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State-of-the-art review of micro to small-scale wind energy harvesting technologies for building integration

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ABSTRACT

The utilisation of wind power in buildings has gained significant interest, but deploying wind turbines in built environments presents unique challenges due to highly turbulent wind patterns. Existing small wind turbines may not be as efficient in such complex conditions, and their transient loads and vibrations can compromise their durability. This study aims to assess the recent status, challenges, and limitations of building-integrated wind turbines and micro or small-scale wind-induced vibration technologies to enhance their performance, efficiency, reliability, and cost-effectiveness. The research evaluates advancements, applications, and technical features that optimise these technologies to function effectively in non-uniform wind flows and a wide range of wind speeds. Modeling conventional systems, including horizontal axis and vertical axis wind turbines, is well-established using computational fluid dynamics and blade element momentum methods. Micro or small-scale wind-induced vibration technologies have demonstrated power outputs ranging from milliwatts to kilowatts, making them suitable for powering actuators and low-powered sensors used in buildings. The study emphasises the importance of harnessing wind velocity acceleration induced by the building's roof shape when incorporating wind energy harvesting technologies. Nevertheless, research on wind-induced vibration harvesting primarily takes place in controlled environments, neglecting the influence of real buildings. This represents a significant research gap, considering the potential for wind-induced vibration technologies to provide power to off-grid communities and facilitate building integration. The lack of comprehensive analysis concerning the energy, economic, and environmental aspects of micro-energy harvesting technologies hinder their widespread adoption and a comprehensive understanding of their potential. Addressing these research gaps is essential to promote the implementation and efficacy of micro-scale wind energy harvesting technologies in various real-world scenarios.

Nomenclature

Symbols	
Velocity (Metre per second)	m/s
Power (Killowatt)	kW
Power (Watt)	w
Power (Milliwatt)	mW
MilliWatt per centimetre	mW/cm
Power (Microwatt)	μW
Power (Nanowatt)	nW
Electric resistance (Kiloohm)	kΩ
Electric resistance (Ohm)	Ω
Volume (Cubic centimeter)	cm^3
Electrical (Voltage)	V
Force (Newton)	N
Length (Millimetre)	mm

(*continued on next column*)

Nomenclature (*continued*)

Symbols	
Energy (Millijoule)	mJ
Abbreviations	
Building Integrated Wind Turbine	(BIWT)
Building Augmented Vertical-Axis Wind Turbine	(BA-VAWT)
Tip-Speed Ratio	(TSR)
Blade-Element Momentum	(BEM)
Heating, ventilation, and air conditioning	(HVAC)
Light-emitting diode	(LED)
Heating, Ventilation, and Air Conditioning	(HVAC)
Fluid-structure interaction	(FSI)
Internet of Things	(IoT)
Wireless Sensor Nodes	(WSN)
Light-emitting diode	(LED)
Fluid-structure interaction	(FSI)

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Nomenclature (*continued*)

Symbols	
Degrees of Freedom	(DOF)
Design of Experiments	(DOE)
Atmospheric Boundary Layer	(ABL)
Vortex Particle Method	(VPM)
Vortex-Induced Vibration	(VIV)
Cross-axis wind turbine	(CAWT)
Ducted-Augmented Wind Turbine	(DAWT)
Vertical-Axis Wind Turbine	(VAWT)
Horizontal-Axis Wind Turbine	(HAWT)
Cross-axis wind turbine	(CAWT)
Wind Lens Turbine	(WLT)
V-Shape Guide Vane	VRGV
Heating, ventilation, and air conditioning	(HVAC)
Triboelectric nanogenerator	(TENG)
Electromagnetic generators	(EMS)
Micro electro-mechanical system	(MEMS)

Introduction

Over the past few decades, wind energy has emerged as a rapidly growing source of renewable energy [1]. Small-scale wind energy harvesting systems have become increasingly popular due to their potential to provide a decentralised, renewable and sustainable source of energy for homes, businesses, and communities. These systems have numerous advantages over large-scale wind energy systems, such as space efficiency, reduced dependence on grid-connected power and long transmission lines and lower costs. Building-integrated wind energy harvesting systems (BI-WEHS) offer a promising solution for generating renewable energy in urban areas, reducing the environmental impact of energy production, and increasing energy independence [2].

Despite these advantages, building integrated wind energy harvesting systems also faces significant challenges. The potential of small-scale wind energy systems depends on factors such as wind speed, location, and the type of wind energy harvesting system used [3]. The unpredictable wind conditions in urban areas can make it difficult to generate a steady and reliable source of energy. Building integrated wind energy harvesting systems comes with its own challenges, such as compatibility with building structures, noise generation, and safety concerns. Compatibility with building structures, strength to withstand wind forces and potential vibrations, high installation and maintenance costs for older buildings [4]. Noise generation from the wind energy harvester operation can be a problem, and safety must be ensured to prevent accidents or damage to the building and its residents. Local permits and regulations must also be followed, adding to the time and cost of installation. Choosing the wrong wind energy harvesting technology can result in subpar performance due to inaccurate assessment of in-situ wind conditions, uninformed decisions about positioning and mounting of urban wind turbines, and a lack of consideration for the impact of roof shape, building height, and surrounding urban configurations on wind acceleration [5].

Research gaps, aims and objectives

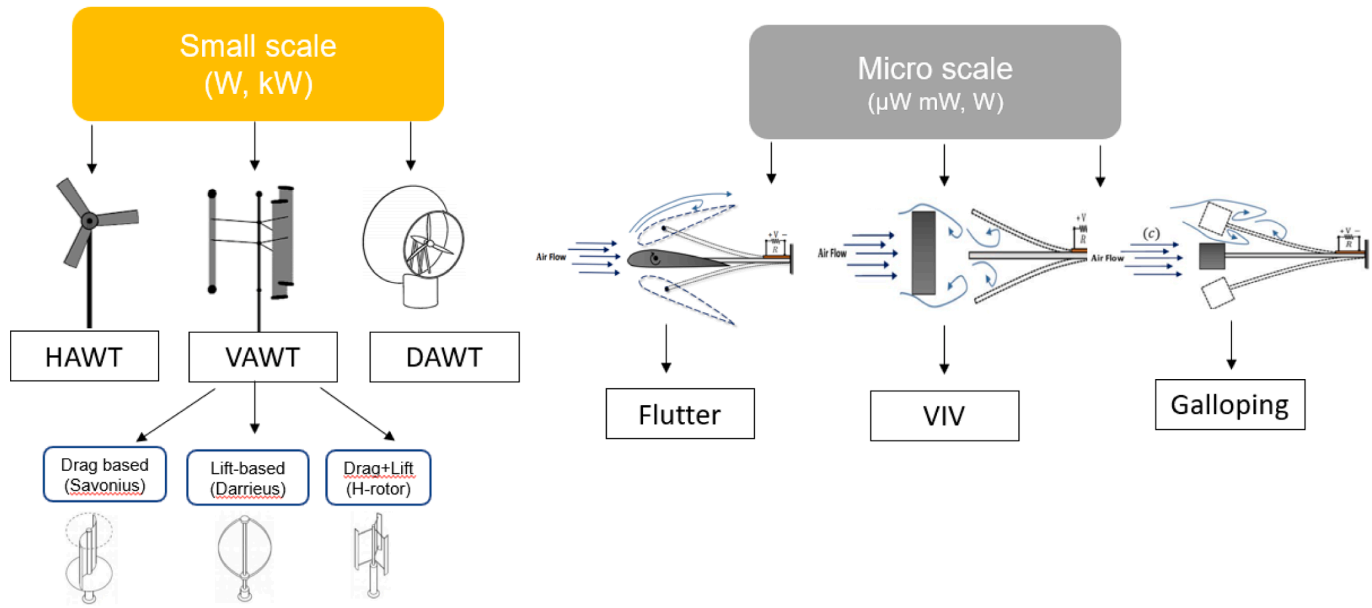
To the author's knowledge, there is a lack of comparative analysis in the existing literature on various micro/small-scale wind energy harvesting technologies integrated into the building structure, which restricts the evaluation of recent advancements. The majority of the studies available for building integrated wind energy harvesting technologies are focused on vertical axis wind turbine (VAWT), horizontal axis wind turbine (HAWT), and ducted augmented wind turbine (DAWT) systems [6–12]. Whilst recent studies related to the micro/small scale wind-induced vibration technologies, such as flutter-based wind-induced vibration, vortex-induced vibration, and galloping mechanism, are not yet explored.

To address these gaps in research, this study will further investigate the performance of wind energy harvesting technologies beyond the conventional VAWT, HAWT, and DAWT systems by exploring flutter-based wind-induced vibration, vortex-induced vibration, and galloping mechanisms that have not been thoroughly examined. Flutter is a self-sustained, periodic oscillation that occurs when a structure is subjected to the interaction between its aerodynamic forces and structural stiffness. It is characterized by high-frequency, low-amplitude vibrations. In wind energy harvesting, flutter-based mechanisms involve the exploitation of the aeroelastic instability of a flexible structure placed in a wind flow. When the wind speed reaches a critical value, the structure starts oscillating, leading to energy generation through piezoelectric, electromagnetic, or other energy conversion methods [4]. Another form of wind-induced vibration is called the vortex-induced vibration. It occurs when an object or structure positioned in a flowing fluid generates alternating vortices on either side. These vortices induce a series of oscillations, leading to the transference of energy to the structure. In the context of wind energy harvesting, vortex-induced vibration mechanisms utilise specially designed structures with specific geometries to harness the energy produced during the interaction of vortices with the structure [4]. Galloping is another wind-induced vibration phenomenon characterized by a low-frequency, high-amplitude oscillation of a structure. It typically occurs when the structure presents an asymmetric shape, causing the wind to exert varying pressure on different sides. The imbalance in the aerodynamic forces results in a self-sustained motion, which can be converted into useful energy through appropriate energy harvesting mechanisms [4].

Fig. 1 demonstrates the different designs of traditional wind turbines and wind-induced vibration systems. The traditional wind turbines include the HAWT, VAWT, and VAWT. Whilst the micro-scale comprises of the flutter-based, VIV, and galloping-based mechanisms. The study will assess the state-of-the-art designs, power, and harvesting performances of each technology to identify the most appropriate design for building-integrated wind energy harvesting systems. These technologies can be integrated into a building and have lower installation and maintenance costs than traditional wind turbines, especially for low wind speed conditions. The efficiency and performance of these systems are analysed using a variety of methods, including numerical CFD analysis, wind tunnel experiments, and field tests, as detailed in the literature.

The review aims to provide a further understanding of the current state, challenges, and limitations of micro/small-scale building-integrated wind turbines and wind-induced vibration technologies. New strategies and solutions to improve their performance, efficiency, reliability, and cost-effectiveness will be discussed. To achieve this, the study will examine various research findings on the advancements and applications of these technologies.

The organisation of this review paper is as follows. Section 2 presents the methods used to select and assess the literature for this review. Section 3 reviews recent developments in building integrated wind energy harvesting systems and explores potential alternatives of wind energy harvesters that can be installed into the building to maximize energy capture efficiency. This section also examines designs, methods, and applications for optimising wind energy capture systems. Section 4 presents a summary of reviewed technical characteristics and comparative analysis for six different wind energy harvesting technologies, including conventional wind turbines and wind-induced vibration technologies. Section 5 discusses the methods for improving wind energy capture technology efficiency through numerical and experimental methods. Section 6 provides a summary of the main findings from reviewed literature. Finally, section 7 discusses the recommendations for future research, highlighting areas that require further investigation, suggesting new research questions and directions, and emphasizing the potential benefits of future research.



(a) (b)

Fig. 1. Designs of (a) traditional wind turbines and (b) wind-induced vibration systems.

Method

This work will review the state-of-the-art for building integrated wind energy harvesting systems and wind-induced vibration technologies, as depicted in Fig. 2. As most current studies on building integrated wind turbines focus on conventional wind turbines such as HAWT, VAWT, and DAWT, this review also explores different wind energy harvesting technologies, including wind-induced vibration technologies such as flutter, vortex-induced vibration, and galloping mechanisms. To achieve this, a comparative analysis of six different wind energy harvester systems was conducted. The review will examine the design, power, and harvesting performance of micro/small-scale wind energy harvesting systems, with the potential for integration into commercial and residential buildings.

To conduct this review, a comprehensive search for research materials was carried out using various keywords such as "small-scale wind energy harvesting system," "building integrated wind energy harvesting system," "roof-mounted wind turbine," and "wind-induced vibration." The search was conducted using various academic search tools, including ScienceDirect, the MDPI, and Nature. Only works published from 2013 to 2023 were included in the review. The selected papers focused on different aspects of micro/small-scale wind energy harvesting systems, including their design, mechanisms, methods of analysis, and power and harvesting performance optimisation. After reviewing the literature, each technology was analysed regarding its performance for different designs and environmental conditions.

The methodology framework for studying the state of the art of building-integrated wind energy harvesting systems and small-scale wind energy harvesting systems involves several steps. Firstly, a comprehensive keyword search is conducted on various sources such as journal articles, books, conference papers, reports, and review papers. Secondly, the relevant articles are selected based on the abstract and their relevance to the topic of study. The next step involves reviewing the selected articles. The analysed articles are then used to find different wind energy harvesting systems designs that can be installed into the building structure, such as HAWT, VAWT, DAWT, flutter-based wind-induced vibration, vortex-induced vibration, and galloping mechanism. The research methods used in the articles are evaluated, such as numerical, experimental, or field tests. The power and energy harvesting performance of the roof-mounted wind energy harvesting systems and small-scale wind energy harvesting systems are also reviewed to determine a suitable wind energy harvester for a particular application. Finally, based on the reviewed literature, a summary of the results, a discussion of the findings, and a conclusion on the state of the art of roof-mounted wind energy harvesting systems and small-scale wind energy harvesting systems are provided.

Recent research on small-scale wind energy harvesting technologies has identified two conventional wind turbine designs, HAWT and VAWT, that can be installed in building structures [13]. However, these designs have limitations in harnessing wind energy, which has led to the continuous development of building integrated wind turbines. As a result, the DAWT was introduced, which involves adding ducts or diffusers to the wind turbine to improve its power coefficient over time [14]. Fig. 3 illustrates the schematic of a building integrated with HAWT, VAWT, and DAWT. Fig. 3(a) illustrates the typical commercial configurations of HAWT. These turbines can be operated either upwind or downwind, with upwind configurations being more common due to their lower noise production and reduced rotor fatigue. HAWT systems can generate a range of energy outputs [13]. In Fig. 3(b), Darrieus VAWT operates using aero blades. Fig. 3(c) illustrates the schematic diagram for DAWT.

Other micro/small-scale wind energy harvesting systems that are increasingly becoming popular such as wind-induced vibration technologies are evaluated. These include galloping-based mechanisms, flutter-based wind-induced vibration, and vortex-induced vibration Wen [4]. However, these systems are still in the early stages of testing for efficiency and performance and have not yet been widely adopted for real-world applications, particularly for building structures [4]. Fig. 4 illustrates potential design solutions for building-integrated wind energy harvesting systems aimed at overcoming the challenges and limitations of traditional wind turbines.

The analysis of papers published in the last 10 years revealed a lack of exploration of micro/small-scale wind-induced vibration technologies integrated or installed at the building structure. Most of the recent developments in wind energy harvesting technologies have been focused on building-integrated wind turbines, specifically horizontal-axis (HAWT), vertical-axis (VAWT), and ducted-augmented wind turbines (DAWT). As a result, this study also explores the potential and presents a solution for an alternative source of wind energy harvesting system that can be integrated into the building structure.

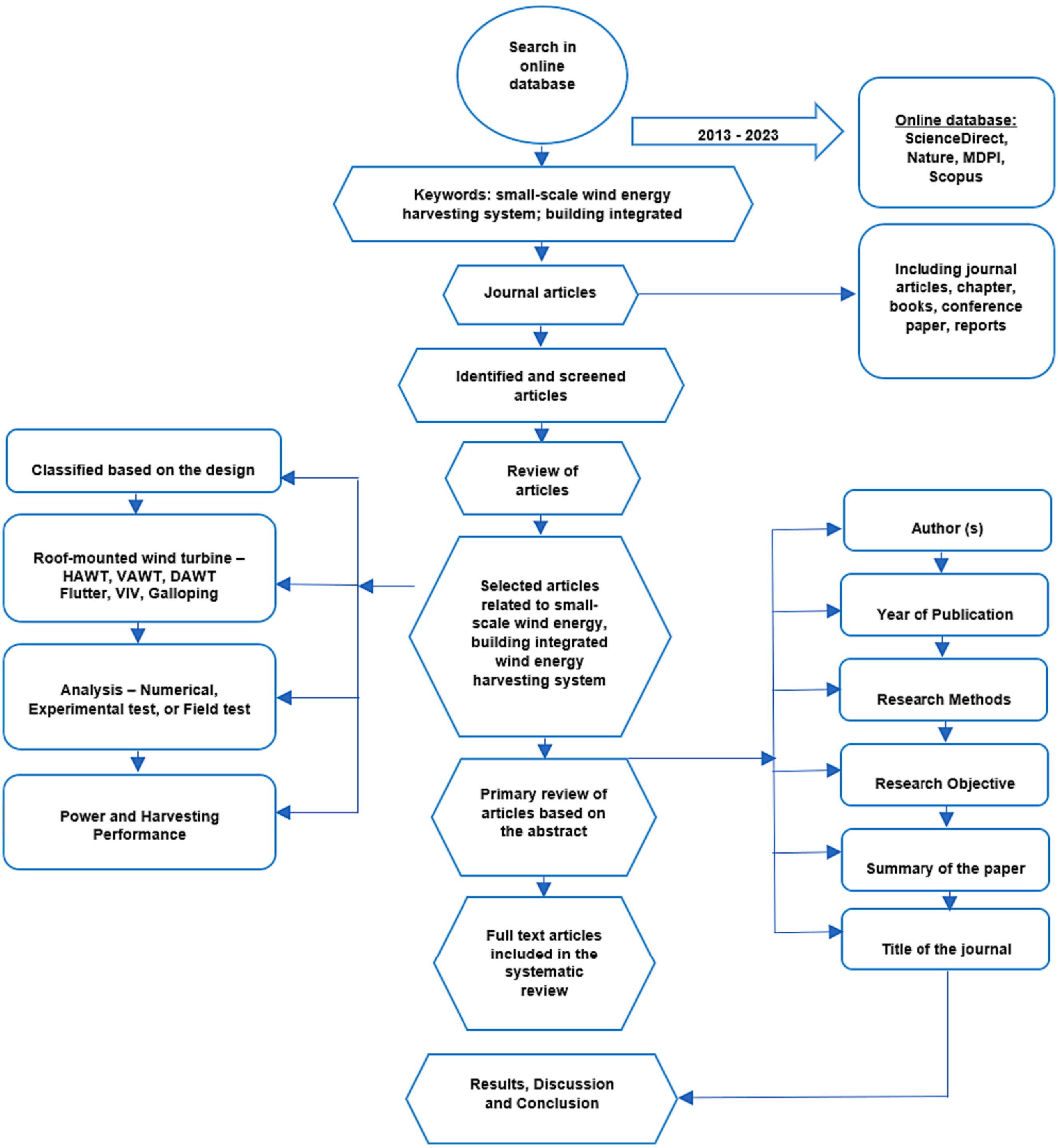


Fig. 2. The methodology framework for the review of micro/small-scale building integrated wind energy harvesting systems and wind-induced vibration technologies.

Wind energy harvesting system for building integration

This section presents an overview of state of the art in building-integrated wind turbines and micro/small-scale wind-induced vibrations as alternative energy sources. HAWT and VAWT are traditional wind energy systems. However, these technologies have evolved into new designs like DAWT, CAWT, and other types of wind energy harvesting technologies. There are also other micro/small-scale wind-induced vibrations that can potentially provide economical and light-weight options with simple structures and compact designs that can easily be integrated into other devices. These systems use flutter-based wind-induced vibration, vortex-induced vibration, and galloping mechanisms. Also, these technologies can potentially be installed on commercial and residential buildings to make the most of wind velocity acceleration. This review will discuss and examine the recent developments in wind energy harvesting technologies, with a particular emphasis on enhancing design and performance through the utilisation of numerical and experimental studies.

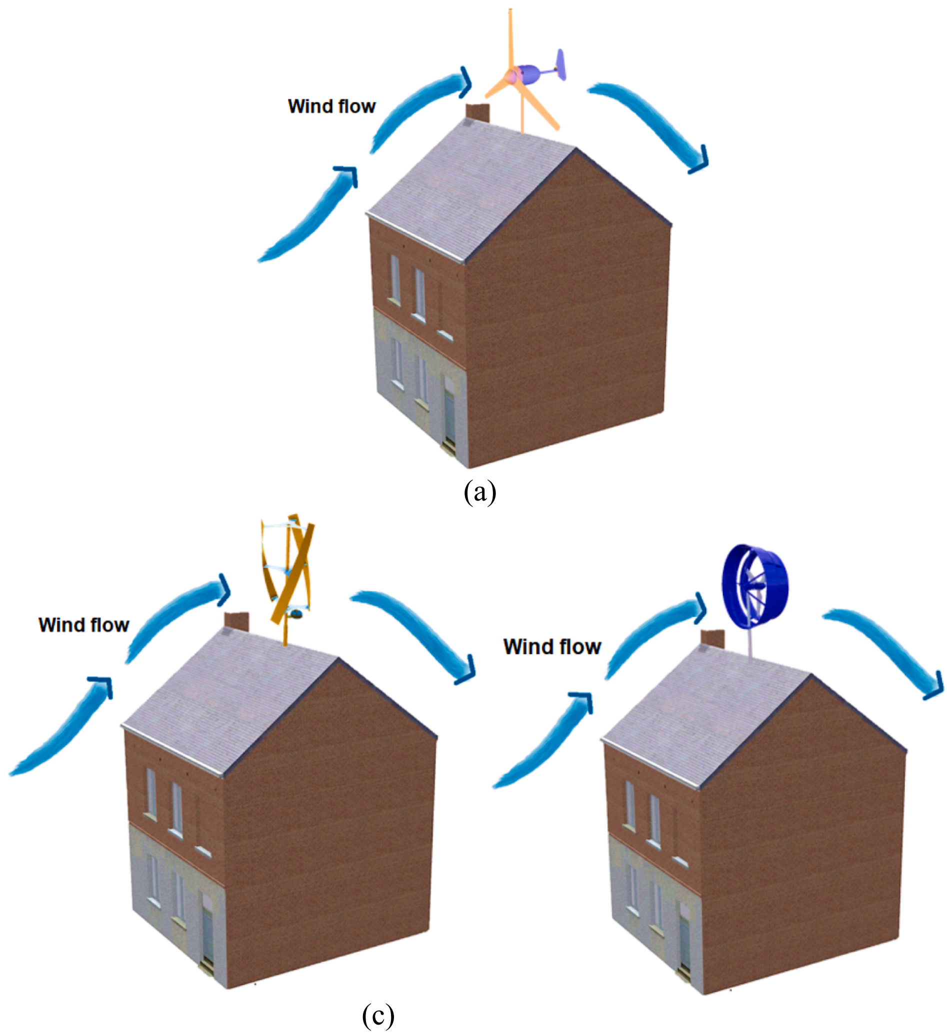


Fig. 3. Schematic diagrams of conventional small-scale wind turbines installed on the roof of a building (a) HAWT, (b) VAWT, and (c) DAWT.

