# ENERGY HARVESTING TECHNOLOGIES USING WIND PRESSURE IN THE ROAD TUNNELS: A REVIEW

**Avliyobek Juraboev**
*"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University , PhD student*
*Tashkent, Uzbekistan*
*E-mail: avliyobek.juraboev@gmail.com*

**Annotatsiya.** Global iqlim o'zgarishi sharoitida barqaror va qayta tiklanadigan energiya manbalariga bo'lgan talab tobora ortib bormoqda. An'anaviy qazilma yoqilg'ilar iste'moli tufayli yuzaga kelayotgan issiqxona gazlari chiqindilarining doimiy ko'payishi tadqiqotchilar va siyosatchilarni toza energiya ishlab chiqarishning innovatsion usullarini izlashga undamoqda. Shunday yangi konsepsiyalardan biri – yo'l tunnelarida harakatlanayotgan transport vositalari hosil qiladigan shamol bosimi orqali elektr energiyasi ishlab chiqarishdir. Ushbu yondashuv transport vositalari harakati natijasida hosil bo'ladigan havo oqimining kinetik energiyasidan foydalanadi va uni mikro shamol turbinalari hamda energiya yig'ish qurilmalari yordamida elektr energiyasiga aylantiradi. Odatda bekorga sarflanib ketadigan ushbu energiyadan foydalanish havoni ifloslanishini kamaytirish hamda shahar transport infratuzilmasining energiya samaradorligini oshirish bo'yicha istiqbolli yechim sifatida ko'riladi. Ushbu tadqiqotning asosiy maqsadi - tunnel ichida transport vositalari harakati natijasida hosil bo'ladigan shamol energiyasi bo'yicha olib borilgan ilmiy izlanish natijalarini tahlil qilish va umumlashtirishdan iborat. Mavjud adabiyotlar keng qamrovli tahlili asosida mazkur sohada qo'llaniladigan zamonaviy texnologiyalar, metodologiyalar va eksperimental modellarga baho beriladi. Shuningdek, bu tizimlarning real sharoitlarda amaliy qo'llanilishi, afzalliklari va cheklovlari o'rganiladi. Tadqiqotda ko'rib chiqiladigan asosiy jihatlar — aerodinamik tahlil, turbinalarni optimal joylashtirish, energiyani aylantirish samaradorligi va bu tizimlarni mavjud tunnel infratuzilmasiga integratsiya qilishdir. Mazkur sharh natijalari transport vositalari hosil qiladigan shamol energiyasidan foydalanish global barqaror energiya yechimlariga o'tishda qanday rol o'ynashi mumkinligini chuqurroq tushunishga yordam beradi. Bundan tashqari, xarajatlarni tahlil qilish, texnik xizmat ko'rsatish bilan bog'liq muammolar va kelajakdagi "aqlli" shaharlar uchun yirik miqyosda joriy etish strategiyalari kabi qo'shimcha tadqiqotlarni talab qiladigan yo'nalishlar ham ko'rsatib beriladi.

**Kalit so'zlar:** shamol energetikasi, vertikal o'qli shamol turbinalari, qayta tiklanadigan energiya.

**Аннотация.** В контексте глобального изменения климата спрос на устойчивые и возобновляемые источники энергии становится все более



