encourage the increased use of BIWTs. However, it is clear that PV technology will take priority in the renovation of buildings, while some investment in BIWT can be expected in new buildings, especially in areas with good wind characteristics. The authors note that, given the complex political and economic situation in the world and the positions of individual presidents, other issues may have a higher priority in the short term than the green transition, which will slow down the implementation of the BIWT.

4.4.2. Long-Term Perspectives (Beyond 2030)

In line with the listed and explained obstacles and opportunities for the development of BIWTs, the long-term perspective of wind turbines in buildings (BIWTs) until 2050 can be assessed as potentially positive, but with several key factors that will influence their development and diffusion:

- Increased demand for renewable energy sources: As part of the global transition to a low-carbon economy, BIWTs can play a role in increasing the share of RES, especially in urban areas where space is limited.
- Technological progress: Technological progress is expected to improve the efficiency and economic justification of BIWT, which would make it more competitive with other renewable energy sources.
- Integration with other technologies: The combination of BIWT with solar energy and energy storage can ensure a more constant flow of electricity and improve the energy security of buildings.
- Economic factors: The high initial installation costs could prevent faster growth in the use of this technology.
- Regulatory framework: The development of clear regulations that support the integration of BIWTs into existing energy systems will be crucial for their diffusion.

5. Conclusions

Global population growth and urbanization are leading to increasing electricity consumption in urban areas, and the need to decarbonize society to mitigate climate change is an incentive to explore the potential of renewable energy sources in cities. In this context, building-integrated wind turbines (BIWTs) represent a complementary technology to rooftop photovoltaic systems and offer the possibility of on-site energy generation with

a minimal spatial footprint. The aim of this study is to comprehensively evaluate the technical, economic and environmental aspects of the application of BIWTs and to analyze their short- and long-term potential, thus closing a gap in the literature.

The main findings of the study show that BIWTs are still a technological challenge due to their low efficiency in urban environments with turbulent wind flows, their low capacity factor (5–30%) and their high investment and maintenance costs. The complexity of integrating turbines into existing or new buildings is particularly emphasized, as architectural adaptations, structural reinforcements and esthetic acceptability requirements are needed. Analysis has shown that the levelized cost of electricity (LCOE) of BIWT is significantly higher than that of large onshore wind farms and photovoltaic systems. However, the use of new technologies such as computational fluid dynamics (CFD), 3D printing, artificial intelligence and advanced materials (e.g., graphene-reinforced composites) is accelerating the development of more efficient turbines that are adapted to the turbulent conditions in cities and help to reduce costs and improve energy efficiency. For example, lightweight composites allow turbines to operate at wind speeds of 2 to 4 m/s using permanent magnet generators, doubling the potential of urban power generation.

BIWT systems are environmentally friendly as they reduce greenhouse gas emissions and local dependence on fossil fuels, but they have issues with public acceptance due to noise, visual impact and potential safety risks. It is important to note that their competitiveness in the market depends on “incentive policies” such as tax incentives, feed-in tariffs and regulatory support that encourage the integration of renewable energy sources into urban planning. The renovation of the building stock promoted by the EU directives and the mandatory use of renewable energy sources in nZEB and ZEB systems should encourage the increased use of BIWTs.

In summary, while BIWTs will remain a niche technology in the coming years, growing technological advances and regulatory incentives could promote their wider application, especially in coastal areas with favorable wind conditions. The future development of BIWTs should focus on addressing their main shortcomings and creating synergies with other renewable energy technologies, such as hybrid systems (solar cells + BIWTs). In the long term, BIWTs have the potential to transform buildings into energy-sustainable facilities, contributing to the global goals of emission reduction and energy independence.

Author Contributions: Conceptualization, M.B.; methodology, M.B.; software, M.B., N.V. and I.H.; formal analysis, M.B.; investigation, M.B.; resources, M.B.; data curation, M.B.; writing—original draft preparation, M.B.; writing—review and editing, N.V.; visualization, I.H.; project administration, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Meaning
3D	Three-Dimensional
AE	Acoustic emission
AEP	Annual Energy Production
AI	Artificial Intelligence
BAWT	Building-Augmented Wind Turbine
BIWT	Building-Integrated Wind Turbine
BMWT	Building-Mounted Wind Turbine
BOS	Balance of System