Small-scale building-integrated wind turbines

Four different types of wind energy harvesting technologies that are installed into building structures to optimise energy capture efficiency will be reviewed in this section. These include the horizontal axis wind turbine (HAWT), vertical axis wind turbine (VAWT), ducted augmented wind turbine (DAWT), and other types of wind energy harvesting technologies. The challenge with harnessing wind energy is that wind speed is often very low, and turbulence intensity is typically high, especially in urban settings.

Horizontal axis wind turbine (HAWT)

HAWT consists of the rotor shaft and electrical generator at the top of a tower, and the rotor is positioned perpendicular to the wind. It typically consists of a gearbox, which converts the slow rotation of the rotor into a faster rotation, suitable to drive an electrical generator. These turbines greatly depend on wind direction and thus operate at higher heights than the VAWT. Fig. 5 demonstrates the aerodynamic profile and schematic of the HAWT that is installed into the structure of a building's roof [15].

The studies of [17–25] focused on the design and optimisation of horizontal axis wind turbine rotors and blades. Different methods were used for evaluation, such as computational fluid dynamics (CFD), Blade-Element Momentum (BEM), and genetic algorithms (GA) for investigating the aerodynamic performance of the rotors. Some studies [26,27] consider the aerofoil profile, blade allowable stress, starting time, and output power. Whilst many of the studies showed that the optimisation of the rotors using the above methods leads to improved power coefficient, starting performance, and annual energy production. The use of linear distributions and 3D stacking lines can also improve performance. The studies demonstrated that the optimised rotors could effectively enhance value addition and energy production. However, in this study, the focus is on the HAWT integrated into the building structure.

Various studies have highlighted the significance of blade design optimisation for achieving optimal performance of HAWTs integrated into buildings. In the study of Singh and Shmed [28], a 2-bladed rotor was designed using a special airfoil and exponential twist and taper distribution to achieve high aerodynamic performance at low wind speeds. The rotor was made from lightweight wood material and had a higher solidity at the outer portion of the blades for fast start-up and low cut-in wind speed. Field tests showed that the 2-bladed rotor performed better at a pitch angle of 18°, with lower cut-in wind speeds and higher power coefficients in the 3–7 m/s wind speed range compared to the baseline 3-bladed rotor. The peak power coefficient achieved by the 2-bladed rotor at 6 m/s wind speed was 0.29.

The QBlade software was utilised by Arumugam et al. [29] to design and simulate the turbine rotor blade under working conditions to evaluate its behaviour. The study examined design variables such as chord length and torsion angle that impact the performance of wind turbines. Sixteen different sections of the blade were selected using an aileron (NACA4711) with a length of 155 cm. High-accuracy results were obtained for power factor, torque coefficient, lift coefficient, drag

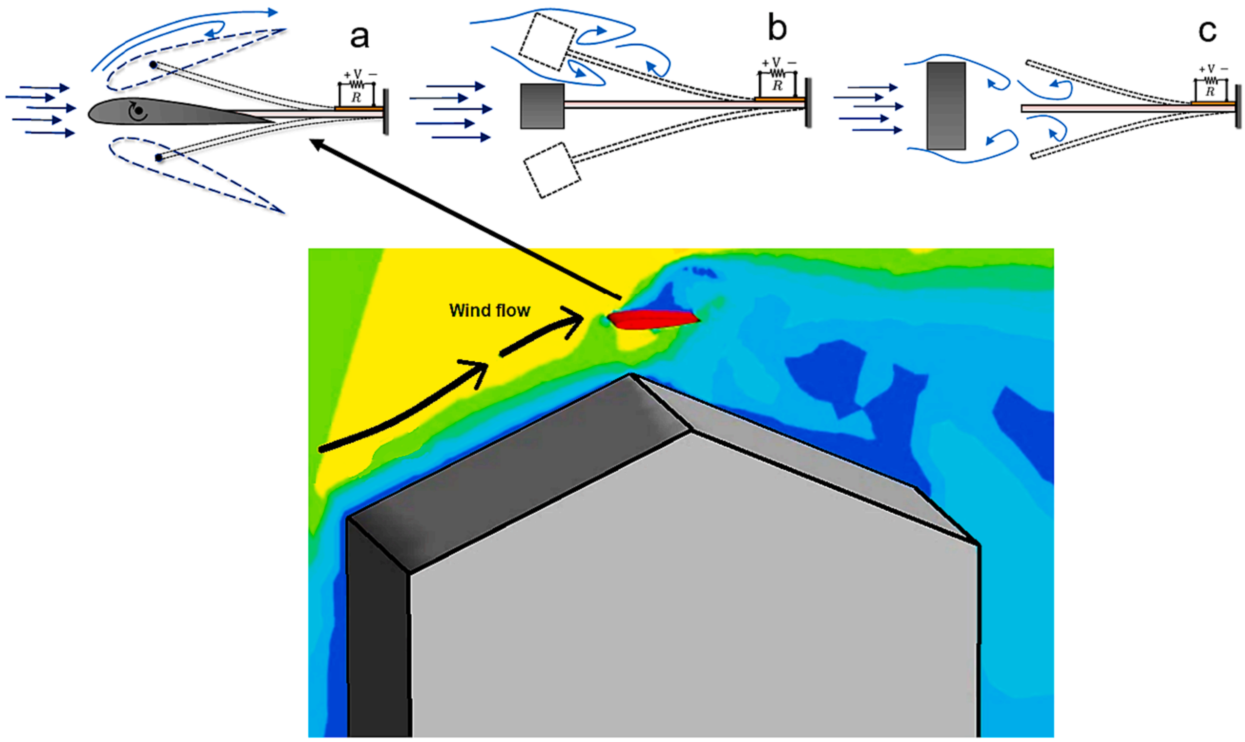
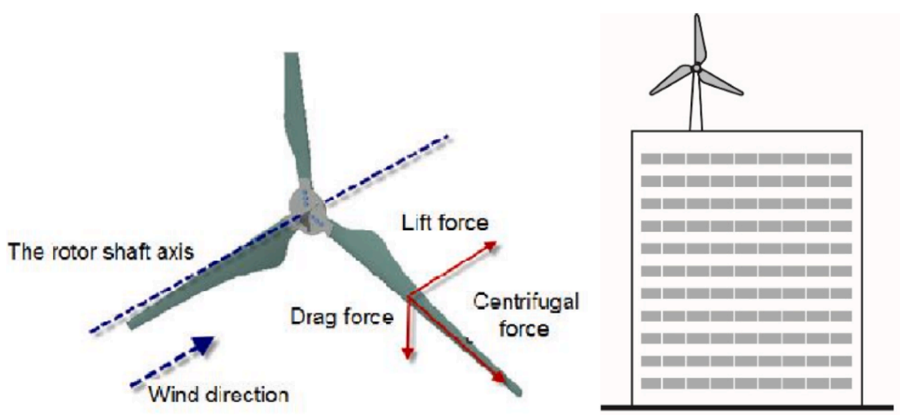


Fig. 4. Schematic of micro/small-scale harvester for roof building integration (a) flutter (b) galloping (c) VIV.



(a) (b)

Fig. 5. (a) Design of the blade and schematic for wind energy harvester [16](b) HAWT installed into the building structure [15].

coefficient, and lift-to-drag coefficient ratio. The optimal performance for the turbine rotor was achieved at a tip speed ratio of 7. The power factor obtained (Cp = 0.4742) was efficient for a small wind turbine and did not surpass the Betz limit (0.59%). Thus, the design of a small horizontal wind turbine with three blades is suitable for low wind speed areas.

Volkmer et al. [30] also investigated the blade design; however, it is more focused on the reduction of aerodynamic noise from modifying the blade design. The three blade modifications were investigated for reducing trailing edge noise in small horizontal axis wind turbines. The modifications were an acoustically optimised blade profile, boundary layer tripping, and trailing edge serrations. Tests were conducted on a three-bladed research wind turbine, and all modifications yielded a reduction of aerodynamic noise. The new 10% thick KV200-profiled blades were found to have substantially lower overall sound power levels than the baseline S834-profile, and tripping and trailing edge serrations were found to be beneficial in terms of noise reduction but led to a reduction of turbine shaft power. Boundary layer tripping applied to the thicker S834-profile resulted in the largest noise reductions but also the largest degradation of turbine shaft power. A combination of tripping and trailing edge serrations had almost the same effect as tripping alone, and the T-KV200 without trips but with trailing edge serrations was found to be the best choice for noise reduction.

In Ghorani et al. [31] study, an optimised geometry of an Invelox wind delivery system using a multi-objective surrogate-based optimization approach was investigated. The objectives were to maximize wind power, net mass flow rate, and minimize backflow. Kriging (KRG) models accurately predicted the outputs, and the optimal Invelox performance improved by 64.7% for P_{Th} and 279.9% for speed ratio. The HAWT designed for the throat had a Cp of 0.46, and the optimal Invelox's entering mass flow rate decreased by 49.6% when the turbine was not rotating.

Whereas for the study of [32], the focus was to investigate the impact of roof edge shapes on wake characteristics and power performance of a wind turbine installed on a roof in an urban setting. Experimental studies were conducted in a wind tunnel to investigate and compare the performance of a sharp 90° edge roof (cube), slightly curved roof edges (round), and a roof with a boundary fence (fence), which are inspired by real-life shapes. The study finds that minor changes to roof edge shapes can significantly impact power performance and wake characteristics, affecting the power available for the turbine. The study observes that the velocity, shear, and turbulence intensity depend on the roof edge shape. The round case performs the best, while the fence case experiences the highest drop in power production and the highest standard deviation. The study also finds that building shape plays a crucial role in estimating power production and wake effects, highlighting the importance of accurate building modelling.

The majority of the studies for HAWT integrated into the building structure are focused more on the aspects of blade design, such as achieving high aerodynamic performance at low wind speeds, reducing aerodynamic noise, and understanding the impact of design variables on wind turbine performance. Additionally, studies have explored other factors that can impact wind turbine performance, such as roof edge shapes and the geometry of the wind delivery system. Accurate modelling and design optimisation techniques have proven effective in improving wind turbine performance. However, it is also important to investigate the wind resource assessment for building integrated wind turbines located in urban, rural, or wind farm layout to further optimise the system's capacity.

Vertical axis wind turbine (VAWT)

VAWT features a rotor axis in a vertical orientation and does not require a yawing mechanism or self-starting capability. Its generator is located on the ground, making maintenance easier, and it operates at low heights. There are two main commercially available types of VAWT; Savonius and Darrieus. Fig. 6 (a) illustrates the Savonius VAWT, which uses drag to convert wind energy into mechanical rotational energy. Fig. 6 (b) shows the Darrieus VAWT, which uses the principle of lift to

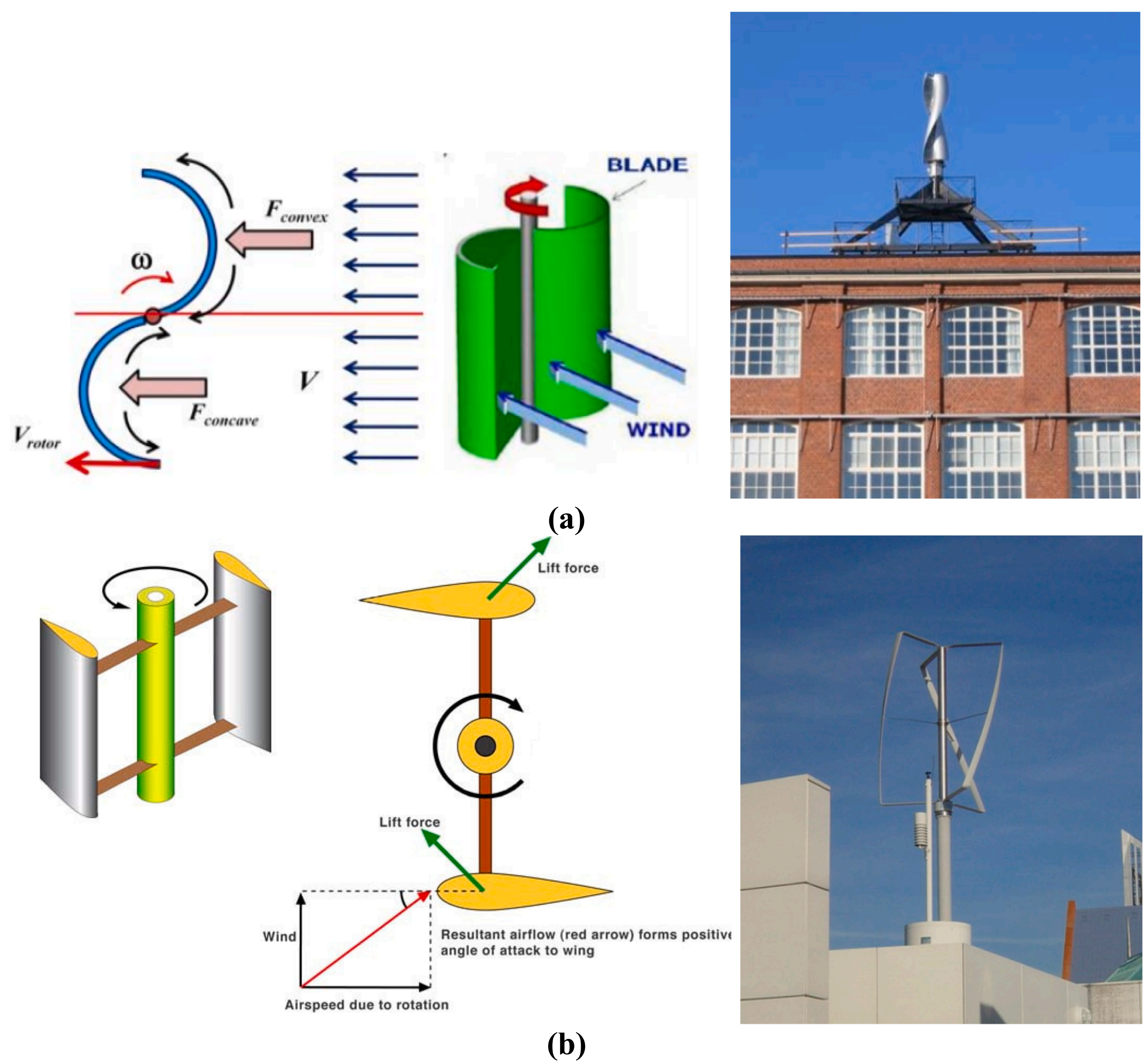


Fig. 6. Working principles and wind turbines installed at the rooftop of the building (a) Savonius [33,34] and (b) Darrieus [35,36].

convert wind energy, making it more efficient than the Savonius design. Whilst the Darrieus VAWT uses aerofoil-shaped blades, producing lift and rotation as the wind passes over the blade [13].

The Savonius and Darrieus wind turbines are two different types of VAWTs that use different aerodynamic principles to generate power from the wind. The Savonius turbine is characterised by its simple S-shaped blade design and reliance on drag force to generate torque, making it an economically viable option for small-scale wind energy production. Fig. 6(a) demonstrates the working principle of the Savonius rotor principle [33]. On the other hand, the Darrieus turbine uses lift force generated by its aerofoil blades to rotate the rotor, which requires the rotor to be initially spun to reach its operating speed. Fig. 6(b) shows the working principle of the Darrieus rotor [35]. The Darrieus turbine is more complex in design and operation than the Savonius turbine, but it has higher energy generation potential due to its blade shape. Ultimately, the choice between these two types of wind turbines will depend on the specific requirements and constraints of each individual project [35].

Savonius and Darrieus wind turbines are integrated into buildings in various ways depending on the design and requirements. They can be mounted on roofs, walls, or as standalone structures. The Savonius turbine is a vertical axis turbine that can be installed vertically, while the Darrieus turbine is a horizontal axis turbine that requires a tall mast or tower. Both turbines can generate electricity or mechanical power for building applications like lighting, ventilation, or water pumping. Integrating wind turbines into buildings can provide a renewable energy source and reduce reliance on traditional power sources.

Kuang et al. [8] proposed the building augmented vertical axis wind turbine (BA-VAWT) design that takes advantage of windy areas in the built environment to generate power. The study was conducted to determine the aerodynamic performance of the turbine using numerical simulations and the NACA 0021 blade aerofoil. Results showed that the wind energy utilisation coefficients of the different building diffusers increased and decreased as the Tip-Speed Ratio (TSR) increased. The trapezium BA-VAWT showed the best performance, with a maximum power coefficient of 1.56 at an optimal TSR of 4.62, whilst the A1 aerofoil had minimal pressure difference and almost no power generation. The torque coefficient and its variance also increased as TSR increased, making the load fluctuation relatively stable. The best aerodynamic performance was found in the trapezium BA-VAWT.

Another study of VAWT design was investigated by Li et al. [37]. The impact of rotor solidity and other factors on the power output of dual vertical axis wind turbines (VAWTs) were studied in an urban setting through twelve wind tunnel experiments. Results showed that the effect of the dual VAWT configuration on power output was limited under low tip-speed ratio conditions. The smaller rotor solidity was found to increase the sensitivity of power output to the spacing between the two rotors. High-rotor solidity dual VAWTs were more suitable for low wind power density areas, while low-rotor solidity dual VAWTs were better for high wind power density areas. The optimal utilisation of urban wind resources can be achieved by combining the layout of multiple VAWTs with the rooftop and building structure, considering factors such as rotor spacing, rotor solidity, high turbulence intensity, and low wind speed conditions. An array of multiple VAWTs is especially suitable for urban environments as it can improve aerodynamic performance and increase power output by improving wake interaction between VAWTs.

The experimental setup for the study Jooss et al. [38] involved two cubes representing buildings with a small VAWT of the Savonius type on top placed on a circular flat plate elevated from the wind tunnel floor. The plate was rotated to simulate varying wind directions, and three different wind turbine positions on the cube were examined. The distance between the turbine blades and the roof of the cube was also varied. The total number of examined cases was 30. The setup was based on a previous study conducted in a large-scale wind tunnel with a constant flow velocity and measured viscosity. The optimal position of a roof-mounted Savonius vertical axis wind turbine using direct measurements of converted power. Three locations at two heights on a building were assessed for five wind directions, and the ideal position for a turbine was found to be in the center of the building for uniform wind rose. However, for individual wind directions, the results were nuanced, with the outside position being best for low turbines for winds from certain directions and the inside position being best for others. The study found that the high turbine was generally less dependent on position, and overall power output exceeded reference measurements for all positions and turbine heights. The study recommends placing turbines in the center of the building and as high as possible, but if there is a dominant wind direction, a specific location may be superior.

A different study on Savonius vertical axis wind turbines on the side of a building using numerical analysis [39]. A cylindrical building with five typical flow regions is used as a simplified model, and simulations of single and multiple turbines at different positions are conducted. Results show that installing turbines on buildings is feasible, with significant improvements in energy output in crosswind and tailwind zones. The power coefficients of arrangements with multiple turbines decrease with increasing numbers, but most are still greater than the reference value. The total power coefficient can be improved by positioning the forward blades of all turbines close to the wall.

Darrieus vertical axis wind turbine (VAWT) under turbulent inflow conditions in urban terrain was examined by [40]. The work presents a numerical study on the performance of a rooftop-mounted High-fidelity scale resolving Delayed Detached Eddy Simulation (DDES) simulations are performed to investigate the behaviour of a scaled-up, generic, two straight-bladed H-VAWT with NACA0021 airfoil at different locations. The study shows that the H-VAWT performs better at heights of 10 m and 12 m from the rooftop of buildings due to the combined influence of turbulence and skewed angle of the flow. The performance also improves at a height of 20 m compared to uniform inflow conditions. The study concludes that turbulence has a positive impact on the turbine's performance.

A numerical analysis was also carried out in [41]. The research conducted wake analysis of a Troposkien-shaped Darrieus wind turbine positioned above a cubic building at two different locations and under different wind flow conditions. The study uses 3D unsteady CFD simulations and validates the methodology by comparing Cp data with experimental data. Results show that positioning the turbine above the building's corner can increase its Cp from 0.318 to 0.549 at a tip speed ratio of 5. The rotor wake's structure is also shorter when operating in a freestream compared to when mixed with the surrounding accelerated flow.

Later Allard and Paraschivoiu [42] examined the performance of a vertical axis wind turbine (VAWT) located at two different positions on a building. The results show that the performance of the VAWT located above the building is improved due to the rotor's placement inside the accelerated flow region above the upstream edge of the building. The study also identifies an even more promising location with higher flow acceleration, namely the side corners of the building. The Cp value of 0.55 achieved for the VAWT is impressive, and future studies should explore different building sizes and turbines. The study concludes that this work should motivate experimental or field studies where VAWTs are placed above the side corners of buildings facing the main wind direction at 45°.

The study by Chen et al. [43] focused on the aerodynamics of micro-wind turbines with large-tip non-twisted blades. Chen et al. investigated the aerodynamics of micro-wind turbines with large-tip, non-twisted blades using a wind tunnel system. The experiment examines the relationships between power coefficient (Cp) and tip speed ratio (TSR), and torque coefficient (CT) and TSR, while considering the effects of rotor position, rotor solidity, and blade number on rotor performance. The NACA4415 airfoil is used for blade cross-section, and the pitch angle and chord length ratio are fixed. The study finds that placing the rotor closer to the diffuser inlet results in higher power output. The 60% solidity rotor performs better, and the number of blades has a small effect on power output. Compared to short-tip blades, the large-tip blades perform better at lower rotor speeds, making them suitable for micro-wind turbines and offering greater flexibility for rotor-generator matching.