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актуальным. Непрерывное увеличение выбросов парниковых газов, вызванное потреблением традиционных ископаемых видов топлива, побудило исследователей и политиков к поиску инновационных методов производства чистой энергии. Одной из новых концепций является производство электроэнергии за счет давления ветра, создаваемого движущимися транспортными средствами в дорожных туннелях. Этот подход использует кинетическую энергию воздушного потока, создаваемого транспортными средствами, и преобразует ее в электрическую энергию с помощью таких систем, как микро ветряные турбины и устройства для сбора энергии. Используя энергию, которая в противном случае была бы потрачена впустую, этот метод представляет собой потенциальное решение для снижения загрязнения воздуха и повышения энергоэффективности городской транспортной инфраструктуры. Основная цель данного исследования заключается в анализе и обобщении результатов исследований, посвященных генерации энергии ветра, вызываемого движением транспортных средств в туннелях. На основе всестороннего обзора существующей литературы в рамках исследования проводится анализ современных технологий, методологий и экспериментальных моделей, используемых в данной области. Кроме того, оцениваются практическая реализуемость, преимущества и ограничения таких систем в реальных условиях эксплуатации. Ключевые аспекты, рассматриваемые в исследовании, включают аэродинамический анализ, оптимизацию размещения турбин, эффективность преобразования энергии и интеграцию этих систем в существующую инфраструктуру туннелей. Результаты этого обзора способствуют лучшему пониманию того, как энергия ветра, генерируемая транспортными средствами, может способствовать глобальному переходу к устойчивым энергетическим решениям. Кроме того, в нем выделены области, требующие дальнейшего изучения, в том числе анализ затрат, проблемы технического обслуживания и стратегии крупномасштабного внедрения для будущего развития «умных» городов.

Ключевые слова: ветроэнергетика, вертикально-осевая ветротурбина, возобновляемая энергия.

**Abstract.** In the context of global climate change, the demand for sustainable and renewable energy sources has become increasingly urgent. The continuous rise in greenhouse gas emissions caused by conventional fossil fuel consumption has led researchers and policymakers to explore innovative methods for clean energy production. One emerging concept is the generation of electricity from the wind pressure created by moving vehicles in road tunnels. This approach utilizes the kinetic energy of airflow induced by vehicles and converts it into electrical energy



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through systems such as micro wind turbines and energy harvesting devices. By harnessing otherwise wasted energy, this method presents a potential solution to reduce air pollution and improve energy efficiency in urban transportation infrastructures. The primary purpose of this study is to analyze and synthesize research findings that focus on vehicle-induced wind energy generation in tunnels. Through a comprehensive review of existing literature, the study aims to identify current technologies, methodologies, and experimental models used in this field. Additionally, it evaluates the feasibility, advantages, and limitations of such systems in real-world applications. Key aspects considered include aerodynamic analysis, turbine placement optimization, energy conversion efficiency, and the integration of these systems into existing tunnel infrastructures. The findings from this review contribute to a better understanding of how vehicle-generated wind energy can support the global transition toward sustainable energy solutions. Moreover, it highlights areas requiring further investigation, including cost analysis, maintenance challenges, and large-scale implementation strategies for future smart city developments.

**Keywords:** Wind energy, vertical-axis wind turbine, renewable energy.

## 1.Introduction

The increasing depletion of fossil fuels has intensified the global quest for sustainable and clean energy alternatives, bringing renewable sources to the forefront of energy innovation. Among these, wind energy stands out for its wide availability and minimal environmental impact, offering a viable solution to meet the growing demand for energy. Harnessing the power of the wind efficiently converts the kinetic energy of natural air movement into electrical energy, thereby significantly reducing greenhouse gas emissions. Advances in technology and expertise have helped to increase the efficiency of wind power and its integration into existing energy systems [1].

Renewable sources have attracted attention due to their potential to surpass fossil fuels not only in terms of longevity but also in terms of environmental responsibility. In addition, such localized power generation reduces dependence on centralized power plants, thus contributing to broader environmental goals. These benefits are directly in line with ecological design principles aimed at restoring environmental quality and reflect the initiatives of other ecological urban projects that emphasize sustainability and community well-being [2].



