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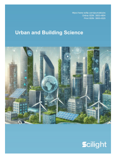

Review

Wind-Driven Triboelectric Nanogenerators: A Critical Review of Research Trends, Structural Principles, and Prospects for the Built Environment

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Abstract: Energy conservation and carbon reduction in the building sector are critical to addressing climate change. This paper presents a building-oriented critical review of wind-driven triboelectric nanogenerators (TENGs), aiming to clarify their research maturity, realistic functional roles, and key limitations in the built environment. Bibliometric analysis reveals a rapid growth of TENG-related studies, with research activity concentrated in East Asia and North America, while work directly connected to architectural applications remains limited. Keyword evolution indicates a shift from fundamental energy-conversion mechanisms toward device optimization and sensing-oriented functions. Based on a structured review, two representative device categories—rotational systems and flutter-based designs—are examined with respect to their operating characteristics and suitability for low-wind building conditions. Reported building-related applications are currently focused on hybrid rooftop harvesting concepts and self-powered sensing components integrated into building systems, particularly for environmental monitoring. However, most demonstrations remain at a laboratory or prototype level, and their architectural integration is constrained by issues including low power output, durability, environmental adaptability, and system-level compatibility. Rather than positioning wind-driven TENGs as near-term power sources for buildings, this review highlights their more realistic short-term potential as supplementary micro-energy units and self-powered sensors, while emphasizing the technical and architectural challenges that must be addressed before broader building adoption can be achieved.

Keywords: triboelectric nanogenerator (TENG); wind energy; smart buildings; hybrid systems; self-powered sensors

1. Introduction

With the rapid development of the global construction industry, the focus of the field is gradually shifting from quantity to quality. In this transition, achieving intelligent and sustainable development in construction has become a critical issue. However, technical challenges such as the deployment of distributed sensors, the construction of sensor networks, and the provision of continuous energy supply still persist. These challenges are directly related to the availability, reliability, and effective utilization of building-generated data, as well as their integration into building design, operation, and management strategies, and are crucial for driving the future development of the construction industry.

In recent years, the rapid advancements in digital technologies such as the Internet of Things (IoT), sensing technologies, cloud computing, and artificial intelligence (AI) have provided new opportunities for the construction sector. The integration of these technologies has not only given rise to computer-aided tools like Building Information Modeling (BIM) for design and construction but has also enabled remote monitoring, management, and intelligent control throughout the design, construction, and maintenance processes [1]. Moreover, advancements in machine learning and deep learning have allowed architects to leverage broader and real-time data feedback to guide construction activities [2]. Despite these advancements, the challenge of providing continuous and stable energy supply for distributed sensors and sensor networks remains a critical technical bottleneck.

To address this issue, significant research efforts have been directed toward the development of innovative energy technologies. In 2012, the concept of the triboelectric nanogenerator (TENG) was first introduced [3], representing a novel technology based on the coupling effects of contact electrification and electrostatic induction, enabling the conversion of mechanical energy into electrical energy. TENG can harvest small-scale environmental energy that is often overlooked, and since its inception, it has garnered widespread attention in the fields of energy harvesting and self-powered sensors [4]. As shown in Figure 1, the working principle of TENG is based on the potential difference generated when two materials with different electronegativities come into contact and separate under external force. During this process, surface charge transfer occurs, driving the movement of charges and generating current [5].

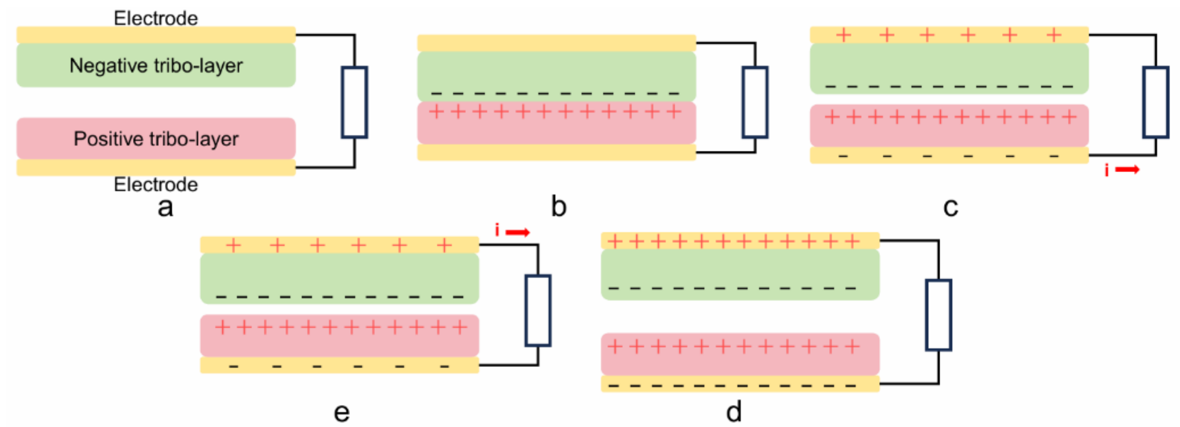

Figure 1. Schematic diagram of the principle of Triboelectric Nanogenerator, based on Ref. [5] . (**a**) Initial state and material layer structure. (**b**) Pressed state. (**c**) Releasing state. (**d**) Released state. (**e**) Pressing state.

Based on this principle, extensive foundational research was conducted on TENG, leading to the development of various applications [6]. Four fundamental theoretical models were proposed for the first time, as illustrated in Figure 2: (a) the contact-separation mode; (b) the lateral-sliding mode; (c) the single-electrode mode; and (d) the freestanding triboelectric-layer mode. These models are designed for different scenarios to harvest various forms of mechanical energy.

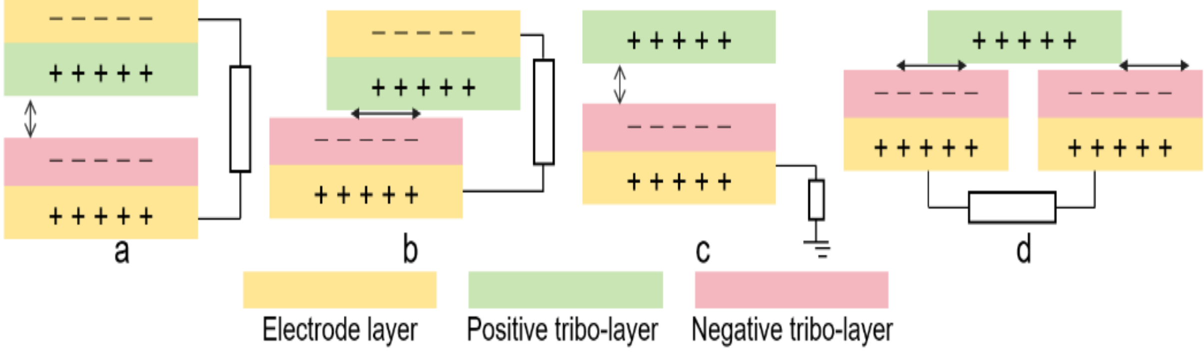

Figure 2. Four common models for TENG, redrawn based on Ref. [7]. (**a**) Contact-separation mode. (**b**) Lateral sliding mode. (**c**) Single electrode mode. (**d**) Freestanding layer mode.

