

Integrated Urban Renewable Energy Generation and Air Purification Systems Using Eco-Gen Vertical Axis Wind Turbine - A Review

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ABSTRACT: As urbanization has progressed rapidly, two key related issues have emerged as a result of this growth: Increased Energy Consumption and Impaired Air Quality. Most urban power generation systems are still reliant on fossil fuels, where regulations and indoor air filtering are the ways to manage air pollution. With this inconsistency in the way energy and air quality are addressed, more recent research has begun to explore the development of an urban infrastructure that integrates energy and environmental benefits into a single design. To evaluate the feasibility of Integrated Urban power Generation Systems using Eco-Gen VAWTs and Active Air Purification, this paper reviews existing literature regarding urban Wind Characteristics, VAWT Technology and Products, Permanent Magnet Synchronous Generators, Battery Energy Storage System, Air Filtration Technology, and Internet of Things-based monitoring capabilities. Evaluating this range of material will help to understand the technical feasibility of integrating these systems in dense urban communities, particularly for telecommunications tower sites where diesel generators are still heavily used. The review identifies key research gaps including urban wind intermittency, limited outdoor air purification effectiveness, maintenance challenges, and lack of standardized performance metrics for hybrid environmental systems. The findings suggest that integrated VAWT-based solutions offer significant potential for multifunctional smart-city infrastructure supporting distributed renewable energy and environmental remediation.

KEYWORDS: Vertical Axis Wind Turbine, Urban Wind Energy, Air Purification, HEPA Filtration, IoT Monitoring, Distributed Renewable Energy

I. INTRODUCTION

Worldwide Urban population, Urban Infrastructure Density and Urban Energy have grown at a level never seen. The World Health Organization estimates that 90 percent of the world's Urban Population will be affected by Pollutant Concentration levels above recommended health standards due to the Fine Particulate Matter; PM 2.5's. There are many documented health conditions associated with long-term exposure to these pollutants (respiratory disease), cardiovascular disease and mortality, and is one of the leading causes related to these health concerns (Brook et al., 2010; Pope & Dockery, 2006).

As cities continue to develop, they also remain heavily dependent on fossil fuel based energy systems, such as in telecommunications base Transmitter Stations . Diesel generators are common in providing the needed electrical supply to ensure an uninterrupted flow of power, which results in contributing to greenhouse gases and creating local Air Pollution (Kumar et al., 2019). Solar Rooftop Photovoltaics have gained momentum; however, there are limits to the amount of space available in densely populated urban areas, as well as the intermittent and shading effects that limit their effectiveness.

Wind energy is an excellent option for obtaining renewable energy, but traditional horizontal axis wind turbines (HAWTs) are not well suited to urban environments due to high noise levels, visual intrusion, as well as the fact that they are very sensitive to turbulent or low-speed winds; therefore, increasing attention has been given to vertical axis

wind turbines (VAWTs). Renewable technologies are increasingly being integrated with environmental remediation technologies and new studies are demonstrating that hybrid systems producing energy, while also providing better air quality, fit within the development of multifunctional and sustainable urban infrastructures. Eco-Gen is an example of this type of hybrid system combining wind energy production, active air purification, and IoT-based monitoring. The goal of this paper is to present an overview of the scientific and technical bases for these systems (Akinsanya et al., 2021).

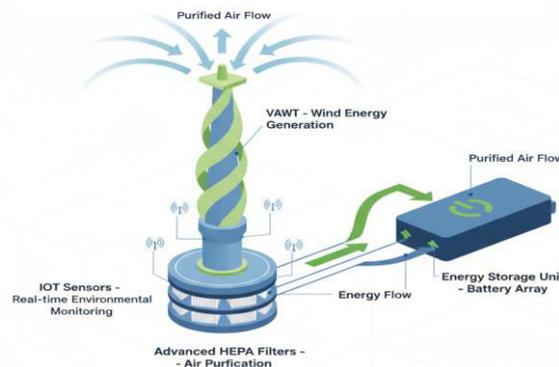


Fig. 1. Eco-Gen VAWT Architecture

II. LITERATURE REVIEW

Urban Wind Characteristics and Renewable Energy Constraints

While conventional wind power modeling has focused on open space, the differences in the urban wind environment create a situation where multiple surfaces (i.e. Buildings, streets, and rooftops) act as barriers to airflow or redirect airflow creating turbulent flow with rapidly changing wind directions and lower average wind speeds (Blocken et al., 2016; Stathopoulos & Alrawashdeh, 2019; Dai et al, 2020). Based on empirical testing and numerical modeling using Computational Fluid Dynamics techniques, the majority of wind speeds measured around urban areas are low (average of 1 to 4 m/s) when compared to the higher average wind speeds needed for optimal Horizontal-axis Wind Turbine (HAWT) operation (Ahmed et al., 2017).

