Active Facades: Scaling Energy Efficiency and Climate-Positive Carbon Neutrality from Every Surface

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ABSTRACT

As fossil fuel reliance grows increasingly unsustainable, large-scale renewable energy capture is vital to achieving carbon neutrality. Due to spatial constraints, traditional on-site renewables like rooftop solar panels and wind turbines often fail to meet the high energy demands of large buildings. In this context, Micro Wind Energy Harvesters (MWEHs) offer a promising, scalable, and low-maintenance alternative for energy generation, capturing and converting ambient wind and vibration into electricity. While individual MWEHs produce modest amounts of renewable energy, their impact becomes significant when employed across large areas, such as building facades. Recent interest in MWEHs has grown as researchers explore alternatives to conventional renewable energy technologies.

This article focuses on designing, fabricating, and optimising MWEHs tailored for architectural integration. The aim is to refine device geometry, material efficiency, and aerodynamic performance to maximise energy output in low-wind conditions typical of urban microclimates. As part of this initiative, a full-scale installation of a self-powered digital display is proposed to serve as a demonstration model of how future active facades could generate renewable energy, extending from individual building surfaces to entire districts or neighbourhoods in a "surface-to-city" concept, integrating into new and existing construction. This display—energised solely by MWEHs—will act as both a proof of concept and an interactive public demonstration. Beyond validating system feasibility, it will also raise awareness, spark dialogue around renewable technologies, and inspire broader adoption by showing how buildings can become active agents of energy production.

I. **Introduction**

According to the US Department of Energy, building operations in the United States account for approximately 40% of total energy consumption and 74% of annual electricity use.[1] Large buildings, in particular, face challenges meeting energy goals solely through on-site renewables due to high energy demands and limited space for generation. In 2015, the United Nations established the 2030 Agenda, a plan of action for all nations to set sustainable development goals, protect the planet, and promote prosperity. Among the seventeen goals and accompanying targets outlined in the agenda, the seventh goal ensures access to clean and affordable energy.[2] Within that goal, target 7.2 addresses the urgent need to increase the share of renewable energy sources within the global energy mix.[3]

However, despite progress in meeting energy targets, energy demand continues to grow,[4] and the need to increase renewable energy sources remains paramount. The International Energy Agency (IEA)'s *Global Energy Review 2025* reports that global energy consumption rose to more than twice the annual average, resulting in the most significant increase ever.[5] As Dr Fatih Birol, Executive Director of the IEA, has emphasised, the climate crisis is fundamentally an energy crisis. This highlights the central role that energy systems play in contributing to and addressing climate change, with renewable energy at the core of the solution.[6] However, overcoming this challenge requires innovative approaches to enhance energy solutions. To maximise the impact of renewable energy generation, non-traditional systems must be integrated with conventional technologies for greater efficiency and effectiveness (Figure 2).

Given the increasing demand for renewable energy production and buildings' impact on energy consumption, alternative technologies are being explored to supplement renewable energy harvesting for on-site production. Growing attention is being given to developing MWEHs, micro (or miniature) wind energy harvesters.[7] MWEHs offer significant advantages over larger wind turbines because they generate electricity from low wind speeds and ambient energy, including vibrations. Although scaling wind turbines to smaller sizes seems plausible, doing so leads to unique challenges. These include higher wind speeds required for start-up rotation, bearing losses, and complex manufacturing processes, hindering widespread adoption and accessibility.[8] Consequently, MWEHs utilise alternative mechanical methods to harvest renewable wind energy. Their simple design enables cost-effective manufacturing and low maintenance, eliminates the need for bearings and associated mechanical losses, operates efficiently in low-speed ambient wind conditions, and allows for versatile installation on diverse surfaces. These advantages have led to increased research interest in recent years.

Electromechanical energy conversion, the conversion of mechanical energy into electrical energy, occurs in MWEHs through fluid-solid interactions combined with conversion mechanisms such as piezoelectric, electrostatic, electromagnetic, and triboelectric methods.[9] There are three elements for MWEH configuration: a component excited by the wind, a structural support for the component, and the conversion method from mechanical action to electrical energy. The fluid-solid interaction is the interaction of a bluff body (solid) excited by the wind (fluid), through which a

[1] "Building Energy Use - GSA Sustainable Facilities Tool." *Sftool.Gov Webpage*, 2020.
[2] United Nations Sustainable Development Goal 7.
[3] ibid, Target 7.2.
[4] "Executive Summary – Electricity 2024 – Analysis." *International Energy Agency Webpage*, 2024.
[5] "Key Findings – Global Energy Review 2025 – Analysis - IEA." *International Energy Agency Webpage*, 2025. Notably, this was the largest increase ever recorded outside of periods of economic recovery following a recession.
[6] Birol, Fatih. *World Energy Outlook 2021*. International Energy Agency, 2021.
[7] Wen, Quan, et al. "A Comprehensive Review of Miniatured Wind Energy Harvesters." *Nano Materials Science*, vol. 3, no. 2, 2021, pp. 170-185.
[8] ibid at 171.
[9] ibid at 172.

mechanical action is converted to electrical energy via a conversion mechanism (Figure 3). The energy harvested decreases as these harvesters are miniaturised to centimetre and millimetre scales. However, despite producing a lower energy output than conventional renewable energy sources, MWEHs offer versatility by enabling productive installations on virtually any surface, even in smaller-scale applications. Unlike traditional wind energy harvesters, such as wind turbines, which function most efficiently at a large scale, the small operating scale of MWEHs is highly adaptable for dense deployment across various surfaces. They can work with other renewable energy harvesting strategies, contributing to overall energy load reduction.

While integrating renewable energy harvesting into buildings has gained significant interest, it also presents several challenges.

Traditional renewable energy systems, such as solar panels and wind turbines, primarily occupy rooftop spaces and are typically limited to horizontal surfaces. While solar panels have increasingly expanded onto façades, they are predominantly restricted to south-facing surfaces due to reliance on direct sunlight, leaving much vertical façade areas underutilised. In contrast, MWEHs can populate any building surface owing to their small-scale and non-rotational energy-harvesting mechanisms. Since the vertical surface area usually exceeds that of horizontal surfaces in buildings, MWEHs effectively transform underused vertical surfaces (in addition to horizontal surfaces) into extensive regions for renewable energy collection.

This article focuses on developing and optimising MWEHs as an effective means for harvesting renewable energy, showcasing this emerging technology while engaging and educating the community through a digital display powered by MWEHs. By demonstrating the viability of micro wind energy, our display will highlight non-traditional renewable energy harvesting measures for adopting alternative energy sources (Figure 1). This research demonstrates the potential to transform buildings into energy-harvesting structures by developing the display as a proof of concept. As a piece for the community, the digital display encourages interaction and engagement in a demonstration of community-driven renewable energy and microgrid development, supporting broader sustainability and innovative smart-city initiatives.

II. **Background and Development of MWEHs**

This study began with the development of a piezoelectric-based MWEH prototype. The piezoelectric effect allows for a compact, bearing-free design suitable for low-speed winds. Piezoelectric transduction takes advantage of the piezoelectric effect—the natural capability of certain materials to convert mechanical energy into electrical charge. Piezoelectric sensors detect vibrations to enable self-powered functionality. Integrating piezoelectric sensors into MWEHs provides a significant advantage: energy can be harvested from wind-induced motion without relying on rotational mechanisms. Instead, these sensors generate an electrical charge when attached to a cantilever beam integrated into the MWEH, deformed by wind excitement. When the wind excites a bluff body attached to the cantilever beam, it generates controlled oscillations by design, causing deformation in the beam. The piezoelectric sensor, typically in the form of a film, deforms along with the beam, thus generating an electric charge.

By leveraging piezoelectric technology, MWEHs can operate without rotational components, enabling miniaturisation, enhanced design flexibility, and seamless integration into building elements. The cantilever design allows energy harvesting at lower wind speeds, while the absence of bearings eliminates mechanical losses. Fewer moving parts also result in improved durability and reduced maintenance requirements.

