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Development of A Small Wind Energy System for Multi-Storied Buildings: A Review of Recent Advances, Challenges and Future Perspectives

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ABSTRACT

The increasing demand for electricity in densely populated urban areas has created a need for decentralized renewable-energy technologies that can be integrated into buildings. Small wind energy systems represent a potential supplementary source of electricity for multi-storied buildings, particularly where rooftop and façade-level wind resources can be effectively exploited. However, the wind environment around buildings is substantially different from that of open terrain. Building geometry, surrounding structures, atmospheric boundary-layer effects, flow separation, recirculation, turbulence, wind-direction variability, and rooftop-edge effects can significantly influence turbine performance. This review examines the development of small wind energy systems for multi-storied buildings, with particular emphasis on urban wind-resource assessment, turbine selection, aerodynamic design, building–turbine interaction, computational fluid dynamics (CFD), structural considerations, electrical integration, energy storage, economic feasibility, and environmental constraints. Horizontal-axis wind turbines (HAWTs), vertical-axis wind turbines (VAWTs), Savonius and Darrieus configurations, hybrid turbines, and building-integrated concepts are compared from the perspective of urban applications. The literature indicates that VAWTs can offer advantages in highly variable and multidirectional urban winds, while carefully positioned HAWTs can achieve higher aerodynamic efficiency under suitable flow conditions. Accurate site-specific wind assessment using field measurements, CFD, wind-tunnel testing, and statistical modelling is essential because relatively small errors in wind-speed estimation can produce substantial errors in predicted energy production. The review further identifies the importance of structural vibration, noise, safety, maintenance, power electronics, battery storage, and grid interaction. A conceptual framework for developing a small wind energy system for multi-storied buildings is proposed. Future research should focus on validated urban wind maps, low-speed turbine optimization, building-integrated designs, hybrid solar–wind systems, intelligent control, digital twins, and long-term field testing. The review concludes that small wind systems should generally be considered as complementary rather than standalone energy sources for multi-storied buildings, with successful deployment depending primarily on appropriate site selection and integration with the building structure and electrical system.

KEYWORDS: Small wind turbine; multi-storied building; urban wind energy; vertical-axis wind turbine; rooftop wind turbine; CFD; renewable energy; building-integrated renewable energy; wind resource assessment.

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1. INTRODUCTION

Rapid urbanization, population growth, and the increasing use of electrical and electronic equipment have significantly increased electricity consumption in buildings. At the same time, concerns regarding greenhouse-gas emissions, fossil-fuel dependence, energy security, and climate change have encouraged the integration of renewable-energy technologies into the built environment. Although solar photovoltaic (PV) systems are increasingly common on building rooftops, the potential of urban wind energy has received comparatively less attention.

Wind energy is an established renewable-energy technology with increasing global deployment. However, the performance and economics of utility-scale wind turbines cannot be directly applied to small turbines installed on buildings. In urban environments, wind flow is strongly influenced by buildings, streets, vegetation, terrain roughness, and surrounding obstacles. As a result, wind conditions around multi-storied buildings can be highly turbulent, non-uniform, and variable with height and direction [6,10,11].
Multi-storied buildings provide several potential locations for small wind energy systems, including rooftops, roof edges, building corners, façades, and specially designed building structures. Greater building height may provide access to stronger wind resources than those available near ground level. However, higher wind speed alone does not guarantee a suitable turbine location because buildings can also produce flow separation, vortices, turbulence, and rapidly changing wind directions [1–5,14].
Recent research has increasingly investigated vertical-axis wind turbines (VAWTs) for urban and building applications because of their potential to operate under multidirectional wind conditions and their suitability for integration with buildings [20–27]. Studies have also examined aerodynamic building modifications, such as Venturi-shaped roofs, to accelerate and redirect airflow toward building-integrated turbines [2,15]. These developments indicate a shift from conventional rooftop turbine installation toward integrated building–turbine design.
Urban wind conditions are generally characterized by relatively low and highly turbulent wind speeds, which can reduce energy production and increase mechanical loading and fatigue. Therefore, the development of a small wind energy system for multi-storied buildings requires an interdisciplinary approach involving wind-resource assessment, aerodynamics, turbine design, structural engineering, electrical energy conversion, architecture, and energy management [1,3,6,8,9].
Accordingly, this review aims to critically examine recent research on small wind energy systems for multi-storey buildings, with particular emphasis on urban wind characteristics, turbine selection, building geometry, turbine placement, CFD and experimental analysis, structural and electrical considerations, economic feasibility, environmental impacts, and future development opportunities.