This is followed by another study by [44], which investigated the design of an exhaust air energy recovery wind turbine generator for energy conservation in commercial buildings. The study concluded that the integration of an energy recovery wind turbine generator with a cooling tower resulted in various benefits, such as a reduction in power consumption of the fan motor, increased intake air speed, and improved performance of the VAWTs, with a 7% increase in rotational speed and a 41% reduction in response time. This system has the potential to generate supplementary power for building lighting or feed it into the electricity grid to meet energy demands in urban buildings. The predictable and consistent energy output of this system makes downstream system design easier. Additionally, as cooling tower applications and unnatural exhaust air resources are prevalent worldwide, this system has significant market potential. Fig. 7 depicts the conceptual design of an exhaust air wind energy recovery turbine generator situated at the outlet of a cooling tower located on the rooftop of a building, as envisioned by an artist.

Most of the studies on VAWTs are focused on the design and power coefficient efficiency when installed into a building. The studies explored the design and placement of vertical axis wind turbines (VAWTs) in urban environments. The studies investigate various factors that affect the performance of VAWTs in urban areas, including the impact of rotor solidity, turbine position, awind flow conditions.

DAWT

Ducted wind turbines increase the power coefficient of horizontal and vertical axis wind turbines by improving their aerodynamic performance through a shroud or duct surrounding the rotor blades. The design increases wind velocity and redirects it towards the blades, increasing the power output while reducing drag and turbulence. For horizontal axis wind turbines, it reduces drag and redirects wind, while for vertical axis wind turbines, it reduces turbulence and channels the wind. Ducted wind turbines offer a promising option for renewable energy generation, but require careful design and implementation for optimal performance [45]. A three dimensional model analysis is performed on a vertical axis wind turbine (VAWT) mounted on a building, which is equipped with a diffuser shaped shroud using CFD [46], to improve the power coefficient for a building-mounted wind turbine. The study focused on improving the power coefficient for a building-mounted wind turbine by using a diffuser-shaped shroud and

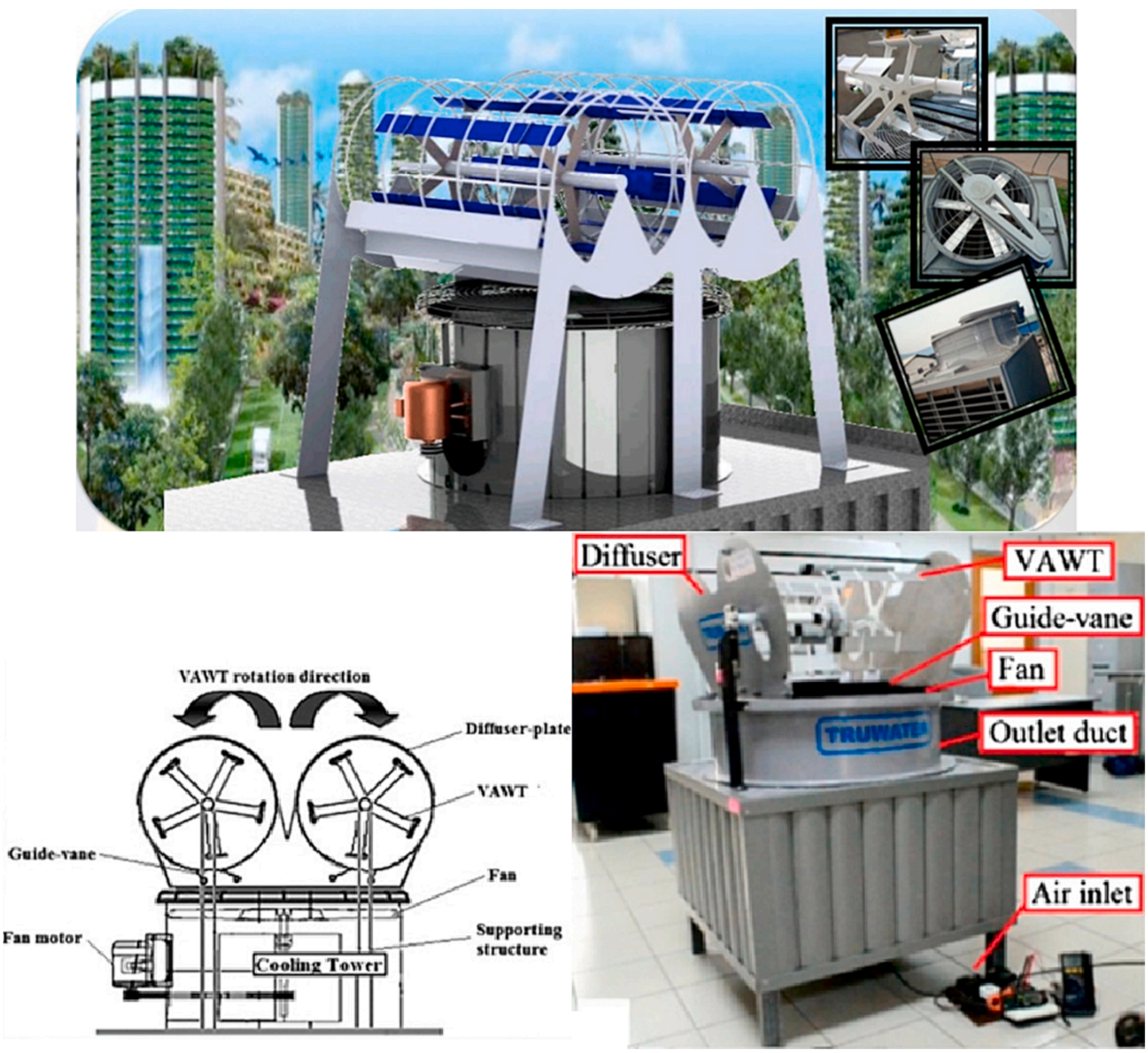


Fig. 7. Test configuration for cooling tower with VAWTs and enclosure [44].

optimizing the turbine blade position and geometry. A 2.5-fold increase in the coefficient of power was achieved, from 0.135 to 0.34, by adding the diffuser and making other changes. They suggested that future works should optimize the diffuser shape, study the effects of changing other turbine parameters, and investigate the turbine's performance under different flow directions. The study also includes findings on the optimal position and geometry of turbine blades.

Bhakare et al. [47] investigated the design of a convergent-divergent duct to power at least one room in an average household in Nasik using a ducted wind turbine on the rooftop while considering space, noise, and safety constraints. Ansys Fluent was used to study different designs of the duct. It was found that the convergent section did not affect the velocity augmentation factor as much as the divergent section, which was optimized to achieve an augmentation factor of 1.35 against the desired value of 1.4. Blade specifications were derived, and a generator was selected to achieve the required power output of 100–250 W for regular wind speeds of 10–14 mph. The expected energy generation was 1.2–2 kWh for 12 h of operation per day at the specified wind speed, but actual results may differ due to mechanical and electrical losses. The power output can be increased by increasing the size of the divergent section or blade length, but space constraints limit their sizes. The study also concluded that using a vortex generator in the duct can increase velocity augmentation by up to 15%.

Agha [48] conducted research to optimise the performance of DAWTs and integrate them into the built environment. The study included numerical and experimental studies on design methodology, ABL profiles, and validation with wind tunnel testing. The key finding was that the Optimum DAWT restored wind speeds lost at the rotor due to building presence and exhibited better responsive behaviour than a test bare wind turbine. The research also employed a new technique in the design, manufacture, and assembly of a full-scale DAWT prototype that is lightweight, portable, durable, and easily accessible for maintenance. CFD results from the study were analysed based on fluid flow characteristics and performance parameters. Fig. 8 shows the velocity contours for both the shroud case and the shroud and building test section. The velocity distribution was observed through velocity contour results, and it was found that wind speeds increased through the shroud to a maximum at the rotor, where power is generated. The distribution of velocity along the rotor diameter was not as uniform for the roof-mounted shroud as it was for the free-stream shroud.

The CFD tool was also used to investigate the airflow distribution around and inside the DAWT installed into the building structure [49]. The CFD results of the test site with the diffuser show that the velocity is magnified by 1.52 times at the diffuser throat, which is close to the predicted value of 1.6 from the earlier design stage. The velocity is calculated using the mass flow average at the throat and compared to the velocity upstream at the same height. Fig. 9 shows the flow pattern near the building with the diffuser is similar to that without the diffuser, but the streamlines at the diffuser inlet indicate that the flow accelerates going into the diffuser. The diffuser on the test building effectively takes advantage of the local flow acceleration as predicted in the design stage.

Abu-Thuraia et al. [50] examined a novel configuration of a building-mounted seven-bladed Savonius turbine enclosed inside a shroud or duct with four deflectable guide vanes attached at the entrance. Simulations are conducted to calculate the power coefficient (Cp) of the turbine for different wind orientations. The Cp value remains relatively high for small deviations of wind, but when the wind direction reaches 45°, it decreases by half. When guide vanes are fixed at 35°, 45°,

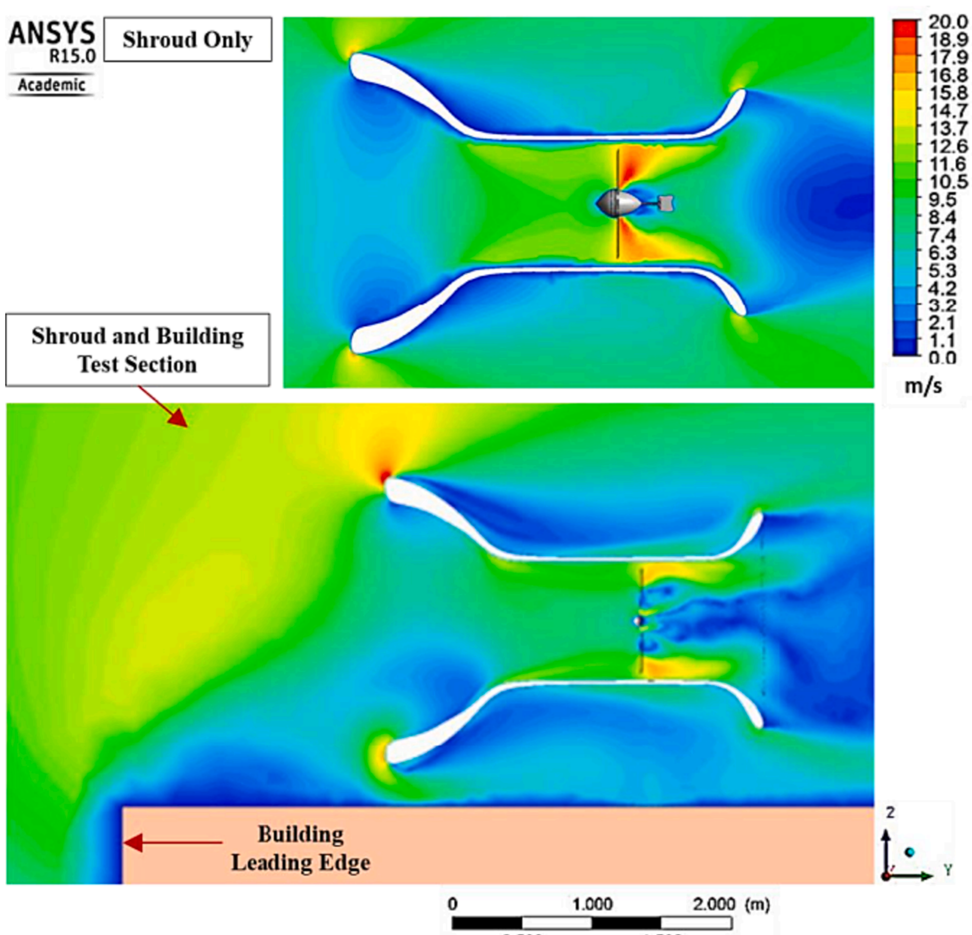


Fig. 8. Velocity contours for both the shroud case and the shroud and building test section [48].

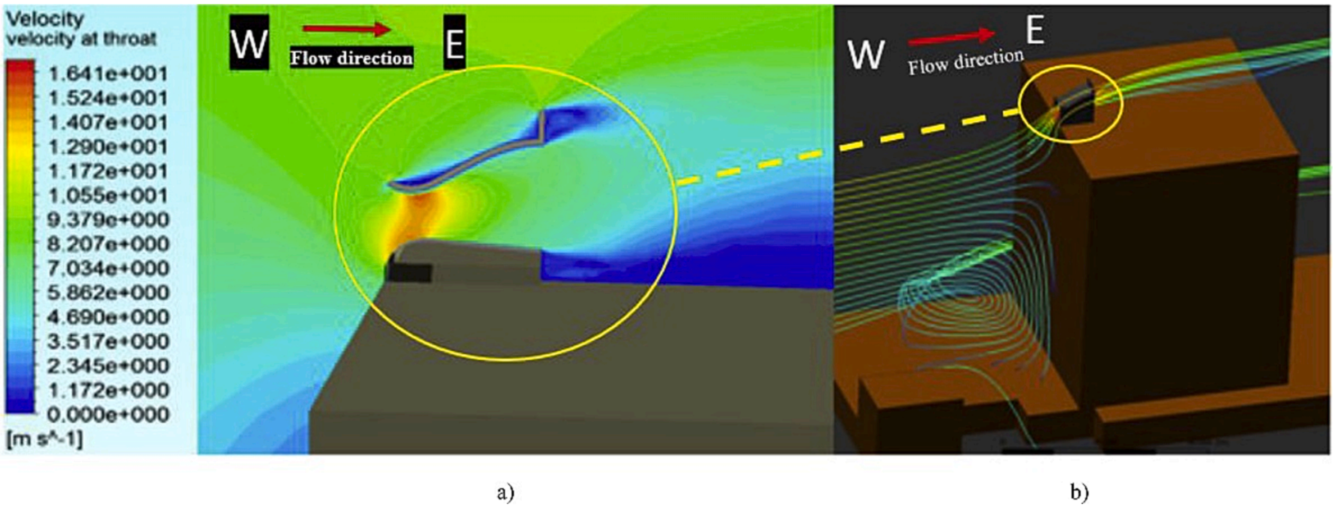


Fig. 9. (a) The velocity contour at the symmetry plane of the diffuser, (b) illustrates the velocity streamlines from a perspective view of the chosen building [49].

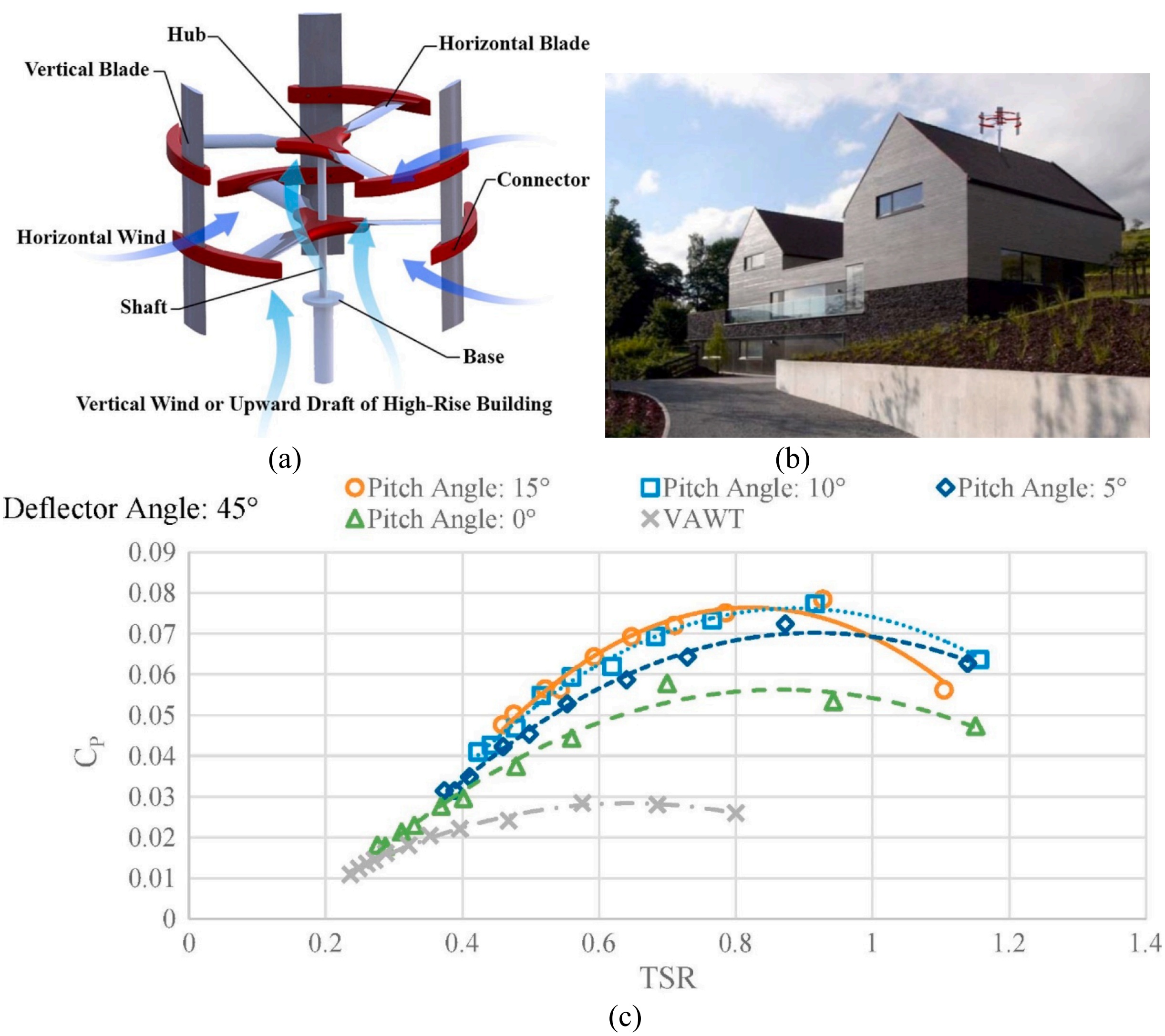


Fig. 10. CAWT (a) configuration and (b) CAWT on top of the building (c) power coefficient against the tip speed ratio for the VAWT and the CAWT models integrated with the 45° deflector in different pitch angles. [51].

and 55° with respect to the horizontal direction, the highest Cp value obtained was 0.333 when guide vanes were set at 55°, and the TSR was 0.5. The guide vanes provide the ability to control the flow through the turbine and can increase the capacity factor of the turbine. Although the performance of the turbine decreases with guide vanes at TSR of 0.5, neighboring TSR values of 0.48 indicate a Cp value of 0.336. It is planned to calculate the power coefficient of the turbine at different vane angles and simulate different wind directions with guide vanes attached in future studies.

Overall, the use of a diffuser-shaped shroud can increase the power coefficient of a vertical axis wind turbine by up to 2.5 times, while the use of a convergent-divergent duct can achieve a velocity augmentation factor of up to 1.35. The addition of guide vanes in a ducted Savonius turbine can also improve its performance by controlling the flow through the turbine. These studies highlight the potential of using shrouds and ducts to increase the power output of building-mounted wind turbines, which can contribute to the development of sustainable and renewable energy sources. Future work in this field includes optimising the design of shrouds and ducts, investigating the effects of changing other turbine parameters and studying the performance of these turbines under different flow directions.

Other types of small-scale wind energy harvesting systems

There is also an increasing interest in alternative designs of small-scale wind energy harvesting systems. Chong et al. [51] proposed the cross-axis wind turbine (CAWT) design. The technology uses both horizontal and vertical turbine blades in a novel cross-linked configuration. As shown in Fig. 10 (a), CAWT consists of six horizontal blades and three vertical blades mounted on a supportive frame, rotating on a vertical axis. The central shaft is directly fixed to the generator, and the horizontal blades act as connectors linking the hub to the vertical blades via six connectors. The upper and lower hubs are connected to the central shaft with a relative height of 10 cm. Whilst in Fig. 10 (b) illustrates the CAWT installed on top of the building. Fig. 10 (c) The results revealed a significant improvement, ranging from 103% to 175%, in the power output of all the Cross-Axis Wind Turbines (CAWTs) compared to the conventional Vertical Axis Wind Turbine (VAWT), as shown in Fig. 15. This indicates the positive impact of the pitched horizontal blades interacting with the deflected wind. [51].

Traditional wind turbines often face limitations in deployment on buildings due to the need for building modifications and limited space. Therefore, the study of [15] proposed a new design of a building-integrated wind turbine system (BIWT) that uses wind pressure on the building skin to generate electricity. The system consists of a guide vane to increase wind speed and a rotor with an optimised shape. CFD analysis was used to determine the optimal configuration of the system. The performance of the system was evaluated through two-step experiments, and it was estimated that it could supply about 6.3% of the electricity needed for a residential building [15]. BIWT systems may necessitate reinforcing the structure as the added wind pressure affects the wind turbine placed on the roof or between buildings. However, the proposed system takes advantage of the wind pressure that acts on the building walls, thus negating the need for any structural fortification or alteration. This is because the wind pressure is already accounted for during the building design stage, as shown in Fig. 11.

In the research work of [52], a design has been developed that utilises vertical axis wind turbines (VAWTs) mounted between a gable roof and a V-shaped roof structure to generate electricity for building usage. The VAWTs are arranged horizontally with the rotational axis parallel to the roof ridge, and the upper V-shaped roof and gable roof create a Venturi effect that increases wind speed, improving the system's performance. The experiment showed a 36% increase in wind speed and an estimated energy generation of 773.16 kWh/year. The design also includes solar photovoltaic panels, water harvesting, a transparent roof, and ventilation vents, but it depends greatly on wind direction.

Fig. 12(a) demonstrates the wind turbines connected to generators mounted on the V-shape roof structure, (b) wind velocity contour distribution, and (c) simulation reveals that the wind speed attains a high velocity in the region between the roofs, attributed to the venturi effect. Specifically, the wind velocity along the centerline of the V-shaped roof measures 2.88 m/s at measurement point '3′ (The average wind velocity in the wind turbine, ranging from −0.06 m to 0.06 m along the centerline between the V-shaped roofs and gable roofs, was found to be 2.50 m/s), resulting in an increase of approximately 44% compared to the inlet wind speed of 2 m/s. Thus, the wind speed augmented factor, *f*, is calculated to be 1.44 [52].

