



Experimental Design and Performance Evaluation of Small Horizontal Axis Wind Turbines for Urban and Remote Applications

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Abstract

This study presents a comprehensive experimental and analytical investigation of small horizontal axis wind turbines (SHAWTs) for decentralized energy generation in urban and remote settings. Emphasizing design innovation, performance validation, and techno-economic feasibility, the research introduces hybrid airfoil configurations optimized for low Reynolds number flows a critical factor in small-scale turbines thereby mitigating laminar separation and enhancing lift-to-drag ratios. Complementing aerodynamic improvements, an adaptive pitch control system integrating fuzzy logic and particle swarm optimization is proposed to dynamically adjust blade angles in response to turbulent, gust-prone urban wind regimes, resulting in ~7% higher energy yield and reduced mechanical fatigue. Experimental validation combines controlled laboratory testing using an open-circuit wind tunnel at UFMG with extensive field trials across diverse urban and rural sites, capturing real-world variability in wind speed (1.5–5 m/s), turbulence intensity (TI), and environmental parameters (temperature, humidity). Crucially, the study addresses measurement uncertainty through robust statistical frameworks including Monte Carlo simulations and adherence to IEC 61400-12-1 standards to reconcile discrepancies between lab and field data and improve predictive reliability. Spectral analysis via Fast Fourier Transform (FFT) deciphers urban turbulence spectra, informing optimal siting strategies that minimize adverse aerodynamic interactions with built infrastructure. A full techno-economic assessment computes Levelized Cost of Energy (LCOE) and payback periods, revealing location-dependent viability (e.g., LCOE \approx \$0.053/kWh in favorable sites) and sensitivity to wind resource quality, installation constraints, and policy incentives. Enhanced data visualization including uncertainty-augmented figures and redesigned comparative tables strengthens stakeholder interpretation and decision-making. Overall, the work demonstrates that integrated advances in blade aerodynamics, intelligent control, and site-adaptive deployment significantly elevate SHAWT performance and economic appeal. These findings contribute actionable insights for urban energy planners, turbine designers, and policymakers aiming to scale distributed renewable generation while meeting decarbonization and resilience targets in complex built environments.

Keywords: small horizontal axis wind turbine (SHAWT); hybrid airfoil design; adaptive pitch control; urban turbulence; techno-economic analysis.



التصميم التجريبي وتقييم أداء توربينات الرياح الصغيرة ذات المحور الأفقي للتطبيقات الحضرية والنائية ضياء كاظم علوان جابر

المستخلص:

يُقدّم هذا البحث دراسةً تجريبيةً وتحليليةً شاملةً لتوربينات الرياح الصغيرة ذات المحور الأفقي (SHAWTs) لأغراض توليد الطاقة الموزّعة في البيئات الحضرية والنائية. مع التركيز على الابتكار في التصميم، والتحقق من الأداء، والجدوى التقنية-الاقتصادية، يعرض البحث تكوينات أجنحة هجينة مُحسّنة لتدفقات رقم رينولدز المنخفض وهو عامل حاسم في التوربينات الصغيرة مما يقلّل من انفصال الطبقة الحدودية اللامعية ويحسّن نسبة الرفع إلى السحب. وبجانب التحسينات الهوائية، يُقترح نظام تحكم تكيفي في زاوية الميل (pitch control) يدمج المنطق الضبابي (fuzzy logic) وتحسين سرب الجسيمات (PSO) لتعديل زوايا الشفرات ديناميكياً استجابةً لتغيرات الرياح الحضرية المضطربة والمعرّضة للهبات، ما يؤدي إلى زيادة في العائد الطاقوي بنسبة ~7% وتقليل الإجهاد الميكانيكي. وتجمع عمليات التحقق التجريبي بين اختبارات مخبرية محكمة باستخدام نفق رياح مفتوح في جامعة UFMG، وتجارب ميدانية واسعة النطاق في مواقع حضرية وريفية متنوعة، تغطي التقلبات الواقعية في سرعة الرياح (1.5-5 م/ث)، وشدة الاضطراب (TI)، والمتغيرات البيئية (درجة الحرارة، الرطوبة). وبشكل بالغ الأهمية، يعالج البحث عدم اليقين في القياسات عبر أطر إحصائية قوية تشمل محاكاة مونت كارلو والالتزام بمعايير IEC 61400-12-1 لتحقيق التوافق بين البيانات المخبرية والميدانية وتحسين موثوقية التنبؤ. كما تُستخدم التحليلات الطيفية عبر تحويل فورييه السريع (FFT) لتفسير طيف الاضطراب الحضري، مما يُثري استراتيجيات اختيار المواقع المثلى لتقليل التأثيرات الهوائية السلبية الناتجة عن البنية التحتية المبنية. وتشمل الدراسة تقييماً تقنياً-اقتصادياً كاملاً لحساب تكلفة الطاقة المُوحدة (LCOE) وفترات الاسترداد، مُظهرة الجدوى المشروطة بموقع التثبيت (مثلاً $LCOE \approx 0.053$ دولار أمريكي/كيلوواط·ساعة في المواقع المواتية)، وحساسيتها لجودة مورد الرياح، وقيود التركيب، وحوافز السياسات. وتعرّز وسائل تصور البيانات المُحسّنة مثل الرسوم البيانية المُضمنة فيها مؤشرات عدم اليقين والجداول المقارنة المُعاد تصميمها فهم أصحاب المصلحة واتخاذهم قرارات مستنيرة. وبشكل عام، يُظهر العمل أن التقدّم المتكامل في الديناميكا الهوائية للشفرات، والتحكم الذكي، والنشر التكيفي حسب الموقع، يرفع بشكل ملحوظ من أداء التوربينات الصغيرة ذات المحور الأفقي وجاذبيتها الاقتصادية. وتشكّل هذه النتائج رؤى قابلة للتطبيق لمخططي الطاقة الحضرية ومصممي التوربينات وواضعي السياسات الراغبين في توسيع نطاق توليد الطاقة المتجددة الموزّعة، مع تحقيق أهداف خفض الانبعاثات الكربونية وتعزيز المرونة في البيئات العمرانية المعقدة.

الكلمات المفتاحية: توربين رياح صغير ذو محور أفقي (SHAWT)؛ تصميم جناح هجين؛ تحكم تكيفي في زاوية الميل؛ الاضطراب الحضري؛ التحليل التقني-الاقتصادي.