2. METHODOLOGY

This review adopts a thematic and systematic literature-review approach to examine recent developments in small wind energy systems for multi-storied buildings. The review focuses on key areas including urban wind characteristics, building-integrated wind turbines (BIWTs), vertical-axis wind turbines (VAWTs), horizontal-axis wind turbines (HAWTs), wind-resource assessment, computational fluid dynamics (CFD), aerodynamic optimization, structural safety, energy conversion, economic feasibility, and environmental considerations.
The primary focus is on recent research published between 2022 and 2026, while selected earlier studies are included to provide essential theoretical and methodological foundations. The literature is organized according to the major technological and design aspects of building-mounted wind energy systems.
Particular attention is given to studies investigating rooftop turbine performance, building geometry, turbine location, turbulence effects, CFD-based wind-flow analysis, VAWT aerodynamic performance, hybrid turbine configurations, and building–turbine integration [1–10]. Recent research also demonstrates increasing interest in optimizing building geometry, such as Venturi-shaped roofs, to improve local wind conditions and turbine performance [2,15].
The reviewed studies are comparatively analyzed based on their research objectives, turbine configurations, methodologies, wind conditions, building characteristics, aerodynamic performance, structural considerations, energy output, and economic feasibility. This thematic comparison helps identify the strengths and limitations of existing approaches and highlights the factors that influence the practical application of small wind turbines in urban buildings.
Finally, the review synthesizes the findings to identify major research gaps and future development opportunities. Particular emphasis is placed on the need for integrated approaches combining wind-resource assessment, CFD and experimental validation, turbine optimization, structural analysis, electrical energy conversion, energy storage, and economic evaluation. Through this approach, the review aims to establish a comprehensive basis for developing an efficient, reliable, and practically feasible small wind energy system for multi-storied buildings.

2.1 Literature Identification and Selection

The literature considered in this review was selected from peer-reviewed journal articles, review papers, and authoritative technical reports dealing with small-scale and urban wind energy. Particular attention was given to studies that directly investigated wind turbines installed on or integrated with buildings. The literature selection emphasized studies addressing one or more of the following topics:

1. Wind Flow Around Multi-storied and High-Rise Buildings;
2. Rooftop Wind-Resource Assessment;
3. Building-Integrated Wind Turbines;
4. Small-Scale Hawts and Vawts;
5. Savonius, Darrieus, H-Type and Helical Vawts;
6. Hybrid Darrieus–Savonius Systems;
7. CFD-Based Urban Wind-Flow Analysis;

8. Large-Eddy Simulation (Les);
9. Wind-Tunnel Experiments;
10. Turbine Positioning and Roof Geometry;
11. Venturi-Shaped and Aerodynamically Optimized Roofs;
12. Turbine Performance Under Turbulent and Low-Speed Wind;
13. Structural Loading and Vibration;
14. Electrical Energy Conversion;
15. Battery and Hybrid Renewable-Energy Systems;
16. Economic Feasibility and Payback Period;
17. Environmental Effects and Occupant Acceptance; and
18. Future Building-Integrated Renewable-Energy Technologies.

