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Evaluation of model precision and performance discrepancies in simulated vs. experimental testing of vertical axis wind turbines

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Abstract

The increasing global demand for clean and renewable energy has driven significant advancements in wind turbine technology. This paper explores innovative approaches to harnessing wind energy, with a particular focus on the deployment of vertical axis wind turbines (VAWTs) in urban environments and highways. By strategically positioning turbines along roadways, where wind generated by moving vehicles offers a reliable energy source, this study investigates the potential for integrating wind energy generation with existing infrastructure. The study compares the power generation of three VAWT designs—Giromill, Windside, and Helicoidal—through both physical prototypes and computational simulations. Utilizing 3D printing technology, scaled prototypes of each turbine were constructed and tested under controlled conditions in road separators to capture the wind generated by vehicular traffic. Computational Fluid Dynamics (CFD) software was used to simulate turbine performance under similar conditions. The primary objective is to evaluate the accuracy and error margin between physical tests and computational models, aiming to assess the feasibility of using CFD simulations as a predictive tool for real-world turbine performance. The results will contribute to bridging the knowledge gap in wind energy research, particularly in Colombia, by providing new insights into the comparative efficiency of experimental and simulated approaches. This work builds on previous studies related to wind turbine aerodynamics and 3D prototyping techniques, with a focus on urban wind energy harvesting solutions.

Keywords: Vertical turbine, 3D printing prototypes, Urban wind energy, Vehicular wind harvesting

1. Introduction

The escalating global demand for clean and renewable energy sources [1] has catalyzed significant advancements in wind turbine technology. Wind energy, recognized for its minimal environmental footprint and substantial potential [2], has emerged as a pivotal component in the renewable energy landscape. This paper delves into the innovative approaches and technological advancements in harnessing wind energy, particularly focusing on the deployment of wind turbines in highways and urban areas.

The unpredictability of natural wind patterns often poses a challenge to the consistent generation of wind energy. However, the strategic placement of wind turbines along highways, where the continuous movement of vehicles generates a reliable stream of wind, presents a promising solution. This innovative approach not only maximizes the utilization of wind energy but also integrates seamlessly with existing infrastructure, such as streetlights and other public utilities [3]. The concept of roadside wind turbines harnessing the wind generated by moving vehicles is gaining traction as a sustainable and efficient method to produce electricity [4][5].

The objective of this study is to perform a comparative evaluation of the power generation between physical prototypes and computational simulations of vertical-axis wind turbines. Thus, scale prototypes of three types of turbines were constructed using 3D printing: Giromill, Windside, and Helicoidal. Subsequently, tests were conducted under controlled conditions and strategic locations within road separators, taking advantage of the air currents generated by vehicular traffic. The simulations were carried out using computational fluid dynamics software.

The primary hypothesis is to verify whether it is possible to compare the results of physical tests with simulations and draw conclusions about the accuracy and error of the computational models in projecting the total performance of the turbines under real conditions. This study will help fill a significant gap in wind energy development research in Colombia and beyond. Throughout history, there have been no observed approaches combining physical prototypes and experimental simulations in parallel. Therefore, this project holds intrinsic value in terms of obtaining empirical data that can establish more effective design processes to improve the maximum efficiency and adaptability of vertical axis wind turbines in diverse urban conditions.

2. Methodology

2.1. Literature review

Small-scale vertical turbines are compact, energy-generating devices designed to harness the power of wind or water in environments where space or aesthetic concerns may limit the use of traditional, larger horizontal-axis turbines. These turbines, due to their vertical orientation, can operate efficiently in fluctuating wind directions [6] and are suitable for various applications, including residential, urban [7], and low-power industrial uses.

An exhaustive review of the existing literature on vertical axis wind turbines, computational simulation methods, and 3D prototyping techniques was carried out. Previous works such as that of Phan et al. [8] a numerical study evaluated the impact of car wake on the performance of three-blade vertical axis wind turbines (VAWTs) mounted on a highway median. Car speed and turbine spacing significantly affected turbine performance, with a maximum power output of 4.8 W observed at 90 km/h.