TENGs based on the aforementioned four fundamental modes have been widely applied to collect mechanical energy in various practical scenarios, such as gentle breezes, ocean tides, tire rolling, human and vehicular pressure, and raindrop impacts [8,9]. Overall, TENG demonstrates interdisciplinary and cross-environmental advantages in capturing and utilizing micro-scale energy, particularly in scenarios involving mechanical energy harvesting. It can produce continuous and stable microcurrents, making it highly suitable for diverse applications. Thus, the integration of TENG with various sensor technologies not only exhibits remarkable practical performance but also promises significant potential.

Beyond solar energy, which has reached a relatively mature stage in architectural integration [9], wind energy stands as another clean energy source that is widely applicable to buildings. Wind energy's efficiency, cleanliness, and sustainability make it an ideal energy source for distributed devices and sensors [10,11]. However, current wind energy harvesting in built environments primarily relies on large-scale wind turbines or small wind turbines installed at optimal locations on building rooftops after simulating wind conditions [12,13]. These approaches remain limited in architectural applicability and often struggle to achieve effective energy utilization under complex and fluctuating urban wind environments.

Against this background, wind-driven TENGs have emerged as a potential approach for harvesting micro-scale wind energy within architectural contexts [14]. Therefore, this paper positions itself as a systematic review focused on building-oriented research of wind-driven TENGs. By combining a structured literature review with targeted bibliometric analysis, the study reviews representative device designs and reported building-related application scenarios to clarify research maturity, realistic functional roles, and potential limitations of wind-driven TENGs in the built environment, providing a grounded understanding of their contributions to building systems and highlighting key challenges for broader architectural integration.

2. Research Framework and State of the Art

This paper focuses on the integration of wind energy-driven TENGs with buildings, setting forth the following four core research objectives: (1) Conduct a bibliometric analysis to summarize the current research scope, functional orientation; (2) Identify structural characteristics and operational mechanisms of wind-driven TENGs relevant to buildings; (3) to identify cutting-edge research findings in this field; and (4) Provide a critical assessment grounded in practical realities and explore future development directions. To achieve the aforementioned objectives, this study established the research framework illustrated in Figure 3, with the specific workflow outlined as follows:

First, a systematic literature review was conducted to investigate the research progress in the field of wind energy TENGs. During the literature survey phase, bibliometric and informetric methods were employed to comprehensively analyze wind energy TENGs as the core research topic. A broad-spectrum retrieval strategy was adopted to extensively collect relevant literature from the Web of Science database.

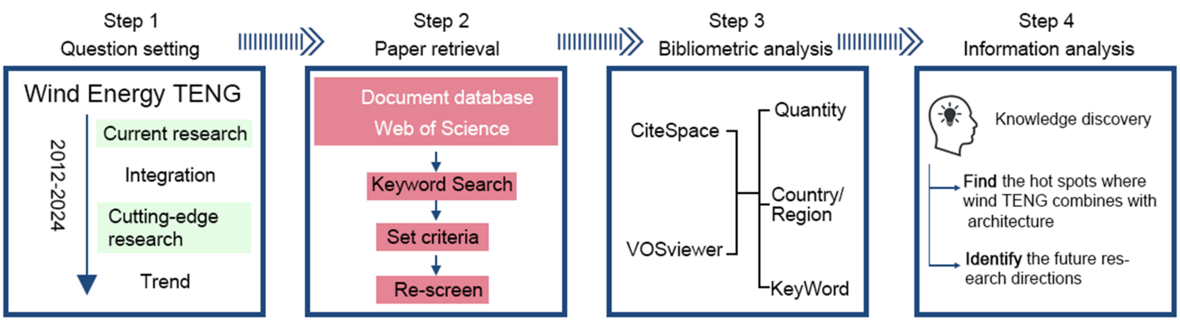

Figure 3. Overview research framework of this paper.

Subsequently, two widely used bibliometric analysis tools, CiteSpace, and VOSviewer were utilized to perform multi-dimensional visual analyses, including annual publication trends and keyword clustering. This approach enables efficient identification of critical information and potential research directions in building energy systems. Through rigorous literature screening, the developmental trends of the field were extracted, thereby providing a comprehensive and in-depth understanding of the current research landscape, potential opportunities, emerging hotspots, and future prospects.

2.1. Data Collection Stage

The data collection phase followed a set of criteria to select relevant papers for this study: (1) The Web of Science, a comprehensive and rigorously curated database, was chosen to ensure a thorough and precise literature analysis; (2) The keyword search strategy for wind energy-driven TENGs is outlined in Table 1, targeting research on the current status of wind energy TENG technology; (3) The search period was set from 2012 to 2024 to comprehensively cover the research progress since the introduction of TENG. Review articles and theses were excluded to avoid redundancy in the retrieved content; (4) Following the search, manual screening was conducted to quickly verify journal titles and article titles, eliminating irrelevant papers resulting from query misinterpretations or ambiguities. Additionally, studies related to the application of wind energy-driven TENGs in the construction sector were specifically identified.

The results of the screening are shown in Table 1, where a total of 429 articles related to wind energy were identified. Of these, 27 articles, accounting for 5.5%, focus on the application of wind energy TENGs in building environments. This highlights the current underrepresentation of wind energy TENG research in the construction industry. These articles were extracted to form our target database for bibliometric analysis, with a particular focus on studies relevant to the application of wind energy-driven TENGs in the field of architecture.

Table 1. keyword search strategies and results of TENG in wind energy from 2012 to 2024.