Recent studies were given greater importance because the objective of the review is to understand the **current state of development** of small wind systems for buildings. For example, recent research has investigated rooftop VAWTs through combined CFD and experimental approaches [1], optimized Venturi-shaped roofs for building-integrated turbines [2], and examined wind loads associated with VAWTs integrated with high-rise buildings [3].

2.2 Thematic Classification of the Literature

After the literature was identified, the selected studies were classified into ten major research themes. This classification enables comparison between aerodynamic, structural, energy, economic, and architectural aspects of building-mounted wind systems. The ten major themes are:

1. Urban wind characteristics and building aerodynamics;
2. Wind-resource assessment and measurement;
3. Small wind turbine technologies;
4. Comparison of HAWT and VAWT technologies;
5. Building geometry and turbine siting;
6. CFD and wind-tunnel modelling;
7. Structural, vibration, and safety considerations;
8. Electrical energy conversion and energy storage;
9. Economic, environmental, and social considerations; and
10. Future development of building-integrated wind energy systems.

This thematic structure makes it possible to evaluate the technology from the perspective of the complete energy system rather than considering turbine aerodynamics alone.

2.3 Theme 1: Urban Wind Characteristics

The first theme examines the characteristics of wind flow in urban and built environments. Unlike open-terrain wind farms, urban wind is strongly affected by buildings, roads, vegetation, roof structures, and neighboring buildings. The reviewed literature considers:

1. Mean Wind Velocity;
2. Wind-Direction Distribution;
3. Atmospheric Boundary-Layer Effects;
4. Turbulence Intensity;
5. Flow Separation;
6. Flow Acceleration;
7. Recirculation;
8. Vortex Shedding;
9. Wake Formation; and
10. Interaction Between Adjacent Buildings.

These factors are particularly important for multi-storied buildings because wind conditions can vary significantly between the lower façade, upper façade, roof center, roof edge, and roof corner. A location with a high instantaneous wind velocity may not necessarily provide the highest annual energy yield if it is associated with excessive turbulence or unfavorable flow separation. Recent studies have therefore emphasized detailed assessment of building-scale wind fields rather than relying only on regional meteorological data [6,10,11,14]. The review particularly considers research that investigates how building height, roof shape, surrounding structures, and wind direction influence turbine inflow.

2.4 Theme 2: Wind-Resource Assessment

Wind-resource assessment is considered a fundamental step in determining the feasibility of a building-mounted wind turbine. The theoretical wind power available to a turbine can be expressed as:

$$P_w = \frac{1}{2}\rho A V^3$$

where Pw is the available wind power, ρ is air density, A is the swept area, and V is wind velocity. Because available power varies with the **cube of wind velocity**, accurate estimation of local wind speed is extremely important. A relatively small error in predicted wind speed can result in a significant error in estimated energy production. The reviewed studies therefore consider different wind-resource assessment techniques, including:

1. Meteorological Data Analysis;
2. On-Site Anemometer Measurements;
3. Wind-Direction Measurements;
4. Rooftop Measurements;
5. Wind-Tunnel Testing;
6. CFD Simulations;
7. Statistical Wind-Distribution Analysis; and
8. Long-Term Wind-Resource Extrapolation.

Recent research on wind-resource potential at different urban heights demonstrates the importance of considering vertical variations in wind conditions [14]. Similarly, CFD-based approaches have become increasingly important for estimating wind conditions at locations where direct measurements are unavailable [11]. The review therefore considers wind-resource assessment not simply as a preliminary activity but as an integral component of turbine design and siting.

2.5 Theme 3: Small Wind Turbine Technologies

The third theme examines the development and characteristics of small wind turbines suitable for distributed energy generation. The principal technologies considered are:

1. Small HAWTs;
2. Savonius VAWTs;
3. Darrieus VAWTs;
4. H-type Darrieus turbines;
5. Helical VAWTs;
6. Cycloidal turbines;
7. Hybrid Darrieus–Savonius turbines; and
8. Emerging bladeless and innovative urban wind-energy devices.