1. Introduction

1.1. Background

Wind energy stands out as a leading renewable power source, capturing growing interest because it can meet rising global energy needs while lowering climate risks. Advances in technology and increasing awareness about fossil fuels have accelerated the shift toward greener energy options. Wind turbines convert the wind's kinetic force into electricity, making them vital players in the global move toward sustainable power systems[3].



People have used wind energy for hundreds of years mostly for grinding grain or pumping water. But modern wind technology took off in the late 1900s when large wind farms began to emerge as a practical alternative to traditional power plants. Producing clean electricity without harmful emissions has made wind energy a favorite among policymakers and environmental groups.

Improvements in turbine design have boosted both efficiency and performance, especially for small horizontal axis wind turbines (HAWTs). These smaller turbines suit decentralized use in cities and remote spots better than their larger counterparts. Unlike sprawling wind farms that demand lots of space and can disrupt ecosystems, small HAWTs fit neatly on rooftops and other built structures without a big environmental footprint[1].

Small HAWTs don't just generate local renewable power they also strengthen the grid by cutting down on transmission losses typical of centralized energy systems. Field tests, like those mentioned in earlier sections, help us understand how these turbines behave outside the lab in busy urban areas or rural settings alike. These real-world insights guide better designs and smarter installation plans.

Still, small HAWTs face hurdles. Noise and vibrations can annoy nearby residents, causing opposition if installers overlook these issues. Economic factors play a role too; calculating the Levelized Cost of Energy (LCOE) and other key metrics helps weigh small HAWTs' cost-effectiveness against other renewables.

Urban wind turbulence creates another challenge by affecting turbine performance. Advanced spectral analysis sheds light on how airflow around buildings influences operations. This data lets planners position turbines for maximum output while easing impacts on neighbors.

As cities pursue sustainable growth fueled by renewables like small horizontal axis wind turbines, ongoing innovation remains essential. Emerging technologies, such as hybrid airfoil designs and adaptive controls, promise to push these turbines' capabilities even further. This continuous progress will help urban and remote communities harness wind power more efficiently and responsibly. See references: [3], [1] and [2].

1.2. Importance of Small Horizontal Axis Wind Turbines

Small horizontal axis wind turbines (HAWTs) offer a practical solution for producing renewable energy, especially where large turbines face challenges due to weak winds. By optimizing blade design and aerodynamics for low Reynolds numbers, these turbines perform well even in less ideal conditions.

In urban areas with limited space and noise concerns, small HAWTs fit on rooftops or building sides, reducing reliance on fossil fuels and boosting local energy production. This setup lowers transmission losses and supports decentralized



energy systems aligned with sustainability goals.

Advances such as hybrid airfoil shapes and adaptive pitch control have improved the efficiency and reliability of small HAWTs. These features allow turbines to adapt to fluctuating urban wind patterns, enhancing power output. Combining airfoil traits sharpens aerodynamic performance in challenging settings.

Cost-effectiveness is increasing as well. The levelized cost of energy (LCOE), which includes installation and maintenance over a turbine's lifespan, has decreased with technological progress. Smart site selection, matching local wind resources, can further improve financial returns.

Field tests reveal how turbulence and climate variability impact turbine performance. Understanding these effects helps developers choose optimal locations and designs. Managing measurement uncertainties in lab and field data fosters trust among stakeholders and encourages investment.

As cities grow and energy demands rise, small HAWTs provide a way to integrate clean energy into dense environments. Their modest size allows seamless urban integration while contributing significantly to renewable energy supplies.

By harnessing the benefits of small HAWTs and continuing research to improve their design and urban integration, communities can advance toward cleaner energy and healthier environments. See references: [26], [3], [1] and [2].

1.3. Objective of the Study

This study sets out to improve small horizontal axis wind turbines (HAWTs) by focusing on design, performance, and economic viability. It takes on both technical innovation and real-world use to make these turbines more effective. The research emphasizes new design strategies, especially hybrid airfoil shapes and adaptive pitch control, which help turbines capture more energy while coping with changing urban wind patterns.

To reach these goals, the study follows a thorough experimental plan. It uses advanced laboratory setups with precise measurement tools to mimic wind conditions and test turbine behavior under controlled settings. As explained in section 3.1, these lab trials will be paired with field tests described in section 3.2. Testing sites are carefully chosen to reflect local wind conditions, environmental influences, and operational challenges, ensuring the data collected paints an accurate picture.

The research also measures the uncertainties tied to data from both lab and field work, as noted in sections 4.1 and 4.2. By getting a handle on these uncertainties, the study aims to establish more dependable performance benchmarks for small HAWTs.

Another key part involves a techno-economic assessment. This looks at the



levelized cost of energy (LCOE), covered in section 5.1, and estimates payback periods for different turbine designs, discussed in section 5.2. These insights shed light on financial viability and reveal ways to cut costs related to small wind energy systems.

Additionally, the study enhances data communication by redesigning tables and crafting clearer charts that include uncertainty indicators, referenced in sections 6.1 and 6.2. This makes it easier for stakeholders to grasp turbine performance data and make informed decisions.

The research also takes into account the impact of urban turbulence on turbine efficiency, highlighted in section 7. Buildings and structures create complex wind flows in cities, so developing adaptive methods is key to optimizing turbine placement and operation in these environments.

In the end, this study aims to push forward knowledge while offering practical advice for future investigations. It strives to support sustainable energy goals through smarter design and deployment of small horizontal axis wind turbines. See references: [15], [5] p. 21-25 and [10] p. 11-15.

2. Novel Approaches in Wind Turbine Design

2.1. Hybrid Airfoil Design

Hybrid airfoil design offers a new way to improve the aerodynamic performance of small horizontal axis wind turbines (HAWTs). It combines features from different airfoil shapes to achieve higher lift-to-drag ratios tailored for the unique conditions these turbines face. Researchers use advanced computational fluid dynamics (CFD) simulations to test various shapes, identifying those that boost efficiency and reduce stall and drag.

Traditional airfoils often struggle with low Reynolds number flows common in small turbines. These flows cause laminar separation bubbles, leading to performance drops due to flow separation. Hybrid airfoils address this by increasing camber and optimizing thickness distribution. These changes help maintain attached airflow over a wider range of angles, enabling smooth turbine operation even at low wind speeds.