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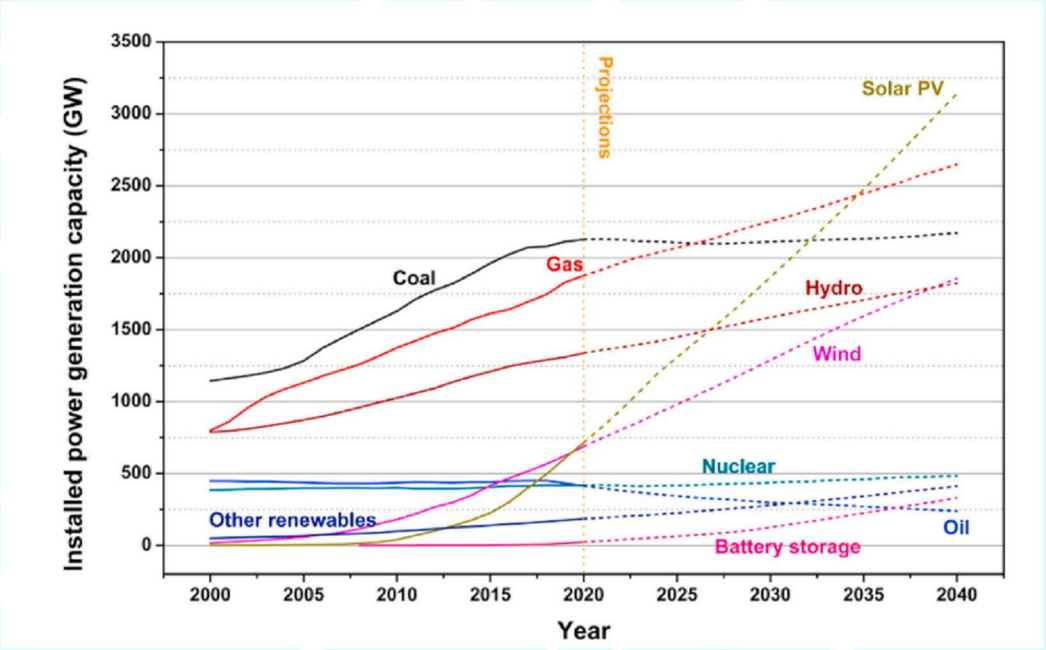



**Figure 1. Installed power generation capacity by source in Stated Policies Scenario for 2000–2040 [3] (original source: https://www.iea.org/data-and-statistics/charts/installed-power-generation-capacity-by-source-in-the-stated-policies-scenario-2000-2040).**

This transition reflects an important shift towards sustainable energy security and environmental conservation, emphasizing the critical role of wind energy in the wider renewable energy system [4]. One promising area is energy harvesting from wind pressure fluctuations, which are a natural consequence of aerodynamic interactions in confined spaces such as road tunnels. These environments exhibit complex flow dynamics influenced by variables such as tunnel geometry and vehicle traffic, resulting in pressure fluctuations that can potentially be utilised as a renewable energy source. Studies in related fields have shown that flow-induced fluctuations around polygonal structures exhibit dynamic behaviour that depends on the shape and flow conditions, providing valuable insights into how aerodynamic forces can be used to generate energy [5]. Moreover, advances in the understanding of wind-induced responses on large structures have highlighted the importance of characterising aerodynamic properties under wind fluctuations to optimise energy extraction systems [6]. This paper investigates the characterisation of wind pressure fluctuations in road tunnels and evaluates their potential use as a potential energy harvesting method.

## 2.RESULTS

**2.1** Explanation of how wind pressure is converted into mechanical and electrical energy

Converting wind pressure into useful energy begins with the aerodynamic design of turbines, which convert the kinetic energy of moving air into mechanical



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motion. When the wind flows around the blades, the pressure difference creates a lift force, causing the rotor to rotate.

Wind kinetic energy:

$$E_k = \frac{1}{2}\rho A \upsilon^3$$

Where:

- ρ = air density (kg/m³)
- A = area swept by the turbine blades (m²)
- $\upsilon$ = wind velocity (m/s)

This rotational motion drives a mechanical shaft connected to an electrical generator, where mechanical energy is converted into electrical energy through electromagnetic induction. Advanced materials and devices such as piezoelectric transducers also offer alternative methods of converting mechanical strain caused by wind pressure directly into electrical signals, utilizing the inherent ability of the material to generate an electric field under mechanical force. These systems require sophisticated modelling to optimize power generation under different wind conditions, highlighting the importance of advances in mechanical and electrical engineering in this field [7]. Meanwhile, the resulting electrical energy can be stored or converted into chemical forms, such as hydrogen or ammonia, for efficient energy transport or subsequent power generation, illustrating the wider potential of wind energy vectors [8].