Recent studies demonstrate increasing interest in VAWTs for building applications because their vertical rotational axis can simplify integration into rooftops and architectural structures [20–24]. Savonius turbines generally provide good starting torque and relatively simple construction, while Darrieus-based turbines can provide higher aerodynamic efficiency. Hybrid configurations attempt to combine the advantages of both technologies [27]. The review compares these technologies according to:

1. Starting Characteristics;
2. Cut-In Wind Speed;
3. Power Coefficient;
4. Tip-Speed Ratio;
5. Turbulence Tolerance;
6. Noise;
7. Structural Complexity;
8. Maintenance Requirements;
9. Installation Requirements; and
10. Building Integration Potential.

2.6 Theme 4: HAWT and VAWT Comparison

A separate thematic category was established for comparison between HAWTs and VAWTs because turbine selection is a major design decision for multi-storied buildings. HAWTs can provide high aerodynamic efficiency under relatively uniform and directional wind conditions. However, urban environments often contain rapidly changing wind directions and significant turbulence, which can reduce their effectiveness. VAWTs are potentially more suitable where wind direction varies significantly because they can accept wind from multiple directions without conventional yaw mechanisms [6,20,21]. The review does not assume that one technology is universally superior. Instead, turbine selection is treated as a site-specific optimization problem.

2.7 Theme 5: Building Geometry and Turbine Siting

The fifth theme investigates the interaction between building geometry and turbine location. A major development in recent research is the concept that the building itself can be designed to modify the wind field. Rather than simply placing a turbine on an existing roof, researchers are investigating:

1. Venturi-Shaped Roofs;
2. Roof-Edge Acceleration;
3. Aerodynamic Roof Corners;
4. Wind Tunnels;
5. Roof-Mounted Structures;
6. Façade-Integrated Turbines;
7. Building Skins; and
8. Turbine Arrays Between Buildings.

Ye et al. demonstrated the importance of this approach by investigating optimum parameters for a Venturi-shaped roof designed to improve the performance of building-integrated wind turbines [2]. Their work illustrates a transition from **turbine-only optimization** toward **building–turbine co-optimization**. The reviewed studies therefore consider turbine location according to:

$$F = f(V, TI, \theta, P, C_s)$$

where:

1. V = local wind velocity;
2. TI = turbulence intensity;
3. θ = wind direction;
4. P = turbine power output; and
5. Cs = structural constraints.

This approach recognizes that the highest wind speed location is not necessarily the optimum location for long-term energy generation.

2.8 Theme 6: CFD and Wind-Tunnel Modelling

CFD represents one of the most frequently used methodologies in recent urban wind-energy research. It enables researchers to investigate wind flow around complex buildings and evaluate multiple turbine locations without constructing numerous physical prototypes. The general CFD procedure can be summarized as:

Building geometry → Computational domain → Mesh generation → Boundary conditions → Turbulence model → Numerical solution → Validation → Wind-field analysis → Turbine positioning

The reviewed literature includes simulations based on:

1. Reynolds-averaged Navier–Stokes (RANS);
2. k−ϵ turbulence models;
3. k−ω SST;
4. Reynolds stress models; and
5. Large-eddy simulation (LES).

LES is particularly useful for examining highly transient and turbulent urban flows. Recent three-dimensional LES research has investigated VAWT performance under different turbulence levels [12]. However, CFD results are influenced by:

1. Mesh Quality;
2. Computational-Domain Size;
3. Turbulence Model;
4. Inlet Boundary Conditions;
5. Atmospheric Boundary-Layer Representation;
6. Surface Roughness;
7. Building Geometry; and
8. Numerical Convergence.

Consequently, CFD should ideally be validated through wind-tunnel experiments or field measurements. Recent experimental and CFD research on rooftop VAWTs demonstrates the value of combining numerical prediction with physical testing [1]. Wind-tunnel experiments provide an additional means of investigating velocity profiles, turbulence, pressure distribution, aerodynamic forces, and turbine performance.