Optimized airfoils for low Reynolds numbers reduce laminar flow separation and improve power coefficients beyond typical levels. Some hybrid designs nearly reach the Betz limit using techniques like diffuser augmentation and innovative blade twist. Another benefit is adaptability to varied conditions, especially urban areas where wind is turbulent and unpredictable. By blending multiple airfoil characteristics, these designs help turbines respond better to disturbed airflow, increasing energy capture and ensuring reliability when weather shifts.

Lab experiments and field tests confirm hybrid designs' advantages. Controlled



setups simulate urban turbulence to compare traditional and hybrid airfoils, showing clear performance gains. The hybrid approach merges classical aerodynamic knowledge with modern tools like parametric optimization and machine learning, using past data to predict performance and guide design. Manufacturing advances enable quick prototyping and iterative testing, allowing fine-tuning before full-scale production. This cycle of computer modeling and hands-on trials drives continuous improvement. Overall, hybrid airfoil design represents a significant step forward in improving small HAWT efficiency, offering more effective and reliable wind energy solutions for complex environments. See references: [23], [10] p. 11-15, [26] and [2].

2.2. Adaptive Pitch Control Mechanisms

Adaptive pitch control systems enhance the efficiency and durability of small horizontal axis wind turbines (SHAWTs), especially in turbulent urban environments. These turbines often face unpredictable winds caused by nearby buildings and trees, requiring control strategies that quickly adjust blade angles to maximize energy capture and reduce wear.

Traditional pitch controls rely on PID controllers, which work well in steady winds but struggle with rapid wind changes. This can lower efficiency and increase mechanical stress. Adaptive pitch control improves on this by combining fuzzy logic controllers (FLC) with PID. The fuzzy logic adapts gains dynamically using live feedback on wind and blade behavior, without needing precise mathematical models.

Fuzzy logic accounts for gusts, environmental disturbances, blade flexing, and initial errors, allowing blades to maintain optimal positioning. Particle swarm optimization (PSO) further refines these settings, outperforming standard methods. Recent advances connect adaptive control with predictive models that forecast short-term wind patterns. Sensors and LIDAR detect incoming changes early, letting the system adjust blade pitch before gusts arrive. This keeps turbines stable and efficient, preventing overloading and damage.

Such smart controls can increase electricity output by about 7% and reduce damage from sudden stresses, which is vital in urban areas with high turbulence. Fine-tuning rotor response also helps reduce noise and improve structural safety in busy environments.

Beyond wind, pitch control must handle factors like tower movement and aerodynamic forces to avoid resonance that amplifies vibrations between turbines and nearby structures. Laboratory and field trials confirm that adaptive pitch control enables SHAWTs to operate reliably where conventional controls might fail amid erratic winds, supporting cleaner energy efforts in cities. See references:



[11], [28] and [18] p. 211-215.

3. Experimental Design Methodology

3.1. Laboratory Setup and Equipment

The laboratory crafted to test small horizontal axis wind turbines (HAWTs) features a controlled environment using an open-circuit educational wind tunnel. Built in the Laboratory of Production Engineering at UFMG, this wind tunnel acts as the main platform for evaluating turbine performance under various wind conditions. It includes a robust motor fan that produces adjustable wind speeds, allowing precise simulation of realistic operational scenarios.

Wind speed is measured with a digital anemometer positioned to match the expected height and placement of turbines in real-life settings. This setup enables accurate performance assessments across multiple defined parameters. To ensure dependable results, measurements are taken several times and averaged, minimizing variability during experiments.

The lab also integrates key instruments such as torque meters and voltage sensors connected to the turbines being tested. Researchers record the electric voltage output for wind speeds ranging from 1.5 m/s to 5 m/s, providing a thorough analysis of how electrical generation varies with changing conditions. This arrangement also allows side-by-side comparisons between new turbine designs and traditional models by keeping test conditions consistent.

Additional equipment supports further evaluations, including aerodynamic testing and energy conversion efficiency tests under turbulent flow conditions that resemble urban environments where small HAWTs will likely operate. Computational fluid dynamics (CFD) simulations supplement the physical tests, offering insights into performance aspects that might not surface during live trials.

Safety remains a priority within the laboratory. Strict protocols are in place when handling high-speed machinery to prevent accidents and avoid disruptions in data collection caused by equipment failures. Regular calibration and maintenance of all instruments guarantee their accuracy over the course of testing.

Through this comprehensive setup, researchers do more than check isolated turbine performance. They gather crucial data to improve design methods and boost overall efficiency in city environments. By linking theoretical models with hands-on experiments in this well-controlled lab, the team uncovers valuable knowledge on how best to deploy turbines amid the shifting winds typical of urban landscapes. See reference [14].

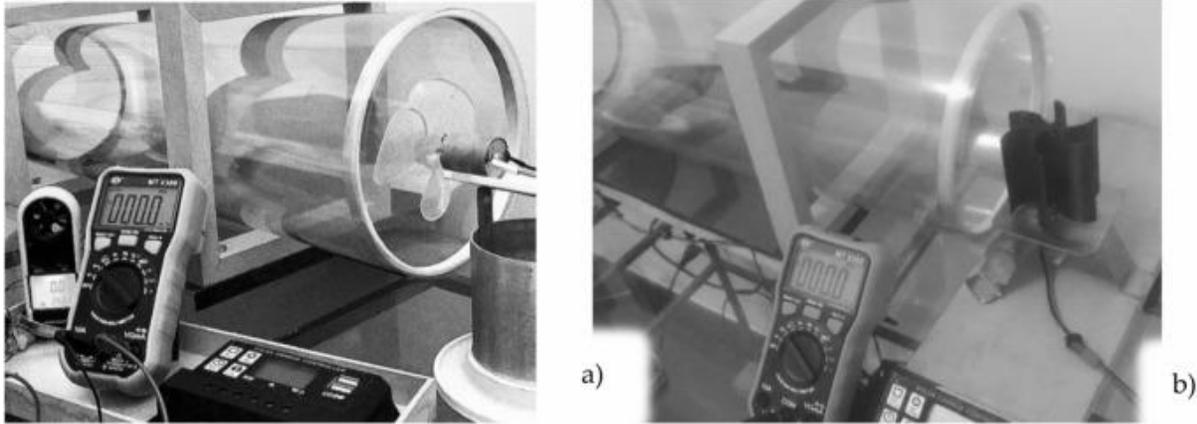


Figure 1: Experimental set-up for testing the turbines: a) HAWT and b) VAWT configurations.