Concept	Keyword and Phrase	Number of Documents
Research on Wind Energy-Based TENGs	(“TENG” OR “Triboelectric Nanogenerator”) AND (“Wind energy”)	429
Applications of Wind Energy-Based TENGs in Architectural	Articles retrieved from TENG’s research on wind energy were screened	27

2.2. Analysis of Annual Paper Publication Volume

From 2012 to 2024, the number of research publications on wind energy-based TENG has shown a significant growth trend, as illustrated in Figure 4. Over the past decade, the growing interest in this field aligns with the increasing focus on technologies such as green energy and the Internet of Things. This publication trend can be divided into three distinct phases. From 2013 to 2015, the growth was slow, with only 2–4 related publications per year. Beginning in 2016, a first phase of growth occurred, with the number of annual publications increasing to 38 by 2018. After a period of stabilization for two years, a second phase of growth began in 2021, with the number of publications rising to 90 by 2024.

The trendline in Figure 4 clearly shows a rapid and steady increase in the number of publications on wind energy-based TENG, indicating ongoing exploration by researchers into various aspects of TENG’s performance under wind conditions, including its structural design, energy conversion mechanisms, and conversion efficiency. Moreover, the rising trend in research interest has not shown signs of diminishing, suggesting that TENG holds substantial potential for wind energy harvesting and warrants further attention from researchers.

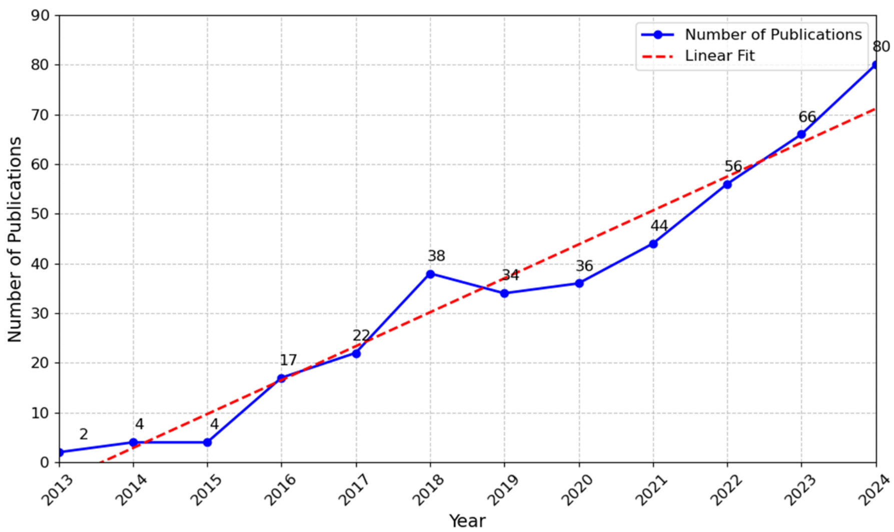

Figure 4. Variation of publication number per year during January 2013–December 2024: topic about wind energy-based TENG.

2.3. Geographical Distribution of Publications

From the perspective of countries and regions, Figure 5 illustrates the distribution of publications in this field. Clearly, China, South Korea, the United States, Singapore, and the United Kingdom are the top five contributors, with China in particular leading in the number of publications, indicating that China is at the forefront of research on wind energy TENG.

To further explore international collaboration, an optimal co-authorship network was constructed based on a minimum citation threshold of four for each country/region. In this network, the thickness of the links represents the strength of collaboration between two countries or regions. As shown in Figure 5, the strongest collaborative link is between China and the United States, suggesting that these two countries possess substantial potential for cooperation in this field.

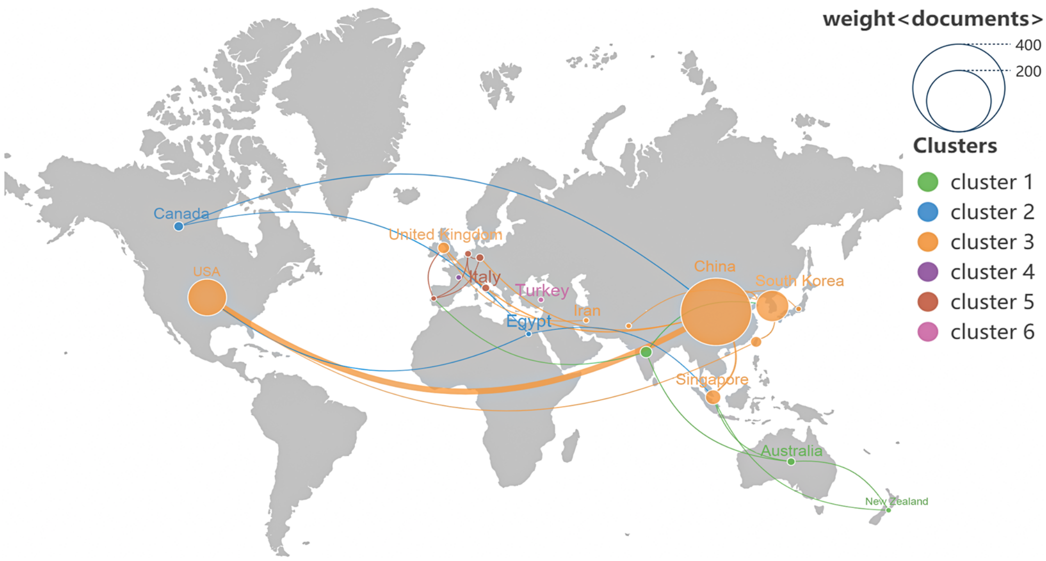

Figure 5. Geographical map of publication volume and collaborative relationships between Countries/Regions.

2.4. Keyword Analysis

To investigate the research hotspots and trends in this field, bibliometric data from the Web of Science were input into VOSviewer to construct a co-occurrence keyword network. The VOSviewer tool supports a network clustering method known as the Smart Local Moving Algorithm, which provides insights into the established network structure. This method has been shown to have the advantage of automatically discovering meaningful clusters with higher modularity values [15].

Under full counting, a total of 1347 keywords were retrieved. To improve the readability and representativeness of the visualization, the minimum frequency for keyword occurrence was set to 3, reducing the total number of keywords to 167. The knowledge mapping network constructed using this approach is shown in Figure 6, where each node represents a specific keyword, and the size of the node is proportional to the frequency of the keyword's occurrence. The different clusters are presented in a vertically linear arrangement, with a total of 9 clusters. The keywords within these clusters are color-coded according to the average publication year, meaning that nodes in blue represent keywords that were identified and discussed earlier, while keywords marked in yellow have attracted significantly more attention from researchers in recent years. Therefore, Figure 6 provides an intuitive representation of the research hotspots and their development trends in this field.