Another design called the Wind Booster was proposed in the study [53] to improve energy generation. The work outlined a methodology

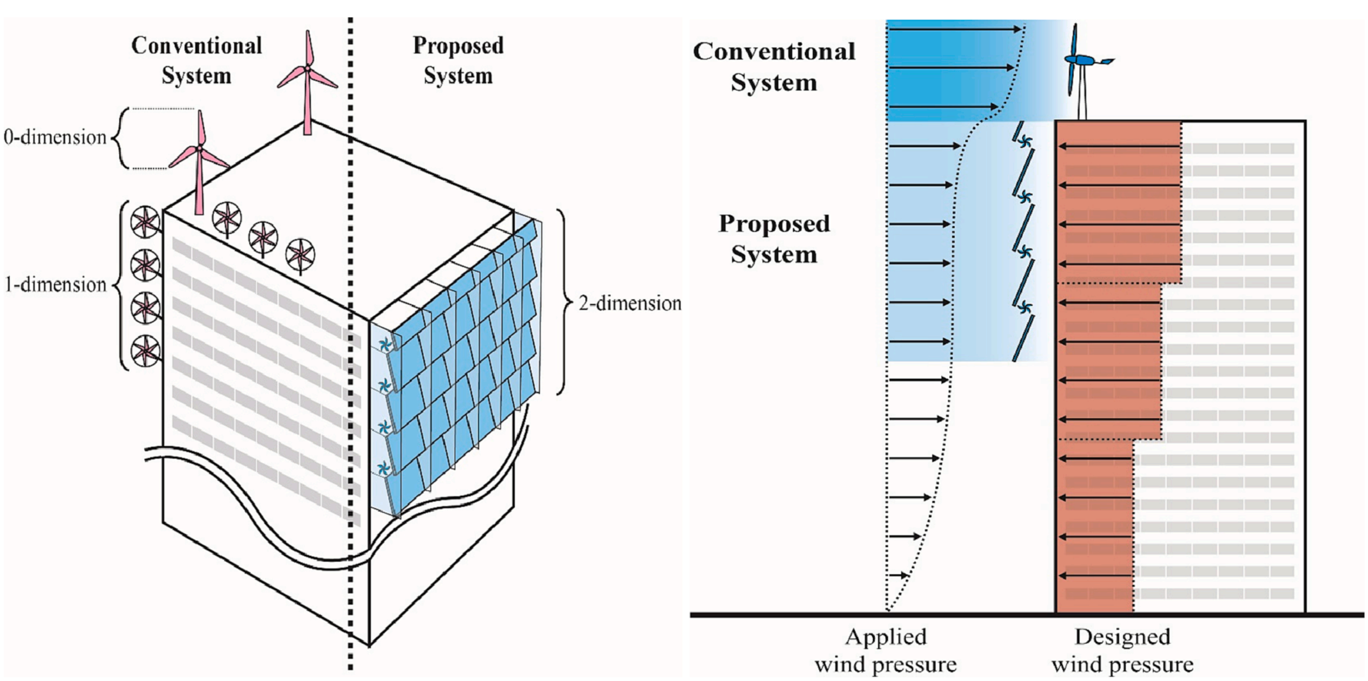
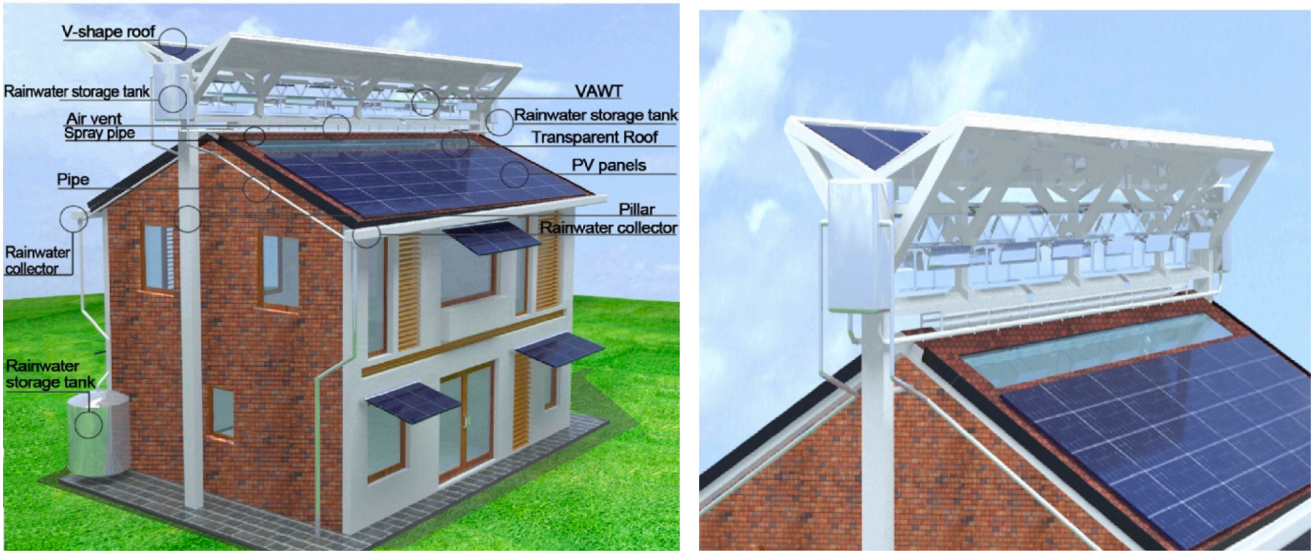
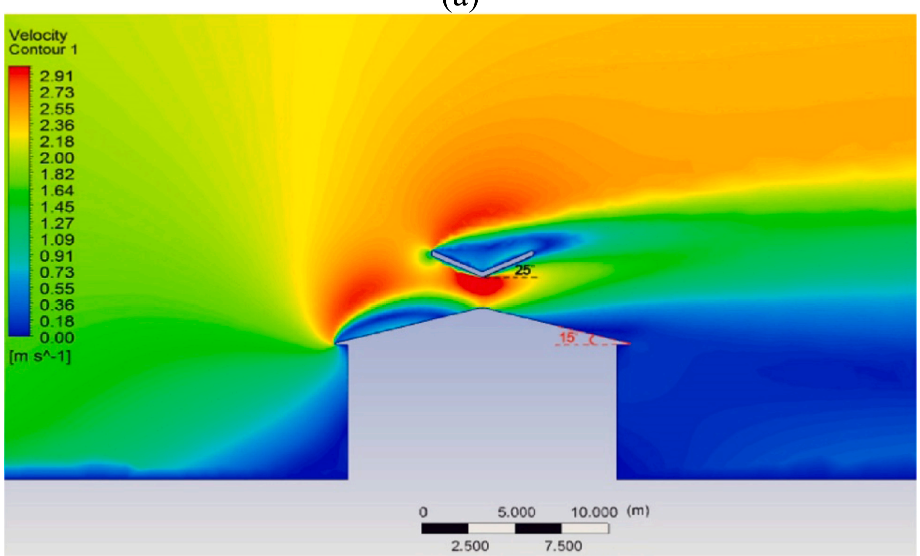


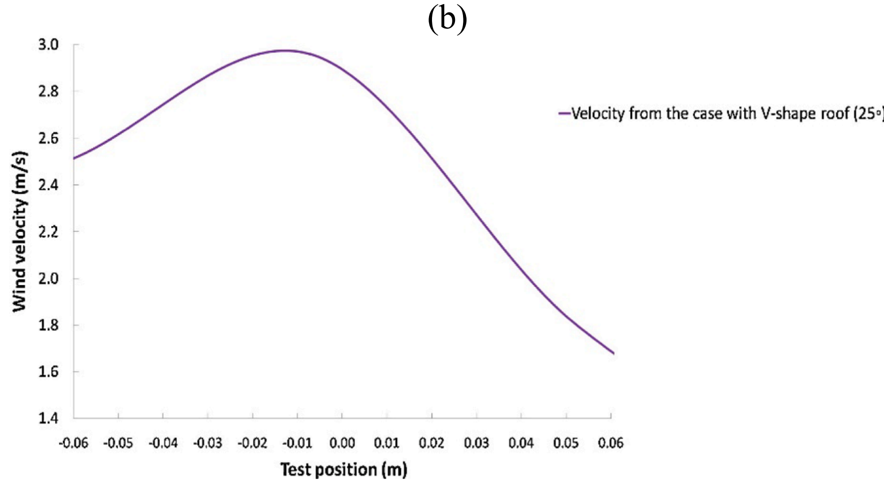
Fig. 11. Comparison of the installation area between the (a) conventional BIWT and proposed system (b) structural aspect of the proposed system [15].



(a)



(b)



(c)

Fig. 12. VAWT with the VRGV (a) design and components, (b) velocity contour surrounding the building, and (c) simulation results for wind velocity [52].

for selecting and optimising the main components of a Wind Booster and presented a case study of a Wind Booster for a VAWT designed for Mexico City using CFD and Design of Experiments (DOE) techniques. The results of the study showed a 35.23% increase in torque with the optimised Wind Booster configuration, highlighting the potential of this methodology to improve the performance of wind turbine systems. As wind behaviour varies greatly in different cities, this proposal could be useful for researchers considering the implementation of the best possible wind turbine in their specific location.

Studies have demonstrated that other proposed new designs of building integrated wind energy harvesting systems showed promising results for energy outputs. However, the design and configuration of each systems have significant impact on its power performance, and further research is necessary to determine the optimal configurations for different locations and conditions.

Wind-induced vibration technologies

With the rapid expansion of the internet of things (IoT) and wireless condition monitoring systems, energy harvesters that utilise ambient energy have become essential for creating energy-autonomous systems. Among these, micro/small-scale wind energy harvesters have gained significant interest due to their high power density potential and the abundance of wind energy in various application areas, such as cities and buildings [4]. This section reviews the latest advancements in micro/small-scale wind energy harvesting systems, which encompass galloping-based, vortex-induced vibration, and flutter-based technologies. Various energy coupling mechanisms were studied, taking into account different designs, environmental conditions, and method analyses. Furthermore, we examined the key factors necessary for achieving high efficiency in these systems when operating under lower wind speeds.

Wen et al. [4] investigated the different designs of energy coupling mechanisms to identify the key factors that contribute to achieving high working efficiency in low operating wind speed conditions. The wind energy harvesting technologies analysed included galloping, flutter, and vortex-induced vibration (VIV) designs. Results indicated that VIV-based technology could attain optimal efficiency at low wind speeds with a suitable design. However, the main challenge with this approach is its narrow operational wind speed range due to its operating mechanism. In contrast, the aeroelastic flutter design employs a different approach and involves divergence and self-excitation. As a result, negative damping occurs during aeroelastic flutter at wind speeds higher than the critical flutter speed. Due to its divergent nature, the vibration amplitude repetitively increases with wind speed, and a sudden unexpected increase in wind speed can cause device damage. Galloping mechanism shares similar positive features with VIV and aeroelastic flutter, including a vast range of operational wind speeds and controllable divergence to a specified level. However, unlike the other two methods, its analytical model has not been established [4].

Wind-induced vibration technology utilises a combination of lift and drag forces to convert wind flow energy into electrical energy. This makes it suitable for low wind speed deployment in the sub-centimeter range as compared to rotational motion, as the vibration on the body structure can be easily converted into electrical energy. Flutter and vortex-induced vibration (VIV) based wind-induced vibration exhibit similar dynamic instabilities generated from the interaction of unsteady inertial, elastic, and aerodynamic forces. Galloping-based wind-induced vibration combines the characteristics of aeroelastic flutter and VIV. These small-scale wind-induced vibration systems can operate under low wind speeds and a broad range of operational wind velocities, making them suitable for building-integrated wind energy harvesting systems. These technologies show potential in harvesting energy from a roof building structure under low wind speeds and operational under non-uniform wind flow, addressing the challenge of conventional wind turbines that are non-operational when subjected to low wind speeds [4].

Galloping-type energy harvesting

Galloping is a phenomenon in which slender bodies subjected to static torsional moments, lift, and drag forces experience self-excited vibrations. Whilst galloping can generate light vibrations in various directions, it can also lead to dynamic instability due to negative damping, as noted by [54]. To incorporate galloping technology into building structures, further research is needed to identify suitable designs for non-uniform wind flows, examine the impact of wind acceleration on the energy harvester, and understand the airflow distribution around the body structure.

In a study by [55], the power and efficiency of different tip cross-section shapes (triangle D-shape, square, and rectangle) for small-scale wind-induced galloping energy harvesters were examined in a wind tunnel, as shown Fig. 13. The results showed that the square profile provided the best performance with a maximum power of 8.4 mW, leading to the proposal of using a square cross-section for future studies.

Zhao et al. [56] also examined various shapes, including funnel, triangle, and square, in a wind tunnel with a closed direct flow. The results showed optimal power densities of 2.34 mW/cm^3, 1.56 mW/cm^3, and 0.207 mW/cm^3 for the funnel, triangle, and square profiles, respectively, at wind speeds of 7 m/s, 9 m/s, and 13 m/s. A design of a wind-induced galloping wind energy harvester with high normalised harvesting power and a wide working wind-speed range was proposed based on these results.

Another design was also introduced by [57]. This design featured quadruple Halbach arrays with transit and main magnets. Numerical and wind tunnel tests were conducted on this design, and it was observed that the electrical load resistance was highly dependent on the onset velocity and vibration amplitude of the harvester during galloping. The study concluded that by adjusting the external load resistance, the harvesting system could generate power even at low wind velocities. For instance, at a wind speed of 12 m/s, the system was able to produce an output power of 8 mW.

In [54], a wind-induced energy harvesting system based on the galloping mechanism was developed using a cut corner prism. As depicted in Fig. 14, the galloping mechanism was established by creating a pressure difference between the upper and lower surfaces of the prism. Computational fluid dynamics (CFD) simulations were conducted to assess the system's efficiency, and the results showed that the cut corner design was able to reduce the shear layer reattachment behaviour and improve backflow between the lateral side and shear layer of the prism, increasing the pressure difference between the upper and lower surfaces. An experimental study was carried out to evaluate the size's impact on harvesting performance, and the results indicated that a parallel side with 0.6B length and a windward side length of 0.4B could achieve 47.5 mW at a wind speed of 6.24 m/s, which is 261% higher compared to the square prism.

Zhang et al. [58] discussed the potential of using energy harvesting technology to extract energy from environmental airflows and convert it into usable electricity for power sensors. However, environmental adaptability and level of output power are important aspects that need to be improved. A novel electromagnetic energy harvester for airflow power generation has been designed, and a theoretical model has been constructed and experimentally verified. The design considers a Y-shaped bluff body subjected to airflows that induce an aeroelastic response and bring the coil to cut magnetic induction lines. The experimental results show that an average power of 2.5 mW is generated at a wind speed of 4 m/s, which is dominant compared to existing aeroelastic energy harvesters. The harvester's environmental adaptability has been demonstrated under the condition of an air-conditioner vent. The research offers guidance on developing an efficient electromagnetic energy harvester for airflow power generation and promotes the realisation of self-powering of structural health monitoring sensors applied in buildings and bridges.

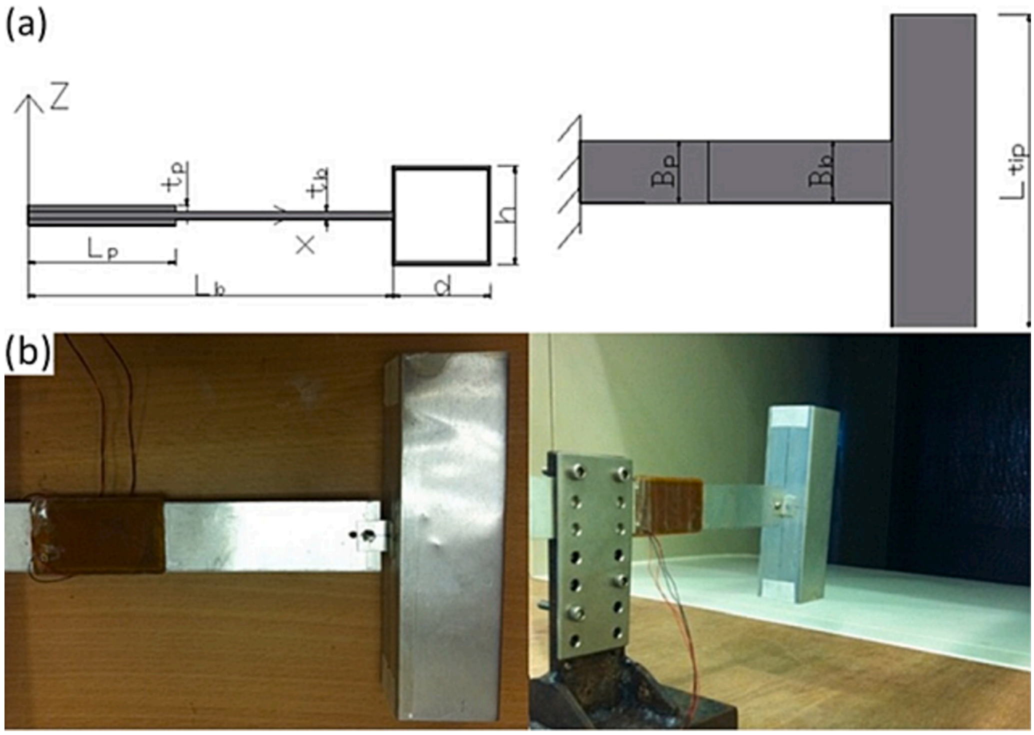


Fig. 13. Proposed galloping energy harvesting system (a) showing top and the side view and (b) experimental setup [55].

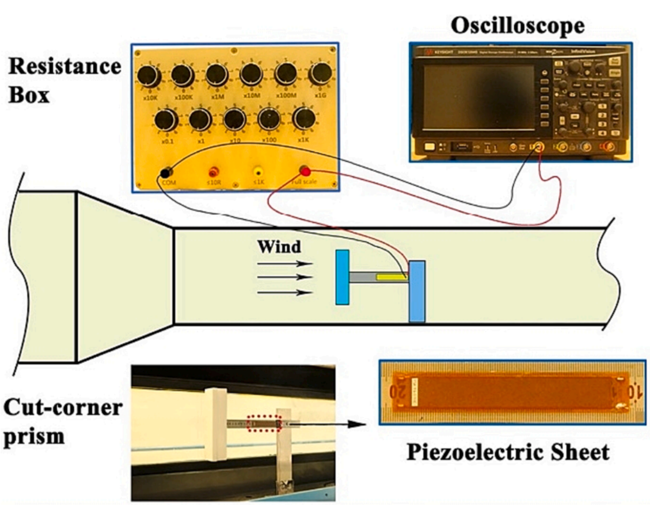


Fig. 14. The design of the energy harvesting system based on the galloping mechanism using the cut corner prism is presented schematically [54].

Another design of a galloping-based wind energy harvester was proposed in [59]. The design comprises of rotatable transverse galloping piezoelectric energy harvester. Tests were conducted for three different cross-section bluff bodies (equilateral triangle, square, and D-section) under natural wind conditions. The study finds that a rotating base (RB) configuration produces a higher cut-in speed than a fixed base (FB) configuration and that the square bluff body is the most effective in terms of voltage production, followed by the triangular shape and then the D-section. This study is the first to use these prisms in an open environment and proposes a tunable harvester that can adapt to varying wind directions. The results provide guidance for optimizing bluff body shape suitable for real-world conditions.

Recent research on galloping-based wind-induced vibration technology has focused on investigating its energy harvesting and power performance in laboratory or numerical simulation settings, but no studies have explored its integration with building structures. However, the technology shows potential for energy harvesting at wind speeds suitable for use on buildings or roofs and has advantages in terms of being lightweight and cost-effective compared to traditional wind turbines. Nonetheless, more information is needed on the costs associated with this technology, and a comprehensive analysis of its techno-economic aspects would be necessary for commercialisation viability.

Flutter-type low-energy harvesting

Aeroelastic instability due to self-excited aerodynamic forces is known as the flutter vibration mechanism. The interaction between a solid structure and fluid can lead to energy extraction by the harvester. However, excessive energy from aerodynamic forces can result in negative aerodynamic damping, which can cause erratic operation if it exceeds mechanical damping. Previous studies on flutter wind energy harvesters have primarily used numerical analysis or wind tunnel experiments, with a focus on stand-alone systems. There is a lack of research on integrated flutter-based wind energy harvesting systems in building structures [60].

A recent study conducted by [61] has highlighted the use of a flutter-based aeroelastic belt as the only device integrated into urban building structures for small-scale wind energy harvesting systems. The device is simple in design and comprises electromagnetic coils, a tensioning membrane, and power conditioning devices. The study evaluated the performance of the device under various wind directions, wind speeds, placements, sizing, and physical parameters using CFD analysis. Results from the study indicated that a roof building with an apex angle of 45°achieved the highest power output of 62.4 mW from an incoming wind speed of up to 6.2 m/s. The device's simplicity makes it cost-effective and easy to integrate with other technologies.

This study was further explored in three additional studies by [62]. The first of these articles, authored by Aquino et al., (2017) focused on integrating aero-elastic belts into the built environment to harness wind energy efficiently. This research examined the status of this integration and included a practical case study, offering an overview of implementation challenges and potential benefits in terms of energy conversion and management within constructed settings. Notably, the peak power output for the aero-elastic belt occurs at the rooftop apex, attributed to optimized flow acceleration in that region. This location yields the highest power output, notably achieving this under a 45° angle of approach and wind speeds of up to 6.2 m/s. At a wind velocity of 10 m/s, the airflow here accelerates to around 14.4 m/s, representing a notable 37.5% increase at that specific height. This occurs when wind approaches the building facade at a 30° angle. Similarly, with a wind velocity of 4.7 m/s and a wind direction of 0°, the edges of the building's facade experience the swiftest airflow at 5.4 m/s, indicating a 15% enhancement along those edges. This study, featured in Energy Conversion and Management (2017), offers insights into the integration's potential, especially in terms of practical implementation challenges and outcomes.