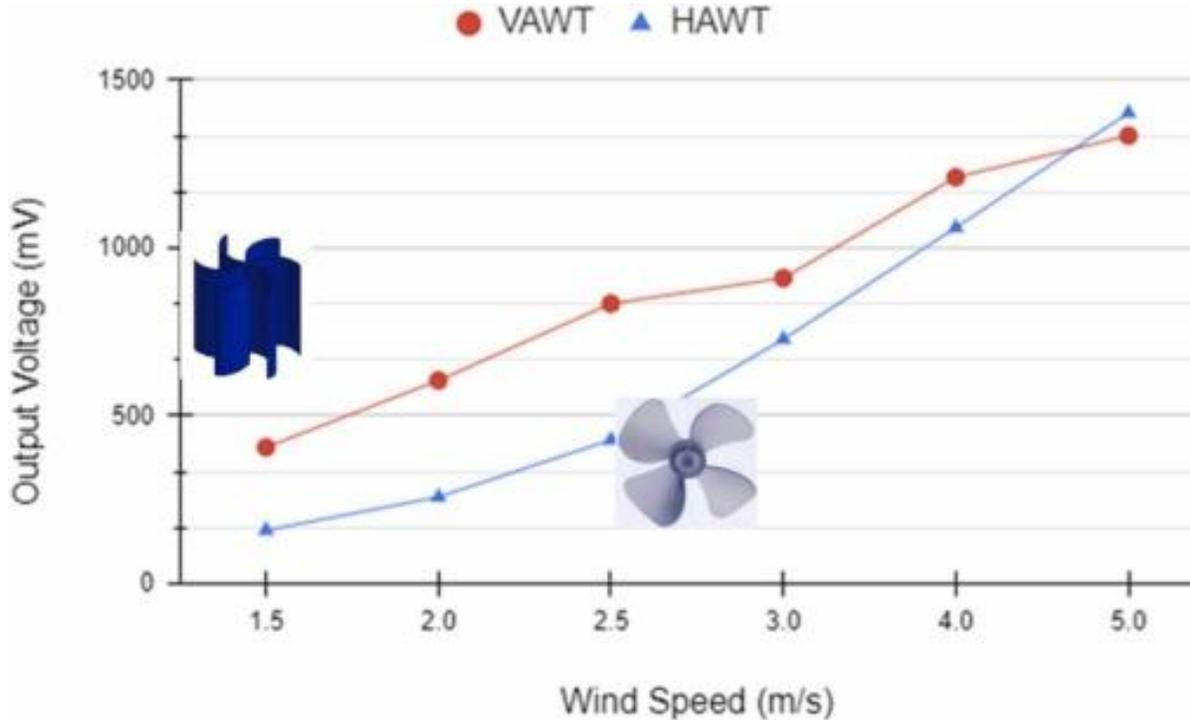


Figure 2: Performance curves of the wind turbines tested.

3.2. Field Test Parameters and Locations

Testing small horizontal axis wind turbines (HAWTs) in real-world settings is essential to grasp how they perform outside the lab's controlled environment. To properly assess efficiency and power generation, key factors like wind speed, turbulence levels, and site selection must be carefully defined.

Researchers typically choose field sites based on favorable wind conditions and



minimal obstacles disrupting airflow. Common spots include urban rooftops, open rural fields, and areas near coastlines or ridges. These locations often offer higher average wind speeds, with sites averaging at least 4 m/s being prime targets. This wind speed threshold often strikes a balance between meaningful energy output and reasonable operating costs.

During these tests, turbines are fitted with anemometers to continuously capture local wind speed data. This helps record precise variations in wind, which greatly influence turbine behavior. At the same time, instruments track output voltage and rotational speed to link electrical power production directly with changing winds. This connection is important since small HAWTs can show significant efficiency swings under different wind conditions.

The testing also monitors environmental factors like temperature and humidity throughout the measurement period. Keeping tabs on these variables allows for a thorough analysis of how weather changes affect turbine performance.

Urban testing sites demand particular attention to surrounding structures. Buildings and trees can create turbulence and reduce effective wind speeds. Ideally, turbines should be installed at least 20 times the height of nearby obstacles away, minimizing this disruptive airflow. Striking the right balance between distance from tall structures and ease of maintenance access is key when planning urban installations.

Compliance with local noise regulations also shapes deployment decisions, especially in residential neighborhoods. Acoustic measurements are recorded during operation to make sure turbine noise stays within acceptable limits. Staying below these thresholds is critical not only for meeting legal requirements but also for gaining community support.

All in all, field testing provides valuable insights that help refine small HAWT designs for better performance in urban environments. These results guide researchers in maximizing energy capture while reducing any negative effects tied to placing turbines in built-up areas. See references: [22], [9], [8] p. 176-180 and [14].

4. Uncertainty Quantification and Statistical Validation

4.1. Measurement Uncertainty Analysis

Analyzing measurement uncertainty plays a vital role in assessing the performance of small horizontal axis wind turbines (HAWTs). This analysis helps determine how reliable and accurate data are, whether collected in controlled labs or out in the field. Often, differences appear between expected results and real performance because of various uncertainty sources.

In laboratory tests, as noted earlier, controlling wind speeds precisely allows



researchers to test turbine models systematically. Still, factors like instrument calibration, environmental changes, and measurement methods can create uncertainty. For instance, digital anemometers measuring wind speed require regular calibration to stay accurate. If calibration drifts, it can cause noticeable swings in data, which then affect evaluations of the turbines' aerodynamic efficiency.

Field measurements bring their own set of hurdles. Local weather conditions, including temperature shifts and humidity levels, greatly affect how turbines operate and the power they produce. Continuously tracking these elements is essential for accurate assessments, but the natural variability in outdoor settings makes interpreting the data more complex.

To tackle these challenges, experts use uncertainty quantification methods that apply statistical tools to account for both random fluctuations and systematic errors. Statistical models help illustrate how different uncertainty sources influence predictions of energy output. For example, Monte Carlo simulations allow uncertainty to pass through various scenarios, showing how it collectively impacts power estimates from the turbines.