A. *Selection and Optimisation of Wind-Induced Oscillation Methods*

Wind energy is an abundant resource that is continually available. Micro wind energy harvesting employs various movement phenomena to generate excitement from the wind for wind energy harvesting. These include fluttering, galloping, and vortex-induced vibrations, among others. Fluttering typically involves a flexible band that is excited by wind. Like a tuning fork, the band must often be carefully tuned to maximise energy harvesting. In contrast, vortex-induced vibrations (VIV) occur due to periodic vortex shedding from a bluff body, producing regular oscillations. Galloping-based oscillation occurs in large, low-frequency motions when the wind is perpendicular in direction, growing in amplitude with the increase in wind speed. The aerodynamic forces reinforce the motion instead of dampening it, leading to a self-sustaining movement.

A galloping-based approach was selected for this study due to its greater potential for substantial energy harvesting and its ability to operate within a broader range of wind speeds, resulting in larger vibration amplitudes.[10] As wind flows around the asymmetrical shape of the bluff body, it creates uneven pressure on opposite sides. This imbalance in aerodynamic forces initiates and sustains a rhythmic oscillating motion, allowing the structure to move continuously without additional external input. The resulting oscillations, developed to a design frequency, can be effectively converted into usable energy with appropriate energy-harvesting mechanisms (Figure 5).

Initial testing comprised twenty-seven preliminary shapes of varying configurations. Those featuring Y-shaped profiles produced higher energy output when employing a single piezoelectric film and were evaluated by a standard micrometre. Testing was conducted in a custom-built wind tunnel using fan speeds of 3.2 m/s, 3.8 m/s, and 4.6 m/s, aligning with U.S. average wind speeds at approximately 4-5 m/s at 30 meters in height.[11] The device was designed with a single cantilever arm to support the bluff body (Figure 6).

B. *Fluid-Structure Coupling and Frequency Tuning*

Fluid-structure interactions are an essential interdisciplinary subject and are important in active scientific research. The complex behaviour of the interplay between the fluid and the solid is not readily available and poses a significant challenge in precisely fine-tuning the system. The optimisation strategy relies on one-dimensional modelling of the structural frequencies coupled with the flow-induced vibrational frequencies. This study considers the fundamental modes (dominant eigenmode) of the flow-induced excitation frequency and the fundamental structural mode, as they have the highest energy content.

The cantilever arm sizing is governed by the fundamental vibrational mode in the lateral / yawing motion. The fixed end is modelled as the contact point on the facade structure, and the free end is subjected to the flow-induced forcing term. The weight of the cantilever beam is modelled as massless with a point mass load at the free end. The design criteria were to identify the nominal thickness, cross-section, area, and length for a given Young's modulus and material density. The equation to determine the fundamental frequency mode, *FF*, is—

$$FF = \frac{1}{2\pi}\sqrt{\frac{3EI}{FL^3}}$$

—where E is the modulus of elasticity (Pa), I is the moment of inertia (kg / m^2), F is the weight of the bluff body (N), and L is the length of the cantilever arm (m).

C. *Aerodynamic Optimisation and Strouhal Training*

[10] Wu, Ying, et al. "Flow-Induced Vibration." *Scholarly Community Encyclopedia*, 29 Nov. 2022.

[11] "WINDExchange: U.S. Average Annual Wind Speed at 30 Meters." *US Office of Energy Efficiency & Renewable Energy Webpage*, 2012.

Due to the consistency in creating flow separation, a Y-shape flanged bluff object was chosen for its simplistic nature to create guaranteed flow separation from the forked flanges at a wide range of inflow angles. The flow-induced oscillation frequency is the priority for the optimisation rather than the magnitude of aerodynamic forces. This assumption is valid if the slender cantilever structure has low inertia such that the flow-induced vibrations activate the fundamental mode. A characteristic feature of the flow separation phenomena on a bluff body is that it creates an oscillating large-scale flow structure called shed vortices. The local pressures at the tip of the forked flanges alternate from high to low pressure, causing a series of shed vortices from the tips (Figure 7). A non-dimensional number captures this shedding mechanism called the Strouhal number, which ranges between 0.2 and 0.3 for the Reynolds numbers relevant to this study.[12]

The Strouhal number is a ratio that describes how often an object vibrates or sheds vortices as fluid flows around it, determined by its size, vibration frequency, and flow speed. In this case, the object is the bluff body, and the fluid is air.

To determine the Strouhal number, N, the following equation was used—

$$N = \frac{1}{2\pi} \cdot \sqrt{\frac{3E}{FIDL^3}} \div S$$

—where E is the modulus of elasticity (Pa), I is the moment of inertia (kg / m²), F is the weight of the bluff body (N), L is the length of the cantilever arm (m), D is the diameter of the bluff body (m), and S is the wind speed (m / s). Factors were added to the equation to adjust for the asymmetrical shape of the cross-section of the bluff body. The tips of the Y-shaped bluff body were fit inside an imaginary circle, thus obtaining the diameter as an equivalent characteristic length. Various wind speeds were tested to identify the frequency at which vortices are shed from the bluff body, a crucial factor in maximising energy output. This frequency was used as an input for the cantilever beam equation to deduce area moments of inertia. Therefore, the cantilever beam's dimensions were defined to evaluate the nominal flow speeds at which the vortex shedding frequency aligns with its fundamental structural mode. A Strouhal number range of 0.2 to 0.3 was considered an acceptance criterion. Based on the equation above, the resultant values within the Strouhal number range are automatically highlighted in green in a spreadsheet, shown as a partial table (Table 1), informing optimal design criteria.

Based on the first-order modelling and sizing, precise tuning of the shedding frequencies based on the flow angles, number, and length of forked flanges is needed. Flow-advanced diagnostics using Particle Image Velocimetry (PIV) and Proper Orthogonal Decomposition (POD) will improve precision in flow interaction analysis, offering quantitative insight into turbulence and energy transfer. PIV and POD provide detailed analysis of how bluff bodies and wind energy harvesters interact with surrounding air currents. PIV visualises airflow by tracking particles suspended in the flow using lasers and high-speed cameras, capturing detailed information on velocity and direction. On the other hand, POD analyses flow data to identify dominant patterns and modes of motion, revealing key features such as vortex formation and energy distribution. However, at this phase in the research, the spreadsheet informed initial iterative development, where performance was measured through testing based on piezoelectric energy harvesting readings from the integrated film. Flow-advanced diagnostics are planned for continued development and fine-tuning.

III. **Electrical Circuitry and Energy Conversion Methods**

A. *Piezoelectric Energy Harvesting*

[12] In many fluid dynamics problems, the Strouhal and Reynolds numbers are loosely related. The Strouhal number indicates how frequently an object vibrates within a flow, while the Reynolds number characterises the nature of the fluid's motion around that object.

While piezoelectric harvesters are prevalent in micro wind energy studies due to their high voltage sensitivity, this article demonstrates their practical limitations for sustained output, especially in high-impedance systems. A flexible piezoelectric polymer film sensor with attached leads bonded to the oscillating cantilever beam was selected to convert mechanical energy into electrical energy. The device operates based on the direct piezoelectric effect, where mechanical strain in the piezo film generates charge separation, resulting in a voltage across the sensor terminals. Since the piezo element is off the cantilever's neutral axis, minor bending induces substantial strain, producing a strong open-circuit voltage. The piezoelectric polymer (PVDF) film is laminated on a thin polyester substrate and fitted with lead. When the cantilever beam deflects due to the excited bluff body, the film deflects and outputs an AC voltage proportional to the deflection velocity and magnitude. The sensor's high internal impedance requires interfacing with a high-resistance load or buffer circuit to capture the full voltage swing. This prevents loading down the sensor so that it can develop its characteristic high voltage (on the order of tens of volts) under strain.