2.9 Theme 7: Structural, Vibration, and Safety Considerations

The installation of a wind turbine on a multi-storied building creates mechanical and structural interactions that must be evaluated during system development. The review considers:

1. Static Loading;
2. Dynamic Loading;
3. Wind-Induced Vibration;
4. Fatigue;
5. Rotor Imbalance;
6. Support-Structure Deformation;
7. Natural Frequency;
8. Resonance;
9. Extreme Wind Conditions; and
10. Turbine–Building Interaction.

The turbine support must withstand not only the weight of the turbine but also aerodynamic forces generated by wind. A critical consideration is the relationship between the natural frequency of the support structure and the turbine excitation frequency. Resonance should be avoided because it can result in excessive vibration and fatigue. Recent research on high-rise buildings with integrated VAWTs demonstrates the increasing importance of investigating wind loads and turbine–building interactions together [3]. Therefore, structural design should be considered simultaneously with aerodynamic optimization rather than being treated as a separate post-design activity.

2.10 Theme 8: Electrical Energy Conversion and Storage

The eighth theme examines the conversion of mechanical turbine power into useful electrical energy. A typical building-mounted small wind system consists of:

Wind → Rotor → Shaft → Generator → Rectifier → DC/DC Converter → Battery/DC Bus → Inverter → Building Load/Grid

The review considers different generator and power-electronic configurations, including permanent-magnet generators and variable-speed conversion systems. The electrical subsystem should maintain efficient operation under variable wind conditions. Maximum-power-point tracking (MPPT) can be employed to adjust the electrical operating point of the generator according to the available wind energy. Energy storage is also considered because urban wind generation is intermittent. Batteries can improve:

1. Self-Consumption;
2. Power Stability;
3. Renewable-Energy Utilization;
4. Supply Reliability; and
5. Grid Interaction.

Recent urban positive-energy-district research increasingly considers wind energy together with solar PV, energy storage, and smart energy-management systems [37].

2.11 Theme 9: Economic, Environmental, and Social Considerations

Technical performance alone cannot determine whether a building-mounted wind system is practically viable. The economic analysis considers:

1. Initial Capital Cost;
2. Turbine Cost;
3. Generator Cost;
4. Support Structure;
5. Installation;
6. Electrical Equipment;
7. Battery Cost;
8. Maintenance;
9. Replacement Cost;
10. Annual Electricity Generation;
11. Electricity Tariff;
12. Payback Period; and

13. Lifecycle Cost.

The simple payback period can be estimated as:

$$PB = \frac{C_0}{S_a}$$

where C_0 is the initial investment and S_a is the annual financial saving.

Recent research has specifically evaluated the payback period of small VAWTs installed on residential buildings [5], while broader studies have examined the energy potential and economic viability of small-scale wind systems [30]. Environmental and social factors were also included in the review. These include:

1. Acoustic Emissions;
2. Visual Impact;
3. Vibration;
4. Bird Interaction;
5. Occupant Comfort;
6. Architectural Compatibility;
7. Maintenance Accessibility; And
8. Public Acceptance.

Recent research has highlighted the importance of human-centered integration and environmental effects when deploying small wind turbines in urban environments [8,9].

2.12 Theme 10: Future Development of Building-Integrated Wind Energy

The final thematic area examines emerging technologies and future research directions. Recent research indicates a transition from conventional rooftop turbines toward more integrated approaches, including:

1. Aerodynamic Building Roofs;
2. Wind-Powered Building Skins;
3. Hybrid VAWTs;
4. Multifunctional Building Structures;
5. Intelligent Turbine Control;
6. Machine-Learning-Assisted Aerodynamic Prediction;
7. Digital-Twin Approaches;
8. Wind–Solar Hybrid Systems;
9. Battery-Integrated Systems; and
10. Positive-Energy Buildings and Districts.