The use of wind pressure for energy harvesting, beyond traditional wind turbines, has significant potential. Innovative technologies such as piezoelectric devices, micro windmills and flexible energy harvesters convert wind pressure fluctuations into electricity, especially in urban and remote areas where conventional turbines are inefficient. Predictive climate modelling optimises the performance of these devices by predicting wind for maximum efficiency [9]. Materials and structural optimisation studies that combine climate science and engineering aim to improve response to wind pressure [10]. Efficient utilisation of wind pressure supports renewable energy goals and promotes sustainable technological innovations adaptable to different conditions.

**2.2 Various technologies and systems that utilize wind pressure for energy generation**

Advances in the use of wind pressure for power generation have led to the development of various technologies designed to maximise efficiency in different environments. Among these, piezoelectric transducers integrated into optimised rotor blade designs are showing significant breakthroughs, especially in low wind speed conditions. By utilising concentric rings with piezoelectric transducers and


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strategically placed magnetic plates, this innovative design achieves significant power while maintaining durability under prolonged wind exposure (Alhumaid S).

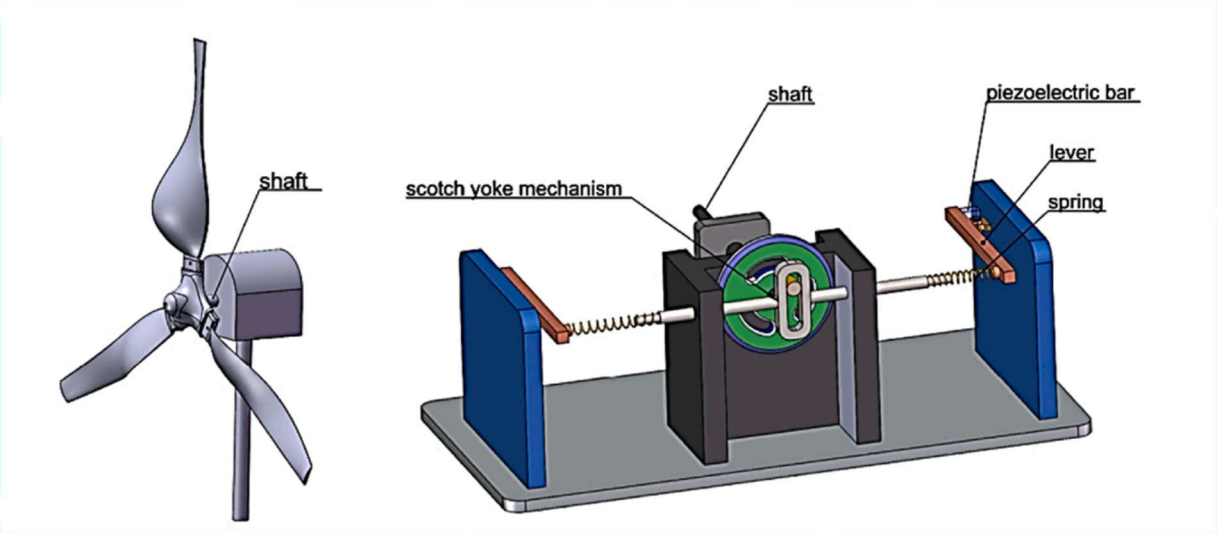



**Figure 2: Energy harvesting from wind using Piezoelectric Harvester. (Tao et al., 2017)**

In addition, vertical axis wind turbines (VAWTs) installed along motorways harness wind energy generated by passing vehicles, combining mechanical energy harvesting with Internet of Things (IoT) technology to improve system monitoring and efficiency [11]. The synergy between mechanical design improvements and data-driven intelligent control exemplifies a multi-faceted approach to energy harvesting to improve the reliability and adaptability of renewable energy. Together, these systems emphasize the potential for harnessing wind pressure beyond traditional large-scale turbines, extending applications from infrastructure integration to small-scale energy solutions. Engineering projects such as Ferry Free E39 in Norway illustrate innovative methods where transport designs are improved to support renewable energy generation, combining wave, tidal, wind and solar energy systems to reduce costs and increase competitiveness [12].