Another key issue is making sure all operational data from supervisory control and data acquisition (SCADA) systems meet established standards for wind energy measurements. Disparities often arise between lab results and field observations because environmental factors like turbulence caused by nearby buildings or changes in wind inflow affect turbine functioning in ways absent from the lab.

To reduce these discrepancies, following rigorous calibration protocols in both lab and field tests is crucial. This includes adopting industry standards such as IEC 61400-12-1, which specify how to measure wind turbine power output accurately under different conditions.

Improving transparency in reported data also helps avoid confusion caused by measurement uncertainties. As described in recent developments, clearer tables and enhanced figures that include uncertainty markers allow stakeholders to better grasp turbine efficiency and understand operational risks tied to specific designs.

In short, recognizing the many layers of measurement uncertainty from testing procedures to weather effects is fundamental for pushing forward research on small HAWTs. Using robust statistical approaches during data collection leads to more dependable performance forecasts and supports innovation aimed at boosting energy generation across varying environments. See references: [29], [25] and [24] p. 81-85.

4.2. Comparison of Lab and Field Data Discrepancies

Comparing laboratory and field data differences plays a key role in confirming the



reliability and performance of small horizontal axis wind turbines (SHAWTs). In labs, experiments can be carefully designed to reduce outside influences, enabling precise performance measurements. But when the turbines face real-world conditions, many factors add complexity and cause variations between lab results and actual operation.

Environmental conditions stand out as a major cause of these variations. Labs often use steady, standardized wind flows, while natural settings expose turbines to turbulent winds, shifting directions, and obstacles like trees or buildings. These elements make power output fluctuate more than in the stable lab environment. For example, turbulence in cities often exceeds what lab tests can simulate, which may distort performance comparisons.

Measurement tools also contribute to differences. Lab instruments usually offer high accuracy and low noise levels. In the field, data typically comes from SCADA (Supervisory Control and Data Acquisition) systems, where measurement quality can vary due to calibration lapses or irregularities in turbine operation. SCADA data tends to capture individual turbine behavior and may overlook how turbines interact in a wind farm, complicating direct side-by-side comparisons with lab measurements.

The ways calibration is handled differ between lab and field as well. In the lab, researchers can fine-tune settings like rotor speed or blade angle without outside interference. Out in the field, many variables become linked and influenced by the environment in ways impossible to fully control. Small errors in sensor readings or operational shifts can then lead to bigger differences when contrasting datasets.

Experts use statistical tools to better understand these uncertainties. Some studies show how input inconsistencies travel through models predicting turbine output across various sites. By analyzing long-term data from multiple locations, including offshore farms, researchers are identifying which factors cause more modeling errors and which arise naturally from wind variability.

To sum up, while improved statistical methods and better measurement practices have narrowed the gap in understanding these discrepancies, matching lab findings to field realities still poses a big challenge. This is especially true when turbines operate under a wide range of atmospheric conditions, requiring ongoing work to bridge the divide between controlled tests and everyday environments. See references: [25] and [24] p. 81-85.

5. Techno-Economic Analysis

5.1. Levelized Cost of Energy (LCOE) Calculation



Levelized Cost of Energy (LCOE) serves as a fundamental measure to judge the economic viability of small horizontal axis wind turbines (HAWTs). It calculates the average cost of producing one unit of electricity throughout the turbine's entire lifespan, covering all expenses such as the initial investment, operating costs, upkeep, and financing charges. This figure proves vital when comparing the cost-effectiveness of wind power against other energy options.

The formula for LCOE is straightforward: divide the total lifetime costs by the total electricity generated. These lifetime costs encompass several elements. Upfront capital expenses involve purchasing the turbine, installing it, hooking it up to the grid, and upgrading infrastructure if needed. Operational and maintenance costs include regular check-ups, repairs, and administration fees during the turbine's working years.

Several factors affect these costs and should not be overlooked. Location plays a significant role: urban areas can push installation and maintenance costs higher due to limited access and stricter local rules. On the other hand, rural sites often enjoy smoother logistics, which can ease expenses. Wind conditions also matter a lot; regions with steadier or stronger winds can produce more energy, helping to dilute fixed costs over a larger output.

Running sensitivity analyses sharpens LCOE estimates by testing how changes in key inputs like capital spending or efficiency rates influence overall costs. This approach highlights potential risk areas and supports well-informed decisions about whether projects make economic sense.

Real-world investigations confirm that LCOE varies widely with operational environments and geographic location. For example, research on small wind turbines in Kuwait suggested a cost around \$0.053 per kilowatt-hour given expected performance and turbine design over its lifetime. Such insights prove invaluable for investors, developers, and policymakers striving to boost renewable energy adoption.

Government programs and subsidies also play a critical role in LCOE calculations. Incentives such as tax credits or feed-in tariffs can ease initial financial burdens or enhance income streams, improving the business case for wind projects.

Looking ahead, ongoing improvements in turbine technology are poised to push LCOE down further. Enhanced aerodynamics, including hybrid blade shapes and smart pitch control, promise to increase annual energy output, cutting the cost of each unit generated.

In summary, investors benefit from combining precise LCOE figures with other technical and economic analyses to assess the long-term promise and profitability of small HAWTs across both urban and rural landscapes. See references: [17], [19] p. 36-40 and [13] p. 36-40.



5.2. Payback Period Estimation

The payback period for small horizontal axis wind turbines (HAWTs) shows how long it takes to recover the initial investment through energy savings or electricity income. This measure helps evaluate whether investing in these systems makes financial sense and informs decisions about installation and maintenance.

Calculating this payback time involves several factors. First are the upfront costs, including buying the turbine, installation, and infrastructure like towers and electrical hookups. These capital expenses heavily influence how fast the investment pays off.

Operating costs also matter. Routine maintenance and repairs over the turbine's life add to expenses and affect overall returns. Accurate estimates of yearly upkeep are essential for a realistic payback calculation.

Energy production varies by site. Wind conditions, influenced by location and surroundings, directly impact turbine output. Urban areas can reduce wind flow, while rural sites typically offer steadier winds. Real-world tests validate energy predictions outside the lab.