As shown in Figure 6, in addition to the most frequently occurring keywords, "triboelectric nanogenerator" and "wind energy," which are directly related to the topic, other commonly occurring keywords include "performance," "nanogenerator," "driven," and "sensor." This indicates that the main research areas of wind energy-based TENG focus on these key aspects. By comparing the colors of these keywords, it is evident that the keywords "nanogenerator" and "driven" are more inclined towards blue, whereas "performance" and "sensor" are more towards yellow. This color mapping suggests that research on wind energy-driven TENG as a generator and driver has been conducted earlier, with initial studies focusing on energy absorption and driving related electrical devices. Over time, the focus has shifted towards sensor applications and performance-related research. Thus, it can be inferred that research on wind energy-driven TENG has established a practical foundation for energy harvesting, and its potential applications in areas such as building-related scenarios are beginning to be explored, although actual building integration remains limited.

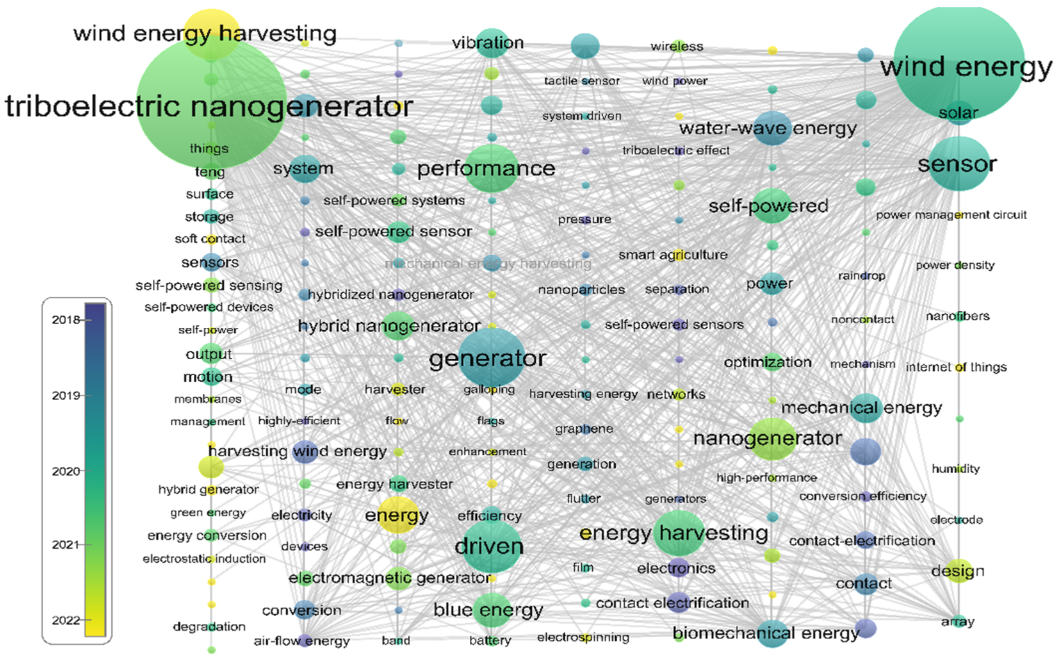

Figure 6. Keyword clustering and temporal view analysis.

3. Two Basic Structures of Wind Energy TENGs

In Chapter 2, a literature review summarizes the research progress of wind energy-driven TENGs. In fact, the structural designs of nearly all relevant studies on wind energy TENGs are primarily focused on two fundamental types: the rotational model based on "wind cups" and the flutter model based on "flutter effect" [16,17], as shown in Figure 7, Nevertheless, innovative designs have been proposed that enable effective harvesting of wind energy [18,19]. Unlike traditional wind turbines, which require strong winds for efficient energy conversion, these TENG structures leverage their unique advantages in micro-energy collection, offering improved energy capture and adaptability under variable wind conditions. They demonstrate significant advantages in efficiently capturing wind energy, improving energy conversion efficiency, and adapting to varying wind conditions.

Therefore, this chapter will provide a detailed introduction to these two core structures, outlining their design principles and key features. This analysis offers a clear theoretical foundation for subsequent discussions on the research status and technological development trends of wind energy TENGs integrated within architectural environments.

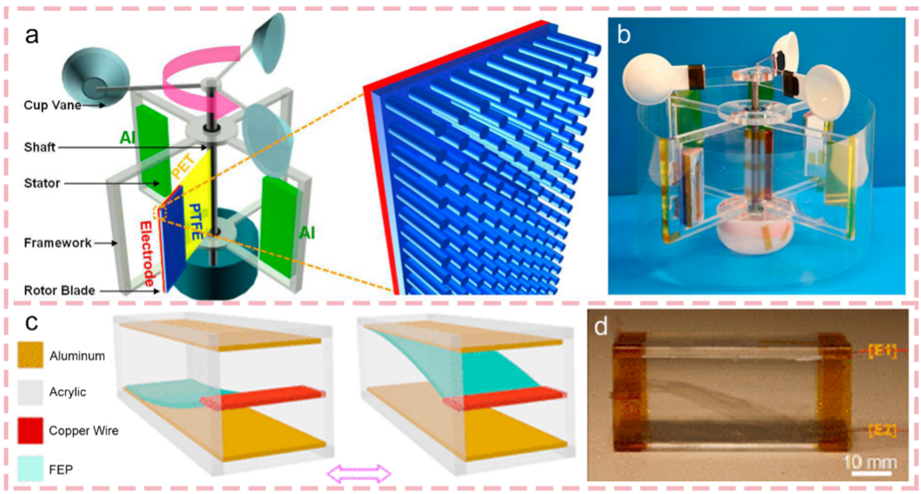

Figure 7. Demonstration of two common structures of wind energy TENG. (**a**) Theoretical model of rotational triboelectric nanogenerator based on wind cups. Adapted with permission from Ref. [16]. Copyright 2013, American Chemical Society. (**b**) Practical model of rotational triboelectric nanogenerator based on wind cups. Adapted with permission from Ref. [16]. Copyright 2013, American Chemical Society. (**c**) Theoretical model of triboelectric nanogenerator based on flutter effect. Adapted with permission from Ref. [17]. Copyright 2013, American Chemical Society. (**d**) Practical model of triboelectric nanogenerator based on flutter effect. Adapted with permission from Ref. [17]. Copyright 2013, American Chemical Society.