The prototype used commercially available piezo film sensors as the transducers. Notably, the selected sensor can produce up to 100 volts in open circuit under strong deflection, but due to its small capacitance, the output current is extremely low. In bench-top wind tests (airflow velocities between 3 and 5 m/s), a single film generated an AC voltage of approximately 0.1 volts to 2 volts peak when measured across a 10 MΩ load. The corresponding current through a 10 MΩ resistor was 0.01 to 0.2 μA, confirming the high source impedance. Using the measured 2 volts output as an upper limit, the instantaneous power available from one piezoelectric film was 0.4 μW with a 0.2 μA current using the following equations—

$$P = \frac{V^2}{R} = \frac{(2\text{V})^2}{10\text{M}\Omega} = 0.4\mu\text{M};$$

$$I = \frac{V}{R} = 0.2\mu\text{A}$$

—where P is power (V), R is resistance (Ω), and I is impedance (Ω). Under more vigorous bending, the piezoelectric harvester output remains in the microwatt range, consistent with literature review[13] noting that piezoelectric vibration harvesters produce only a few volts and microamp-level currents. These levels are well below what is needed to drive high-power devices directly.

B. *Limitations of Piezoelectric Systems*

Given the above output, the number of piezo sensors was calculated to determine the quantity required to meet the power demand of a typical outdoor LED display. A one-square-foot LED panel used for signage consumes roughly 50 to 100 W/ft^2. This was the basis for determining a mid-range estimate of 75W per square foot for the target output. Assuming an optimistic 11 mW electrical output per piezo device, thousands of piezoelectric harvesters would be needed to produce 75W of power.

Experimental findings corroborated this rough order-of-magnitude result: the small piezo films yielded negligible power, and attempting to scale up would require nearly 7×10^3 devices to sustain a 75W draw. While piezoelectric films are commonplace in similar studies developing micro wind energy harvesters, a standard commercial harvester output would rarely, if ever, reach the maximal 11 mW per device simultaneously. At the same time, any mismatch or partial loading would further reduce the net power.

Another challenge with the piezoelectric approach was converting the sensor's AC output, oscillating with the cantilever's vibration frequency, into a proper DC power supply for the LED display. A passive

[13] Mustapha, Ain Atiqa, et al. "Experimental Comparison of Piezoelectric Rectifying Circuits for Energy Harvesting." *IEEE Student Conference on Research and Development*, Dec. 2013, pp. 556-559.

rectification stage using low-drop Schottky diode bridge rectifiers was considered, followed by a smoothing capacitor and a storage element via a battery or a supercapacitor. Schottky diodes were chosen for their low forward voltage (~0.3 to 0.4 V), critical for energy harvesting since voltage from piezoelectric harvesters is often in the sub-volt range during regular operation. The ultra-low current, in the μA range, meant that even a small diode drop or leakage could significantly impact efficiency. For this reason, active rectifier ICs or op-amp-based precision rectifiers were avoided, as their quiescent power draw would eclipse the harvested energy. The initial attempt implemented a passive full-wave rectifier using Schottky diodes due to their low forward voltage (~0.3 to 0.4 V). However, it was quickly evident that the output voltage from the piezoelectric sensor was too low and inconsistent to overcome even the minimal diode threshold reliably. As a result, rectification was largely unsuccessful, with the output collapsing under any load. Additionally, due to the very high source impedance, the piezo's voltage collapses when any substantial load is connected, requiring a buffer via a capacitor and intermittent draw.

When addressing the issues of low voltage and the need for a buffer, an initial consideration is to introduce a step-up transformer to boost the AC voltage before rectification. Theoretically, this would have multiplied the signal amplitude 500 times to drive the rectifier and charge a storage capacitor sufficiently. However, the piezoelectric sensor behaved like a high-impedance current source, delivering only nanoamp to microamp-level currents. This posed a significant challenge as transformers, especially at low frequencies, require milliamps of current to effectively transfer energy to the secondary winding and maintain flux linkage. The transformer could not operate efficiently at such low input current levels, rendering voltage boosting infeasible. Thus, both the initial rectification and transformation stages failed to function effectively due to the inherent limitations of the piezoelectric source: extremely low current, high impedance, and insufficient driving strength. This necessitated the exploration of an alternative mechanism for energy conversion.

A commercially available LDT-series laminated piezoelectric sensor[14] was used for the MWEH's energy harvesting integration. As a result of further study, Macro Fibre Composite (MFC) patches present a viable alternative to improve micro wind energy harvesting capability. MFC piezoelectric elements consist of piezoceramic fibres embedded in a polymer matrix, forming a flexible composite with markedly different electrical properties than monolithic piezo-film sensors, exhibiting a much higher effective capacitance. This higher capacitance corresponds to a lower output impedance and more significant charge transfer for a given mechanical strain, enabling more efficient energy conversion. Under similar cantilever deflection conditions, an MFC transducer can source significantly higher current than an LDT, allowing substantially greater power output from the harvester.

Future experiments will quantitatively compare MFC-based and LDT-based harvesters in identical cantilever configurations to validate the observed performance gains. Preliminary measurements with the MFC sensor show AC voltage outputs ranging from 1.8 to 3.5 V across a 10 MΩ resistor, corresponding to unrectified peak power values between 0.3 and 1.2 μW. After full-bridge rectification, 5 to 35 mV DC voltages were observed across a 1 kΩ load, resulting in rectified power between 0.02 μW and approximately 1 μW. While modest, it is significantly higher than LDT-based harvesters under the same excitation. This improvement stems from the MFC's larger active piezoelectric volume and superior charge transfer characteristics, yielding greater energy conversion efficiency during oscillatory motion.

[14] *MEAS LDT Series LDT1-028K Specifications*. TE Connectivity, 2017.

Given the inherently low power levels in the sub-microwatt to low-microwatt range, efficient power extraction becomes critical. Passive full-bridge rectifiers introduce significant forward voltage drops, which are especially problematic when working with millivolt-level signals. Integrating an ultra-low-voltage, high-efficiency energy harvesting IC is a practical solution. An LTC (linear technology) harvester can begin operating from input voltages as low as 20 mV and is specifically designed to harvest energy from high-impedance, low-voltage sources like piezoelectric and thermoelectric generators. Such active rectification and boost circuitry could substantially improve the adequate power available for downstream storage or load activation. These findings reinforce the superior performance of MFCs over traditional LDTs in wind-induced vibration harvesting and highlight the importance of system-level optimisation—particularly in rectification and power management—to fully capitalise on the potential of micro-scale energy harvesters.

C. *Electromagnetic Energy Harvesting as an Alternative*

An alternative approach is explored through a traditional electromagnetic configuration consisting of a cantilever-mounted magnet and a stationary coil.[15] While the existing structure of the MWEH, in essence, will remain, a magnet situated upon the bluff body oscillates relative to an adjacent coil. This motion generates electricity via Faraday's law of induction—

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t}$$

—where ε is the voltage or electromotive force generated in the conductor due to a changing magnetic flux (V), N is the number of coil loops, ϕ is the magnetic flux (Wb), and t is the change in time (s).

In contrast to the earlier piezoelectric setup, which yielded 1.8 to 3.5 V across a 10 MΩ resistor with unrectified power in the range of 0.3 to 1.2 μW, the electromagnetic approach demonstrated 10 to 20 mV voltage levels under wind-induced cantilever motion. While the voltage magnitude is lower than the piezoelectric counterpart, the coil's source impedance is significantly lower—on the order of tens of ohms—resulting in greater current output and unrectified power in the 8.3 to 33.9 μW range. However, these voltage levels remain insufficient to forward-bias a passive diode-bridge rectifier, highlighting the need for an active rectification and step-up solution employing an LTC, which can operate from inputs as low as 20 mV.

Electromagnetic harvesters remain well-suited for low-frequency vibrational sources due to their simple construction, robustness, and capacity to produce usable power at just a few hertz. While Faraday's law does predict voltage induction proportional to the rate of flux change, experimental constraints such as low peak magnet velocity (~0.5 m/s), coil resistance, and parasitic losses limit the voltage to the tens of millivolts range. Nonetheless, the measured power output remains significantly higher than typical LDT-based piezoelectric films, making electromagnetic harvesting a compelling complementary method to piezoelectric energy capture.