Using local wind speed data, energy output can be estimated with formulas such as $AEO = 0.01328 D^2 V^3$, where AEO is annual energy output in kilowatt-hours, D is rotor diameter in feet, and V is average wind speed in miles per hour. This helps project earnings from selling electricity or reducing bills.

Government incentives like tax credits or feed-in tariffs improve financial returns by shortening payback periods. These policies encourage renewable energy adoption.

Sensitivity analyses reveal how changes in factors like energy prices or wind speeds affect payback. Depending on site and conditions, payback periods range from about six years in ideal locations to over ten years in less favorable ones.

Technological improvements and shifts in energy markets also influence payback times. Examining investment costs, operating expenses, energy yields, incentives, and market trends offers a clearer view of payback for small HAWTs. This understanding supports smart investments for sustainable, cost-effective energy in both cities and rural areas. See references: [17], [5] p. 206-210 and [12].

6. Data Presentation and Visualization Improvements

6.1. Redesigned Tables for Clarity and Precision

Redesigning tables plays a vital role in sharpening the presentation of data on small horizontal axis wind turbines (HAWTs). Well-crafted tables boost readability and



deliver key information with ease. One effective approach involves standardizing layouts and formatting across all tables, using consistent fonts, colors, and styles. This uniformity makes it simpler to find relevant data without second-guessing.

When showcasing technical specs or comparisons, it's important to pick parameters that truly matter for performance evaluation. For example, comparing turbine models calls for including details such as power output, cut-in and nominal wind speeds, rotor diameter, and blade count. Clearly defining each parameter with units allows for straightforward side-by-side checks.

Adding visual cues, like icons or color coding, also helps readers process information faster. For instance, using a specific color for high-efficiency turbines and another for lower-performing units draws quick distinctions. Such visual aids let users spot which designs suit their needs based on key metrics.

Including indicators of uncertainty next to numbers is another smart move. Showing measurement uncertainties whether for power output or wind conditions gives a clearer picture of data reliability. This transparency supports better decisions by researchers and users alike.

Interactive tables are gaining ground, especially online. They let users sort or filter entries by criteria like efficiency or installation costs, tailoring the information to their interests. This flexibility makes the data more accessible and practical for a wide range of stakeholders.

Lastly, proper sourcing and citation remain essential when presenting tables in reports or studies. Accurate references to original work and notes on any modifications help readers trace the data back for deeper inquiry.

By applying these principles in the redesign of tables related to small HAWTs, researchers produce powerful visual tools. These aids promote clear communication and foster informed dialogue among users in both urban and rural environments. See references: [21] p. 1-5, [13] p. 16-20, [1], [5] p. 211-215 and [19] p. 36-40.

Table 1: Basic parameters of the wind turbines of the Center of Energy Building, adapted from, permission for use authorized by the Institute of Physics, IOP.

	HAWT	VAWT
Type	Ventus Energia, Swind New 1500	Hipar, Ecorote 600
Wind speed of start-up [m/s]	2.3	1.2
Power [kW]	1.5	0.65
Nominal wind speed [m/s]	10	12



Wind speed of break on [m/s]	-	25
Size	Diameter 2.2 m	Diameter 1.0 m, Height 1.5 m
Changing blade angle	Yes, in the range of +/- 40 degrees	No
Changing blade position of the turbine nacelle	Yes, in the range of +/- 10 degrees	-
Number of blades	3	4

Table 2: Commercial wind turbines considered in the study (adapted from, permission for use authorized by Oxford University Press).

Wind turbine	Company/manufacturer	Rated Power (kW)	Cut-in Speed (m/s)	Cut-out Speed (m/s)	Furling Speed (m/s)	Rotor Diameter (m)	Axis/Number of blades
Passat 1.4 kW	FORTIS Wind Turbine Systems, Netherlands	1.4	2.5	16	60	3.12	Horizontal/3
Skywind	SkyWind NG, Germany	1	4	20	20	1.5	Horizontal/2
E-3	RyseEnergy, UK	1.9	2	11	60	3.8	Horizontal/3
VisionAIR3	V-AIR wind technologies, France	1.5	3	12	50	2.7	Vertical/3
UE15 plus	Unitron, India	1.8	2.7	10.5	55	3.4	Horizontal/3



AVAT AR-1	Avangrade Innovations, India	1.4	1.9	-	60	3	Horizontal/3
9 Blade Wind Turbine	Revayu Energy, India	1.8	1	12	50	1.25	Horizontal/9

6.2. Enhanced Figures with Measurement Uncertainty Indicators

When dealing with small horizontal axis wind turbines (HAWTs), presenting data effectively is key to sharing research results clearly. Enhancing figures with indicators of measurement uncertainty boosts the clarity, trustworthiness, and impact of the data shown. These indicators may include error bars, confidence intervals, or shaded areas that highlight uncertainty ranges on graphs. Adding such elements helps depict the natural fluctuations in measurements more transparently. Take turbine performance, for instance displaying power output at various wind speeds along with error bars gives a visual cue about the potential spread in results caused by measurement uncertainty. This approach matters a lot because real-world factors like site conditions and mechanical issues often cause actual performance to stray from predictions. By portraying these variations graphically, researchers not only deepen understanding but also earn the confidence of stakeholders weighing the technology's merits.

Advanced visualization methods let researchers show how uncertainty affects derived figures, such as Levelized Cost of Energy (LCOE) across different scenarios. Using color gradients or contour lines to represent confidence levels adds depth to these images and helps viewers appreciate the risks tied to decisions based on the data.

Including measurement uncertainty in comparison charts also sharpens decision-making for engineers and policymakers. When judging multiple small HAWT designs against key benchmarks like efficiency or cost-effectiveness displaying uncertainty openly keeps users aware of the potential pitfalls in predicted performance.

It pays to keep uncertainty representation consistent throughout a report or presentation. This uniformity helps audiences absorb the information quickly without being thrown off by changing formats or symbols.

In short, integrating measurement uncertainty into figures makes research on small horizontal axis wind turbines more transparent and easier to interpret. By honestly



showing the variability woven into data collection and calculations, researchers communicate their findings more effectively and encourage better-informed discussions on the technology's future. See references: [13] p. 51-55, [16] p. 21-25 and [20].