The rotational wind-cup-based TENG and the flutter-effect-based TENG represent two classical designs of wind-driven TENGs. As shown in Figure 7a,b, the wind-cup structure captures wind energy and converts it into rotational motion to drive the frictional interface, enabling charge separation and collection. This design excels in achieving stable energy output under low wind-speed conditions, with theoretical and experimental studies validating the optimization of parameters such as wind-cup diameter, friction materials, and rotational speed [16]. On the other hand, as shown in Figure 7c,d, the flutter-effect structure utilizes flexible materials to generate periodic vibrations under wind excitation, eliminating the need for complex mechanical transmission systems. This design allows the accumulation and release of triboelectric charges and exhibits significant flexibility in adapting to turbulent and non-uniform airflow conditions. Each structure has distinct advantages: the wind-cup model is ideal for stable energy output in low wind environments, while the flutter-effect model demonstrates superiority in lightweight design and complex wind scenarios, making it suitable for wind energy harvesting and engineering applications [17,20]. Collectively, these two designs cover the primary application scenarios in wind-energy TENG research and provide critical technological support for energy harvesting and sustainable applications in building applications. Future discussions will build on these two designs to analyze the current research status and practical application cases of wind energy-driven TENGs in architectural environments. Additionally, future development trends will be explored, along with proposals for performance optimization and scalable applications based on these two structural models.

4. Wind-Driven TENGs as Self-Powered Functional Modules in Buildings

The two fundamental structures of wind energy-driven TENGs, based on wind cups and the fluttering effect, have been the subject of continuous in-depth research and application [21,22]. In the context of architecture, the primary areas of focus are reflected in these following aspects.

4.1. Hybrid Energy Module: Wind-Solar Integration

In building environments, rooftops and facades provide abundant exposure to both sunlight and wind, making them ideal locations for hybrid energy systems. Combining wind-driven TENGs with solar cells can significantly enhance distributed energy harvesting under varying weather conditions, thereby improving a building's energy recovery and supporting self-powered devices within smart buildings.

Since 2014, a hybrid energy system that combines solar cells, electrochemical batteries, and wind-driven rotating frictional generators, such as cylindrical TENGs, has been proposed [23]. The TENG module within this system demonstrated a maximum open-circuit voltage of approximately 90 V, a short-circuit current density of about 0.5 mA/m^2, and a maximum power density of 16 mW/m^2, sufficient to directly power 20 blue light-emitting diodes (LEDs) [23]. Subsequent studies further achieved the independent or synchronous collection of mechanical, solar, and wind energy [24].

Later research employed actual building models, deploying hybrid nanogenerators combining fluttering triboelectric TENG structures with solar cells (SC) on model building rooftops. The hybrid system showed superior charging performance compared to standalone TENGs or solar cells, successfully charging a custom-built lithium battery [25]. These studies lay a foundation for practical integration of wind energy-driven TENGs with solar cells and indicate the potential for large-scale rooftop installations in urban environments, providing continuous energy supply for building sensors and smart-city applications.

Over the past decade, research on wind energy TENGs has gradually shifted from theoretical innovation to practical application, showing vast prospects. Hybrid wind-solar energy systems not only expand energy recovery across different weather conditions but also enhance buildings' ability to capture natural energy. Their applications in self-powered sensors, wireless devices, energy storage, and autonomous lighting hold practical value, and their integration into buildings will help promote the intelligent development and energy-efficient green transformation of buildings [26–28].

4.2. Self-Powered Sensor Module

Due to their limited power output, wind-driven TENGs are primarily applied in low-energy-demand scenarios, particularly for various self-powered sensors [29–31]. In the context of smart city and smart building development, the unique advantages of TENGs in self-powered sensing show potential for applications in the architectural field [32].

Buildings, as large structures standing in the natural environment, are constantly exposed to significant wind energy externally. Internally, numerous wind pathways exist, including equipment ducts and window openings, all of which require continuous monitoring. This abundant wind environment provides considerable opportunities for wind-driven TENG-based self-powered sensors [33,34].

As shown in Figure 8a, researchers have approached this from the perspective of building rooftop greening, utilizing wind-driven motion of grasses and leaves. By using artificial or leaf-based materials to construct plant-like wind energy-driven TENGs, these systems capture wind-induced contact-separation and friction processes, converting wind energy into electricity to supply building components [35–37]. On the other hand, as shown in Figure 8b, wind energy-driven TENGs have been developed for integration with architectural elements, with designs based on rooftop turbine ventilation devices and window components. These systems not only provide power for sensors but also enable electrochromic devices, where electrical fields induce redox reactions to alter optical properties [38–40]. Furthermore, in interior building scenarios, such as fluid flow within pipelines, TENGs can also be driven to supply energy to required sensors [41].

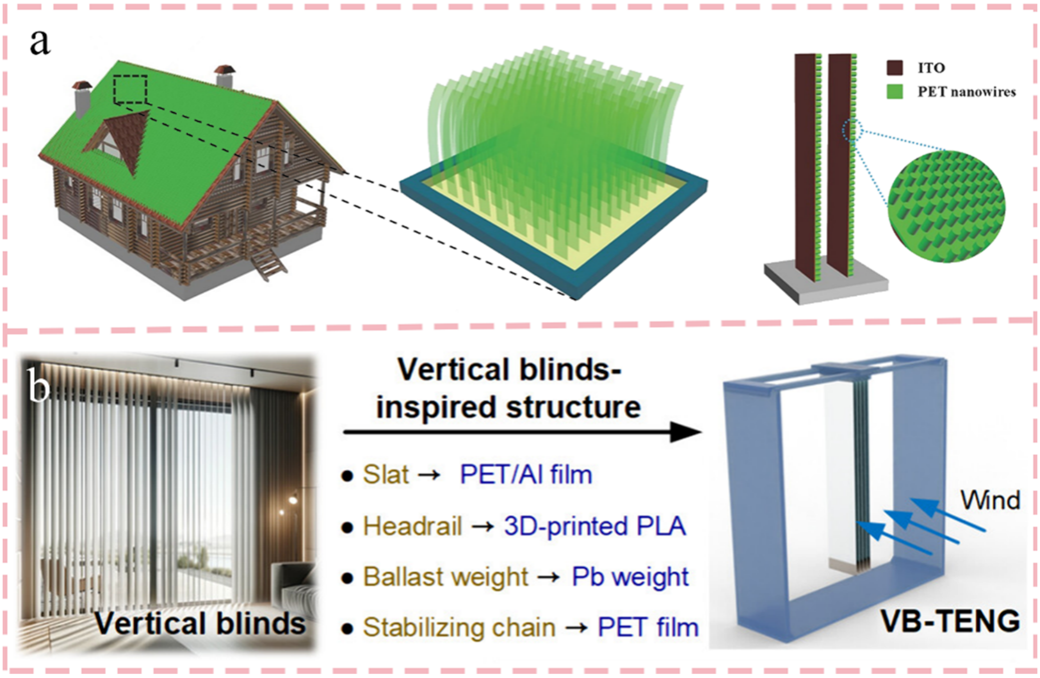

Figure 8. Two applications of wind energy triboelectric nanogenerators in buildings. (**a**) Lawn structured TENG. Adapted with permission from Ref. [36]. Copyright 2016, Wiley-VCH GmbH. (**b**) Vertical blinds-inspired TENG. Adapted with permission from Ref. [39]. Copyright 2024, American Chemical Society.