CapEx	Capital Expenditure
CFD	Computational Fluid Dynamics
CFRP	Carbon fiber reinforced polymers
CO ₂	Carbon Dioxide
C _p	Coefficient of performance
EU	European Union
FBG	Blade-embedded fiber Bragg grating
HAWT	Horizontal-Axis Wind Turbine
IoT	Internet of Things
ITC	Investment Tax Credit
LCOE	Levelized Cost of Electricity
LEED	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
nZEB	nearly Zero Energy Building
PAGV	Power Augment Guiding Vanes
PCM	Phase change materials
PV	Photovoltaic
RES	Renewable Energy Sources
ROI	Return on Investment
VAWT	Vertical-Axis Wind Turbine
ZEB	Zero Emission Building

References

1. Sim, G.Y.; Ariff, M.A.M.; Goh, H.H.; Ramli, S.N.; Sim, S.Y.; Chien, S.K. The Impact of the Guide Vane on the BIWT System for the Distributed Wind Generation in the Urban Area. *Int. J. Integr. Eng.* **2021**, *13*, 42–52. [\[CrossRef\]](#)
2. Park, J.; Jung, H.-J.; Lee, S.-W.; Park, J. A New Building-Integrated Wind Turbine System Utilizing the Building. *Energies* **2015**, *8*, 11846–11870. [\[CrossRef\]](#)
3. Smith, R.F.; Killa, S. Bahrain World Trade Center (BWTC): The First Large-Scale Integration of Wind Turbines in a Building. *Struct. Des. Tall Spec. Build.* **2007**, *16*, 429–439. [\[CrossRef\]](#)
4. Li, Q.; Shu, Z.; Chen, F.B. Performance Assessment of Tall Building-Integrated Wind Turbines for Power Generation. *Appl. Energy* **2016**, *165*, 777–788. [\[CrossRef\]](#)
5. Kim, H.-G.; Jeon, W.-H.; Kim, D.-H. Wind Resource Assessment for High-Rise BIWT Using RS-NWP-CFD. *Remote Sens.* **2016**, *8*, 1019. [\[CrossRef\]](#)
6. Banger, D.N.; Sudhakar, Y.N.; Nazareth, R.A. Concrete-Based Energy Storage: Exploring Electrode and Electrolyte Enhancements. *RSC Adv.* **2024**, *14*, 28854–28880. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Han, D.; Huang, S.; Abia Hui, P.K.; Chen, Y. Development of a New Type of Vortex Bladeless Wind Turbine for Urban Energy Systems. In Proceedings of the 2024 9th International Conference on Power and Renewable Energy, Guangzhou, China, 20–23 September 2024; pp. 973–978. [\[CrossRef\]](#)
8. Rodriguez, C.V.; Ríos, A.; Luyo, J.E. CFD Design of Urban Wind Turbines: A Review and Critical Analysis. *Int. J. Renew. Energy Res.* **2021**, *11*, 618–638. [\[CrossRef\]](#)
9. Mao, Z.; Yang, G.; Zhang, T.; Tian, W. Aerodynamic Performance Analysis of a Building-Integrated Savonius Turbine. *Energies* **2020**, *13*, 2636. [\[CrossRef\]](#)
10. Calautit, K.; Johnstone, C. State-of-the-Art Review of Micro to Small-Scale Wind Energy Harvesting Technologies for Building Integration. *Energy Convers. Manag. X* **2023**, *20*, 100457. [\[CrossRef\]](#)
11. Huang, C.; Liu, C.; Zhong, M.; Sun, H.; Gao, T.; Zhang, Y. Research on Wind Turbine Location and Wind Energy Resource Evaluation Methodology in Port Scenarios. *Sustainability* **2024**, *16*, 1074. [\[CrossRef\]](#)
12. Alam, F.; Jin, Y. The Utilisation of Small Wind Turbines in Built-Up Areas: Prospects and Challenges. *Wind* **2023**, *3*, 418–438. [\[CrossRef\]](#)
13. Zagubień, A.; Wolniewicz, K. Energy Efficiency of Small Wind Turbines in an Urbanized Area—Case Studies. *Energies* **2022**, *15*, 5287. [\[CrossRef\]](#)
14. Zhang, Z.; Liu, X.; Zhao, D.; Post, S.; Chen, J. Overview of the Development and Application of Wind Energy in New Zealand. *Energy Built Environ.* **2023**, *4*, 725–742. [\[CrossRef\]](#)
15. Kwok, K.C.S.; Hu, G. Wind Energy System for Buildings in an Urban Environment. *J. Wind Eng. Ind. Aerodyn.* **2023**, *234*, 105349. [\[CrossRef\]](#)