7. Urban Turbulence Effects on Wind Performance

7.1. Spectral Analysis (FFT) of Urban Turbulence Patterns

Small horizontal axis wind turbines (HAWTs) face a tough nut to crack in urban environments because of the swirling, unpredictable wind flows. The way these turbines interact with chaotic airflow is key to grasping their performance and potential energy output. Using spectral analysis through Fast Fourier Transform (FFT) techniques, researchers break down wind speed data into frequency components, shedding light on the turbulence patterns turbines face in cities.

FFT breaks apart time-series wind speed signals into their basic frequencies, helping pinpoint dominant scales and turbulence behaviors. This matters a great deal in urban settings, where buildings and other structures throw all kinds of curveballs into the airstream. By applying FFT to fine-grained wind measurements taken at different heights above rooftops, it's possible to map how turbulence intensity shifts with building shapes and elevations.

The results show that urban turbulence spans a wide range of frequencies. Most energy clusters in the lower-frequency bands, linked to large flow disruptions, but the higher-frequency fluctuations those quick, jerky changes also carry a fair share of energy. Getting a handle on these frequency patterns helps forecast how much power a turbine can wring out of gusty winds common in cities.

Spectral analysis also aids in measuring turbulence intensity (TI), a vital factor for judging turbine performance. High TI usually means a more turbulent, choppy wind flow that can sap efficiency and put extra strain on turbine parts. Spotting locations with steady average wind speeds while keeping TI in check is crucial for making the most of small HAWT installations in tricky urban landscapes.

This insight feeds into smart control systems designed to help turbines roll with changing winds. Real-time FFT data can guide adjustments in blade pitch or rotor angles depending on expected gusts or spikes in turbulence. Such adaptive strategies boost energy capture and cut down on mechanical wear.

Field tests back up these FFT findings by offering real-world proof of how turbulent winds affect turbine behavior. This hands-on data helps engineers fine-tune blade designs and check structural durability for city-based turbines.

All told, FFT and related spectral tools give researchers powerful lenses to understand and tame urban wind chaos. Armed with this knowledge, developers and planners can make savvy choices for placing and managing small HAWTs



amid the complexity of city airflow. See references: [9], [16] p. 16-20, [6] and [1].

8. Discussion of Findings

8.1. Interpretation of Results in Contextual Relevance

This study reveals important insights into how small horizontal axis wind turbines (HAWTs) perform in urban environments. Laboratory tests provide consistent conditions that differ from those in the field. Comparing lab and real-world data shows how environmental factors like turbulence and site-specific features affect turbine efficiency and energy production.

Hybrid airfoil designs improve aerodynamic efficiency in varying conditions. These blades address challenges faced by HAWTs operating at low Reynolds numbers, where laminar separation bubbles reduce performance. The higher power output of hybrid blades helps handle the gusty, uneven airflow common in cities, making them suitable for urban installations.

Adaptive pitch control adjusts blade angles in real time based on wind data. This optimization increases energy capture and reduces mechanical stress. Such flexibility not only boosts output but also enhances reliability and simplifies maintenance.

Statistical validation methods assess measurement uncertainties both in labs and the field. Understanding these uncertainties allows engineers to make informed design and operational decisions that better cope with real-world challenges.

Economic analysis evaluates the financial viability of small urban HAWTs using metrics like levelized cost of energy and payback periods. These studies highlight how design improvements can lower costs, strengthening wind energy's competitive edge among renewables.

Spectral analysis of urban turbulence shows how building shapes influence local wind patterns near turbine sites. Recognizing these effects is critical when choosing installation locations to minimize turbulence and maximize wind resource use.

Overall, integrating small HAWTs into urban areas offers both opportunities and challenges. Success depends on balancing technology advances with environmental and public considerations. The findings demonstrate how combining innovation with practical conditions can unlock small wind turbines' potential as a green energy option in cities. See references: [19] p. 36-40, [4] and [1].

Table 3: Amount of pollution reduced, in kg/year, permission for use authorized by



International Energy Journal.

Year	Dust	SO ₂	NO _x	CO ₂
2019	0.082345	0.957965	1.301098	441.9573

8.2. Recommendations for Future Research

Future research on small horizontal axis wind turbines (HAWTs) must tackle several vital topics to boost their performance and usability in both urban and rural areas. One priority is expanding experimental designs to better match lab results with on-site performance, as highlighted in section 4.2. Since notable gaps exist between controlled and field data, more thorough studies should explore a broader range of environmental factors. This approach will sharpen predictive models and make performance evaluations reflect the realities turbines face outside the lab.

Moreover, as discussed in section 5.1, improving levelized cost of energy (LCOE) estimates calls for investigating fresh financing options and incentives that support small HAWT deployment. Research should also focus on discovering new materials and technologies to cut production costs while boosting efficiency and durability. Specifically, developing lightweight yet sturdy components suited for urban use where space is tight and aesthetics matter will make a real difference.

Beyond the technical side, noise reduction deserves attention since many small turbines operate near homes. Future studies could aim at advanced blade designs and vibration control methods that reduce noise without hurting turbine performance, building on findings from previous urban wind energy research.

Understanding urban turbulence patterns remains key for fine-tuning turbine designs tailored to city landscapes. As pointed out in section 7.1, spectral analysis through Fast Fourier Transform (FFT) techniques sheds light on the complex airflow around buildings. Applying these insights, researchers can develop turbine models better equipped to handle turbulent winds while maximizing power extraction.

Additionally, integrating adaptive pitch control systems in small HAWTs mentioned in section 2.2 needs more exploration to enhance responsiveness to the variable wind speeds common in urban environments. Future work might explore using machine learning algorithms to predict and adjust blade angles in real time, improving energy capture and reducing stress on components.

Finally, collaboration across disciplines is essential for addressing the wider challenges of embedding small HAWTs into existing urban infrastructure. Working closely with city planners and policymakers will help ensure that deployment fits sustainability goals and respects community concerns, as this text emphasizes. Research should also explore ways to foster local acceptance by



examining the social and economic factors that influence public support for renewable energy projects.

These recommendations map out a clear path for advancing research on small horizontal axis wind turbines, helping them become a more practical and effective solution for clean energy in diverse environments. See references: [7], [5] p. 206-210 and [1].

9. Conclusion

9.1. Summary of Key Findings

This study reveals notable progress and insights into small horizontal axis wind turbines (HAWTs). Exploring new design strategies, like hybrid airfoil shapes, proves that blending different aerodynamic features boosts efficiency, especially in the turbulent winds common in cities. As covered in section 2.1, these hybrid airfoils tackle low Reynolds number challenges by fine-tuning camber and thickness, leading to higher power output.