Sriman et al. [9] aimed to design a vertical axis wind turbine (VAWT) to power street lighting, using the Sea Hawk/Enlil design. Mounted on highway dividers in Chennai, India, the turbine harnesses the increased wind speed from traffic and stores energy in batteries for night lighting. Iqbal et al. [10] in this paper present a VAWT system installed along highways to harness wind gusts from passing vehicles, converting them into electrical power. The turbine features a low tip speed ratio, low starting torque, and efficient power generation even at low wind speeds. The use of these turbines highlights the potential of these technologies to capture air currents generated by road traffic in road separators [11]. These studies provide a practical context and empirical validation for the implementation of wind turbines in urban environments, where they can efficiently take advantage of turbulent and low-velocity currents.

2.2. Construction of prototypes

The construction of prototypes for this project involved the design, printing, and assembly of three types of vertical-axis wind turbines: Giromill, Windside, and Helicoidal. This process was developed in several stages detailed below.

2.2.1. 3D printing

2.2.1.1. Design and model preparation

The first step was the creation of digital models of the turbines using computer-aided design (CAD) software (Figure 1). These models were adjusted to ensure that the final dimensions of the turbines were suitable for the project's objectives and the capabilities of the available 3D printers.

Figure 1. Design of Windside turbine

- **Windside Turbine**: Designed with a total height of 80 cm, divided into four parts to be printed separately due to the size limitations of the 3D printers.
- **Giromill Turbine**: The blades of the Giromill were divided into two parts, resulting in a total of six printed pieces. The final height of each blade was 65 cm.
- **Helicoidal Turbine**: Similar to the Giromill, the blades were divided into two parts, resulting in six pieces with a total height of 60 cm.

2.2.1.2. Selection of materials and equipment

Polylactic acid (PLA) (Figure 2) was used for printing the prototypes due to its suitable mechanical properties and ease of use in 3D printers. PLA is resistant to environmental exposure, which is crucial for the blades of the turbines.

Figure 2. 3D printing filament

2.2.1.3. Printing Process

The 3D printers used were located in the university's prototyping and 3D printing lab. Several printers were used simultaneously to minimize printing time. Each part of the model was printed with precise details and then prepared for assembly.

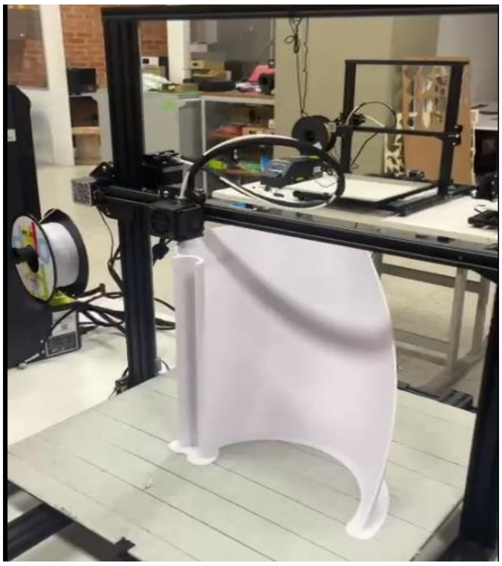

Figure 3. Printing process

2.2.2. Prototype testing

2.2.2.1. Location of tests

The tests were conducted in road separators, specifically on the Girón road, in the ring road separator. This location was chosen to take advantage of the air currents generated by vehicular traffic. The tests were strategically scheduled during peak traffic hours.