16. Ding, S.; Yang, C.; Zhang, S. Acoustic-Signal-Based Damage Detection of Wind Turbine Blades—A Review. *Sensors* **2023**, *23*, 4987. [CrossRef]
17. Le, A.D.; Doan, V.H.; Thi Thu, P.N.; Tran, H.T.; Truong, V.A.; Do Van, M.; Nguyen, D.D.; Banh, M.D. Performance Assessment of Savonius Wind Turbine: Impact of the Cylindrical Deflectors with Natural Shapes. *Ocean Eng.* **2025**, *315*, 119900. [CrossRef]
18. Alanis Ruiz, C.; Kalkman, I.; Blocken, B. Aerodynamic Design Optimization of Ducted Openings through High-Rise Buildings for Wind Energy Harvesting. *Build. Environ.* **2021**, *202*, 108028. [CrossRef]
19. Li, D.; Li, C.; Zhang, W.; Zhu, H. Effect of Building Diffusers on Aerodynamic Performance for Building Augmented Vertical Axis Wind Turbine. *J. Renew. Sustain. Energy* **2021**, *13*, 23306. [CrossRef]
20. Zhang, S.; Du, B.; Ge, M.; Zuo, Y. Study on the Operation of Small Rooftop Wind Turbines and Its Effect on the Wind Environment in Blocks. *Renew. Energy* **2022**, *183*, 708–718. [CrossRef]
21. Garcia, O.; Ulazia, A.; del Rio, M.; Carreno-Madinabeitia, S.; Gonzalez-Arceo, A. An Energy Potential Estimation Methodology and Novel Prototype Design for Building-Integrated Wind Turbines. *Energies* **2019**, *12*, 2027. [CrossRef]
22. Stathopoulos, T.; Alrawashdeh, H. Urban Wind Energy: A Wind Engineering and Wind Energy Cross-Roads. In Proceedings of the XV Conference of the Italian Association for Wind Engineering; Ricciardelli, F., Avossa, A.M., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 3–16.
23. IEC 61400-2:2013; International Electrotechnical Commission Wind Turbines—Part 2: Small Wind Turbines 2013. International Electrotechnical Commission: Geneva, Switzerland, 2013.
24. Zhou, H.; Wu, Q.; Nan, D. Analysis of Feasibility on Integration of High-Rise Building and Wind Power. In Proceedings of the 18th International Symposium on Advancement of Construction Management and Real Estate; Yang, D., Qian, Y., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 91–101.
25. Stehly, T.; Beiter, P.; Duffy, P. *2020 Cost of Wind Energy Review*; National Renewable Energy Laboratory: Golden, CO, USA, 2022.
26. Bošnjaković, M.; Martinović, M.; Đokić, K. Application of Artificial Intelligence in Wind Power Systems. *Appl. Sci.* **2025**, *15*, 2443. [CrossRef]
27. The International Finance Corporation (IFC). *Environmental, Health, and Safety Guidelines Wind Energy Environmental, Health, and Safety Guidelines for Wind Energy*; The International Finance Corporation: Washington, DC, USA, 2015.
28. Awada, A.; Younes, R.; Ilinca, A. Review of Vibration Control Methods for Wind Turbines. *Energies* **2021**, *14*, 3058. [CrossRef]
29. Lecheb, S.; Chellil, A.; Mechakra, H.; Safi, B.; Beggah, Y.; Lounici, Y. Material Fracture of Dynamic VAWT Blade. In Proceedings of the Third International Symposium on Materials and Sustainable Development; Abdelbaki, B., Safi, B., Saidi, M., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 189–196.
30. Wu, X.; Feng, K.; Li, Q. A Numerical Method for the Dynamics Analysis of Blade Fracture Faults in Wind Turbines Using Geometrically Exact Beam Theory and Its Validation. *Energies* **2024**, *17*, 824. [CrossRef]
31. Yun, F.; Liu, J.; Liu, C.; Zhao, X. Analysis and Research on the Cause of Wind Turbine Blade Bolt Fracture. *J. Phys. Conf. Ser.* **2021**, *2133*, 012028. [CrossRef]
32. Chen, X.; Eder, M.A. A Critical Review of Damage and Failure of Composite Wind Turbine Blade Structures. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *942*, 12001. [CrossRef]
33. Howard, J. Netting for Construction: Keeping Debris and Dust Contained. Available online: <https://www.borisnets.co.uk/netting-for-construction-keeping-debris-and-dust-contained/> (accessed on 15 January 2025).
34. Karadag, I.; Kuruçay, E. Noise Emission from Building Integrated Wind Turbines: A Case Study of a Tall Building. *Sak. Univ. J. Sci.* **2021**, *25*, 563–570. [CrossRef]
35. de Santoli, L.; Albo, A.; Astiaso Garcia, D.; Bruschi, D.; Cumo, F. A Preliminary Energy and Environmental Assessment of a Micro Wind Turbine Prototype in Natural Protected Areas. *Sustain. Energy Technol. Assess.* **2014**, *8*, 42–56. [CrossRef]
36. Bošnjaković, M.; Hrkać, F.; Stoić, M.; Hradovi, I. Environmental Impact of Wind Farms. *Environments* **2024**, *11*, 257. [CrossRef]
37. Wei, L.; An, G. Optimization of Building Integrated Energy Scheduling Using an Improved Genetic Whale Algorithm. *Sci. Rep.* **2024**, *14*, 2386. [CrossRef]
38. Schuh, P.; Schneider, D.; Funke, L.; Tracht, K. Cost-Optimal Spare Parts Inventory Planning for Wind Energy Systems. *Logist. Res.* **2015**, *8*, 4. [CrossRef]
39. Katsaprakakis, D.A.; Papadakis, N.; Ntintakis, I. A Comprehensive Analysis of Wind Turbine Blade Damage. *Energies* **2021**, *14*, 5974. [CrossRef]
40. Florescu, A.; Barabas, S.; Dobrescu, T. Research on Increasing the Performance of Wind Power Plants for Sustainable Development. *Sustainability* **2019**, *11*, 1266. [CrossRef]
41. Stewart, S.W. The Challenges Involved in Building Integrated Wind Energy Include Wind Flow, Structure Siting, Unit Certification, and Aesthetics, Wind Systems Magazine. Available online: <https://www.windsystemsmag.com/technology-21/> (accessed on 15 January 2025).
42. Castellani, F.; Natili, F.; Astolfi, D.; Hirschl, A.; Peppoloni, M. Vibration Damping of a Vertical Axis Wind Turbine in Operating Conditions. *J. Phys. Conf. Ser.* **2022**, *2265*, 042081. [CrossRef]