Adaptive pitch control systems play a key role in capturing more energy from changing wind speeds. Section 2.2 explains how these systems use smart algorithms to adjust blade angles on the fly, improving performance and easing mechanical wear in variable conditions. The comparison between lab tests and real-world data spotlights how important it is to understand environmental influences on turbines. Section 4.2 shows that differences between controlled and field conditions call for strong statistical tools to handle uncertainties, helping to align theory with actual results.

From a cost and performance perspective, the Levelized Cost of Energy (LCOE) poses a twofold challenge: keeping operations efficient while cutting expenses is vital for wider acceptance of small HAWTs. According to section 5.1, sensitivity studies demonstrate how changes in wind speed impact LCOE greatly, making location-based evaluations essential.

The way data is presented has also improved, with better figures showing measurement uncertainties so stakeholders can more easily grasp risks linked to predicted performance. This clarity is critical for making well-informed decisions about where and how to deploy turbines in urban environments, as noted in sections 6.1 and 6.2.

Moreover, the research examines the effects of urban turbulence on wind behavior by using spectral analysis methods described in section 7.1. Knowing how turbulence works helps shape rules for placing turbines in cities, maximizing energy output while managing disruptions in local airflow.



To wrap up, the study stresses that while small HAWTs offer great potential as green energy solutions in urban areas, continued efforts are needed to refine aerodynamic designs and reduce noise. These steps will unlock their full promise in supporting sustainable urban energy goals. See references: [16] p. 31-35, [1], [4], [22] and [5] p. 196-200.

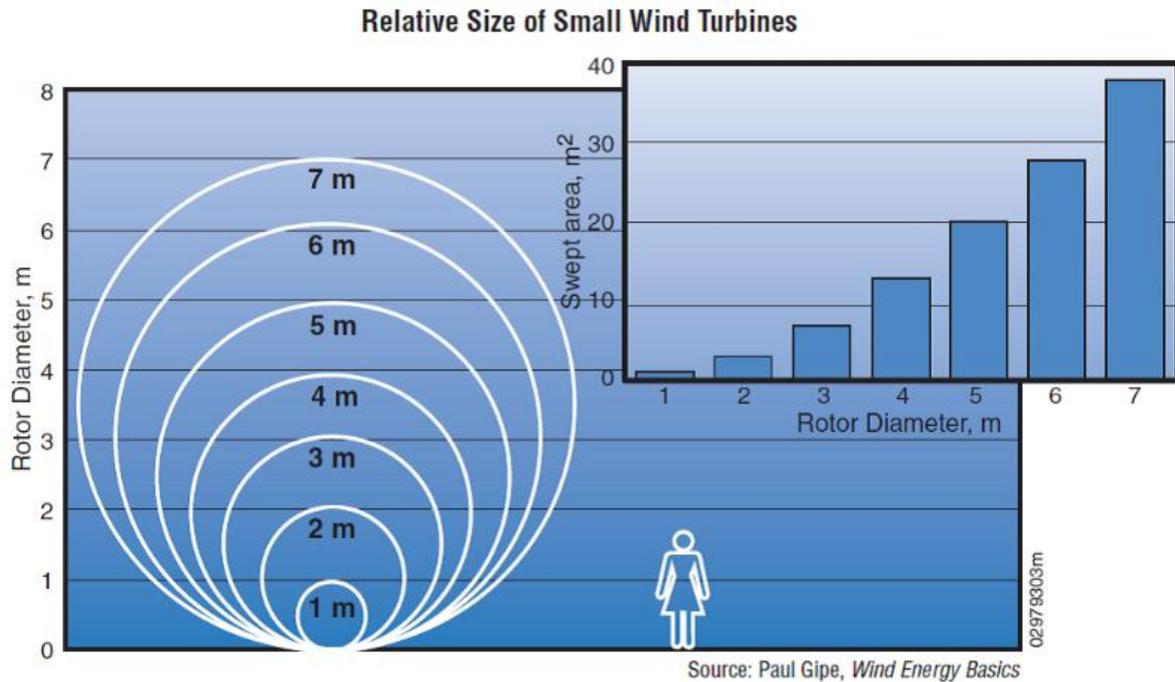


Figure 3: chart showing the relative size of small wind turbines by illustrating that the rotor diameter of a 2-meter turbine is about as tall as a person

9.2. Impact on Future Applications in Urban and Remote Areas

Small Horizontal Axis Wind Turbines (SHAWTs) show great potential for future use in urban and remote areas alike. As cities work harder to cut carbon emissions and switch to renewable power, SHAWTs fit in well with these goals. Their compact design and ability to capture wind energy even amid the turbulent airflows common in cities make them excellent for rooftop setups. This approach reduces the need for sprawling power lines and gives local communities a way to produce clean energy on their own.

Studies show small wind turbines perform well when placed on rooftops or building sides, where wind speeds often pick up due to tall structures nearby. The urban landscape poses challenges, such as unpredictable wind caused by nearby buildings and obstacles, but advances like hybrid airfoil designs help turbines thrive under these tricky conditions. Also, as more towns recognize the perks of



local energy production, policies encouraging SHAHT installations are likely to grow.

In places far from the grid, where electricity access is spotty or missing, SHAHTs offer a solid option for off-grid power. They can reliably serve isolated communities or support remote equipment like telecom towers and monitoring stations. When paired with battery storage, these turbines provide steady power despite the natural ups and downs of wind availability.

Collaboration between city planners and lawmakers is key to building frameworks that encourage SHAHT integration in both city and country settings. Smart policies might include speeding up permit approvals, offering financial help or tax breaks for renewable upgrades in homes, and rolling out programs that educate the public about the benefits of generating power locally.

Pilot studies in various urban areas can provide useful insights into how well SHAHTs work and how communities feel about them. This real-world feedback will help fine-tune installation practices and tackle any regulatory hurdles that slow their spread.

Looking ahead, ongoing innovations such as adaptive pitch control systems and tougher materials designed for city environments will likely push small horizontal axis wind turbines into wider use. They stand to play an important role in meeting clean energy targets in bustling cities as well as remote regions off the grid. See references: [8] p. 116-120, [27] and [1].

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