D. *Comparative Performance Metrics*

The experimental data suggests that while the electromagnetic harvester (Figures 8-10) does not achieve the theoretical milliwatt-level outputs previously anticipated, it still delivers 10 to 30 times more power than traditional LDT-based piezoelectric setups under the same excitation. The coil demonstrated consistent production in the tens of microwatts range, with a low internal impedance that makes it capable of driving current even into low-resistance loads, something that stiff, high-impedance

[15] Muscat, Andrew, et al. "Electromagnetic Vibrational Energy Harvesters: A Review." *Sensors*, vol. 22, no. 15, 2022, 5555.

piezoelectric devices struggle with at low frequencies.

Compared to the MFC, which produces higher voltages but suffers significant rectification losses with passive circuits, the electromagnetic harvester can provide more usable current if paired with a suitable active rectifier. The trade-off between voltage and current can be tuned through coil geometry and wire gauge: increasing the number of turns or stacking magnets can enhance voltage output. In contrast, a thicker wire reduces resistance and boosts current output. While voltage levels from electromagnetic harvesters are typically lower than piezoelectrics, their superior current-driving ability and mechanical robustness make them attractive for integration into wind-powered micro energy harvesting systems.

In summary, although the raw voltage levels remain modest, the electromagnetic harvester demonstrates strong potential when used with ultra-low-voltage energy harvesting ICs. Its compatibility with existing cantilever and bluff-body geometries, scalability, and enhanced power density at low frequencies reinforce its value as part of a hybrid energy harvesting strategy alongside piezoelectric elements like the MFC (Table 2).

IV. **Development of an Energy-Responsive Digital Display**

A. *Real-World Testing Environment*

A digital display powered entirely by MWEHs will act as a real-world testing platform and an outreach mechanism. This responsive interface validates energy generation and transforms otherwise imperceptible wind activity into a public narrative of environmental awareness. A significant limitation for predicting MWEH performance and applicability is the study's reliance on controlled testing conditions, which fail to reflect the complexities of real-world environments and expose a gap in current research, especially with integration into buildings.[16] Unlike lab tests, fluctuating wind speeds and turbulence significantly impact the energy-harvesting capabilities of these devices, while nearby obstacles affect optimal placement. As a real-world testing ground, the digital display will offer valuable insights into ideal device positioning, predictive placement, and the effects of non-uniform airflow—critical factors for assessing MWEH performance outside of controlled settings. Another key gap in recent studies is the emphasis on testing MWEHs as standalone devices, overlooking their primary advantage when deployed in an array. Arranging MWEHs in an array enhances their collective energy-harvesting potential, improving efficiency and effectiveness while refining their design to accommodate real-world conditions.

B. *Interactive Feedback and LED Visualisation*

Recent advancements seek to develop a real-time feedback system within the display, employing colour-coded LEDs powered directly by the MWEHs to visualise wind activity and device performance. The LED colours dynamically respond to variations in wind speed and cantilever deflection, offering an intuitive depiction of energy generation in real time. This feature demonstrates functional energy harvesting and provides an immediate visual cue of environmental interaction, fostering public engagement with the relationship between wind, motion, and power. Owing to their differing forward voltage thresholds—red LEDs activate at approximately 1.6 to 1.8 V, while blue LEDs require at least 2.2 V—this setup enables a vivid, responsive display in which color transitions reflect voltage fluctuations induced by changing wind conditions across the harvester circuit (Figures 11-12).

C. *Pedagogical and Public Engagement Roles*

The digital display also offers a pedagogical function, a small-scale demonstration of a system that could be expanded for large-scale implementation. Public demonstrations of this technology foster a deeper understanding of

[16] Calautit, Katrina, and Cameron Johnstone. "State-of-The-Art Review of Micro to Small-Scale Wind Energy Harvesting Technologies for Building Integration." *Energy Conversion and Management: X*, vol. 20, 2023, 100457.

non-traditional renewable energy sources, stimulating discussions on energy harvesting challenges and their intersection with revitalising existing buildings and integrating into new buildings. Through visible oscillation and illumination, the system makes invisible energy flows tangible, enhancing public understanding and acceptance of distributed renewable technologies. Additionally, real-world feedback is essential for further optimisation. It provides critical insights into design and implementation challenges while highlighting opportunities for scaling the technology.

Interacting with the digital display is expected to spark interest among researchers, students, and entrepreneurs, encouraging further exploration of micro-energy harvesting advancements. This engagement will promote interdisciplinary collaboration in innovative building design and renewable energy integration, fostering a deeper understanding of traditional systems and emerging technologies. By bridging the gap between research and real-world applications, the digital display plays a crucial role in advancing the development and adoption of these innovative energy solutions.

D. *Immediate Research Optimisations and Future Development Pathways*

As ongoing research to construct an energy-independent digital display, the immediate development of these explorations into micro wind energy harvesters (MWEHs) will begin with targeted technical optimisations to enhance power density and overall efficiency.

Effective management of energy harvested by MWEHs is critical to ensuring stable and practical usage, particularly for real-world applications such as the proposed digital display. Given harvested energy's intermittent and low-power characteristics, implementing energy storage and management solutions is essential. Initial strategies involve low-loss rectification and voltage regulation circuits combined with supercapacitor or battery storage systems, ensuring a stable DC power supply despite variable wind conditions. This includes improving magnetic flux linkage, tuning mechanical resonance, and refining electrical conversion. Both the introduction of electromagnetic and MFC conversion methods will be further experimented with. For electromagnetic conversion, precise coil-magnet alignment and optimised coil geometry are essential to maximise magnetic field interaction. At the same time, electrical efficiency can be improved significantly through advanced rectification using low-dropout and low-power active circuits and better impedance matching with capacitors.

To support and accelerate these optimisations, flow-advanced diagnostics using Particle Image Velocimetry (PIV) and Proper Orthogonal Decomposition (POD) can provide critical insights into the system's dynamic behaviour. These tools enable high-resolution visualisation and quantitative analysis of flow-induced motion around the MWEH, helping identify dominant modes of energy transfer and revealing key design parameters that influence mechanical and electromagnetic performance.

Looking toward future development, research will expand to include strategies for large-scale deployment and long-term feasibility of MWEHs in real-world environments (Figure 13). Continued system design optimisation, placement, and environmental integration will maximise energy capture and reliability. PIV and POD will remain vital throughout this phase, enabling detailed, data-driven refinement of harvester configurations under varied operating conditions.

In the broader context of carbon neutrality and sustainable development, MWEHs represent a promising solution for distributed, renewable energy generation. Through advanced diagnostics, thoughtful integration, and system-level innovation, MWEHs have the potential to become a key component in building resilient, energy-efficient environments.

E. *Local and Global Impacts*

Integrating MWEHs into building surfaces presents a scalable strategy for enhancing urban energy resilience and autonomy, particularly in dense environments where conventional renewable systems face spatial limitations (Figure 13). By offering a decentralised alternative, MWEHs reduce dependence on centralised utilities while supporting low-impact retrofitting. Unlike traditional upgrades that often require substantial structural intervention, MWEHs can be embedded into facades, enabling emission reductions without large scale redevelopment. This is crucial as projections indicate that by 2040, two-thirds of the global building stock will consist of existing structures.[17] With demolition accounting for over 90% of construction and demolition (C&D) waste, the need to retrofit rather than rebuild is both an environmental and architectural imperative.

This research extends beyond infrastructure, introducing a public-facing, energy-independent display powered entirely by MWEHs as a demonstrative platform for renewable technologies. The project also advances the 'surface-to-city' framework, a model for distributed energy deployment across diverse building typologies. It fosters climate awareness, promotes interdisciplinary collaboration, and explores new spatial and material aesthetics emerging from integrating environmental systems into the urban fabric.