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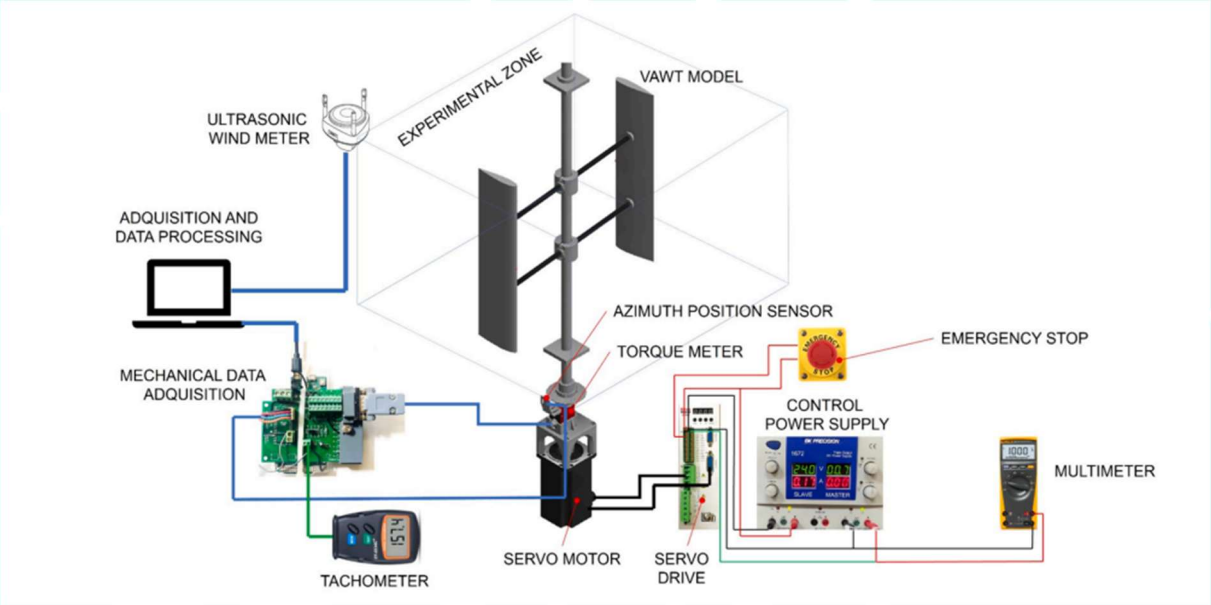



**Figure 3: System combined with VAWTs and IoT [13]**

In this context, energy harvesting technologies utilizing wind pressure fluctuations, especially in closed environments such as road tunnels, represent a promising frontier. Studies on flow-induced oscillations in specific geometries such as polygonal cylinders demonstrate how aerodynamic forces and vortex-induced vibrations can be utilized for energy extraction, with variations in the angle of incidence and shape of the structure significantly affecting performance [5]. These results suggest that wind pressure fluctuations in tunnels can be optimized for efficient energy conversion, using their inherent flow dynamics to capture kinetic energy that is otherwise wasted, and contribute to the renewable energy challenge in transport infrastructure.

### 2.3 Analysis of wind pressure dynamics in confined spaces

Understanding the behavior of wind pressure in confined spaces is critical to optimizing energy harvesting techniques in road tunnels. Enclosed spaces such as tunnels experience complex air flows that are influenced by factors such as vehicle traffic, ventilation systems and tunnel geometry.

Dynamic Pressure from vehicle-induced wind:

$$P = \frac{1}{2}\rho V^2$$

*Where V is vehicle-induced air velocity (not just natural wind)*

These interactions result in wind pressure fluctuations that are significantly different from open air conditions, creating opportunities to capture mechanical energy that is otherwise lost. The dynamic nature of these pressures is due to turbulence and vortex disruption, processes that cause periodic force fluctuations on tunnel structures.