43. Fields, J.; Oteri, F.; Preus, R.; Baring-Gould, I. Deployment of Wind Turbines in the Built Environment: Risks, Lessons, and Recommended Practices. *Natl. Renew. Energy Lab.* **2016**, *46*, 1260340.
44. Kumar, N.; Prakash, O. Analysis of Wind Energy Resources from High Rise Building for Micro Wind Turbine: A Review. *Wind Eng.* **2023**, *47*, 190–219. [[CrossRef](#)]
45. IEA PVPS Task 15: *Enabling Framework for the Acceleration of BIPV*; IEA PVPS: Paris, France, 2018; ISBN 9783907281369.
46. Garcia Hernandez, O.; Mario, R.; Ulazia, A.; Osa, J.; Ibarra-Berastegi, G. ROSEO: Novel Savonius-Type BIWT Design Based on the Concentration of Horizontal and Vertical Circulation of Wind on the Edge of Buildings. In Proceedings of the 8th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2019), Dublin, Greece, 3–5 May 2019; pp. 172–178.
47. Wenxin, W.; Kexin, C.; Yang, B.; Yun, X.; Jianwen, W. Influence of Wind Energy Utilization Potential in Urban Suburbs: A Case Study of Hohhot. *Sci. Rep.* **2021**, *11*, 11567. [[CrossRef](#)]
48. Available online: <https://www.consilium.europa.eu/en/policies/european-green-deal/> (accessed on 15 January 2025).
49. Kolawole, A.; Hassan, K.; Ajewole, T. Micro-Grid Wind Energy Conversion Systems: Conventional and Modern Embedded Technologies—A Review. *J. Digit. Food Energy Water Syst.* **2024**, *5*, 1–16. [[CrossRef](#)]
50. Rouhani, A.; Abasi, M.; Joorabian, M.; Davatgaran, V. Designing a Novel Optimal Energy Management to Determine the Contribution and Effect of Primary Sources on the Structure and Components Size of Smart Microgrids and Smart Buildings. In Proceedings of the 2024 9th International Conference on Technology and Energy Management, Mazandaran, Iran, 14–15 February 2024.
51. Serero, D.; Couton, L.; Parisse, J.D.; Le Roy, R. Design Methodology and Evaluation of Wind Harvesting Devices Integrated to Buildings Conference on Advanced Building Skins. In Proceedings of the Advanced Building Skins International Conference, Bern, Switzerland, 10–11 October 2016.
52. Bobrova, D. Building-Integrated Wind Turbines in the Aspect of Architectural Shaping. *Procedia Eng.* **2015**, *117*, 404–410. [[CrossRef](#)]
53. Wood, D. Small Wind Turbines for Remote Power and Distributed Generation. *Wind Eng.* **2010**, *34*, 241–254. [[CrossRef](#)]
54. Eldawy, R. A State-of-the-Art Review on Vortex Induced Vibrations Phenomenon Bladeless Wind Turbine Technology. *J. Sci. Res. Rep.* **2024**, *30*, 1045–1056. [[CrossRef](#)]
55. Nord-Lock Group. Good Vibrations: Innovating Small-Scale Wind “Turbines”. Available online: <https://www.nord-lock.com/learnings/knowledge/2022/bladeless-wind-turbine/> (accessed on 15 January 2025).
56. Consultants, U. Bladeless Turbines: What Are They and How Do They Work? Available online: <https://www.utmconsultants.com/news/bladeless-turbines-what-are-they-and-how-do-they-work/42157/> (accessed on 27 February 2025).