At a systemic level, MWEHs contribute to decarbonisation by capturing ambient wind energy in locations unsuitable for traditional renewables. Their integration repositions buildings as consumers and energy producers, aligning with global climate targets and supporting the transition to net-zero cities. While long-term operational costs are low, initial investment remains challenging due to advanced materials, precision fabrication, and specialised installation. Achieving economic feasibility requires economies of scale and manufacturing efficiencies. Furthermore, widespread adoption depends on overcoming regulatory barriers, including zoning laws, building codes, and facade standards, necessitating ongoing engagement with policymakers and the development of standardised protocols.

With their minimal maintenance requirements and adaptability, MWEHs are particularly viable for deployment in underserved regions, advancing global energy equity and decentralising access to clean technologies. Adopting micro-scale, building-integrated systems can mitigate urban environmental stresses, such as air pollution and the heat island effect, while contributing to a resilient, distributed energy future.

V. **Conclusion**

This article advances renewable energy harvesting through the design and experimental validation of Micro Wind Energy Harvesters (MWEHs) optimised for low-speed urban wind conditions via galloping-induced vibrations. Integrating architectural design with advanced engineering analysis, the study refines MWEH geometry and performance while exploring both piezoelectric and electromagnetic methods for efficient energy conversion. The work culminates in a self-powered digital display that serves as both a functional prototype and a tool for public engagement, introducing a scalable surface-to-city model for distributed energy generation, particularly suited for retrofitting the existing urban built environment.

MWEHs offer a low-maintenance, adaptable solution for embedding renewable energy systems into building facades, converting underutilised surfaces into productive infrastructures. Their compact, modular form makes them exceptionally viable in dense urban settings where traditional systems are often impractical. As retrofitting grows increasingly urgent, given that two-thirds of

[17] "Sustainable Management of Construction and Demolition Materials." *US Environmental Protection Agency Webpage*, 22 Aug. 2018.

the global building stock projected for 2040 already exists, MWEHs present a feasible pathway to enhance energy performance without requiring major redevelopment.

Despite their promise, MWEHs face challenges such as energy intermittency, structural fatigue, and limited per-unit power output. These constraints demand precise material selection, aerodynamic tuning, and array-scale deployment. This article provides a comparative analysis of piezoelectric and electromagnetic harvesting strategies, showing that while piezoelectric devices like Macro Fibre Composites (MFCs) deliver higher voltages, electromagnetic systems generate greater current and yield superior power output at low frequencies, particularly when paired with active rectification circuits.

The resulting interactive display—powered entirely by MWEHs and visualised through responsive LEDS—demonstrates the system's viability while fostering public awareness and interdisciplinary collaboration. By reimagining building surfaces as energy-generating interfaces, the project contributes to climate-positive design at both local and global scales. Broader deployment of MWEHs will also benefit from proactive policy alignment and standardised integration protocols within architectural and urban design frameworks.

Ultimately, this work bridges innovation and application, positioning MWEHs as a pragmatic and symbolic strategy for decentralised renewable energy integration. It underscores the potential for buildings to consume and produce energy, advancing the next generation of resilient, self-powered, and climate-responsive urban infrastructure.

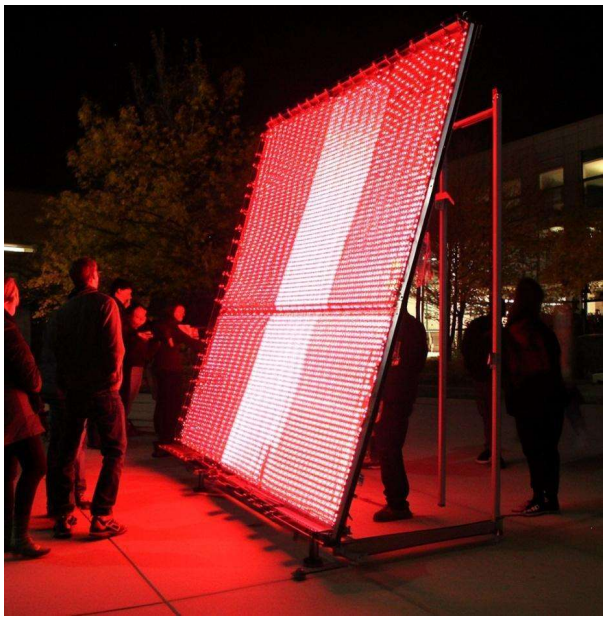


Figure 1: Conceptual Rendering of a Self-Powered Display Powered Solely by Ambient Wind and Vibration, Harnessed by Integrating Micro Wind Energy Harvesters. The Energy Is Captured and Converted into Electricity Using Piezoelectric or Electromagnetic Mechanisms, Demonstrating the Potential of MWEHs in Architectural Applications.

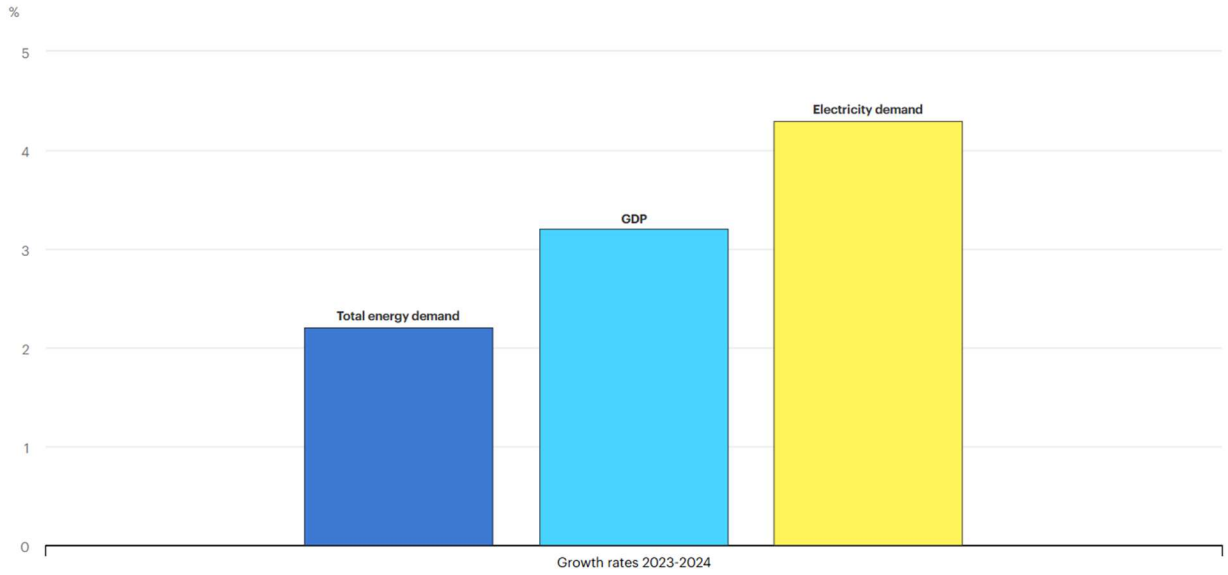


Figure 2: This Global Energy Demand Growth Rate Chart in 2023-2024 Demonstrates a 2.2% General Energy Increase (Source: IEA).

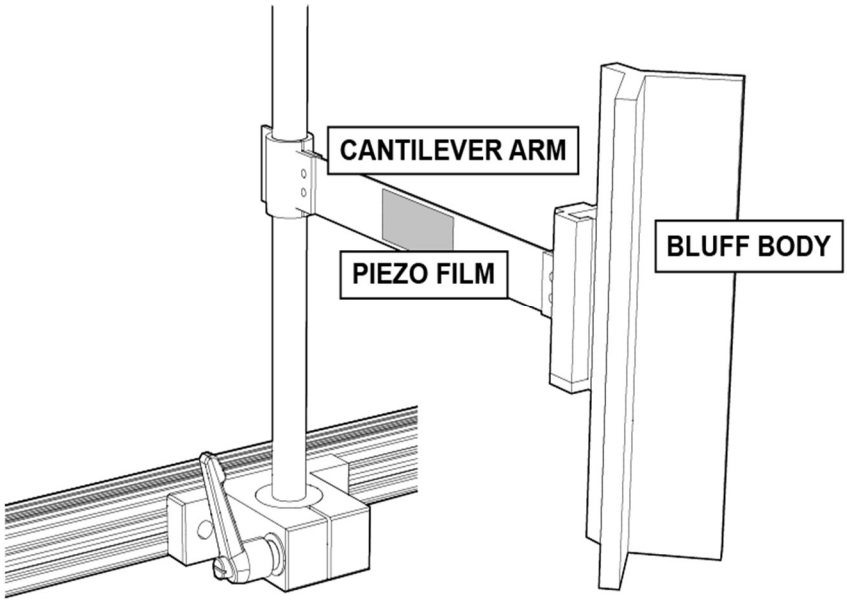


Figure 3: Components of a Galloping-Based MWEH. Wind Excites the Bluff Body, Causing the Cantilever Arm to Bend. This Deformation Strains the Attached Piezoelectric Film, Generating an Electrical Charge.