The subsequent two studies, both conducted by [63], which employed a combination of experimental and numerical analyses to delve into the integration of the Wind-Induced Flutter Energy Harvester (WIFEH) into building structures. These studies emphasised detailed procedural considerations, practical insights, and potential implications of the integration process. The research comprises two primary components: empirical assessment of a WIFEH in a wind tunnel and Computational Fluid Dynamics (CFD) analysis of a building incorporating the WIFEH system. Experimental trials encompass a range of wind speeds within the wind tunnel, from 2.3 to 10 m/s, aiming to quantify the WIFEH's capacity for electromotive force generation. The results demonstrate that, at an airflow of 2.3 m/s, the WIFEH produces an RMS voltage of 3 V, a peak-to-peak voltage of 8.72 V, and a short-circuit current of 1 mA. When wind speed escalates to 5 m/s, coupled with appropriate membrane re-tensioning, these metrics also rise to 4.88 V, 18.2 V, and 3.75 mA, respectively. The CFD modeling utilizes a gable-roof building model featuring a 27° pitch, sourced from existing literature. Incorporating the WIFEH into the building structure, the rooftop apex emerged as the site of highest power generation due to optimized flow acceleration in that vicinity. Remarkably, this point achieved maximal power output under a 45° angle of approach, yielding approximately 62.4 mW under intensified wind conditions with device velocities of up to 6.2 m/s. These findings and research methodology lay the groundwork for further explorations into the integration of the WIFEH technology within urban environments. This study, featured in Energy Procedia (2017), contributes practical insights into the integration process and the potential benefits of WIFEH implementation.

The final study, also by Aquino et al. [64], examined the integration of the WIFEH into the built environment. This research delivers comprehensive outcomes through a combination of real-world experiments and computational simulations. This study offers insights into the WIFEH's performance across various conditions and its potential role in energy harvesting within constructed environments. The experimental phase subjects the WIFEH to varying wind speeds within a wind tunnel, ranging from 2.3 to 10 m/s, to assess its potential for electromotive force generation. Meanwhile, the CFD simulation employs a building model with a 27° pitch, taken from existing literature, and employs the atmospheric boundary layer (ABL) flow to simulate wind conditions. The research explores the interplay between different wind speeds and the placement of the WIFEH device, uncovering insights into the feasibility of integrating the energy harvester into constructed settings. The study's findings reveal that, at an airflow of 2.3 m/s, the WIFEH generates root-mean-square (RMS) voltage of 3 V, a peak-to-peak voltage of 8.72 V, and a short-circuit current of 1 mA. With an increase in wind velocity to 5 m/s and subsequent membrane re-tensioning, these metrics also increase to 4.88 V, 18.2 V, and 3.75 mA, respectively. In the realm of CFD modeling, the rooftop apex emerges as the point of greatest power output due to optimized flow acceleration in that region. Specifically, this point achieves maximal power generation under a 45° angle of approach, resulting in an estimated 62.4 mW of power under intensified wind conditions with device velocities of up to 6.2 m/s. At a wind velocity (U_H) of 10 m/s, the airflow in this location accelerates to around 14.4 m/s, representing a notable 37.5% increase in speed at that specific height.

Different design of flutter-based energy harvesting technology was presented in [65], which consisted of a cuboid chamber, a piezoelectric cantilever, and a resonant cavity. The device was able to monitor temperature and transmit data to a receiver. The experimental results showed a power output of 1.59 mW for a 20 kΩ resistor at a wind speed of 11.2 m/s. The self-powered wireless sensor network (WSN) also functioned properly as the wind speed increased from 6 to 11.5 m/s.

Chawdhury et al. [60] also incorporated a cantilever into the energy harvester for their study. The performance of aeroelastic instabilities and flutter phenomena through numerical modelling and simulations were evaluated using utilising fluid–solid interaction (FSI) simulation. The study also examined the susceptibility of a T-shaped cantilever beam to small-scale wind energy harvesters using a CFD solver based on the vortex particle method (VPM). The coupled solver was validated and utilised for a strategic optimisation study of the T-shaped wind energy harvesting system to measure the generated energy and wind speeds. Results from the CFD simulations were consistent with wind tunnel test data, indicating that the projected energy output and wind flutter speed were consistent under various electrical resistances. The highest power output achieved was 5.3 mW under 8 m/s.

The piezo-electric energy harvesting system presented in [66], comprises of a piezoelectric cantilever beam with a proof mass attached to its free end. The cantilever beam is fixed at its base to a mounting block, which is connected to the structure being monitored, as shown in Fig. 15. When the structure experiences vibration, the proof mass on the cantilever beam oscillates, and this causes a deformation in the piezoelectric material, resulting in the generation of an electrical charge. This electrical charge is collected by electrodes attached to the piezoelectric material and is transmitted to a storage device, such as a battery, through a rectifying circuit. The piezo-electric energy harvesting system is a compact and versatile device that can be installed in a wide range of applications to monitor vibrations and convert them into useful electrical energy.

A bionic dipteran piezoelectric-electromagnetic composite energy harvester (BCEH) for ultra-low frequency vibration energy harvesting, based on the flutter wing-flapping system of dipteran insects, was proposed in [67]. The BCEH design is verified by finite element analysis, reducing the inherent frequency and optimizing parameters for efficient vibration energy harvesting. The experimental results show that BCEH can generate an average power of 69.14 mW under 5 Hz ultra-low frequency vibration, making it a promising method for obtaining energy under low excitation.

With the research work of [68] a coupled formulation for modelling piezoelectric energy harvesters based on vortex-induced vibration (VIV) was examined. The formulation includes multiple piezoelectric materials and can model arbitrary locations. The numerical simulations were validated using experiments for single and two cylinder piezoelectric energy harvesters in tandem. The model was then used to evaluate the performance of three piezoelectric energy harvesters in tandem. Results showed that the proposed model could provide accurate results and be cost-effective compared to other experiments.

In the study of [69], an aerofoil flutter-based wind energy harvesting system utilising a numerical simulation that considered pitch and plunge motion degrees of freedom (DOF). The system's design consisted of an aerofoil section with piezoelectric coupling and pseudo-elastic hysteresis of shape memory springs to capture wind energy. The study analysed the post-flutter mechanism and found that the amplitudes of electrical and mechanical outputs increased with airflow speed for load resistance. The highest power output achieved was 120 mW for the best load resistance at 4.5 N and 14 m/s^{-1}. Fig. 16 illustrates the peak electrical power output from plunge displacement. Based on their numerical projections, De Sousa [69] concluded that incorporating pseudo-elastic hysteresis is a beneficial addition to the design of aerofoil flutter wind-induced energy harvesters. This design element was found to improve power performance when compared to hardened steel springs.

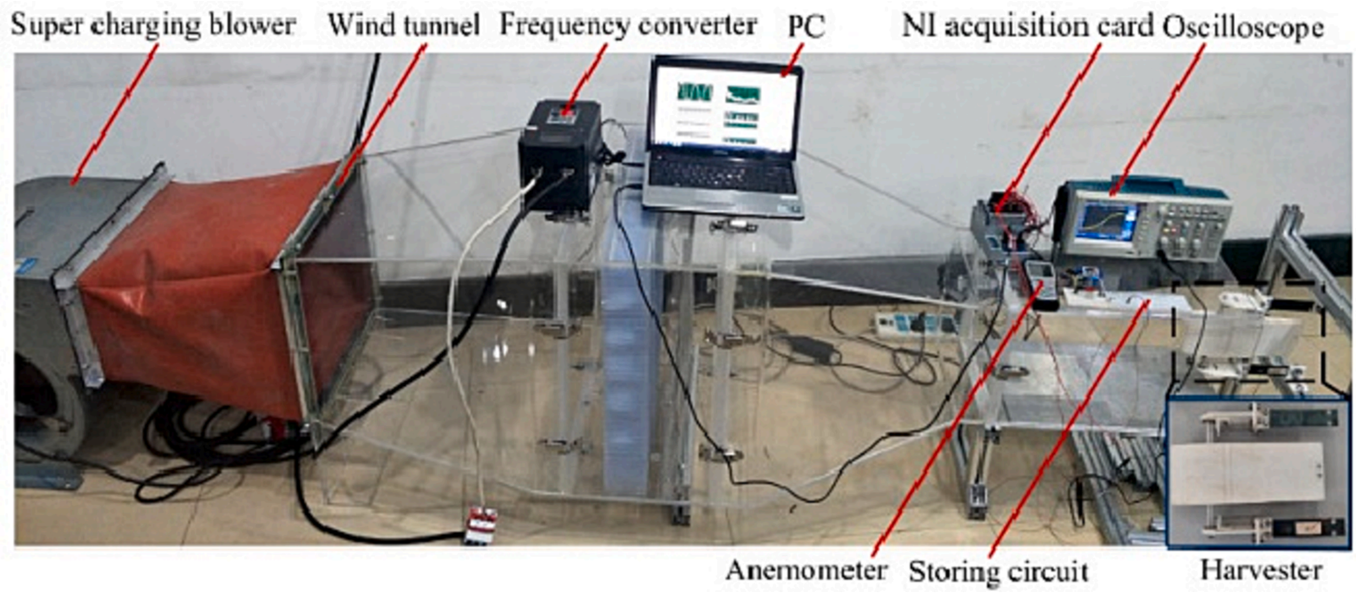


Fig. 15. Schematic design of a piezo-electric energy harvesting system [66].

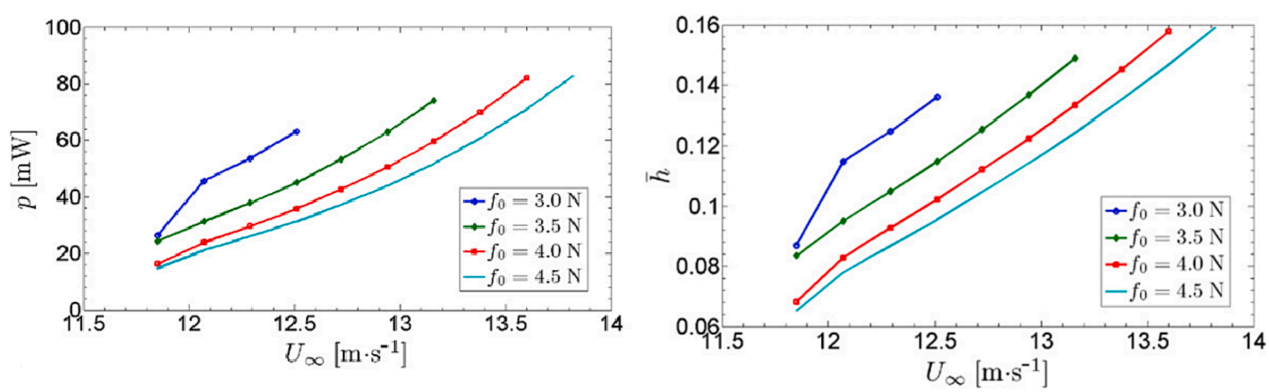


Fig. 16. Maximum electrical power output obtained from the amplitude of plunge displacement was analysed and reported [69].

A different transducer was applied to the energy harvester in [70]. A novel design of an aeroelastic flutter wind energy harvesting system was developed, which incorporated an electret transducer to convert the motion induced by the flow of air over a membrane into electrical power. The system utilised the flutter effect, where the membrane started to oscillate and continuously interacted with the two flat electrodes. As a result, the motion was directly transformed into electrical power by the electret transducer. The study evaluated several models and demonstrated that a 2.7 cm^3 prototype could produce a power output of 481 μW (178 μW cm^{-3}) under 15 m s^{-1} and 2.1 mW (782 μW cm^{-3}) at 30 m s^{-1} when the electret is charged at 650 V.

Whereas in [71], a hybrid nanogenerator composed of a triboelectric nanogenerator (TENG) and electromagnetic generators to collect wind energy and convert it into electrical energy for small electronic devices and microsensing systems was developed. The triboelectric nanogenerator (TENG) film shape and structure were optimized for maximum stable output, and the electromagnetic generator (EMG) was designed for peak power output. The combined system improves energy collection and reduces charging time. The self-powered system was created by integrating the hybrid generator with a capacitor, which achieved real-time sensing detection of temperature and humidity in greenhouses and fan malfunctions. This study contributes to the development of practical wind energy harvesting devices for sensing systems.

Upon reviewing the available studies, it was noted that only a few explored the energy harvesting capabilities of an aeroelastic belt integrated into a building's roof structure using wind-induced vibration caused by flutter. Whilst this study exhibited potential for the technology, the testing was restricted to laboratory-scale experiments and numerical analyses conducted via CFD simulations. The findings demonstrated that the proposed design could be effectively integrated into buildings to harvest energy from flutter-based wind-induced vibrations whilst also offering benefits such as low cost, simple structure, and modularity. However, the other designs investigated were standalone wind energy harvesters, not integrated into the building, and were only evaluated through laboratory or numerical simulations. Further research is required to assess the performance of these technologies in real-world field test conditions and conduct techno-economic analyses.

Vortex-induced vibration-type low-energy harvesting

Vortex induced vibration (VIV) occurs when vortices shed from a bluff body that is exposed to incoming flow, resulting in recurring forces that can cause significant oscillations through resonance. By attaching a transducer, the mechanical energy of the oscillator can be converted into electrical energy, making it possible to harvest energy from vortex-induced vibration [72].

Lee et al. [72] developed and tested a microelectromechanical wind energy harvesting device based on vortex induced vibration (VIV) in reference. The device comprised a cylindrical oscillator connected to a piezo-electric microelectromechanical system. To assess the power performance of the harvester, a wind tunnel experiment was conducted. The study demonstrated that the harvester generated a power output in the nanowatt range, with increased output observed when multiple cylinders were used compared to a single cylinder. Furthermore, CFD simulations were performed to examine the behaviour of vortex shedding from the cylinder. The results indicated that vortex shedding took place from upstream cylinders, leading to a high periodic transverse velocity component on the approaching wind stream facing the downstream cylinders, which enhanced the vortex-induced vibration response. The study concluded that the proposed model has the potential to provide cost-effective power for small-scale off-grid WSNs, with a straightforward integration of the sensor and harvester.

In [73], a bionic structure was added to a vortex-induced vibrations (VIV) model to enhance amplitude response and reduce the VIV threshold wind velocity. Twelve prototypes were created using pit sizes and hemispheric protrusions attached to a smooth cylinder. The harvester with the bionic structure outperformed the smooth cylinder in energy harvesting. When the threshold wind speed decreased from 1.8 m/s to 1 m/s, the bandwidth increased from 39.3% to 51.4%. The 10 mm pit with 5 columns produced the highest power output of 1.2 mW with 800 kΩ resistance, which was 0.57 mW more than the smooth cylinder. The hemispherical structure harvesting system had a smaller voltage than the smooth cylinder, with a maximum voltage below 15 V and a decreased bandwidth. However, the hemispheric with three columns performed better for energy harvesting, with 35 V and 800 kΩ resistance at 3.097 m/s wind speed. The power output was improved from 0.48 to 0.56 mW.

A different shape of the body bluff structure was proposed by [74]. The design was a novel e-shaped piezoelectric energy harvesting system that was proposed for the VIV mechanism using folded beams. The experimental setup and harvester design are illustrated in Fig. 17. The harvester was equipped with tuned mass blocks on vice beams and drive sheets to move the first two-order resonant frequencies as required, resulting in an exceptional capability to widen the frequency bandwidth with two adjacent power peaks. By efficiently utilising the space and energy in the flow field behind the cylinder through interaction between the beam and the other two beams, the power output, efficiency, and output voltage of the harvesting system were significantly increased. The e-shaped piezoelectric energy harvesting system demonstrated up to 70% increase in efficiency and 3 times increase in power compared to traditional piezoelectric harvesting systems based on VIV. The maximum output power reached 3.35 mW when the resistive load, mean fluid velocity, and scale factor were set at 105 Ω and 1.5 m/s. The study concluded that the proposed design could power actuators and micro electro-mechanical system (MEMS) sensors at low velocities.

Using an indirectly stimulated composite piezoelectric transducer, a novel non-contact vortex-induced vibration-based wind energy harvester is being researched to improve the dependability and environmental adaptability [74]. The results showed that as the wind speed increased, the wind speed bandwidth, vibration displacement, and output voltage increased with increasing transducer mass and decreasing shell mass. To maximise output power, an optimal load resistance was used. Maximum power of 1.438 mW was recorded in terms of a single piezoelectric pre-bending beam at a wind speed of 40.0 ms-1 and transducer mass of 65 g. Meanwhile, when an output voltage of 5 V was used as the reference value, the non-contact piezoelectric wind energy harvester could be effectively operated over a wide wind speed range of 5.5 ms1 to 40.0 m/s (corresponding to a wind speed bandwidth of 34.5 m/s).

Zhang et al. [75] proposed a new method for efficiently harvesting energy from low-speed wind using a vortex-induced vibration (VIV) based triboelectric nanogenerator (TENG). A theoretical model was constructed and validated with experiments, showing a lock-in region with significant vibration amplitude and output voltage. The tandem VIV-TENG model was designed to further increase the lock-in region, achieving higher power and power density than previous studies. The practical application of the VIV-TENG was demonstrated by continuously powering wireless sensors, enabling self-powered wireless sensing under low wind speed environments. The study has significant implications for developing sustainable energy sources.

The Vortex Bladeless company has created a wind energy generator, as illustrated in Fig. 18, which operates based on vortex-induced vibration (VIV). This technology captures wind energy by utilizing a phenomenon known as vortex shedding, taking advantage of fluid mechanics. As wind flows past a blunt body, it creates vortices that have a cyclical pattern. The VIV technology matches the frequency of these forces with the frequency of the structure. This causes the system to oscillate and enter resonance with the wind, generating up to 100 W of power. The design is intended for use in farmlands and for residential self-generation purposes [76].

Although VIV wind-induced vibration energy harvesting has shown potential for building integration applications, it is notable that none of the research has yet integrated this specific type of wind energy harvester into building structures. Most evaluations have been conducted through wind tunnel testing or numerical simulations. It has also been demonstrated that the technology can function effectively at low Reynolds numbers and produce power outputs ranging from nW to mW. However, by increasing the device's size and integrating it into the roof structure of pitched or curved buildings, it may be possible to further improve these power output ranges, taking advantage of the accelerated wind velocity in such locations. This analysis pertains to the study conducted by [5], which compares various roof shapes to harness their accelerated effects for wind energy harvesting.

Modelling methods for the evaluation and optimisation of wind energy harvesting systems

While conventional wind turbines integrated into building structures

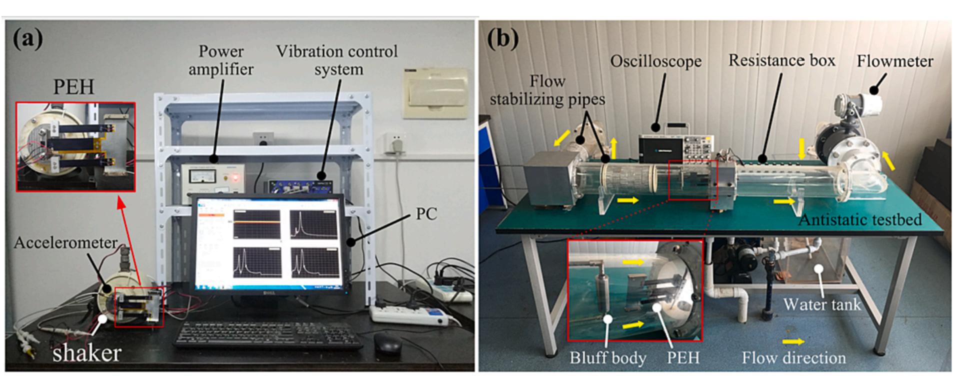


Fig. 17. (a) Experimental setup (b) piezo-electric energy harvester in the circular flow arrangement [74].

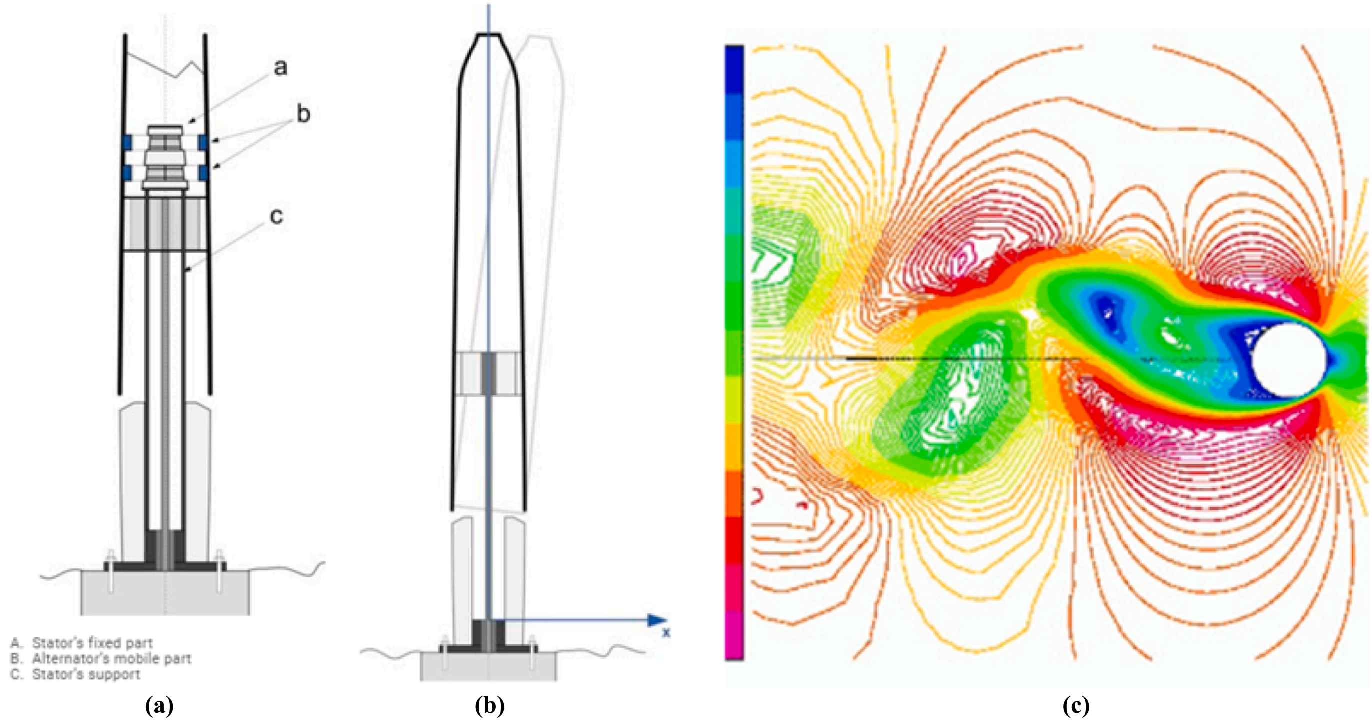


Fig. 18. Vortex Bladeless (a) the configuration, (b) schematic design, and (c) VIV phenomenon in fluid dynamics [76].

have been designed for decades [77], it is crucial to acknowledge that their efficiency is influenced by environmental conditions and wind resources. As a result, researchers and engineers are exploring alternative methods for wind resource assessment that are more affordable. Wind resource assessment has become increasingly important in recent years as it is critical to optimising energy capture and harvesting efficiency for conventional wind turbines. Various methods and software tools are used to precisely measure wind speed, direction, and ambient turbulence. By employing cutting-edge software tools, researchers and engineers can create computer-generated environments to test their ideas and potentially disruptive technology before proceeding with development [78,79]. All of these methods aid in evaluating wind resources and determining the potential for wind energy development.