57. Graciano, D.M.; Sierra-espinosa, F.Z.; García, J.C. Numerical Simulation of Vortex-Induced Vibration in a Bladeless Turbine: Effects of Separation Distance between Tandem Harvesters. *Metascience Aerosp.* **2024**, *1*, 309–328. [[CrossRef](#)]
58. University of Birmingham. The Birmingham Blade: The World’s First Geographically Tailored Urban Wind Turbine Designed by AI. Available online: <https://www.birmingham.ac.uk/news/2024/the-birmingham-blade-the-worlds-first-geographically-tailored-urban-wind-turbine-designed-by-ai> (accessed on 27 February 2025).
59. Juan, Y.-H.; Rezaeiha, A.; Montazeri, H.; Blocken, B.; Yang, A.-S. Improvement of Wind Energy Potential through Building Corner Modifications in Compact Urban Areas. *J. Wind Eng. Ind. Aerodyn.* **2024**, *248*, 105710. [[CrossRef](#)]
60. Teng, H.; Li, S.; Cao, Z.; Li, S.; Li, C.; Ko, T.J. Carbon Fiber Composites for Large-Scale Wind Turbine Blades: Applicability Study and Comprehensive Evaluation in China. *J. Mar. Sci. Eng.* **2023**, *11*, 624. [[CrossRef](#)]
61. Mishnaevsky, L.; Branner, K.; Petersen, H.N.; Beauson, J.; McGugan, M.; Sørensen, B.F. Materials for Wind Turbine Blades: An Overview. *Materials* **2017**, *10*, 1285. [[CrossRef](#)] [[PubMed](#)]
62. Kapil, A.; Raju, N.S.; Dharmaraju, D.; Sateesh, D.N. Design and Specific Strength Analysis of Carbon Fiber-Reinforced Thermoplastic Wind Turbine Blade Using Fem Method. *Int. J. Creat. Res. Thoughts* **2024**, *12*, 794–801.
63. Wind Power: What Are the Challenges and How Can Graphene Meet Them? Available online: <https://www.carbon-waters.com/en/wind-power-what-are-the-challenges-and-how-can-graphene-meet-them/> (accessed on 17 February 2025).
64. Maity, S.K.; Tyagi, U.; Kumar, R.; Kumar, K.; Sheoran, N.; Singh, S.; Kumar, G. Graphene-Enhanced Polymer Composites: A State-of-the-Art Perspective on Applications. *FlatChem* **2025**, *49*, 100797. [[CrossRef](#)]
65. Gesellschaft, F.; Der, Z.U.R.F.; Forschung, A. Wind Blade Using Cost-Effective Advanced Composite Lightweight Design Final Report Summary—WALID (Wind Blade Using Cost-Effective Advanced Composite Lightweight Design). 2024, pp. 1–16. Available online: <https://cordis.europa.eu/project/id/309985/reporting> (accessed on 15 January 2025).
66. The Climate Technology Centre and Network (CTCN). Building-Integrated Wind Turbines. Available online: <https://www.ctc-n.org/technologies/building-integrated-wind-turbines> (accessed on 17 February 2025).
67. Yavuz, H. Hybrid Composites for Very Large Lightweight Wind Turbine Blades: Structural and Materials Aspects. In *Advanced Composites in Aerospace Engineering Applications*; Mazlan, N., Sapuan, S.M., Ilyas, R.A., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 421–433, ISBN 978-3-030-88192-4.