In fact, more researchers have focused on advancing the fundamental understanding of wind-driven TENGs rather than their immediate applications, aiming to design structures with higher energy conversion efficiency [42], expand the wind speed operating range of wind-driven TENGs [43,44], and improve sensing accuracy [45]. Although wind energy is abundant in nature, it is not a stable, long-term power source. To address this, more efficient TENG designs have been explored, including mechanisms involving multiple TENGs operating simultaneously, structural optimizations accounting for the chaotic nature of wind, and hybrid structures combining TENGs with electromagnetic generators (EMGs) to enhance electrical output under weak or multi-directional wind conditions [45,46].

Despite the abundant wind environments inside and outside buildings that could provide energy support for wind-driven TENGs, these studies largely focus on experimental and structural improvements of TENGs in building-relevant scenarios, rather than centering on actual applications in real architectural systems.

4.3. Self-Powered Air System Module

Air quality regulation in the built environment has long been a central issue in environmental engineering and building physics, encompassing multiple application scenarios such as fresh air systems, indoor air purification, and local exhaust ventilation [47]. Among existing indoor air management strategies, in addition to source control through environmentally friendly materials during building design and decoration, and pollutant dilution via ventilation systems, air filtration remains a critical technical approach for further improving indoor air quality. In this context, electrostatic-enhanced filtration, as an emerging technology, has gradually attracted increasing attention [48].

In studies related to TENG technology, a wind-driven R-TENG has been developed and coupled with an electrochemical system to realize self-powered oxidative removal of SO_2. The reaction mechanisms are described as follows:

$$\text{Anode: } SO_2 + 2H_2O \rightarrow 4H^+ + SO_4^{2-} + 2e^-$$

$$\text{Cathode: } 4H^+ + O_2 + 4e^- \rightarrow 2H_2O$$

Experimental results confirmed that this system could effectively oxidize SO_2 into sulfuric acid. Furthermore, comparative experiments with and without R-TENG demonstrated that the system significantly enhanced particulate matter removal based on electrostatic precipitation principles. The removal rate was positively correlated with the wind speed driving the R-TENG, indicating that higher rotational speed and output power led to faster purification. Notably, all TENG-based systems achieved zero ozone emission and low pressure drop, effectively avoiding the ozone generation and high energy consumption associated with conventional high-voltage electrostatic technologies and certain ionization-based oxidation filtration methods [49].

Further studies showed that R-TENG can establish a high electrostatic field within conventional filtration media. The enhanced nanofiber membranes increased the average capture efficiency of nanoscale particles from approximately 50% to about 80%, while maintaining $PM_{2.5}$ removal efficiencies above 94% and approaching 100% under optimized conditions. Moreover, these devices exhibit advantages including low cost, simple structure, and ease of integration. Their surface charges can be regenerated through friction, enabling the filters to be reusable after cleaning and thus offering long service life and low maintenance potential [50–52]. Consequently, TENG-enabled filtration systems demonstrate promising prospects for indoor air hygiene and environmental regulation in building applications.

However, existing studies have largely focused on performance validation of wind-driven TENGs for air purification functions, while systematic investigations targeting building-scale engineering applications remain limited. Under continuous operation conditions typical of buildings, such as hundreds or even thousands of hours of runtime, experimental data on long-term voltage stability and filtration efficiency degradation are still lacking. Moreover, the environmental adaptability of these systems under complex conditions involving high temperature, high humidity, and heavy particulate loading has yet to be sufficiently examined. Therefore, although wind-driven TENG-enabled self-powered, low-energy, and sustainable air purification technologies provide a new technical pathway for the built environment, their engineering feasibility still requires more comprehensive studies in realistic building operation scenarios.

5. Critical Assessment and Challenges of Wind-Driven TENGs in Building Applications

Although substantial progress has been achieved in the development of wind-driven TENGs and their potential building-related applications, most existing studies primarily focus on functional demonstrations under laboratory conditions. A critical assessment of their scalability, environmental adaptability, and engineering feasibility in real building contexts remains limited.

5.1. The Challenge of Transitioning from Microsystems to the Building Scale

From the perspective of building energy systems, there exists a significant order-of-magnitude gap between the experimental scale of current wind-driven TENGs and the actual requirements of building applications. In existing studies, the typical output power of wind-driven TENGs predominantly falls within the microwatt to milliwatt range. Their primary application scenarios largely remain at the level of powering LEDs, charging capacitors, and driving low-power sensor systems [38,39,41,44,45,53]. This is substantially mismatched with the energy consumption levels required for building operational systems. Table 2 compares the typical power output of experimental wind-driven TENGs with the power demand of building-related sensors and systems. As shown, TENG output is generally sufficient for low-power devices such as sensors and microcontrollers but is far below the demands of core building loads such as lighting, HVAC, pumps, and elevators. Therefore, the potential role of TENGs in buildings is more realistically positioned as an energy source for sensing, perception, and localized intelligence rather than for core operational functions. The power output of wind-driven TENGs is taken from the cited literature, whereas the power consumption of sensors and building systems is compiled from publicly available specifications and typical design references.

Table 2. Comparison between typical power output of wind-driven TENGs and power demand of building-related devices.