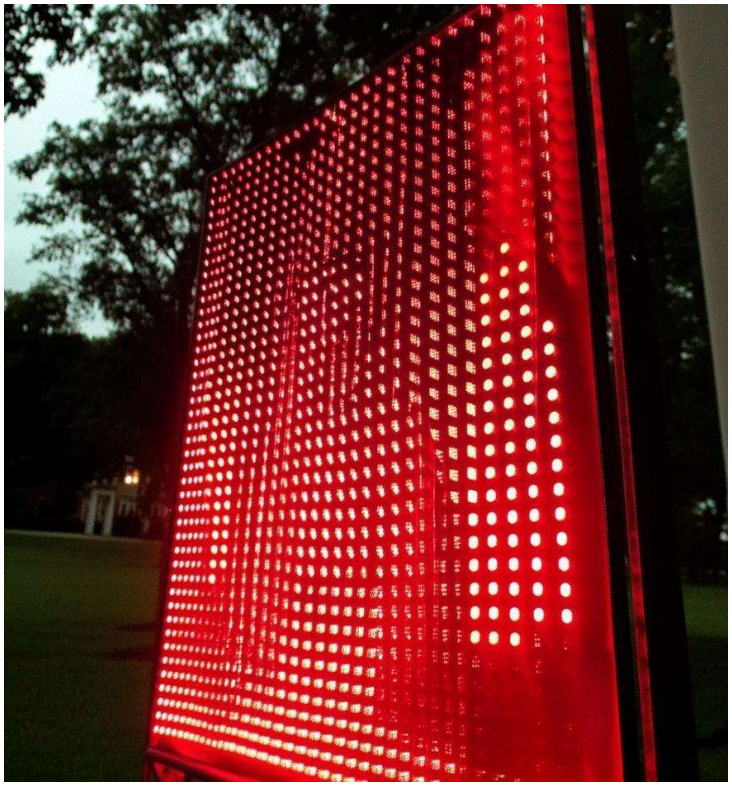


Figure 4: Conceptual Rendering of the Visual Impact of a Self-Powered Display Driven by Energy Generated by Micro Wind Energy Harvesters.

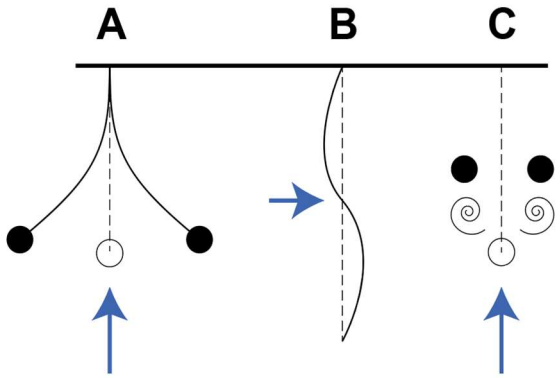


Figure 5: Diagram Showing Top-View Representations of Three Wind-Induced Vibration Phenomena. Galloping (A), Fluttering (B), and Vortex-Induced Vibration (VIV) (C). The Black Shapes Depict Bluff Bodies in Motion, Responding to the Predominant Wind Direction in Blue. Dashed Lines and White Bluff Bodies Represent the Neutral, Undisturbed Position. In Galloping (A), Motion Occurs Primarily Perpendicular to the Wind. Fluttering (B) is Typically Excited along a Broad Surface Area Aligned with the Wind. VIV (C) Results from Alternating Vortex Shedding around the Bluff Body, Inducing Oscillatory Movement.

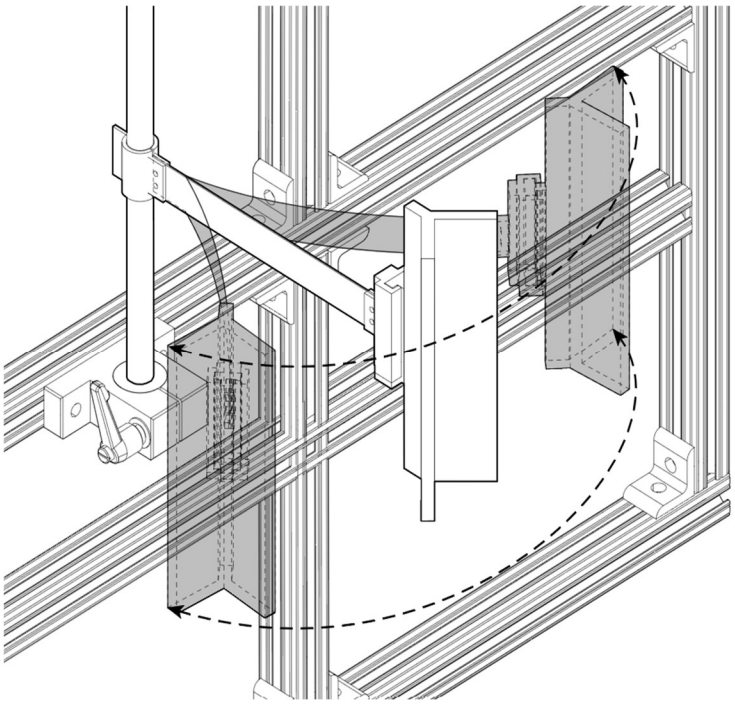


Figure 6: Diagram Illustrating the Galloping Motion of the MWEH Induced by Wind Excitation.

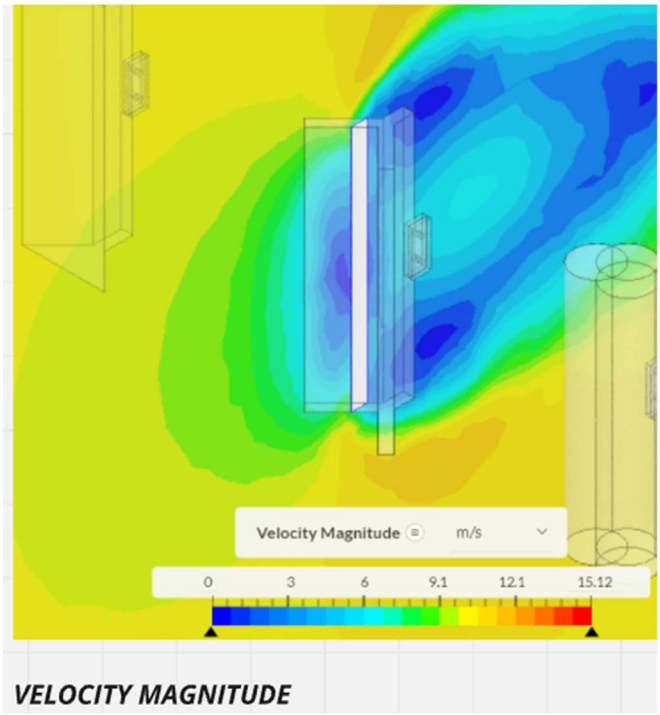


Figure 7: CFD Rendering of Vortex Shredding from a Y-Shaped Bluff Body.