Micro/small-scale wind-induced vibration technologies pose unique challenges due to their smaller size and shape and are frequently installed in limited spaces, such as on buildings or in urban areas with many obstacles that can create turbulence and drag. To ensure the efficiency and durability of these technologies, designers must choose materials that can withstand harsh weather conditions and carefully consider the placement of the wind energy harvester.

Wind resource assessment tool for wind energy harvesting systems

Different methods have been used in the literature to evaluate wind resources, such as WAsP, and Computational Fluid Dynamics (CFD). These methods are crucial in comprehending wind conditions for small wind turbines in the built environment, which include acceleration zones, recirculation, blocking, and channeling. CFD is a numerical simulation method that employs mathematical models to resolve fluid flow problems and predict wind speeds and patterns in a specific location. CFD analyses for building integrated wind turbines reveal that results are sensitive to building height and shape, roof shape, wind direction, and turbine installation height and location. Nevertheless, most CFD studies [72,80,81] for micro-scale wind-induced vibration technologies focus on dynamic behaviour such as vortex-induced vibration, galloping, and flutter-based mechanisms. These technologies are still in their initial stages of research and development. Nonetheless, investigations into wind resource assessment are necessary to improve the design and increase the energy harvesting efficiency of micro-scale wind energy harvesting systems.

Another study based on CFD was conducted by [82]. The research provides a comprehensive review of recent studies on CFD simulations for micro to small wind turbines and wind turbines integrated with buildings [79]. The findings indicate that CFD simulations can be effective in predicting and optimising the performance of small-scale wind turbines, with ongoing improvements necessary to handle the complexity of turbulent flow. The review highlights the importance of CFD in reducing design costs, improving wind turbine performance, and enhancing wind power utilisation, particularly in urban areas.

In the study of [83], combined long-term wind data analysis, weather patterns and domain topography with CFD to enhance wind power utilisation for designing wind turbines in Hong Kong's high-rise buildings. Results indicate that wind power density was 1.3–5.4 times higher at 4 m above the roof, with 5–7 m/s inlet velocity. The windward top roof is the most favourable location for wind power utilisation under the dominant wind direction. The thickness of wind speed below 8 m/s is only 3.6 m in these areas. High-rise building height and concentration effects result in 4 times higher wind power enhancement for 7 m/s inlet velocity compared to 5 m/s, exceeding the expected 2.7 times enhancement based on general velocity-power models.

Various methods exist for accounting for orography's impact on wind flows. WasP software is widely used and employs a linear flow model that utilizes terrain and roughness data to describe the wind climate in an extended area based on local wind observations. The latest version of WasP includes a computational fluid dynamics module that overcomes linear model limitations in steep terrain. Computational fluid dynamics methods solve Navier-Stokes equations that govern fluid motion using numerical techniques, which can be applied to detailed terrain models with high-resolution meshes, allowing for more complex flows to be resolved at a higher computational cost [84].

A study conducted by researchers from the University of Leeds also utilized WasP to evaluate the wind resource potential for a small-scale wind energy harvester installed on a building rooftop. The study suggested that the harvester could generate significant amounts of energy if installed in a location with optimal wind conditions. The accuracy achieved for identifying viable sites for small-scale turbines is reasonable, considering the complexity of the urban surface. However, even the most complex methodology used resulted in significant predictive errors at some validation sites. This can be attributed to uncertainties in building height data, especially for locations near the top of the building canopy, where small changes in local building data can highly affect predicted wind speeds. To enhance the accuracy of wind speed predictions, it is vital to estimate height-based inputs such as average building heights and displacement heights with high precision. Achieving this may necessitate providing a detailed description of the shapes and heights of the local building roofs. Consequently, using more detailed input-building data may improve the accuracy of the model's predictions [85]. However, it should be noted that the Wasp software has not yet been explored for wind-induced vibration technologies such as vortex-induced vibration, and research on flutter-based and galloping-based mechanisms using this software is not yet available in the literature.

In [86], a combination of CFX and WasP software was used to investigate the local micrometeorological features of the wind flow and the effects of the complex urban topography by identifying zones of wind acceleration, recirculation, and blocking. An understanding of zones of wind recirculation and turbulent wakes is important in terms of high energy production and protection of the machine from excessive loading from gusts by avoiding installation in such areas. The turbulent setting of the rooftop of a large building provides guidance in the micro-siting of wind turbines. The specific objective was to assess the combination of the CFD package CFX with the wind atlas software WasP as a wind energy resource assessment tool for the application of small rooftop wind turbines in a built environment. Moreover, the investigation of wind power or turbulence kinetic energy on the rooftop.

Numerous scholars have utilised computational fluid dynamics (CFD) simulations to determine the viability of constructing wind turbines integrated into buildings. CFD allows for an examination of various factors, such as wind patterns and the impact of wind speed, direction, and turbulence on the building, as well as the influence of neighboring structures or buildings. Accurately evaluating the placement of wind turbines on buildings is crucial for maximising the amount of power that can be generated.

Modelling of HAWT

Various CFD tools were employed to model HAWT incorporated into buildings. Arteaga-López et al. [87] used CFD simulations to identify wind stream contours around buildings with the HAWT. Fig. 19 shows the results showed a growing wake effect on the roof of the building from the northern facade to the rear, indicating that the location may not be suitable for installing small wind turbines. The study suggested a height of 21 m above ground level for the installation of the turbines. However, the building was found to be a good site for wind projects as there were no structures to interrupt the flow of wind resources in the area. This information was then used to select the best place to install the turbines on the building.

Heo et al. [88] also used CFD tool to conduct a comprehensive study using CFD was conducted to analyse the aerodynamic characteristics of the 110-kW building augmented wind turbine (BAWT). A 3D model was utilised to investigate wind speeds and incoming flow angles of atmospheric boundary layers. Wind speed in the axial direction increases as it passes through the buildings, due to flow separation from sharp corners. The 110 kW BAWT demonstrated higher aerodynamic power output than the 110-kW stand-alone wind turbine, as wind speed acceleration occurs between buildings, creating a concentration effect. The BAWT can achieve its designed power at lower wind speeds compared to the rated wind speed, which is an advantage. Additionally, the role of the buildings is similar to that of ducts or shrouds, allowing the power coefficient of the BAWT to exceed the Betz limit. The effect of incoming flow angle on flow patterns and aerodynamic power output was also examined. Flow patterns and power output were found to be asymmetric with respect to 0° of flow angle due to the fixed rotating direction of the turbine blade and confinement of flows by the buildings. The maximum aerodynamic power occurred when the incoming flow angle was near −10°. The aerodynamic power output of the BAWT with the incoming flow angle between −30° and +20° was higher than the designed power of the stand-alone wind turbine. However, when wind direction has higher yaw angles than ±30°, power output decreases sharply.

CFX tool was used in [89] to assess the accuracy of simulated flow around obstacles, a test case was performed using a rectangular structure with dimensions of 125 mm height, 100 mm width, and 150 mm length. The simulation results were compared with high-quality CEDVAL wind tunnel datasets from Hamburg University, which included complete documentation of boundary conditions and quality assurance checks during measurements. The CFX simulation domain and obstacle were set up similarly to the configuration used in the CEDVAL data set, with a mesh size of 125 mm cell edge length and two inflation layers of 10 mm thickness near the walls. The wind flow in the CFX model was set to give a Reynolds number of 37,250, and an equation was used to simulate the inlet velocity profile with a ground roughness of 0.007 m. The data set provided values for longitudinal and vertical wind components at 603 points in the vertical plane and longitudinal and lateral wind components at 660 points in the horizontal plane, as well as a visualization of flow around the structure in both horizontal and vertical planes.

CFD simulations have been effective in modelling the aerodynamic characteristics of HAWT integrated into buildings. They help identify the optimal location and height for installing small wind turbines based on wind stream contours and wake effects. CFD simulations also highlighted the effectiveness of BAWT in increasing aerodynamic power output due to wind speed acceleration between buildings. Additionally, CFD simulations' accuracy was assessed by comparing simulation results with high-quality wind tunnel data, demonstrating the reliability of CFD

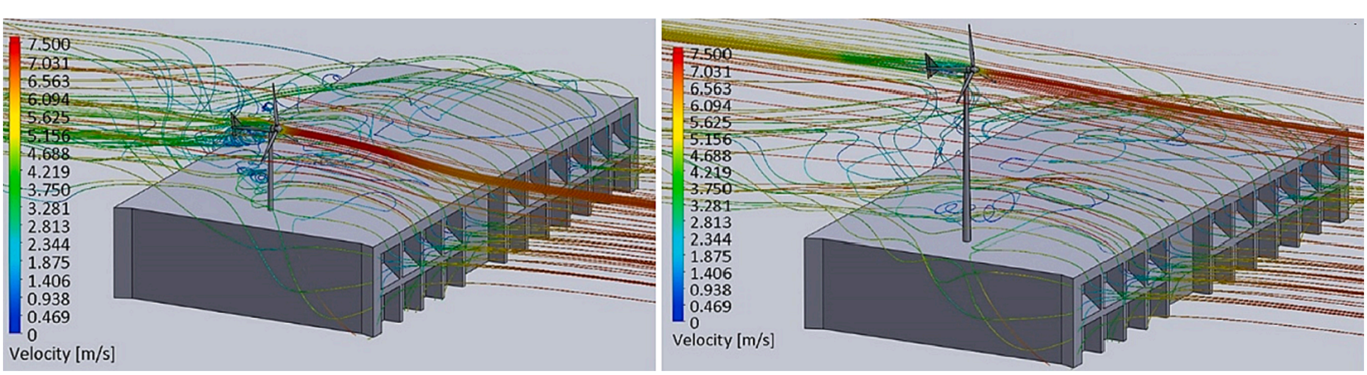


Fig. 19. CFD modelling of a) turbine-building array at 13.5 m height streamlines b) turbine-building array at 21 m height streamlines [87].

tools in modelling wind flow around obstacles. Overall, CFD simulations are a valuable tool in assessing wind turbines' aerodynamic performance in buildings, providing useful insights for optimal design and installation.

Modelling of VAWT

Similarly, various CFD tools were employed to model VAWT incorporated into buildings. Larin et al. [90] proposed a horizontal Savonius wind turbine configuration mounted on the upstream edge of a building to improve its low performance by utilising flow acceleration. The study emphasizes the importance of integrated simulations of both the building and the turbine and investigates the position, blade number, and circumferential length of the turbine when mounted on a building to understand its behaviour in low-speed urban environments. The study used CFD tool to solve flow fields of conventional and cup type turbines and shows that cup type turbines perform well in the right environment, resulting in a 450% improvement in the power coefficient from 0.043 to 0.24.

The study of Elbakheit [91] aimed to optimise wing parameters for wind turbine applications. Optimized wing parameters resulted in lower resistance to the flow, enabling higher wind speeds to be harnessed. Wind speed jets under the wing were found to be suitable for Savonius turbines. The introduction of turbine resistance lowered wind acceleration but did not significantly affect the pressure drop, indicating more power potential can be extracted. The optimized wing case yielded a higher potential power output of 650.8 W/m^2 compared to the unoptimized case, that yielded 400 W/m^2. Varying turbine resistance did not change the resulting wind speed and pressure drop. Finally, placing the turbine at 2 m behind the wing tip on the opposite windward side produced the maximum pressure drop for more power generation.

Bayoumi et al. [92] introduced the wind energy optimisation tool (WEOT), which can be used by architects during the early design phase to plan the incorporation of VAWTs in high-rise buildings. The tool provides recommendations for achieving a desired energy yield by exploiting wind power potentials at certain zones along the building skin. WEOT integrates CFD-simulations, wind characteristics, and optimisation algorithms. The tool's application on case study high-rise models shows that it can help architects determine the positions, numbers, and sizes of VAWTs early in the design process, which is advantageous for the project's time plan, expenses, and aesthetics. However, the limitation of the study is that CFD analyses are done for generic buildings not surrounded by a built context. Nevertheless, WEOT is flexible enough to incorporate the results of any CFD-analysis, and it can be useful when optimizing more complex building forms.

The use of CFD tools in modelling VAWT incorporated into buildings has been shown to be effective in improving the performance of the turbines. Studies reviewed in this text demonstrate that CFD simulations were used to identify the optimal location, blade number, and circumferential length of the turbine, as well as the wing parameters for wind turbine application, resulting in higher power output. The use of CFD simulations also led to the development of the wind energy optimization tool (WEOT), which can be used by architects to plan the incorporation of VAWTs in high-rise buildings. The tool provides recommendations for achieving a desired energy yield and can help architects determine the positions, numbers, and sizes of VAWTs early in the design process. Overall, CFD simulations have proved to be a valuable tool in assessing the aerodynamic performance of wind turbines integrated into buildings and can provide useful insights for the optimal design and installation of such systems.

Modelling of DAWT

Chaudhry et al. [93] investigated the feasibility of implementing building-integrated wind turbines by studying the effect of the structural morphology on the extraction of wind. The study used CFD simulations to determine the power generation capacity of wind turbines in buildings with triangular, square, and circular cross-sections and compared them against the Bahrain Trade Centre benchmark model. The results showed that circular cross-sections had the highest extraction of incoming wind streams, with a capacity factor of 19.9% and an estimated power production capability of 35.1 kW. The study suggests that circular cross-sections are the most viable building orientation for regions with a dominant prevailing wind direction, as they achieved a mean wind speed augmentation of 5% at the turbines.

A different tool was used to examine [94] how the pressure drop between two buildings accelerated air velocity through a duct and a turbine and how different building geometries and wind input angles affected power augmentation. A simplified turbine model was used to compare the total power captured by various building configurations and an adaptive neuro fuzzy (ANFIS) application. The network was developed to predict building augmented power and estimate wind. ANFIS was chosen for its computational efficiency and adaptability with complex parameters. Wind power output is directly proportional to wind speed, and diffuser-augmented wind turbines concentrate wind energy for more power. However, the use of architectural structures for wind augmentation is still limited due to technical and architectural barriers.

Studies have shown that CFD simulations are effective in assessing the feasibility of building-integrated wind turbines. Circular cross-sections have been found to be the most viable building orientation for regions with a dominant prevailing wind direction, resulting in the highest extraction of incoming wind streams and power production capability. The use of an adaptive neuro-fuzzy application has also shown promise in optimizing wind turbine performance. However, technical and architectural barriers still limit the use of building structures for wind augmentation. These studies provide valuable insights for the optimal design and implementation of building-integrated wind turbines.

Modelling of other configurations

Fig. 20 (a) shows a diagram from the CFD work of [95] indicating the most appropriate type of wind turbine for each region based on the turbulence intensity that indicates the map and velocity field. The recommended height for installing horizontal axis wind turbines (HAWT) is above $z/77 = 0.19$ from the roof surface upstream and above $z/77 = 0.31$ downstream, and it is suggested to incline the HAWT 5° downwards at the upstream region below $z/77 = 0.31$. Vertical axis wind turbines (VAWT) are more suitable below these heights as they are not affected by wind direction fluctuations and resist velocity fluctuations better. The VAWT can be installed in a horizontal position at the central-upstream region close to the roof surface to take advantage of the flow's recirculation. However, further investigation is needed to fully understand the behaviour of VAWT in highly turbulent environments. Fig. 20(b) depicts a ducted wind turbine positioned at the upstream corner of the roof, taking advantage of the pressure field.

Wang et al. [96] also used CFD tool to conduct a parameter study on two symmetrical perpendicular buildings forming a corner for wind energy assessment. The study considers various parameters such as building lengths, widths, and heights, size of corner openings, inlet angles and modes, and assessment altitudes. The main findings include the optimal inlet direction, the effect of corner separation and inlet mode on wind energy over the roof, and the impact of the building plan area and altitude on energy production. The paper provides general trends for various configurations, but further simulations and evaluation are needed for the practical application of wind turbines into architecture. Future work will explore other building configuration types and more complex models to contribute to urban planning proposals on wind energy development.

Another CFD numerical analysis of wind conditions of building integrated wind turbines was conducted by [97] to examine the effects of

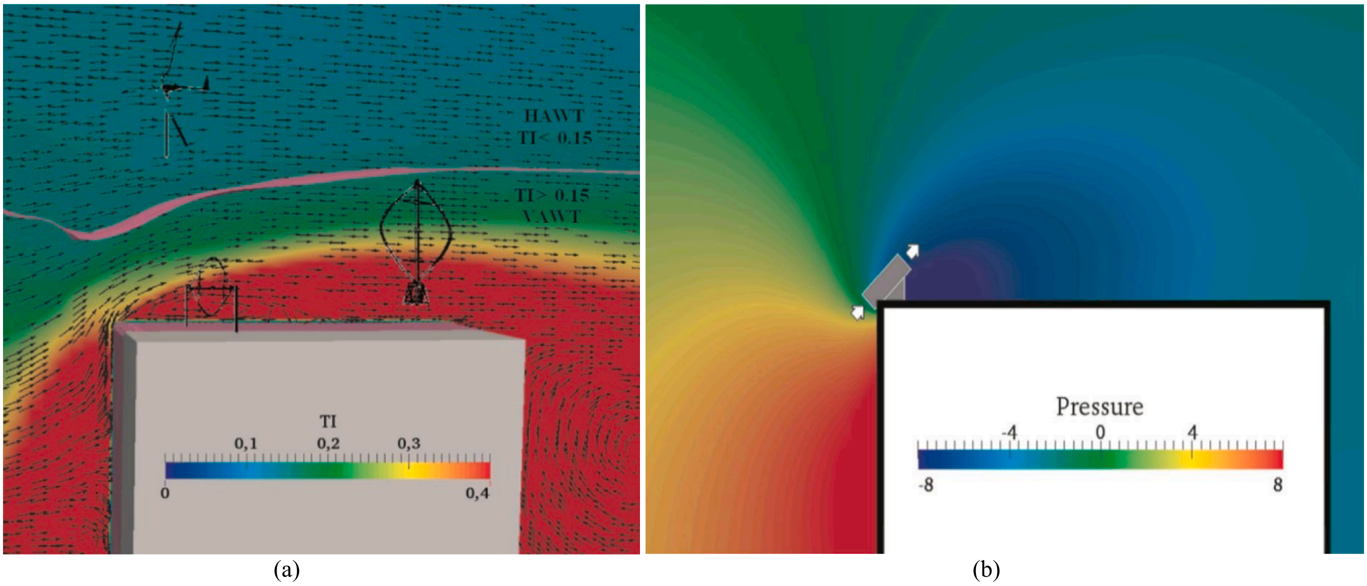


Fig. 20. Wind turbine positioning. (a) most suitable wind energy exploitation systems for HAWT, VAWT, and DAWT (b) ducted wind turbine positioned at the upstream corner of the roof [95].

wind direction in a high-rise building. The computational simulations were carried out in OpenFOAM software. This is to investigate the optimal siting of wind turbines over high-rise buildings, using realistic wind profiles derived from a numerical weather prediction model. The study found that for a single tall building, there is a significant fraction of which winds are sufficient for wind power generation. For twin buildings, wind turbines can be placed not only on the roof but also in between the buildings, with a velocity of 2 m/s achievable at a separation distance fraction of 0.2 and 2–2.8 m/s achievable at a separation distance fraction of 0.5. Results were dependent on the exact geometry of the building.

Kono et al. [98] examined the effects of wind direction and the horizontal aspect ratio of a building on wind conditions over its roof for the installation of small wind turbines. Large eddy simulations are performed for a scale model building with varying aspect ratios and wind directions. The main findings show that wind conditions at the windward corners and midpoint of the longer edge are generally unfavourable at low heights, and leeward locations have better wind conditions. The center and midpoints of the shorter edges are the most optimal locations for installing SWTs. Further studies are suggested to investigate the effects of increasing building sides and Reynolds number on flow characteristics.

Nishimura et al. [99] highlighted the significance of integrating renewable energy into smart cities and analysed the wind velocity profile to assess the potential energy in the wind and the performance of wind turbines. CFD simulation is used to model wind velocity distribution across buildings, and the power output of wind turbines is estimated. The research recommends installing wind turbines at the back of buildings, located in the center between two buildings, to take advantage of the accelerated wind in the intervening space. The study also identifies an optimal wind velocity distribution for maximizing wind energy output.

The use of CFD simulations has provided valuable insights into the optimal positioning and design of wind turbines for harvesting wind energy in urban environments. Various studies have explored the effects of building configurations, wind direction, and turbulence intensity on the performance of wind turbines. The recommended height and incline of HAWT and the suitability of VAWT have been determined based on the wind velocity profile. The placement of wind turbines in between buildings and at the back of buildings has been suggested to take advantage of the accelerated wind in the intervening space. However, further studies are needed to evaluate the practical application of these findings in urban planning proposals for wind energy development.

Modelling of micro scale wind induced vibration technologies

Sun [100] conducted a study to evaluate the design and performance of micro/small-scale flapping cantilevered beams for wind energy harvesting systems using CFX-ANSYS. The study employed the design optimisation feature of the ANSYS commercial package to compare and present the results of various configurations. A 3-dimensional static model, encompassing essential components of the mechanical structure, was developed using ANSYS software to examine aeroelastic phenomena. The lift force acting on the aerofoil was utilized to determine the minimum wind speed required for operation, which helped in identifying the optimal structural design for achieving a low threshold wind speed. The wind energy harvester functions by causing oscillations in a cantilevered beam aligned with the direction of the airflow.

The work of [101] used detailed CFD modelling to investigate the effect of wind speed and aeroelastic belt location on power generation. The results show that the apex of the roof or highest point of the building yields the highest power output, with a 45-degree wind approach relative to the building being the most efficient. Intelligent placement of the aeroelastic belt prioritizes the roof and trailing edges of the building. Further scaling up of the system is possible, with the potential for an array of aeroelastic belts. The study demonstrates the importance of CFD analysis in assessing the optimum location of wind energy devices around buildings and provides a modelling procedure and data for further investigation of the urban integration of the aeroelastic belt.