Category	Typical Devices/Examples	Power Range
Wind-driven TENGs (experimental level)	Flutter-driven TENG	~1.2 Mw (25 m/s) [45]
	Hybrid micro-energy system (TENG + EMG + SC)	TENG: ~0.33 mW (9 m/s); EMG: up to ~46.8 mW [43]
	Lawn-structured TENG (single strip)	~2.76 W/m^{-2} (27 m/s) [36]
	Leaf-inspired TENG	~17.9 mW (7 m/s) [9]
Building sensor and microsystems	Temperature and humidity sensors	~0.1–1 mW
	CO_2/indoor air quality sensors	~1–5 mW
	Microcontrollers/wireless modules	~1–20 mW
	Indicator LEDs	~10–50 mW
Typical building energy loads	Residential lighting (per lamp)	~5–50 W
	HVAC/ventilation equipment	~50–500 W
	Pumps and fans	~100 W–5 kW
	Small elevators	~2–10 kW

To transition from a microscale energy harvester to a functional unit integrated into building systems, the most straightforward technical path for wind-driven TENGs seems to lie in scaling up the total output through methods such as array configurations and dimensional enlargement, similar to solar panel systems. However, existing research indicates that wind-driven TENGs do not possess ideal linear scaling characteristics. On one hand, their inherent energy density per unit area is relatively low. For example, flutter-type structures are constrained by material flexibility and safe deformation limits, making it difficult to infinitely increase vibration amplitude and effective contact area. Expanding the contact area does not necessarily lead to a proportional increase in power output [36,42,45]. On the other hand, the inherent ultra-high internal impedance and strong transient output characteristics of TENGs pose significant challenges in impedance matching and energy transmission efficiency when multiple units are connected in series or parallel. This often results in limited improvement—or even significant degradation—in system-level effective output power as the array scale increases [38,46].

From the perspective of building integration, the output characteristics of wind-driven TENGs—characterized by high voltage, low current, and high internal impedance—along with their high sensitivity to instantaneous wind speed and flow field disturbances, lead to significant instability in voltage amplitude, frequency, and power density. This makes them difficult to directly interface with building electrical systems or to power continuous loads. In practical applications, reliance on rectification, voltage regulation, and energy storage units for secondary power management is often necessary. In this process, energy conversion efficiency losses, impedance matching challenges, and increased system complexity further diminish their effective output capacity [38,40,46]. Consequently, from a building integration standpoint, wind-driven TENGs currently function more as energy sources capable of generating trigger signals rather than as stable, controllable power supplies.

From the perspective of deployable surface density, most existing wind-driven TENGs are composed of lightweight flexible structures or rotating components, whose effective output is highly dependent on local wind field conditions and installation orientation. Within the architectural context, even if individual units can operate stably, increasing deployment density inevitably introduces issues such as structural shading, flow field interference, array coupling effects, and elevated maintenance complexity [35,36]. Furthermore, given the stringent constraints on building envelopes and ventilation spaces—including safety, aesthetics, structural load, and maintenance accessibility—it is challenging to implement large-scale, high-density installation of wind-driven TENGs on real buildings, as is commonly done with solar photovoltaic panels. This limits the effective energy yield obtainable per unit building area, thereby reinforcing their systemic positioning as supplementary function-specific energy sources.

In summary, constrained by power scale, power quality, and deployable density, the practical value of wind-driven TENGs in buildings is more likely to manifest as energy-supplementing units for distributed sensing networks, localized functional modules, and smart building microsystems, rather than serving as an energy solution targeting the overall energy consumption of buildings.

5.2. Performance Uncertainty in Complex Wind Environments

Existing research on wind-driven TENGs is primarily conducted under laboratory conditions, with performance evaluations mostly based on stable airflow environments constructed using wind tunnels or controlled air supply systems. The experimental wind speeds employed in the literature typically range from 0.2 to 29 m/s, but most studies are only applicable to a limited portion of this range [36,39,43,54,55]. These experiments often assume constant inflow velocity, stable wind direction, and low turbulence intensity, representing highly idealized conditions. While such studies are valuable for elucidating the fundamental relationships between structural parameters and output performance, they significantly differ from real-world wind environments in architectural contexts [56].

In actual building and urban environments, wind fields are shaped by the combined effects of urban morphology, building layouts, and thermal dynamics, exhibiting pronounced heterogeneity, strong turbulence, and unsteady characteristics [57]. Such complex flow fields directly influence the probability of wind-driven TENGs reaching their activation wind speed, the proportion of effective operational time, and output stability. Furthermore, flow separation, recirculation, and multi-scale vortex structures under turbulent conditions may weaken or even negate the structural advantages established in laboratory flutter-based designs. When devices are integrated into building surfaces in array configurations, issues such as self-shading effects and localized wind field alterations may arise, making it difficult to directly extrapolate optimal parameters from individual units to array applications.

Currently, there is a scarcity of field studies on wind-driven TENGs in real-world scenarios such as building facades, ventilation ducts, roof edges, and urban wind canyons. The lack of multi-condition and long-term operational data leads to significant uncertainty when translating laboratory performance metrics to practical applications. Although wind-driven TENGs have demonstrated functional feasibility for building-integrated use, substantial research is still required to bridge the environmental disconnect between idealized laboratory conditions and engineering realities.

5.3. Deficiencies in Durability, Reliability, and Maintenance Mechanisms

As an energy conversion device reliant on continuous mechanical contact or periodic deformation, wind-driven TENGs inherently face durability bottlenecks related to material wear, surface structure degradation, and charge density decay due to their operating mechanism. Performance output exhibits significant time-dependent decline due to factors such as the deterioration of micro/nanostructures in triboelectric layers, interfacial contamination, and reduced charge-trapping capacity [35,40,43,45,54].

Existing durability tests show that some devices can maintain stable output over relatively extended periods, such as up to 30 days or 135,000 operating cycles [35,55], even under conditions of high temperature, high humidity, or light water exposure [38,54]. However, these test durations remain negligible compared to the full lifecycle of buildings, which typically require stable operation over thousands to tens of thousands of hours. This makes it difficult to reflect the actual conditions of long-term operation. Moreover, there is a notable lack of long-term aging experiments and reliability assessments for wind-driven TENGs in simulated or real building environments.

Building operation demands that energy systems maintain stable performance over thousands to tens of thousands of hours. Long-term exposure to complex environmental factors—such as dust accumulation, humidity fluctuations, thermal cycling, ultraviolet radiation, and wind load impacts—can accelerate material aging and potentially lead to structural fatigue and electrical performance instability. Even if some devices demonstrate good short-term stability in controlled experiments, their capability to serve as long-term energy solutions for buildings remains constrained. Consequently, their application is more likely to be confined to low-power sensing and microsystem levels, functioning as supplementary units for distributed sensing or localized self-powered functions, rather than serving as a primary energy solution for overall building energy consumption [58].

6. Future Research and Integration Trends of Wind-Driven TENGs in Building Applications

Rather than serving as a scalable power supply for building energy systems, wind-driven TENGs are more realistically positioned as supplementary energy sources for distributed sensing networks and localized building microsystems. As demonstrated in the previous section, fundamental constraints related to power scale, environmental uncertainty, and long-term reliability significantly limit their feasibility as building-level energy technologies. Accordingly, future development should move away from the pursuit of large-scale energy harvesting and toward clearly bounded, function-oriented integration pathways.