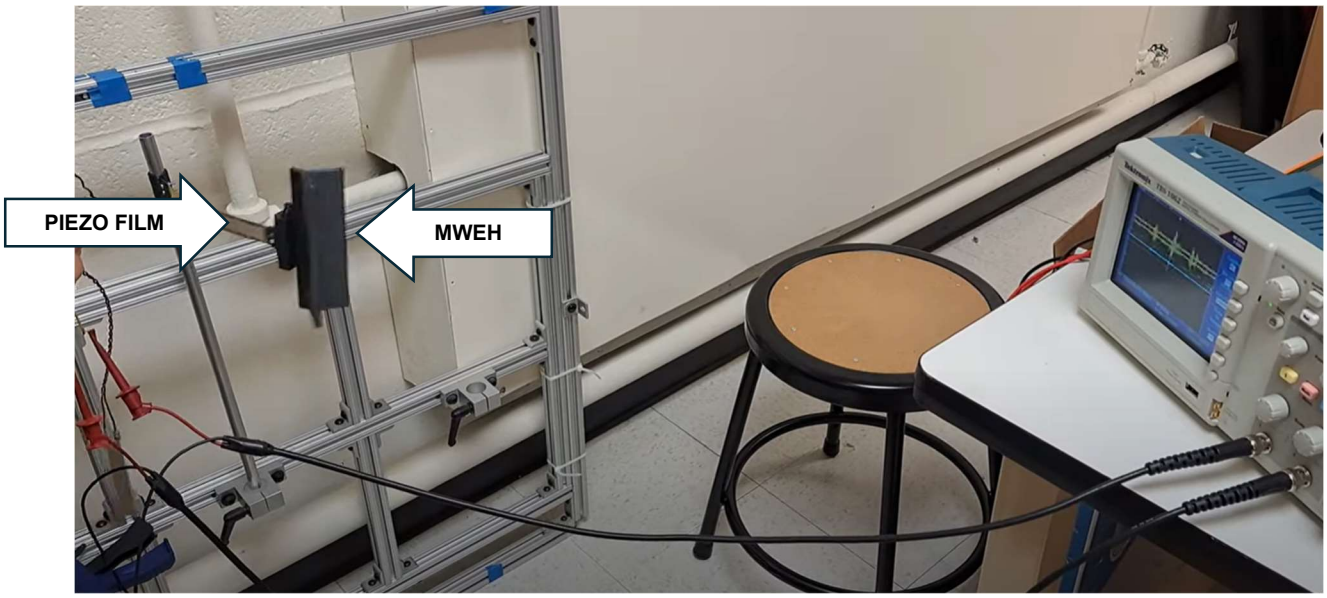


Figure 8: Image Showing Experimental Testing and Data Collection for the MWEH. The Device is Mounted on a Frame to Fit a Future Wind Tunnel Setup. Although the Blower Unit (Used to Excite the MWEH) is Out of Frame, Power Output and Oscillation Frequency (in Hertz) Are Measured Using a Micrometre and Oscilloscope (Shown) Respectively. Voltage Readings Were Also Recorded Using the Oscilloscope for Comparative Analysis.

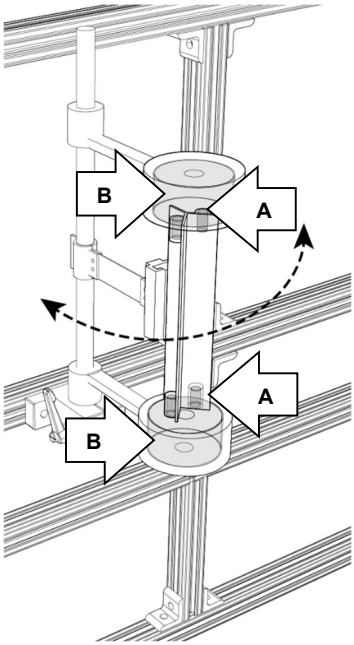


Figure 9: This Schematic Design Demonstrates an Electromagnetic Option that Integrates Two Magnets into Opposite Sides of the Bluff Body (A). Coils (B) Are Positioned Above and Below. As the Bluff Body Undergoes a Galloping Motion, the Magnets Sweep across the Coils, Inducing an Electrical Current as They Move through the Magnetic Field.

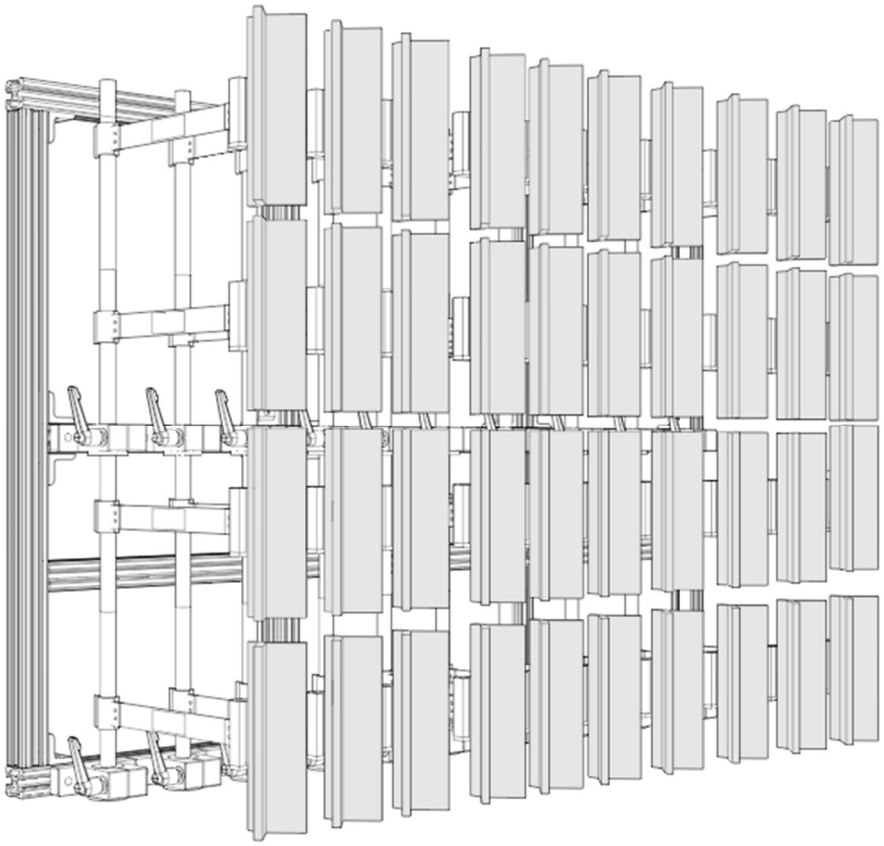


Figure 10: Drawing Demonstrating the MWEHs Configured into an Array.

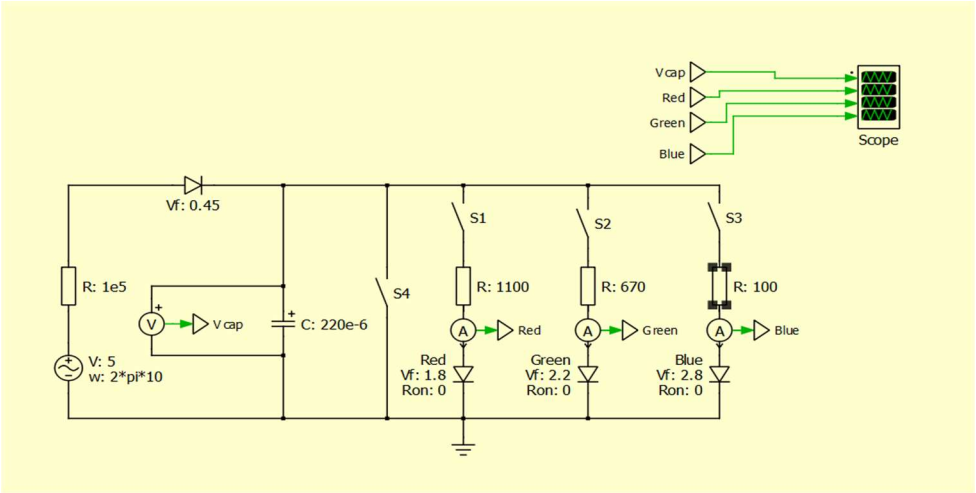


Figure 11: Circuit Schematic Illustrating Voltage-Dependent Activation of Red, Green, and Blue LEDs.