As opposed to HAWT, which suffers from increased fatigue loads due to turbulence and reduced aerodynamic efficiency, VAWT has much less turbulence dependence and is less impacted by yaw alignment, therefore allowing better operation in turbulent conditions (Blocken et al., 2016). As such, this allows VAWT to be a good candidate for vertical and horizontal wind turbine applications in urban settings where the building height restrictions and obstacles present challenges (Saidur et al, 2011).

Vertical Axis Wind Turbine Technologies

VAWTs can be classified into drag and lift types, with the Savonius turbine known for its high starting torque and ability to begin working at very low wind speeds (Sharma et al., 2018; Kulkarni & Das, 2020; Roy & Saha, 2018). This is beneficial for use in city atmospheres because of an increase in wind's ability to start and maintain rotation at lower velocities as well as produce more power while running than an equivalent lift-based turbine (Fazylova et al., 2024). The aerodynamic performance of a Savonius turbine is typically lower than that of a lift-type turbine, with power coefficients usually below 0.3.

Darrieus turbines, on the other hand, are constructed to use lift and can achieve greater efficiencies than Savonius turbines. They have improved CPs of nearly 0.4 in ideal operating conditions (Eriksson et al., 2016). The main disadvantage of the Darrieus system is that they require some mechanism of providing start-up torque (e.g., external powered motors or wind assisted) to enable them to begin generating power on their own (Islam et al., 2013). According to (Gupta & Biswas, 2019), hybrid Savonius-Darrieus turbine designs are an attempt to benefit from the drag-based turbine's outstanding starting performance while also taking advantage of the lift turbine's superior

efficiency. Helical blade configurations and multi-blade designs also help limit the amount of torque ripple and noise emissions produced by these wind turbine designs (Li et al., 2021).

Power Generation and Energy Storage Technologies

Selecting the appropriate generator is one of the most significant factors that affects the efficiency and reliability of small wind systems. Permanent Magnet Synchronous Generators are a popular choice for variable-speed operation of VAWT's because of their high efficiency, small size, and ability to be driven directly (Chen et al., 2019). Eliminating gearboxes reduces the mechanical losses, mechanical noise, and maintenance costs that are associated with gearboxes in PMSG systems

The efficiency of direct-drive PMSG's is generally over 90%, and they function well at a large range of rotor speeds, which is crucial to cope with the unpredictable nature of urban wind regimes (Polinder et al., 2013). However, due to the fact that PMSG's rely on the use of rare-earth magnets, they face the same supply-chain challenges and cost factors that are still being researched.

Battery Energy Storage Systems provide a way to moderate the impact of wind energy intermittency, thus providing a continuous and dependable source of electricity for essential loads like telecommunication devices. Lithium-ion storage has the highest energy density and is experiencing declining costs, yet there are challenges regarding lifetime management and thermal safety issues (Luo et al., 2015).

Urban Air Pollution and Filtration Technologies

The main air pollutants in cities are fine particulate matter (PM_{2.5}) along with other pollutants produced from combustion including gases. PM_{2.5} is especially dangerous because it can travel deep into your lungs and bloodstream (Querol et al., 2014). While current legislation is aimed at decreasing the level of pollution produced by businesses and homes, fans and other methods of moving clean air into buildings are also valuable ways to address air quality improvement.

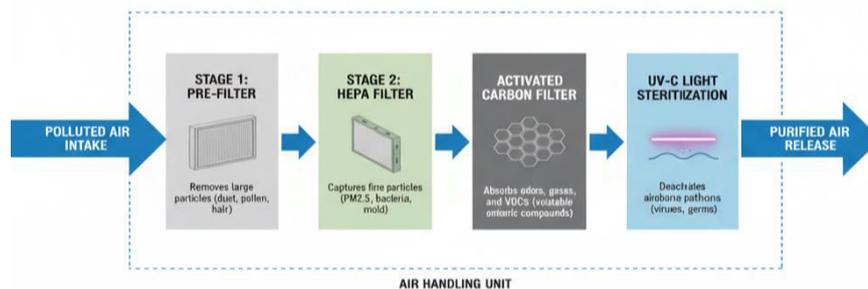


Fig. 2. Air Filtration Process

High efficiency particulate air (HEPA) filters, particularly those classified as H13 grade filter, appear to remove at least 99.95% of PM and gas particles sized 0.3 μm or greater (U.S. EPA, 2023). Additionally, activated carbon filters are often used in conjunction with HEPA filters to remove VOCs, NO₂, SO₂s and other gases. Although air purification systems are useful, they also come with pressures which lead them to be more expensive over time due to increased energy use. Additionally, air filtration systems require periodic replacement and upkeep. The clogging of an air filter can have negative environmental and practical implications for outdoor environments (Zhang et al., 2020).