In [104], a study on the design and modelling of electrostatic-based wind energy harvesting systems was conducted. The proposed harvester was simulated using Matlab and Simulink to investigate energy transfer during the three harvesting phases, and energy analysis was performed to examine the impact of modifying the structure of the multi-pole capacitor on the amount of harvested energy. Simulation results showed that an 8 pole variable capacitor with capacitance ranging from 2.5 nF to 0.6 nF could produce 29.43 μJ/sec of energy at 10 m/s, whilst an array of 10 capacitors with the same capacitance variation could produce 295 μJ/sec of energy at 10 m/s. Better performance is expected to achieve if the wind energy harvester is installed in the building [88].

Wind speeds in urban areas are lower than in open areas, and wind energy harvesting systems will be subjected to complex and turbulent flows. Different studies used CFD and WAsP software to assess the local micro-meteorological features of the wind flow and identify zones of wind acceleration, recirculation, and blocking for building integrated wind turbines. Moreover, the modelling of small scale systems such as HAWT and VAWT are well established in the literature. HAWT and VAWT are increasingly being installed into building structures to harness wind energy in urban areas. CFD is a well-established modelling technique used to determine the efficiency of these wind turbines. Software tools like ANSYS, SolidWorks, and MATLAB are commonly used to design and simulate small scale wind turbines integrated into building structures. CFD simulations enable the prediction of turbine energy output and can identify areas for optimisation of blade design for maximum energy extraction. However, there are limited modelling studies evaluating micro-scale energy harvesting installations in buildings. The modelling of wind-induced vibration technologies, in most cases, did not include the impact on the building or surrounding buildings. This is important when evaluating the performance of these devices and should be considered in future works.

From the reviewed studies, several works have been conducted to evaluate the design and performance of wind energy harvesting systems. CFX-ANSYS was used in Sun [100] to examine the optimal structural design for achieving a low threshold wind speed using micro/small-scale flapping cantilevered beams. The study of wind speed and aeroelastic belt location on power generation in [61] employed detailed CFD modelling, while [98] simulated electrostatic-based wind energy harvesting systems using Matlab and Simulink. The modelling of small scale systems such as HAWT and VAWT are well established in the literature, and CFD simulations enable the prediction of turbine energy output and can identify areas for optimisation of blade design for maximum energy extraction. However, future studies should also consider the impact of wind-induced vibration technologies on the building and surrounding buildings when evaluating the performance of these devices.

Discussion

The assessment presented in this study is focused on the latest developments in building-integrated wind turbines and wind-induced vibration energy harvesters that can be potentially installed in building structures. Tables 1–6 summarises the system designs, evaluation methods utilised, energy efficiency, and power output of these technologies. It provides a comparative analysis of various studies on building-integrated wind turbines and wind-induced vibration technologies to identify their respective harvesting and power performance for different applications.

Table 1 summarises the reviewed studies on the recent developments in building integrated horizontal axis wind turbines. Volkmer et al. [30] found that KV200-profiled blades have lower sound power levels than S834-profile blades and that tripping and trailing edge serrations can reduce noise but also reduce turbine shaft power. Singh and Shmed [28] showed that a 2-bladed rotor performed better than a 3-bladed rotor in the 3–7 m/s wind speed range, achieving a peak power coefficient of 0.29. Arumugam et al. [29] determined that a small horizontal wind turbine with 3 blades designed for low wind speed areas performed optimally at a tip speed ratio of 7. Ghorani et al. [31] showed that a HAWT designed for the throat had a Cp of 0.46 and achieved optimal performance improvements of 64.7% for PTh and 279.9% for SR. Dar et al. [32] found that the smoothness of roof edges is inversely proportional to wake recovery and expansion rates in wind tunnel experimental tests.

For the building integrated vertical axis wind turbine in Table 2, Kuang et al. [8 found that an external diffuser system for VAWT can increase power generation and flow field stability, with $L1/D = 2$ and $\theta 1 = 20^\circ$ resulting in a 51.73% increase in power coefficient. Mohammed et al. [11] demonstrated that a hybrid VAWT generates 63% more energy than a traditional VAWT. Emejeamara et al. [9] proposed a methodology for mapping potential power generated by a turbine system across city regions, using CFD and BEM analysis. Siddiqui et al. [10] found that maximum efficiency is achieved at a tip speed ratio of 3 and a ground clearance of 7.5c, with performance reduced by 30.10%, 20.65%, and 10.65% at ground clearances of 1.0c, 2.5c, and 4.0c, respectively. Allard et al. [41] found that placing the turbine above a building's corner increased its Cp from 0.318 to 0.549 at a tip speed ratio of 5, with CFD analysis showing differences in rotor wake structure when operating in a freestream versus mixed with surrounding accelerated flow.

In the context of wind turbine performance, various studies have investigated the effect of adding a diffuser to a wind turbine. Table 3 demonstrates the studies on DAWT integrated into the building

Table 1
Summary of reviewed technical characteristics for reviewed building integrated horizontal axis wind turbine.

Author (s)	Power capacity (W, kW)	Analysis		Applications/Purpose	Key Findings
		Numerical	Experimental		
[30]	1.6 kW	–	✓	Reduction of aerodynamic noise	• KV200-profiled blades (10% thickness) have lower sound power levels than S834-profile blades. • Tripping and trailing edge serrations can reduce noise but also reduce turbine shaft power.
[28]	Micro (1 kW), mid-range (5 kW)	–	✓	Design and performance test	• 2-bladed rotor performed better at a pitch angle of 18°. • The 2-bladed rotor had lower cut-in wind speeds and higher power coefficients in the 3–7 m/s wind speed range compared to the baseline 3-bladed rotor. • The peak power coefficient achieved at 6 m/s wind speed was 0.29.
[29]	1–5 kW	✓QBlade	–	Design and Aerodynamic assessment	• The optimal performance for the turbine rotor was achieved at a tip speed ratio of 7 • Power factor obtained (Cp = 0.4742) did not surpass the Betz limit (0.59%) and was efficient for a small wind turbine • The design of a small horizontal wind turbine with 3 blades is suitable for low wind speed areas
[31]	48.3 W 204.4 W 551.7 W 1330.9 W	✓CFD	–	Design and Aerodynamic assessment	• Optimal performance improved by 64.7% for PTh and 279.9% for SR • The HAWT designed for the throat had a Cp of 0.46 • The optimal Invelox's entering mass flow rate decreased by 49.6% when the turbine wasn't rotating
[32]	1.2 kW	–	✓ Wind Tunnel	Power production and wake characteristics to the roof edge shape	• Fence case exhibits the highest wake recovery and expansion rates • Smoothness of roof edges is inversely proportional to the recovery and expansion rates • As the roof edges become smoother, the wake recovery and expansion rates decrease

Table 2
Summary of reviewed technical characteristics for building integrated vertical axis wind turbine.

Author (s)	Power capacity (W, kW)	Analysis		Applications/Purpose	Key Findings
		Numerical	Experimental		
[8]	1 kW	✓CFD	–	Device for Accelerating Wind Energy Capture	• External diffuser system has shown promising results in increasing power coefficient of VAWT at TSR = 1.5 • Specifically, L1/D = 2 and θ1 = 20° resulted in a 51.73% increase in power coefficient • Flange and ejector can further enhance system capabilities by increasing pressure differences and stabilizing flow fields • External diffuser system has potential applications in specific urban areas • Key benefits of external diffuser system for VAWT include increased power generation and improved stability of the flow field
[11]	0.922 W to 1.431 W	–	✓	Design and testing	• Hybrid VAWT generates 63% more energy than a traditional VAWT
[9]	600 W	✓CFD/ BEM	–	Analyse the local wind flow patterns and turbulence using CFD	• Proposed methodology offers the chance to map potential power generated by a turbine system across city regions for different mast heights • This will enable the evaluation of urban wind project feasibility by mapping the capacity factor over built environments. • Methodology will consider the spatial variability in both mean winds and turbulence intensities
[10]	1.5 kW	✓CFD	✓	Impact of turbulence and ground clearance on the performance	• Maximum efficiency is achieved when the tip speed ratio is 3 and ground clearance is 7.5c (wire length) • With a ground clearance of 1.0c, 2.5c, and 4.0c, the turbine performance is reduced by 30.10%, 20.65%, and 10.65%, respectively • If the ground clearance exceeds 7.5c, the turbine performance remains constant
[41]	2.5 kW	✓CFD	✓	Optimal placement	• Placing the turbine above the building's corner increased its Cp from 0.318 to 0.549 at a tip speed ratio of 5 • The rotor wake's structure was shorter when operating in a freestream compared to when mixed with the surrounding accelerated flow

Table 3
Summary of reviewed technical characteristics for reviewed building integrated ducted augmented wind turbine.

Author (s)	Power capacity (W, kW)	Analysis		Applications/Purpose	Key Findings
		Numerical	Experimental		
[46]	1 kW	✓CFD	–	Design and placement of blade	• Optimised turbine blade position and geometry result in a 2.5-fold increase in the coefficient of power from 0.135 to 0.34
[47]	100–250 W under 10 ~ 14 mph 300 W	✓CFD	–	Design optimisation	• Blade and generator achieved 100–250 W under 10–14 mph • The expected energy generation was 1.2–2 KWh for 12 h of operation per day at the specified wind speed, but actual results may differ due to mechanical and electrical losses
[48]	500 W 0.66 kW	✓CFD	✓	Design optimisation and air flow distribution	• CFD results showed increased wind speeds through the shroud to a maximum at the rotor where power is generated • Optimum DAWT was found to restore wind speeds lost at the rotor due to building presence and exhibited better responsive behaviour than a test bare wind turbine • Velocity distribution along the rotor diameter was not as uniform for the roof-mounted shroud as it was for the free-stream shroud
[49]	0.6 kW and 5.8 kW	✓CFD	–	Design optimisation and air flow distribution	• Velocity amplification of 1.52 times at the diffuser throat, close to the predicted value of 1.6 from the earlier design stage CFD
[50]	1–3 kW	✓CFD	–	Design optimisation, wind direction, and air flow distribution	• Highest Cp value obtained was 0.333 with guide vanes set at 55° and TSR of 0.5.

structure. Krishnan and Paraschivoiu [46] optimized turbine blade position and geometry, resulting in a 2.5-fold increase in the coefficient of power. Bhakare et al. [47 achieved 100–250 W of power from the blade and generator under 10–14 mph winds. Agha [48] found that CFD results showed increased wind speeds through the shroud to a maximum at the rotor where power is generated, and Dilimulati et al. [49] found a velocity amplification of 1.52 times at the diffuser throat through CFD analysis. Abu-Thuraia et al. [50] obtained the highest Cp value of 0.333 with guide vanes set at 55° and TSR of 0.5 through CFD analysis.

Overall, Tables 1 to 3 present the power capacity of roof-mounted Horizontal Axis Wind Turbines (HAWT), Vertical Axis Wind Turbines (VAWT), and Ducted Axis Wind Turbines (DAWT), ranging from 48.3 W to 5 kW.

Table 4 outlines the technical characteristics evaluated for galloping based wind energy harvesting technologies. The designs currently under development include square, rectangle, D-shape, or funnel-shaped bluff bodies, and piezoelectric transducers. These systems are typically tested in laboratory settings or through numerical simulations to assess their power and harvesting performance. The results have demonstrated that these systems can produce power in the milliwatt range, which can be used to power wireless sensor nodes for environmental monitoring and structural health monitoring. This indicates that the technology has the potential to harvest energy and convert it into electric power. However, this study highlights that these technologies are still in their preliminary

Table 4
Summary of reviewed technical characteristics for galloping based wind induced vibration technologies.

Authors	Transducer	Body shape	Power capacity (nW, μW,mW)	Analysis		Purpose	Applications	Key Findings
				Numerical	Experimental			
[57]	Piezoelectric	Quadruple Halbach Arrays	8 mW	✓	✓	Use halbach arrays to enhance performance	Experimental and numerical study	• External load resistance was found to have a significant impact on the galloping onset velocity and vibration amplitude of the harvester
[54]	Piezoelectric	A cut-corner prism	47.5 mW	✓	✓	Use enclosure effect to enhance perfromance	Experimental test	• Optimal windward side length for the cut-corner prism energy harvester was found to be 0.4B, resulting in the highest power output. Parallel side with a length of 0.6B was able to produce 47.5 mW
[56]	Piezoelectric	Square, triangular and funnel-shaped	0.207 mW/cm, 1.56 mW/cm, and 2.34 mW/cm	✓	✓	Improve aerodynamic model to enhance performance	Experimental and numerical study	• The maximum power achieved were 2.34 mW/cm, 1.56 mW/cm and 0.207 mW/cm under 7, 9 and 13 m/s for the 3 different shape designs
[55]	Piezoelectric	D-shape, Square, rectangle, and triangle	8.4 mW	–	✓	Improve power and harvesting performance with efficient strategy	Sensors	• Square section exhibited the highest performance for a low cut-in wind speed of 2.5 m/s and achieved a peak power output of 8.4 mW
[58]	Electromagnetic	Y-shaped cross-section	2.5 mW	–	✓	Enhance energy capture efficiency	Sensors	• Average power up to 2.5 mW at wind speed of 4 m/s,

stages and require further improvements to transition from proof-of-concept or laboratory testing to real-world applications.

Table 5 provides a summary of the reviewed technical features for innovative flutter-based wind energy harvesting systems, including T-shaped, aerofoil, and cantilever beam designs with piezo-electric, electro-magnetic, or electro-static transducers. Each design can generate power from wind-induced vibration, and the power output is relative to wind velocity. The simple structure, low cost, and lightweight materials have demonstrated the ability to power LED lights, pedometers, and wireless temperature sensor nodes. It highlights the potential of galloping and flutter-based wind-induced vibrations for isolated wind energy harvesters, showing power output in mW for wind tunnel tests and numerical simulations. Scaling up and integrating the technology into roofs or building structures with high wind velocity acceleration can lead to higher harvesting and power generation. The aerofoil-based piezo-electric design with pseudo-elastic hysteresis produced the highest power output of 120 mW. Only limited studies, including [61–64] in Table 5, reviewed and assessed the influences of wind direction, size, physical parameters, wind speed, and optimal position for harvesting and power performance of the flutter-based wind-induced vibration technology integrated into roof building structures. Future research should consider non-uniform flow conditions in external simulations.

Table 6 compares different studies on VIV (vortex-induced vibration) energy harvesting systems. The technical features of these systems show that lower power output was achieved as compared to other wind-induced vibration technologies, with harvested power output in the nano-watt to milliwatt range. The performance of VIV harvesters was found to be highly affected by wind flow speed, as observed in the table. While VIV energy harvesting systems were able to produce power at low wind speeds, as shown in one study by [4], it is important to consider the stability and performance of the technology when exposed to higher wind speeds in future studies.

The micro/small scale wind induced energy harvesting systems showed that these can power IoT devices in buildings. Low-power sensors designed for remote monitoring typically require only milliwatts to a few watts of power and often feature energy-efficient components and microcontrollers to extend battery life. Additionally, choosing low-power communication technologies like Bluetooth Low Energy (BLE) or Zigbee can reduce overall power consumption in the IoT ecosystem. Modern buildings heavily rely on IoT devices for improved convenience, energy efficiency, and security. Energy-efficient IoT devices not only save costs but also contribute to environmental sustainability. By incorporating energy harvesting techniques, such as solar panels or piezoelectric elements, IoT devices can become more self-sustainable and eco-friendly. Efficient power management and energy harvesting are crucial for reliable and long-lasting IoT solutions, promoting the widespread adoption of smart buildings. As IoT technology advances, further improvements in power efficiency will enhance the capabilities and benefits of these smart building systems.

It can also be noticed that there are available studies on micro-scale energy harvesters, however, there are a limited number that have focused on evaluating their performance when integrated into buildings in the last 10 years. These studies include [61–64], which explores the incorporation of an aeroelastic belt into the building roof structure for low wind energy harvesting. The aeroelastic belt is a simple device consisting of a tensioned membrane connected to electromagnetic coils and power conditioning components, offering cost-effectiveness and modularity. The primary objective of their research is to assess the potential of integrating the aeroelastic belt into the built environment using Computational Fluid Dynamics (CFD) simulations.

The findings also demonstrated that the research on recent developments in wind energy harvesting technologies has provided valuable insights into design, technical aspects, and research methods. However, it is crucial to acknowledge the limitations of the tools used in the study, such as Computational Fluid Dynamics (CFD), Blade Element Momentum (BEM) theory, and software tools like QBlade. These methods may not fully capture the complexities of real-world wind behaviour, especially in complex terrain or urban environments where building-integrated wind turbines are installed. High-fidelity CFD simulations can be time-consuming and computationally expensive, limiting their use in extensive parametric investigations or optimization studies. Obtaining accurate and comprehensive validation data for numerical simulations can also be challenging, leading to uncertainties in the results. Additionally, the dynamic behaviour of wind-induced vibration systems, including aeroelastic effects like flutter and galloping, must be considered, which introduces further complexities and

Table 5
Summary of reviewed technical characteristics flutter based wind induced vibration technologies.

Authors	Transducer	Body shape	Power capacity (nW, μW, mW)	Analysis		Purpose	Application (s)	Key Findings
				Numerical	Experimental			
[23]	Piezoelectric	Aerofoil	0.764 mW	–	✓	Examine the power and harvesting efficiency of aerofoil flutter	LED light, pedometer, and sensor,	• 0.764 mW obtained at 17.48 V maximum power voltage during 16.32 m/s conditions.
[61]	Electromagnetic	Aeroelastic belt	62.4mW	✓ Incorporated into building	✓	Analyse the power and harvesting efficiency of integrating an aeroelastic belt into the building	WSN, RF transceivers, charging devices, small-scale electronic devices	• 62.4 mW generated from wind acceleration up to 6.2 m/s
[62]	Electromagnetic	Aeroelastic belt	62.4 mW		✓	WIFEH technology interaction with building structures and the energy yield achievable through its integration.	WSN, RF cameras charging devices,, transceivers,	• The apex of the roof of the building yielded the highest power output for the aero-elastic belt due to flow speed-up maximisation in this region.
[63]	Electromagnetic	Aeroelastic belt	62.4 mW	✓	✓	WIFEH implementation, its challenges, and potential benefits in terms of energy conversion and management within the built environment.	Transmitters, data loggers, and WSN	• Results indicate that at an airflow of 2.3 m/s, the WIFEH produced an RMS voltage of 3 V, a peak-to-peak voltage of 8.72 V, and a short-circuit current of 1 mA.
[64]	Electromagnetic	Aeroelastic belt	62.4 mW	✓	✓	Performance of the WIFEH under different conditions and its potential contributions to energy harvesting within the built environment	Small-scale electronic devices, transmitters, data loggers, and WSN	• At a wind velocity (UH) of 10 m/s, the airflow in this location accelerated to around 14.4 m/s, constituting a 37.5% speed-up at that specific height. This acceleration occurred when wind approached the building facade at a 30° angle
[70]	Electrostatic	Teflon electret layers with 25 μm-thickness	481 μW (178 μW/cm^3) and 2.1mW (782 μW/cm^3)	–	✓	Enhance power and harvesting efficiency via electrets	WSN	• Compact design generates 481 μW (178 μW/cm^3) at 15 m/s and 2.1mW (782 μW/cm^3) at 30 m/s
[69]	Piezoelectric	Aerofoil	120 mW	✓	–	Examine power and harvesting efficiency of aerofoil flutter	WSN for aircraft health monitoring and rotorcraft structures	• Optimal load resistance produced 120 mW power output at 14 m/s
[65]	Piezoelectric	Chamber with a cuboid shape and cantilever design	1.59 mW	–	✓	Examine the power performance of temperature sensor	WSN with self-powering capability	• 1.59 mW power generated with 20 kΩ electrical load at 11.2 m/s

uncertainties in numerical simulations. Representing wake interactions between wind turbines accurately in simulations is also challenging, impacting the optimal placement of wind energy harvesting technologies in wind farms or arrays. To address these limitations, a balanced approach combining numerical simulations, experimental data, and innovative modeling techniques is crucial for improving wind energy harvesting technology design and performance. Conducting experimental laboratory tests for micro/small-scale wind-induced vibration technologies is essential for understanding their performance under controlled conditions. However, real-world field tests are necessary to validate their effectiveness under varying environmental conditions, and a comparison between laboratory and field results can enhance accuracy and inform necessary adjustments for successful deployment of wind energy harvesting technologies in diverse settings.

Conclusion and future works

Over the past few decades, the emphasis in building integrated wind energy harvesting systems has been on enhancing the design of conventional wind turbines. However, there are still ongoing reports of challenges and limitations during both construction and operation. Typical hindrances to the implementation of such systems include high levels of turbulence due to ground-level surface roughness, low wind speeds at building heights, and the substantial cost associated with equipment and installation required for building integration. Moreover, most of the studies are for the urban, whilst rural applications are very rare to see in the literature for building integrated wind turbines. However, it has been recognised its potential in rural areas, where it is expected to have fewer obstacles and neighbouring structures.

Based on the reviewed studies on building integrated wind turbines,

Table 6
Summary of reviewed technical characteristics VIV based wind induced vibration technologies.

Authors	Transducer	Body shape	Power capacity (nW, μW, mW)	Analysis Numerical	Experimental	Purpose	Application (s)	Key Findings
[73]	Piezoelectric	Bionic bluff body with 10 mm pits structure	1.21 mW	–	✓	Assess various VIV designs and their performance	Experimental study	• Maximum power output of 1.21 mW achieved with 800 kΩ resistance, 0.57 mW higher than smooth cylinder
[72]	Piezoelectric	Cylindrical oscillator	1.6 nW 1.2 nW 0.8 nW	✓	✓	Investigate the power and energy harvesting performance of a cylindrical oscillator	MEMS	• Cylinder-shaped harvester generated nano-watt power output and performed better when incorporated into a formation to improve power output
[74]	Piezoelectric	E-shaped piezoelectric based on vortex induced vibration	3.35 mW at 1.5 m/s	✓	–	Investigate the harvesting performance of an E-shaped piezoelectric wind energy harvester	Numerical study	• Power output of 3.35 mW generated at 1.5 m/s through vortex excitation, while E-shaped piezoelectric system exhibits improved performance over traditional designs in adjusting to a wider range of wind velocities
[75]	Triboelectric	Cylindrical oscillator	392.72 μW	–	✓	Design and testing	Experimental study	• Average power generated by a wind turbine is 392.72 μW under 2.78 m/s

it is clear that these technologies can provide useful power output that can directly power electronic devices within the building. However, due to the costs, aerodynamic noises, structural issues, and turbulence caused by neighbouring structures, it is also practical to explore different designs and mechanisms for wind energy harvesting systems. Therefore in this study, the micro-scale wind-induced vibrations technologies were also explored to see their potential to provide useful power output. The present study investigated the latest designs and methods of galloping, flutter, and VIV technologies for energy harvesting and power performance, to address existing issues. Specifically, the study examined the potential of micro/small-scale devices that are cost-effective, compact, easy to construct and install, and capable of operating at low wind speeds, thereby making them suitable for use in rural communities with poorly constructed buildings. However, there is a lack of research on the integrated design of small-scale wind-induced vibration and building structure, which makes it impossible to conduct a comparative analysis of different designs. Most of the available studies only focus on stand-alone wind-induced vibrations that have been evaluated in wind tunnels or analysed using numerical simulations.