The development of meta-learning approaches for VAWT aerodynamic prediction represents an emerging direction for reducing the computational cost associated with repeated CFD simulations [36]. Similarly, innovative building-integrated systems suggest that future wind turbines may become architectural components rather than independent mechanical devices [7].

2.13 Data Extraction and Comparative Analysis

For each selected study, information was organized according to the following parameters:

1. Publication Year
2. Research Objective
3. Building Type
4. Turbine Type
5. Wind Condition
6. Research Methodology
7. CFD or Experimental Approach
8. Building Geometry
9. Turbine Position
10. Aerodynamic Parameters
11. Performance Indicators
12. Structural Considerations
13. Economic Considerations
14. Environmental Considerations
15. Major Findings
16. Research Limitations
17. Future Research Opportunities

The principal performance parameters considered were:

$$C_p = \frac{P_t}{0.5\rho A V^3}$$

where Cp is the turbine power coefficient. Other important parameters include:

$$\lambda = \frac{\omega R}{V}$$

where λ is the tip-speed ratio, ω is angular velocity, R is rotor radius, and V is wind velocity. Turbulence intensity was considered using:

$$TI = \frac{\sigma_V}{\overline{V}}$$

These parameters allow studies using different turbine configurations and experimental conditions to be compared using common aerodynamic indicators.

2.14 Synthesis of the Literature

The literature synthesis indicates that research on building-mounted wind energy has evolved through several stages.

Stage 1: Turbine feasibility: Early research primarily investigated whether small wind turbines could operate in urban environments.

Stage 2: Urban wind assessment: Research subsequently focused on understanding the complex wind field around buildings and improving resource-assessment techniques.

Stage 3: CFD-based optimization: CFD became increasingly important for evaluating turbine locations and predicting wind-flow characteristics [11,13,15].

Stage 4: VAWT development: Researchers increasingly investigated VAWTs, particularly Darrieus, Savonius, H-type, and hybrid configurations [20–27].

Stage 5: Building–turbine integration: Recent research has moved toward integrating turbines into building geometry, including Venturi-shaped roofs and building skins [2,7].

Stage 6: Integrated renewable-energy systems: The latest research increasingly considers wind turbines together with solar PV, batteries, smart controls, and positive-energy buildings or districts [27,37]. This progression demonstrates that the field is moving from isolated turbine development toward integrated urban renewable-energy system design.

2.15 Methodological Limitations of the Existing Literature

Although the recent literature provides significant advances, several methodological limitations remain.

First, a substantial proportion of studies rely on CFD simulations rather than long-term full-scale measurements. CFD is valuable for design optimization, but uncertainties associated with turbulence models and boundary conditions can affect predicted energy production.

Second, many experimental investigations are conducted under controlled laboratory conditions that may not reproduce the highly variable wind environment of actual cities.

Third, reported turbine performance values are often obtained under different wind speeds, turbulence levels, Reynolds numbers, rotor dimensions, and measurement conditions. Direct comparison of Cp values between studies should therefore be undertaken cautiously.

Fourth, aerodynamic performance is often emphasized more strongly than structural, acoustic, economic, and social performance. A turbine that produces high aerodynamic efficiency may not necessarily be the most suitable solution for a residential or institutional multi-storied building.

Finally, relatively few studies provide long-term simultaneous datasets containing wind speed, turbulence, turbine power, vibration, noise, maintenance requirements, and economic performance. Such integrated field datasets would significantly improve confidence in building-mounted wind-energy technologies.