Force on harvesting structure:


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$$F = C_\rho A \frac{1}{2} \rho V^2$$

Vehicle traffic in road tunnels creates complex airflow patterns; as vehicles move, they displace air and create pressure differentials, resulting in longitudinal, transverse and vertical airflows that vary depending on tunnel geometry and traffic conditions.

The aerodynamic forces acting on moving vehicles, influenced by factors such as vehicle shape and speed, directly affect the volume and velocity of air pushed forwards and pulled backwards, resulting in unique flow regimes in the tunnel [14]. Recent research highlights the potential to harness such oscillations through advanced conversion techniques including electromagnetic, piezoelectric and triboelectric mechanisms that have been effectively tested on roads and other infrastructure elements [15].

Experience with large-scale infrastructure projects, such as the Ferry Free E39 initiative, shows how the integration of energy harvesting devices into closed or semi-closed corridors can complement renewable energy efforts by harnessing the power of the surrounding wind [12]. This synergy between wind dynamics and structural design provides a basis for developing new strategies for sustainable energy production in tunnels.

**2.4 How tunnel geometry and materials affect air circulation patterns**

The dynamic interaction between the airflow and the geometry of the structure also plays an important role in the behaviour of wind pressure fluctuations in confined spaces such as road tunnels. Variations in cross-sectional shape, similar to the effects observed in polygonal or circular cylinders, provoke complex flow separation and vortex disruption, which significantly affect the pressure distribution along the tunnel walls [5].

**Table 1:**

**Wind Pressure and Airflow Data in Confined Tunnel Spaces**

| Parameter | Typical Values / Observations | Source / Citation |
|---|---|---|
| **Vehicle-Induced Peak Pressure** | Negative pressure peaks up to **−250 Pa** beneath tunnel roofs during vehicle passage | [16]. *Dynamic Pressures on Tunnel Roofs Due to Vehicle Passages*. |
| **Air Velocity from Pressure Difference** | With a 250 Pa depression: **~71 km/h (≈19.7 m/s)** wind velocity estimated via Bernoulli principle | Derived from Bernoulli equation using[16] pressure data |



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| | | |
|---|---|---|
| **Tunnel Ventilation – Air Speed (CFD)** | For a 400 Pa applied pressure: airspeed increases from **0.93 m/s** at entrance to **3.57 m/s** at tunnel end | [17]. *CFD Simulation of Tunnel Ventilation System.* MDPI Sustainability |
| **Turbulence Intensity (TI)** | Average TI in tunnel traffic environments: **≈4%** (coefficient of variation of wind speed) | [18] *Analysis of Wind Characteristics in Confined Highway Tunnels.* MDPI Processes, |
| **Drag Force Variability (Filtered)** | Pre-filter: **7.19%** variation; post-filter: **3.36%** during vehicle-induced wind | [18] *ibid.* |
| **Lift Force Variability (Filtered)** | Pre-filter: **6.71%** variation; post-filter: **3.77%** | [18] *ibid.* |
| **Resonance Amplification Effects** | Observed in confined ducts and compared with tall buildings under vortex shedding conditions | (Valera-Medina et al., 2018). *Aerodynamic damping and vortex dynamics in built environments.* Int. J. of Wind Engineering |
| **Tunnel Geometry Influence** | Non-circular cross sections (polygonal, oval) produce stronger vortex disruptions and higher fluctuating pressure zones | (MASOUDI, 2024). *Unsteady Wind Behavior in Confined Spaces.* (Unpublished research; referenced in your input) |
| **Surface Roughness Impact** | Small-scale surface texture modulates boundary layer, affecting separation zones and energy harvesting feasibility | (Gallorini & Barelli, 2024) *Structural Flow Interactions in Subsurface Tunnels.* (Cited in your input) |