Recent advances in stand-alone wind-induced vibration have demonstrated the viability of micro/small-scale wind-induced vibration technologies for powering small-scale devices such as wireless sensor nodes, LED lights, smart building systems, and HVAC monitoring devices. Through a comparative analysis of three different mechanisms of wind-induced vibration systems, it was found that the aerofoil flutter design yielded the highest power output of 120 mW at wind speeds of 14 m/s-1. This result clearly indicates a positive correlation between power output and wind velocity and suggests that the design is effective across a wider range of wind velocities. To conduct a thorough evaluation of the three different wind induced vibration systems, a critical analysis should be performed under similar external conditions to compare their harvesting and power performance. It should be noted that although the cylinder-shaped structure based on VIV mechanism produced the lowest power output, ranging from 0.8 nW to 1.6 nW at wind speeds from 0.8 m/s to 6.4 m/s, this does not necessarily imply that the design is better than the galloping or VIV mechanisms.

Overall, this study demonstrated significant potential for providing cost-effective power to off-grid communities due to the harvester's simple structure and easy integration with wireless sensors, LED lights, and other electronic devices. As more research is conducted on small-scale wind induced vibration and self-powered electronic devices, it is expected that wind-induced vibration technology will be deployed on a larger scale with appropriate designs. The installation of wind energy harvesting systems on roof building structures offers several advantages, such as delivering power generation closer to users, improving energy efficiency, reducing carbon footprint, and reducing reliance on energy companies and diesel generators. Additionally, decentralising power supply can lower power transmission costs.

In future studies, it is suggested to investigate the effects of wind direction and accelerated wind velocity, as well as the optimal location for installing wind-induced vibration technology on building structures for energy harvesting. This is expected to enhance the power output of the harvester, there are several methods that can be employed, including increasing the harvester's scale, incorporating wind energy harvesting technology into roof building structures to increase wind velocity, and adding power management devices. Moreover, the analysis will provide a more comprehensive understanding of the physical structure of the energy harvester, which can be optimised for a wide range of wind velocities and various atmospheric boundary layer conditions suitable for wind-induced vibration mechanisms. Additionally, it is crucial to conduct economic and environmental analyses of these technologies, including operational performance, construction, and maintenance costs. Such considerations are crucial for the overall development of wind energy harvesting technology.

CRediT authorship contribution statement

Katrina Calautit: Conceptualization, Methodology, Writing – original draft. **Cameron Johnstone:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] International Energy Agency, Population without access to electricity falls below 1 billion, IEA, Paris, 2018 (Accessed at: https://www.iea.org/commentaries/population-without-access-to-electricity-falls-below-1-billion [Accessed: 10-Jan-2022].
[2] Perera SMHD, Putrus G, Conlon M, Narayana M, Sunderland K. Wind Energy harvesting and conversion systems: a technical review. Energies 2022;15(24):9299.
[3] Joaquim A, Fábio M. Small scale wind energy harvesting with maximum power tracking. AIMS Energy 2015;2(3):297–315.
[4] Wen Q, He X, Lu Z, Streiter R, Otto T. A comprehensive review of miniatured wind energy harvesters. Nano Mater Sci 2021;3(2):170–85.
[5] Abohela I, Hamza N, Dudek S, Roof Mounted wind turbines: A methodology for assessing potential roof mounting locations, 2013.
[6] Verma N, Baloni BD. Influence of Reynolds number on the performance of small horizontal axis wind turbine with fixed speed operation. Energy Sources Part A 2022;44:4016–31.
[7] Yin R, Xie J-B, Yao Ji, Bontempo R. Optimal design and aerodynamic performance prediction of a horizontal axis small-scale wind turbine. Math Probl Eng 2022;2022:1–19.
[8] Kuang L, Su J, Chen Y, Han Z, Zhou D, Zhang K, et al. Wind-capture-accelerate device for performance improvement of vertical-axis wind turbines: External diffuser system. Energy 2022;239:122196.
[9] Emejeamara FC, Tomlin AS. A method for estimating the potential power available to building mounted wind turbines within turbulent urban air flows. Renew Energy 2020;153:787–800.
[10] Siddiqui MS, Khalid MH, Zahoor R, Butt FS, Saeed M, Badar AW. A numerical investigation to analyze effect of turbulence and ground clearance on the performance of a roof top vertical–axis wind turbine. Renew Energy 2021;164:978–89.
[11] Mohammed G, Ibrahim A, Mohammed Kangiwa U, Wisdom JB. Design and testing of building integrated hybrid vertical axis wind turbine. J Electr Electron Eng 2021;9(3):69.
[12] Irawan Y, Harianto H. Numerical simulation of the effect of wind velocity on the diffuser augmented wind turbines performance. J Energy Mech Mater Manuf Eng 2019;4(2):pp.
[13] (Energy Follower, 2022) Energy Follower (Accessed at: https://energyfollower.com/types-of-wind-turbines/ [Accessed: 10-Mar-2022].
[14] Kasinadhuni C, Experimental Investigation of Wind Loading on a Ducted Wind Turbine, PhD Thesis, 2022.
[15] Park J, Jung HJ, Lee S-W, Park J. A new building-integrated wind turbine system utilizing the building. Energies 2015;8:11846–70.
[16] Stanciu, MD. The design of a test bench for wind blades bending with small dimension. 2015.
[17] Sugathapala TM, Boteju S, Withanage PB, Wijewardane S. Aerodynamic modeling of simplified wind turbine rotors targeting small-scale applications in Sri Lanka. Energy Sustain Dev 2020;59:71–82.
[18] Abdelsalam AM, El-Askary WA, Kotb MA, Sakr IM. Experimental study on small scale horizontal axis wind turbine of analytically-optimized blade with linearized chord twist angle profile. Energy 2021;216:119304.
[19] Lee M, Shiah YC, Bai C. Experiments and numerical simulations of the rotor-blade performance for a small-scale horizontal axis wind turbine. J Wind Eng Ind Aerodyn 2016;149:17–29.
[20] Rahgozar S, Pourrajabian A, Kazmi SAA, Kazmi SMR. Performance analysis of a small horizontal axis wind turbine under the use of linear/nonlinear distributions for the chord and twist angle. Energy Sustain Dev 2020;58:42–9.
[21] Pourrajabian A, Nazmi Afshar PA, Ahmadizadeh M, Wood D. Aero-structural design and optimization of a small wind turbine blade. Renew Energy 2016;87:837–48.
[22] Gupta RK, Warudkar V, Purohit R, Singh Rajpurohit S. Modeling and aerodynamic analysis of small scale, mixed airfoil horizontal axis wind turbine blade. Mater Today: Proc 2017;4(4):5370–84.
[23] Hasan M, El-Shahat A, Rahman M. Performance investigation of three combined airfoils bladed small scale horizontal axis wind turbine by BEM and CFD analysis. J Power Energy Eng 2017;05(05):14–27.
[24] Muhsen H, Al-Kouz W, Khan W. Small wind turbine blade design and optimization. Symmetry 2019;12(1):18.
[25] Pholdee N, Bureerat S, Nuantong W. Kriging surrogate-based genetic algorithm optimization for blade design of a horizontal Axis Wind turbine. Comput Model Eng Sci 2021;126(1):261–73.
[26] Maheri A. Multiobjective optimisation and integrated design of wind turbine blades using WTBM-ANSYS for high fidelity structural analysis. Renew Energy 2020;145:814–34.
[27] Shen X, Yang H, Chen J, Zhu X, Du Z. Aerodynamic shape optimization of non-straight small wind turbine blades. Energ Conver Manage 2016;119:266–78.
[28] Singh R, Ahmed M, R.,. Blade design and performance testing of a small wind turbine rotor for low wind speed applications. Renew Energy 2013;50:812–9.
[29] Arumugam P, Ramalingam V, Bhaganagar K. A pathway towards sustainable development of small capacity horizontal axis wind turbines – Identification of influencing design parameters & their role on performance analysis. Sustainable Energy Technol Assess 2021;44:101019.
[30] Volkmer K, Kaufmann N, Carolus T. Mitigation of the aerodynamic noise of small axial wind turbines - methods and experimental validation. J Sound Vib 2021;500:116027.
[31] Ghorani M, M., Karimi, B., Mirghavami, S., M., Saboohi, Z.,. A numerical study on the feasibility of electricity production using an optimized wind delivery system (Invelox) integrated with a Horizontal axis wind turbine (HAWT). Energy 2023;268:126643.
[32] Dar AS, Armengol Barcos G, Porté-Agel F. An experimental investigation of a roof-mounted horizontal-axis wind turbine in an idealized urban environment. Renew Energy 2022;193:1049–61.
[33] Ali MH. Experimental comparison study for savonius wind turbine of two & three blades at low wind speed. Int J Mod Eng Res (IJMER) 2013;3(5):2978–86.
[34] Windside, https://windside.com/products/ws-4/ [Accessed on January 2023].
[35] Ragheb M, Vertical Axis Wind Turbines, 2015.
[36] Kumara EAD, Hettiarachchi N, Jayathilake R. Review Paper: overview of the vertical axis wind turbines. Int J Sci Res Innov Technol 2017;4:2313–3759.
[37] Li S, Li Ye, Yang C, Wang Q, Zhao B, Li D, et al. Experimental investigation of solidity and other characteristics on dual vertical axis wind turbines in an urban environment. Energ Conver Manage 2021;229:113689.
[38] Jooss Y, Rønning EB, Hearst RJ, Bracchi T. Influence of position and wind direction on the performance of a roof mounted vertical axis wind turbine. J Wind Eng Ind Aerodyn 2022;230:105177.
[39] Xu W, Li G, Zheng X, Li Y, Li S, Zhang C, et al. High-resolution numerical simulation of the performance of vertical axis wind turbines in urban area: Part I, wind turbines on the side of single building. Renew Energy 2021;177:461–74.
[40] Zamre P, Lutz T. CFD analysis of a Darrieus Vertical-Axis Wind turbine installation on the rooftop of a buildings under turbulent inflow conditions. Wind Energy Sci 2021.
[41] Allard MA. Performance and wake analysis of a darrieus wind turbine on the roof of a building using CFD. Concordia University; 2020. Masters thesis.
[42] Allard MA, Paraschivoiu M. Power enhancement CFD based study of Darius wind turbine via roof corner placement. J Renewable Sustainable Energy 2022;14:033301.
[43] Chen TY, Hung CW, Liao YT. Experimental study on aerodynamics of micro-wind turbines with large-tip non-twisted blades. J Mech 2013;29(3):N15–20.
[44] Chong WT, Yip SY, Fazlizan A, Poh SC, Hew WP, Tan EP, et al. Design of an exhaust air energy recovery wind turbine generator for energy conservation in commercial buildings. Renew Energy 2014;67:252–6.
[45] Sridhar S, Zuber M, B. SS, Kumar A, Ng EYK, Radhakrishnan J. Aerodynamic comparison of slotted and non-slotted diffuser casings for Diffuser Augmented Wind Turbines (DAWT). Renew Sustain Energy Rev 2022;161:112316.
[46] Krishnan A, Paraschivoiu M. 3D analysis of building mounted VAWT with diffuser shaped shroud. Sustain Cities Soc 2016;27:160–6.
[47] Bhakare A, Ranka P, Telkapalliwar A. Design and analysis of ducted wind turbine for rooftop installation. Thesis 2018.
[48] Agha A, The integration of Diffuser Augmented Wind Turbines (DAWT) into the built environment. *Doctoral Thesis*, 2018.
[49] Dilimulati A, Stathopoulos T, Paraschivoiu M. Wind turbine designs for urban applications: A case study of shrouded diffuser casing for turbines. J Wind Eng Ind Aerodyn 2018;175:179–92.
[50] Abu-Thuraia H, Aygun C, Paraschivoiu M, Allard MA. Computational fluid dynamic analysis of roof-mounted vertical-axis wind turbine with diffuser shroud, flange, and vanes. Trans Can Soc Mech Eng 2018;42(4):404–15.
[51] Chong W-T, Muzammil WK, Wong K-H, Wang C-T, Gwani M, Chu Y-J, et al. Cross axis wind turbine: Pushing the limit of wind turbine technology with complementary design. Appl Energy 2017;207:78–95.
[52] Chong WT, Wang XH, Wong KH, Mojumder JC, Poh SC, Saw LH, Lai SH. Performance assessment of a hybrid solar-wind-rain eco-roof system for buildings. Energ Buildings 2016;127:1028–42.
[53] Moreno-Armendáriz MA, Duchanoy CA, Calvo H, Ibarra-Ontiveros E, Salcedo-Castañeda JS, Ayala-Canseco M, et al. Wind Booster Optimization for On-Site Energy Generation Using Vertical-Axis Wind Turbines. Sensors 2021;21(14):4775.
[54] Wang W, Huang J, Yao Z. Cut-corner prism piezoelectric energy harvester based on galloping enhancement mechanism. Energy Rep 2021;7:6366–74.
[55] Yang Y, Zhao L, Tang L. Comparative study of tip cross-sections for efficient galloping energy harvesting. Appl Phys Lett 2013;102:064105.
[56] Zhao D, Hu X, Tan T, Yan Z, Zhang W. Piezoelectric galloping energy harvesting enhanced by topological equivalent aerodynamic design. Energ Conver Manage 2020;222:113260.
[57] Le D, Kwon SD. Design and experiments of a galloping-based wind energy harvester using quadruple Halbach arrays. Energies 2021;14:6094.
[58] Zhang LB, Dai HL, Abdelkefi A, Lin SX, Wang L. Theoretical modeling, wind tunnel measurements, and realistic environment testing of galloping-based electromagnetic energy harvesters. Appl Energy 2019;254:113737.
[59] Lim YY, Padilla RV, Unger A, Barraza R, Thabet AM, Izadgoshasb I. A self-tunable wind energy harvester utilising a piezoelectric cantilever beam with bluff body under transverse galloping for field deployment. Energ Conver Manage 2021;245:114559.
[60] Chawdhury S, Morgenthal G. Numerical simulations of aeroelastic instabilities to optimize the performance of flutter-based electromagnetic energy harvesters. J Intell Mater Syst Struct 2018;29(4):479–95.

[61] Aquino A, Calautit JK, Hughes B. Urban integration of aeroelastic belt for low-energy wind harvesting. Energy Procedia 2017;105:738–43.
[62] Aquino A, Calautit J, Hughes B. Integration of aero-elastic belt into the built environment for low-energy wind harnessing: Current status and a case study. Energ Conver Manage 2017;149:830–50.
[63] Aquino A, Calautit J, Hughes B. A study on the wind-induced flutter energy harvester (WIFEH) integration into buildings. Energy Procedia 2017;142:321–7.
[64] Aquino AI, Calautit JK, Hughes BR. Evaluation of the integration of the Wind-Induced Flutter Energy Harvester (WIFEH) into the built environment: Experimental and numerical analysis. Appl Energy 2017;207:61–77.
[65] Zhang C, He XF, Li SY, Cheng YQ, Rao Y. A wind energy powered wireless temperature sensor node. Sensors 2015;15:5020–31.
[66] Shan X, Tian H, Cao H, Feng J, Xie T. Experimental investigation on a novel airfoil-based piezoelectric energy harvester for aeroelastic vibration. Micromachines 2020;11:725.
[67] Bo F, Jiwen F, Jiuchun Z, Chong L, Jia W, Mingming L. Bionic flutter w, ing piezoelectric-electromagnetic composite energy harvesting system. Energ Conver Manage 2022;271:116319.
[68] Ramírez JM. A coupled formulation of fluid-structure interaction and piezoelectricity for modeling multi-body energy harvester from vortex-induced vibrations. Energ Conver Manage 2021;249:114852.
[69] De Sousa VC, Junior DC. Airfoil-based piezoelectric energy harvesting by exploiting the pseudoelastic hysteresis of shape memory alloy springs. Smart Mater Struct 2015;24(12):pp.
[70] Perez M, Boisseau S, Gasnier P, Willemin J, Reboud JL. An electret-based aeroelastic flutter energy harvester. Smart Mater Struct 2015;24:035004.
[71] Pang Y, Cao Y, Derakhshani M, Fang Y, Wang Z, Cao C. Hybrid Energy-Harvesting Systems Based on Triboelectric Nanogenerators. Matter 2021;4(1):116–43.
[72] Lee YJ, Qi Y, Zhou G, Lua KB. Vortex-induced vibration wind energy harvesting by piezoelectric MEMS device in formation. Sci Rep 2019;9(20404):pp.
[73] Jin Z, Li G, Wang J, Zhang Z. Design, Modeling, and experiments of the vortex-induced vibration piezoelectric energy harvester with bionic attachments. Complexity 2019:13.
[74] Hu Y, Yang B, Chen X, Wang X, Liu J. Modeling and experimental study of a piezoelectric energy harvester from vortex shedding-induced vibration. Energ Conver Manage 2018;162:145–58.
[75] Zhang L, Meng B, Tian Y, Meng X, Lin X, He Y, et al. Vortex-induced vibration triboelectric nanogenerator for low speed wind energy harvesting. Nano Energy 2022;95:107029.
[76] Vortex Bladeless, 2022, (Accessed at: https://vortexbladeless.com/technology/ [Accessed: 10-May-2022].
[77] Hemida H, Šarkić Glumac A, Vita G, Kostadinović Vranešević K, Höffer R. On the flow over high-rise building for wind energy harvesting: an experimental investigation of wind speed and surface pressure. Appl Sci 2020;10:5283.
[78] Navas Raja Mohamed KB, Prakash S, A systematic review on wind energy resources forecasting by neural network. In: *Proceedings of the 2020 5th IEEE international conference on recent advances and innovations in engineering, Institute of Electrical and Electronics Engineers Inc*, 2020.
[79] Wu Z, Luo G, Yang Z, Guo Y, Li K, Xue Y. A comprehensive review on deep learning approaches in wind forecasting applications. CAAI Trans Intell Technol 2022;7(2):129–43.
[80] Wang J, Zhou S, Zhang Z, Yurchenko D. High-performance piezoelectric wind energy harvester with Y-shaped attachments. Energ Conver Manage 2019;181: 645–52.
[81] Zhao L, Yang Y. On the modeling methods of small-scale piezoelectric wind energy harvesting. Smart Struct Syst 2017;19(1).
[82] Calautit K, Aquino A, Calautit JK, Nejat P, Jomehzadeh F, Hughes BR. A review of numerical modelling of multi-scale wind turbines and their environment. Computation 2018;6(1):24.
[83] Lu L, Sun K. Wind power evaluation and utilization over a reference high-rise building in urban area. Energ Build 2014;68(Part A):339–50.
[84] Weekes SM. Small-scale wind energy: methods for wind resource assessment. Integrated Doctoral and Master thesis. University of Leeds; 2014.
[85] Millward-Hopkins JT. Predicting the wind resource available to roof-mounted wind turbines in urban areas. Doctoral Thesis. University of Leeds; 2013.
[86] Bashirzadeh A, Whale J, Lyon T, Urmee T. Performance and safety of rooftop wind turbines: Use of CFD to gain insight into inflow conditions. Renew Energy 2013;67.
[87] Arteaga-López E, Ángeles-Camacho C, Bañuelos-Ruedas F. Advanced methodology for feasibility studies on building-mounted wind turbines installation in urban environment: Applying CFD analysis. Energy 2019;167: 181–8.
[88] Heo Y, G., Choi, N., K., Choi, K., H., Ji, H., S., Kim, K., C.,. CFD study on aerodynamic power output of a 110 kW building augmented wind turbine. Energ Buildings 2016;129:162–73.
[89] Tabrizi AB, Whale J, Lyons T, Urmee T. Performance and safety of rooftop wind turbines: Use of CFD to gain insight into inflow conditions. Renew Energy 2014; 67:242–51.
[90] Larin P, Paraschivoiu M, Aygun C. CFD based synergistic analysis of wind turbines for roof mounted integration. J Wind Eng Ind Aerodyn 2016;156:1–13.
[91] Elbakheit AR. Effect of turbine resistance and positioning on performance of Aerofoil wing building augmented wind energy generation. Energ Build 2018; 174:365–71.
[92] Bayoumi M, Fink D, Hausladen G. Extending the feasibility of high-rise façade augmented wind turbines. Energ Build 2013;60:12–9.
[93] Chaudhry HN, Calautit JKS, Hughes BR. The influence of structural morphology on the efficiency of building integrated wind turbines (BIWT). AIMS Energy 2014; 2:219–36.
[94] Petković D, Shamshirband S, Ćojbašić Z, Nikolić V, Anuar NB, Sabri AQM, Akib S. Adaptive neuro-fuzzy estimation of building augmentation of wind turbine power. Comput Fluids 2014;97:188–94.
[95] Toja-Silva F, Peralta C, Lopez-Garcia O, Navarro J, Cruz I. Roof region dependent wind potential assessment with different RANS turbulence models. J Wind Eng Ind Aerodyn 2015;142:258–71.
[96] Wang B, Cot LD, Adolphe L, Geoffroy S, Morchain J. Estimation of wind energy over roof of two perpendicular buildings. Energ Buildings 2015;88:57–67.
[97] Veena K, Asha V, Shameem CA, Venkatesh TN. CFD analysis for siting of wind turbines on high-rise buildings. J Phys Conf Ser 2017;822:012013.
[98] Kono T, Kogaki T, Kiwata T. Numerical investigation of wind conditions for roof-mounted wind turbines: effects of wind direction and horizontal aspect ratio of a high-rise cuboid building. Energies 2016;9(11):907.
[99] Nishimura A, Ito T, Murata J, Ando T, Kamada Y, Hirota M, et al. Wind turbine power output assessment in built environment. Smart Grid Renew Energy 2013;4: 1–10.
[100] Sun H, Miniature wind energy harvesters. *University of Southampton*, *Doctoral Thesis*, 2017.
[101] Aljadiri RT, Modelling and design of electrostatic based wind energy harvester. *Doctoral Thesis*, 2014.