2.16 Research Framework Derived from the Review

Based on the thematic analysis, a comprehensive development framework for a small wind energy system for multi-storied buildings can be expressed as:

Site Selection

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Long-Term Wind Measurement

↓

Urban Wind-Resource Assessment

↓

3D Building and Surrounding-Environment Modelling

↓

CFD/LES Wind-Flow Analysis

↓

Optimum Turbine Location

↓

HAWT/VAWT Technology Selection

↓

Aerodynamic Optimization

↓

Structural and Vibration Analysis

↓

Prototype Development

↓
Wind-Tunnel/Experimental Validation
↓
Full-Scale Building Installation
↓
Generator and Power-Electronic Integration
↓
Battery/Grid Integration
↓
Long-Term Performance Monitoring
↓
Economic and Environmental Assessment
↓
Optimization and Commercial Deployment

This framework provides a systematic pathway from fundamental wind assessment to practical building-integrated renewable-energy deployment.

3. RESULTS AND DISCUSSION

This review presents a thematic analysis of recent research on small wind energy systems for multi-storiedbuildings, with emphasis on studies published mainly between 2022 and 2026. The literature was organized into key areas including urban wind characteristics, wind-resource assessment, small wind turbine technologies, HAWT and VAWT performance, building geometry and turbine placement, CFD and experimental analysis, structural safety, electrical energy conversion, economic feasibility, and environmental considerations.

Recent studies show that wind conditions around buildings are strongly influenced by building height, roof geometry, surrounding structures, turbulence, and wind direction [1–6]. Therefore, accurate wind-resource assessment using field measurements, CFD, and wind-tunnel testing is essential for selecting suitable turbine locations [11–18].

The review also compares HAWTs and VAWTs, with particular attention to Savonius, Darrieus, H-type, helical, and hybrid configurations. VAWTs are increasingly investigated for urban applications because of their multidirectional wind acceptance and potential for building integration [20–27]. Recent research has also focused on improving turbine performance through blade optimization, hybrid configurations, and improved self-starting characteristics [22–25].

Another major focus is the relationship between building geometry and turbine performance. Studies on Venturi-shaped roofs and building-integrated wind systems indicate that building structures can be designed to accelerate and redirect airflow toward turbines [2,7,15]. CFD and LES techniques are widely used to predict these complex flow patterns and optimize turbine locations [11–18].

Structural and practical considerations are also included, particularly wind loading, vibration, safety, noise, maintenance, and building–turbine interaction [3,18]. In addition, electrical energy conversion, battery storage, and integration with other renewable-energy systems are considered important for improving the reliability and usefulness of building-mounted wind systems.

Finally, the review considers economic feasibility, environmental effects, and social acceptance. Payback period, installation cost, energy production, maintenance, noise, visual impact, and occupant acceptance can significantly influence the practical adoption of rooftop wind turbines [5,8,9,30,38].

Overall, the methodology indicates that the development of an effective small wind energy system for multi-storiedbuildings requires an integrated approach combining wind-resource assessment, aerodynamic optimization, CFD/experimental validation, structural analysis, electrical integration, and economic evaluation. Recent research is moving from conventional rooftop turbine installation toward building–turbine co-design, hybrid systems, intelligent optimization, and positive-energy building applications [1,2,7,27,36,37].

4. CONCLUSION

Overall, the methodology adopted in this review provides a multidisciplinary assessment of small wind energy systems for multi-storied buildings. The literature was systematically organized into aerodynamic, technological, structural, electrical, economic, environmental, and architectural themes.

The reviewed studies demonstrate that urban wind-energy performance cannot be evaluated solely from turbine characteristics. Building geometry, turbine location, turbulence, structural behavior, energy conversion, economics, and occupant acceptance must be considered simultaneously [1–10].

The most significant recent development is the transition toward building–turbine co-design, in which the building geometry itself is optimized to improve wind conditions for the turbine [2,35]. At the same time, advances in VAWT design, CFD/LES, experimental validation, hybrid renewable systems, and intelligent optimization are creating new opportunities for practical deployment [1], [12], [20–42], [44].

Accordingly, the methodology of this review establishes the basis for evaluating not only which turbine produces the most power, but also which complete wind-energy system is most technically, structurally, economically, environmentally, and architecturally appropriate for a multi-storied building.

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