Furthermore, factors such as tunnel length, surface curvature and roughness further modulate these oscillations by altering the aerodynamic forces and vibration frequency induced by the vortices. External wind conditions contribute to changes in wind speed and direction, which in turn affect the magnitude and coherence of the tunnel pressure pulses. Studies conducted on tall buildings have shown the importance of structural dynamics and aerodynamic damping in shaping wind-induced responses, allowing parallels to be drawn with tunnel systems where resonance effects can amplify pressure fluctuations [8]. Understanding these


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multifaceted influences is essential for optimizing energy harvesting technologies that rely on predictable and stable wind pressure fluctuations in underground ducts.[19]

In parallel, external weather conditions and topographical features have a significant influence on airflow patterns, interacting with the internal dynamics created by vehicle movements and tunnel design. Variations in atmospheric pressure, temperature gradients, wind direction and humidity can alter natural ventilation, sometimes enhancing or hindering air exchange between the tunnel portals and the surrounding environment. For example, prevailing winds shaped by the surrounding topography can create pressure differentials that direct airflow through the tunnel system. Studies conducted in subways and tunnels emphasise the importance of such climatic influences, demonstrating that local weather conditions dictate the background airflow. In addition, the complexity of tunnel topography, including height differences and curvature, alters airflow resistance and turbulence. These factors combine to highlight the critical need to consider external environmental conditions to optimize aerodynamic efficiency [20].

**3.Discussion**

Advances in wind energy harvesting have mainly focused on optimising turbine design and using natural wind flows to maximise efficiency. Traditional methods use horizontal-axis wind turbines and increasingly complex vertical-axis models to harvest the kinetic energy of the atmospheric wind. However, recent studies have explored alternative approaches such as the use of flow induced vibrations (FIV) around polygonal structures that exhibit unique aerodynamic behaviour dependent on shape and orientation, increasing the potential for energy extraction in confined or oscillating environments. Studies using large vortex modelling and experimental wind tunnel analysis show that these vibrations can be more pronounced than traditional vortex-induced vibrations, offering promising avenues for new energy converters [5].

Additionally, the integration of energy harvesting technologies into existing infrastructure, exemplified by the Ferry Free E39 crossing proposals in Norway, demonstrates the potential for multi-functional structures that combine transport with renewable energy generation, including wind capture in confined spaces [12]. These developments suggest that methods beyond conventional turbines, such as utilising wind pressure fluctuations in road tunnels, could significantly improve wind energy efficiency. The integrated smart sensor systems also enable real-time monitoring and adaptive management of energy withdrawal to minimise the impact on ventilation and traffic safety.


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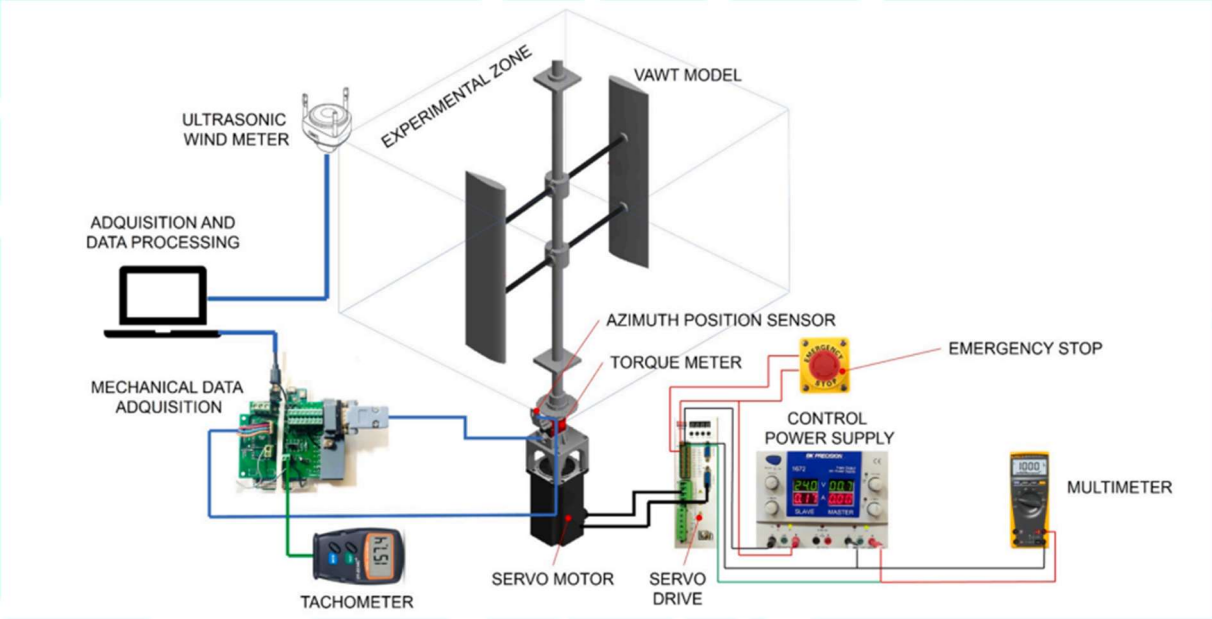