Existing studies indicate that wind-driven TENGs can generate high-voltage, low-current outputs under a range of airflow conditions, making them inherently suitable for low-power electronics, intermittent sensing, and event-driven microsystems. From the perspective of building applications, their primary value lies not in contributing to the building's overall energy balance, but in enabling autonomous sensing units, distributed perception nodes, and auxiliary micro-energy inputs embedded within architectural environments.

Based on a critical reassessment of building energy demands and the operational characteristics of wind-driven TENGs, this paper proposes that future research trends should shift from output-centered performance enhancement to system-level architectural adaptation. Accordingly, prospective directions are discussed from two perspectives: (1) the development of TENG-based hybrid and auxiliary energy integration strategies within building systems; and (2) the construction of TENG-enabled self-powered sensor networks compatible with smart building management and long-term operation.

6.1. Building Hybrid Energy Integration Systems Based on TENGs

Wind energy-driven TENGs can be deployed in various scenarios both inside and outside buildings as auxiliary micro-energy units rather than primary power sources. Externally, they may be integrated into building facades, rooftops, enclosures, and windows to scavenge localized and low-density environmental wind energy. Existing experiments have demonstrated that combining wind energy TENGs with solar cells can enhance the functional diversity of hybrid systems and improve energy utilization under specific low-power scenarios, rather than significantly increasing building-level energy supply [24,59].

Internally, TENGs can be embedded in equipment and infrastructure pathways, such as ventilation ducts, shafts, and gas pipelines, where airflow already exists. In such contexts, TENGs are more appropriately positioned as localized energy providers for nearby sensors, low-power electronic components, and intermittent microsystems, forming self-sustained micro-energy loops within buildings, instead of being fed into the main building energy network.

Moreover, TENGs have demonstrated good structural adaptability in experimental hybrid systems harvesting multiple ambient energy forms, including mechanical disturbances such as wind, raindrops, and human motion. Rather than functioning as independent energy technologies, integrating TENGs into existing building energy frameworks (e.g., photovoltaic systems, small wind devices, and rainwater or motion-based harvesters) is more realistically understood as a way to construct hybrid supplementary energy layers that support distributed sensing, status monitoring, and localized intelligence, instead of supplying continuous building power [32,60].

At present, experimental investigations of wind-driven TENGs remain limited to a small number of building-related scenarios. There is an urgent need to validate their long-term operational behavior, functional reliability, and system compatibility across a broader range of architectural contexts. In particular, how to effectively organize TENG-based micro-harvesters together with the sensor units they support, and how to integrate them into building service systems without increasing maintenance complexity, remains a key research issue requiring further exploration.

6.2. Integration of TENG-Based Building Sensor System Networks with Smart Building Management

TENG-supported sensors provide a feasible pathway for constructing distributed, self-powered sensing layers in buildings. By enabling grid-like or node-based deployment, wind-driven TENGs are particularly suitable for supporting low-power perception units that monitor localized environmental and operational conditions, thereby supplementing conventional wired or battery-dependent sensor networks [61–63].

Sensors based on TENG technology can be embedded into building sensing systems and interfaced with intelligent building management platforms. Given their flexible structures and diverse transduction modes, TENG-based devices can be coupled with existing environmental sensors to support real-time monitoring of parameters such as airflow conditions, temperature, humidity, vibration, and illumination. In this context, the primary value of TENG-enabled sensors lies not in contributing to building energy supply, but in enabling self-sustained, maintenance-reduced sensing nodes that alleviate wiring constraints and battery replacement demands in large-scale or hard-to-access architectural spaces [64–66].

The key challenge, however, lies in how to systematically deploy heterogeneous sensor networks within buildings to ensure data reliability, spatial representativeness, and long-term operational stability. Practical implementations of wind-driven TENG self-powered sensors in areas such as safety surveillance, fire and disaster monitoring, and occupant-behavior sensing remain limited. These application domains require further scenario-oriented experiments, field validations, and system-level case studies to clarify deployment strategies, data integration methods, and maintenance mechanisms, and to ultimately establish a technically robust framework for integrating wind-driven TENG sensing networks into real-world building management systems.

7. Conclusions

This paper provides a comprehensive review of the integration between building technologies and TENG power generation, with a particular focus on wind energy—a relatively underexplored renewable resource. By combining bibliometric analysis with in-depth content review, this study clarifies the current research landscape and the technical status of wind-driven TENGs in building-related contexts. The review indicates that, at present, the practically feasible contributions of wind-driven TENGs to buildings are mainly confined to micro-scale applications, such as self-powered sensors, localized functional components, and distributed microsystems. Existing studies have demonstrated their ability to support low-power sensing, signal transmission, and energy supplementation under controlled conditions, highlighting their potential value in perception-oriented and function-specific building applications. However, this paper also emphasizes that most wind-driven TENG applications remain at a laboratory or proof-of-concept stage. Their limited power output, strong dependence on complex and unstable wind environments, non-linear scaling behavior, and insufficient long-term durability and reliability data significantly constrain their applicability in real buildings. These factors currently prevent wind-driven TENGs from serving as stable or scalable energy solutions within building energy systems.

From a building-oriented perspective, future development should therefore shift from pursuing large-scale energy substitution toward realistic integration pathways, including the development of TENG-based self-powered sensor networks, hybrid micro-energy systems coupled with photovoltaics and energy storage, and building-adapted designs emphasizing environmental compatibility, durability, and maintainability. Currently, most research remains confined to laboratory conditions, while building environments are complex and variable. Future work should involve simulated experiments in real-life scenarios, using actual feedback to evaluate and optimize wind-driven TENGs in terms of energy conversion efficiency, durability, and energy recovery management under practical building conditions. Only through such real-world building pilot studies can more authentic success cases be accumulated, promoting the standardization and wider adoption of the technology. More scholars need to conduct experiments and collect data in realistic scenarios to achieve substantive breakthroughs in integrating wind-driven TENGs with building systems.

Author Contributions

Y.L.: conceptualization, methodology, framework development, supervision, funding acquisition, writing—original draft preparation. H.P.: methodology, formal analysis, data curation, visualization, writing—original draft preparation. Y.Z.: methodology, framework development, validation, writing—reviewing and editing. X.L.: methodology, validation, writing—reviewing and editing. X.C.: methodology, validation, writing—reviewing and editing. S.W.: methodology, formal analysis, writing—reviewing and editing. S.A.: supervision, writing—reviewing and editing.

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Data Availability Statement

The datasets used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editorial Board Member, Yanan Liu had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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