Integrated Systems

Incorporating renewable energy to power the purification of air through electric or mechanical means, is one area of interest for researchers interested in maximizing the utility of urban infrastructure. While there are many experimental setups in place that illustrate the potential of both wind and solar energy to provide an electrical source for air purification systems, the application of these systems on a broader scale is still not widespread (Gubbi et al., 2013; Li et al., 2020; Zanella et al., 2014).

The concept of a hybrid configuration called Eco-Gen VAWT combines the production of wind-generated electricity with the use of active air purification systems that use electricity to purify the air, as well as utilize IoT based monitoring and control to facilitate such use (Kim & Kim, 2015; Rezaeiha et al., 2020).

Although these systems may provide an environmentally beneficial clear benefit, their effective inbound radius for outdoor air purification is still limited. There are no industry standard metrics for assessing purification effectiveness in real-world applications, and this is an area of substantial research opportunity.

Urban Applications: Telecom Towers

Due to their height, structural integrity, and ongoing energy requirements, Telecom Towers show significant potential as sites for Integrated VAWT Systems. BTS usually have a power consumption in the range of 3-10 kW (Kumar et al., 2019), and diesel generators are frequently used in areas with unreliable electric grid supply.

According to research, networks that are powered by renewable energy may significantly decrease costs/improve the environment (Gutti et al. 2025, Chavan et al. 2025). However, it should be noted that the issues of structural loading and electromagnetic interference, as well as ease of accessing/maintaining the system, must be taken into consideration (Mahendra & Velusamy, 2019).

III. RESEARCH GAPS AND CHALLENGES

Although increased interest exists, many obstacles remain unsolved. Urban wind intermittency results in unpredictable energy production, and the air purification effect provided by outside filtration systems is generally limited. Maintenance obligations associated with filters and batteries create the need for additional operational complexity. Lastly, existing regulatory structures for integrating energy and environmental systems continue to be developing. Further studies must be conducted about the effectiveness of hybrid wind-solar systems to increase the reliability of collected energy, as well as the use of AI to control adaptive filtration by means of pollution levels measured in real-time. Investigations into connected systems for use in smart cities should continue, and consideration must be given to developing new advanced materials for example, self-cleaning filters and recyclable blades.

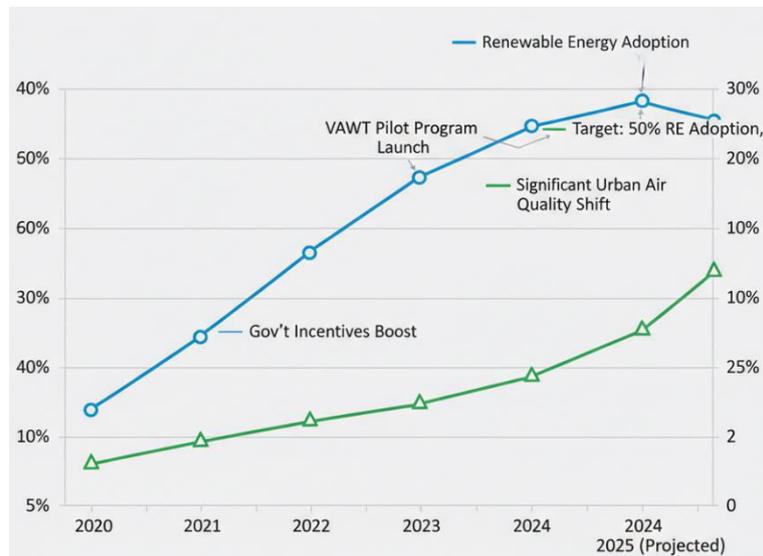


Fig. 3. Year-wise Data Trends and Projections (2020-2025)

IV. CONCLUSION

The current research review shows that integrated VAWT systems may provide an exciting means to solve both urban energy issues and urban air quality problems at the same time. Although the technical and operational limitations still exist, there are many similarities between the existing Eco-Gen VAWT design and the types of distribution networks and multifunctional urban infrastructure that are prevalent in today's research. While interdisciplinary collaboration and

longer-term testing will be needed for actual implementation in the field, the evidence presented in this paper provides significant support for VAWT-based solutions

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