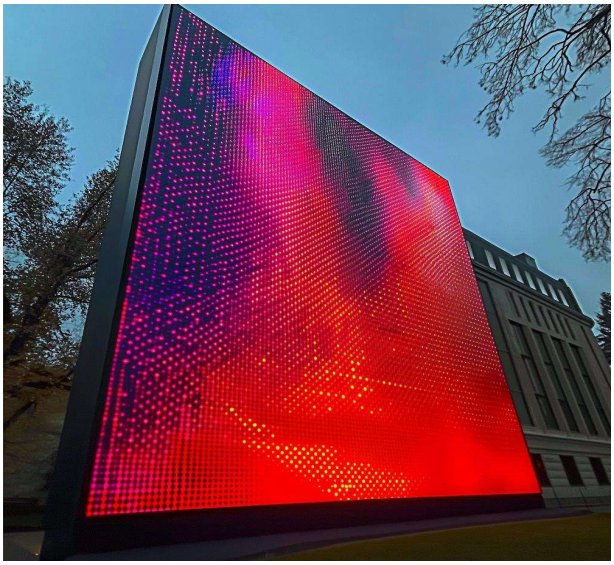


Figure 12: Conceptual Image Demonstrating Voltage-Dependent Activation of Multi-Coloured LEDs within the Display due to Increasing Wind Speed. At Low Wind Speeds, Same-Coloured LEDs Activate First due to Their Lower Voltage Threshold; as Wind Speed Increases, Other LEDs of Different Colours Illuminate, Reflecting Higher Voltage Outputs from the Energy Harvesters.



Figure 13: Conceptual Image Demonstrating a Secondary Skin Attached to an Existing Building Consisting of MWEHs Excited by the Wind, Harnessing Renewable Energy in Their Movement.

Moment of Inertia	Diameter (cm)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
9.2930E-11	0.00E+00	6.76E-02	9.56E-02	1.17E-01	1.35E-01	1.51E-01	1.66E-01	1.79E-01	1.91E-01	2.03E-01
1.1430E-10	0.00E+00	7.50E-02	1.06E-01	1.30E-01	1.50E-01	1.68E-01	1.84E-01	1.98E-01	2.12E-01	2.25E-01
1.3872E-10	0.00E+00	8.26E-02	1.17E-01	1.43E-01	1.65E-01	1.85E-01	2.02E-01	2.18E-01	2.34E-01	2.48E-01
1.6639E-10	0.00E+00	9.04E-02	1.28E-01	1.57E-01	1.81E-01	2.02E-01	2.22E-01	2.39E-01	2.56E-01	2.71E-01
1.9751E-10	0.00E+00	9.85E-02	1.39E-01	1.71E-01	1.97E-01	2.20E-01	2.41E-01	2.61E-01	2.79E-01	2.96E-01
2.3229E-10	0.00E+00	1.07E-01	1.51E-01	1.85E-01	2.14E-01	2.39E-01	2.62E-01	2.83E-01	3.02E-01	3.21E-01
2.7093E-10	0.00E+00	1.15E-01	1.63E-01	2.00E-01	2.31E-01	2.58E-01	2.83E-01	3.05E-01	3.26E-01	3.46E-01
3.1364E-10	0.00E+00	1.24E-01	1.76E-01	2.15E-01	2.48E-01	2.78E-01	3.04E-01	3.28E-01	3.51E-01	3.72E-01
3.6061E-10	0.00E+00	1.33E-01	1.88E-01	2.31E-01	2.66E-01	2.98E-01	3.26E-01	3.52E-01	3.77E-01	3.99E-01
4.1206E-10	0.00E+00	1.42E-01	2.01E-01	2.46E-01	2.85E-01	3.18E-01	3.49E-01	3.77E-01	4.03E-01	4.27E-01
4.6817E-10	0.00E+00	1.52E-01	2.15E-01	2.63E-01	3.03E-01	3.39E-01	3.72E-01	4.01E-01	4.29E-01	4.55E-01
5.2917E-10	0.00E+00	1.61E-01	2.28E-01	2.79E-01	3.23E-01	3.61E-01	3.95E-01	4.27E-01	4.56E-01	4.84E-01
5.9524E-10	0.00E+00	1.71E-01	2.42E-01	2.96E-01	3.42E-01	3.82E-01	4.19E-01	4.53E-01	4.84E-01	5.13E-01
6.6660E-10	0.00E+00	1.81E-01	2.56E-01	3.14E-01	3.62E-01	4.05E-01	4.43E-01	4.79E-01	5.12E-01	5.43E-01
7.4344E-10	0.00E+00	1.91E-01	2.70E-01	3.31E-01	3.82E-01	4.27E-01	4.68E-01	5.06E-01	5.41E-01	5.73E-01
8.2597E-10	0.00E+00	2.01E-01	2.85E-01	3.49E-01	4.03E-01	4.51E-01	4.94E-01	5.33E-01	5.70E-01	6.04E-01
9.1440E-10	0.00E+00	2.12E-01	3.00E-01	3.67E-01	4.24E-01	4.74E-01	5.19E-01	5.61E-01	6.00E-01	6.36E-01
1.0089E-09	0.00E+00	2.23E-01	3.15E-01	3.86E-01	4.45E-01	4.98E-01	5.45E-01	5.89E-01	6.30E-01	6.68E-01
1.1097E-09	0.00E+00	2.34E-01	3.30E-01	4.05E-01	4.67E-01	5.22E-01	5.72E-01	6.18E-01	6.61E-01	7.01E-01

Table 1: An Excerpt from the Table Showing Design Input Results that Fall within the Optimal Strouhal Range, Highlighted in Light Green. The Vortex Shedding Frequency Determined from Strouhal Analysis Directly Informs the Resonant Tuning of the Cantilever Beam to Maximise Energy Conversion Efficiency.

Performance Metric	***Piezoelectric MWEH Array***	***Electromagnetic MWEH Array***
Estimated power output per unit *(in moderate wind)*	***Very low*** *0.1 to 10 uW per device*	***Higher*** *1 to 100 uW per device*
Voltage output (AC, open-circuit)	***High voltage, low current*** *Up to ~100 V*	***Low to moderate voltage*** *Typically in the 0.001 to 5 V range*
Current output (short-circuit)	***Microamp-range currents*** *Ranges in tens of μA or less under load*	***Milliamp-range currents*** *Ranges in mA under load*
Typical source impedance	***High*** *~1 to 10 MΩ*	***Low*** *~ 10 to 100 MΩ*
Integration complexity	***Electrical:*** *It requires high-impedance interface circuits and rectifiers to collect energy without excessively loading the piezo. Managing many high-voltage outputs in parallel adds complexity.*	***Electrical:*** *Simpler rectification and power combining. With more moderate voltages, standard power electronics can be used.*

Performance Metric	***Piezoelectric MWEH Array***	***Electromagnetic MWEH Array***
	Mechanical: *Piezo elements are compact and light, simplifying mechanical integration on the façade with no heavy magnets.*	***Mechanical:*** *Slightly more complex: magnets add weight and must be securely mounted; coils must be positioned and wired. However, only minimal modifications to the original design are needed, and the system remains passive, requiring no additional power.*

Table 2: Theoretical Performance Comparison: A Side-By-Side Comparison of Expected Electrical Performance for a Piezoelectric vs an Electromagnetic MWEH Array, Assuming Similar Conditions (Wind ~5 m / s, Devices Tuned to Resonance, Using Typical Commercial Piezo Elements, and N52 Neodymium Magnets). This Theoretical Comparison Illustrates Design Trade-Offs (Not Based on Measured Data).