68. Halli, S.K.; Meti, N.G.; Hittalamani, S.J.; Dandinavar, M.M.; Reddy, A.S. International Journal of Current Engineering and Technology Design and Development of Low Friction More Efficient Magnetically Levitated Wind Turbines. *Int. J. Curr. Eng. Technol.* **2017**, *7*, 907–914.
69. Lalit Uttamrao, N.; Ajinkya Uttamrao, C.; Kiran Bhausaheb, D.; Jitendra Shravan, D. Review Paper on Maglev Vertical Axis Wind Turbine. *Int. J. Creat. Res. Thoughts* **2018**, *6*, 442.
70. Azad, D.D.; Sai, D.S.; Ramakrishna, K.; Raviteja, P.; Gowtham, K.; Kumar, R.K. Performance of Wind Turbine with Magnetic Levitation. *Int. J. Res. Appl. Sci. Eng. Technol.* **2023**, *11*, 2627–2632. [[CrossRef](#)]
71. Navaneethakrishnan, P.L.; Ramesh Kumar, K.V.; Karthikeyan, V.; Deepakkumar, C.; Nandhakumar, T. An Experimental Investigation on Magnetically Levitated Vertical Axis Wind Mill: A Review. *J. Res.* **2019**, *4*, 1–4.
72. Muhammad, N.; Hosnan, A.M.; Anuar, K.; Nor, M.; Ahmad, N.I.; Mokhtaruddin, H.; Hidayah, D.; Rahman, A.; Saad, S.S.; Zakariya, M.Z.; et al. Development of Vertical Axis Wind Turbine (VAWT) Using Magnetic Levitation (MAGLEV). *J. Adv. Res. Eng. Knowl. J. Homepage* **2020**, *10*, 23–35.
73. Manoj, L.; Nithesh, J.; Manjunath, T.; Gowreesh, S.S. Power Generation Using Magnetic Levitation Vertical Axis Wind Turbine. *Int. J. Eng. Adv. Technol.* **2019**, *9*, 365–369. [[CrossRef](#)]
74. Liu, S.; Bian, Z.; Cheng, Z. The Application of the Permanent Magnet Bearings in the Vertical Axis Wind Turbine 2 The Structure Design of the Permanent Magnetic Axial Bearing in the Wind Turbine. pp. 1–6. Available online: https://www.magneticbearings.org/app/uploads/publications/ismb13/ismb13_submission_48.pdf (accessed on 15 January 2025).
75. Al-Talib, A.A.M.; Md Redzuan, M.R.; Hamid, A.R.A. A Levitating Frictionless_Vertical Windmill. In Proceedings of the 2022 International Conference on Artificial Life and Robotics, Oita, Japan, 20–23 January 2022; pp. 892–899. [[CrossRef](#)]
76. Lee, J.; Park, J.; Jung, H.-J.; Park, J. Renewable Energy Potential by the Application of a Building Integrated Photovoltaic and Wind Turbine System in Global Urban Areas. *Energies* **2017**, *10*, 2158. [[CrossRef](#)]
77. WindStream Technologies: Tehnical Manual. Available online: [https://d1io3yog0oux5.cloudfront.net/windstreaminc/files/pages/resources/technical-support/SolarMill+Tech+Manual+\(Updated\).pdf](https://d1io3yog0oux5.cloudfront.net/windstreaminc/files/pages/resources/technical-support/SolarMill+Tech+Manual+(Updated).pdf) (accessed on 15 January 2025).
78. Odukamaiya, A.; Woods, J.; James, N.; Kaur, S.; Gluesenkamp, K.R.; Kumar, N.; Mumme, S.; Jackson, R.; Prasher, R. Addressing Energy Storage Needs at Lower Cost via On-Site Thermal Energy Storage in Buildings. *Energy Environ. Sci.* **2021**, *14*, 5315–5329. [[CrossRef](#)]
79. Choorikat, A.; Pazhamannil, R.; Alkhedher, M.; Kumar, P. Experimental and CFD Performance Analysis of 3D Printed Seashell Type Wind Turbine. *Prog. Addit. Manuf.* **2025**, *10*, 1–12. [[CrossRef](#)]
80. Zarzoor, A.; Jaber, A.; Shandookh, A. 3D Printing for Wind Turbine Blade Manufacturing: A Review of Materials, Design Optimization, and Challenges. *Eng. Technol. J.* **2024**, *42*, 895–911. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.