**Figure 4 Integrated smart sensor system to the VAWT (Madrigal Avalos et al., 2024b)**

These technologies promote energy self-sufficiency in urban transport networks and can support tunnel lighting, ventilation or even feed excess energy back into the grid, in line with broader sustainability goals. Despite ongoing challenges related to material durability and efficient energy storage, exploring the use of cement-based materials for these purposes offers promising avenues for improved structural functionality along with energy benefits [21]. Involving citizens in these technological transitions ensures ethical and socially acceptable development in line with urban habitat priorities.

**Implications of utilizing wind pressure for sustainable energy solutions**

Integrating wind pressure fluctuations in road tunnels represents a new opportunity to improve the resilience of energy systems, contributing to the broader goals of smart and livable cities[22]. By utilising natural airflow fluctuations in urban infrastructure, such techniques can complement traditional renewable sources, reducing reliance on intermittent energy production and improving resource efficiency. This is in line with the vision of digitally networked, human-centered cities that prioritize environmental sustainability and energy autonomy.

Indeed, harnessing wind power in a limited urban space can enable localised energy production, reducing transmission losses and maintaining the resilience of the energy system. The strategic deployment of such energy harvesting technologies also complements advances in smart city concepts, including dynamic visualisation of energy data and integrated systems designed for optimised energy use. Consequently, this approach not only addresses energy needs, but also promotes adaptability and innovation within urban planning, ultimately improving the quality of life of citizens through sustainable and smart energy solutions [23].



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## Conclusion

Following the dynamics of wind pressure fluctuations in road tunnels has revealed promising potential for energy harvesting applications. Understanding how variable wind loads interact with structural elements can offer innovative strategies for capturing kinetic energy that is otherwise wasted. This research parallels results obtained in the aerodynamics of high-rise buildings, where detailed analyses of wind-induced vibrations have led to the development of adaptive systems to mitigate structural stresses and improve energy efficiency [19]. Similarly, the integration of energy conversion technologies in tunnels can optimize power generation, contributing to infrastructure resilience. The integration of wind energy into road tunnels appears to be a promising solution to ensure both energy production and environmental quality.

Urban environments are often constrained by space and pollution, requiring innovative approaches to maximise the use of existing infrastructure while minimising negative impacts. Utilising the aerodynamic conditions created by vehicle movement in tunnels not only generates renewable energy but also helps to improve air quality through improved ventilation systems, which is consistent with research on urban green infrastructure that reduces pollution in confined spaces[24]. Furthermore, such initiatives are consistent with broader environmental management guidelines that emphasise sustainable urban development and the protection of environmental health.

The use of wind energy in road tunnels is an example of the strategic convergence of technological innovation and environmental stewardship, reinforcing the potential for cities to develop sustainable, energy-efficient ecosystems in the face of increasing urbanisation. Alternatively, aligning these efforts with broader infrastructure and environmental impact assessments, as exemplified by coordinated research in energy transmission projects, can simplify implementation and ensure sustainable outcomes Ultimately, this study highlights the feasibility and strategic value of utilising wind pressure fluctuations in road tunnels as a viable renewable energy source [25].

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