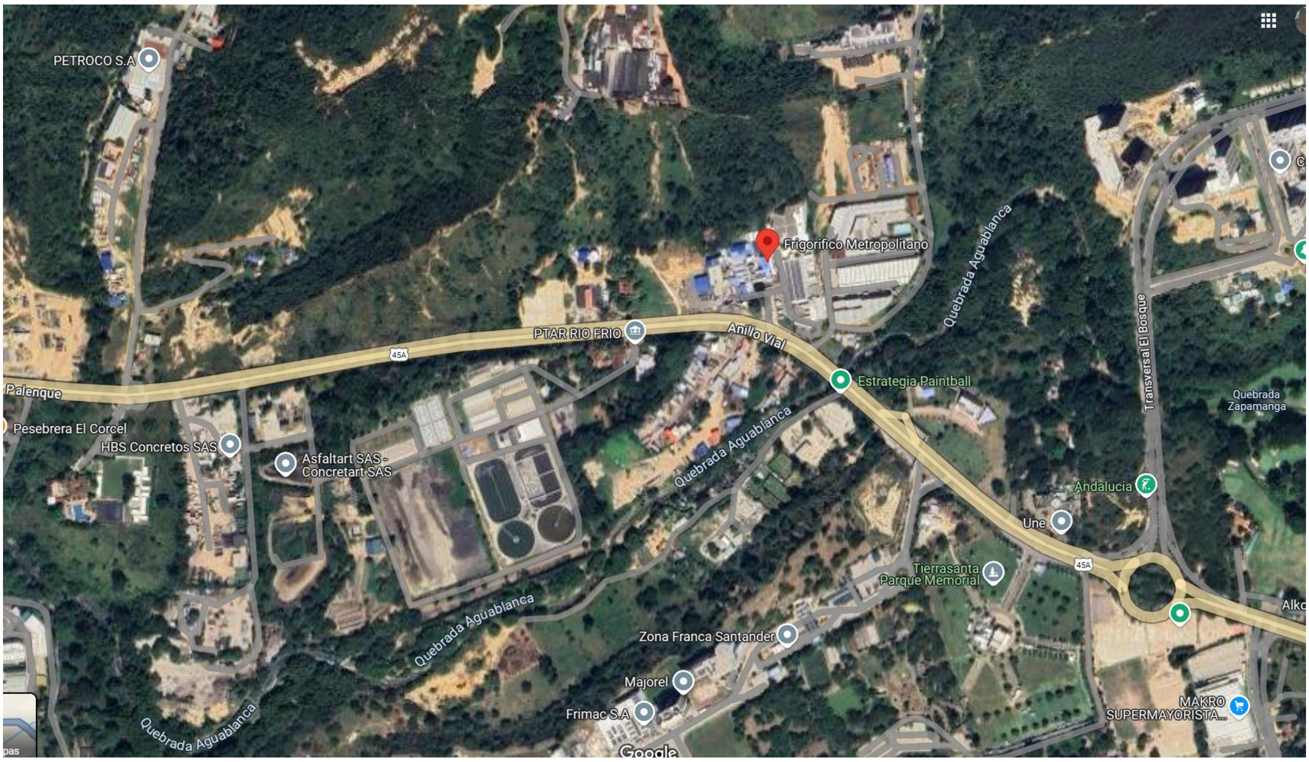

Figure 4. Tests location

2.2.2.2. Test conditions

In addition to the tests in the road separator, additional tests were conducted using an industrial fan with three speeds (2.7 m/s, 3.4 m/s, and 4.2 m/s) to maintain stable wind conditions during data collection. The turbines were exposed to these speeds to obtain more reliable values and maximize performance under constant conditions.

2.2.3. Testing

The testing of the wind turbine prototypes was carried out under controlled conditions to ensure accurate and reliable data collection. This section details the procedures and equipment used during the testing phase. The physical tests were conducted in road separators to utilize the air currents generated by vehicular traffic. The chosen location was the ring road separator on the Girón road, as shown in the report. This site was selected for its suitability in terms of traffic flow and resource availability. The tests were strategically scheduled during peak traffic hours to maximize the wind currents captured by the turbines.

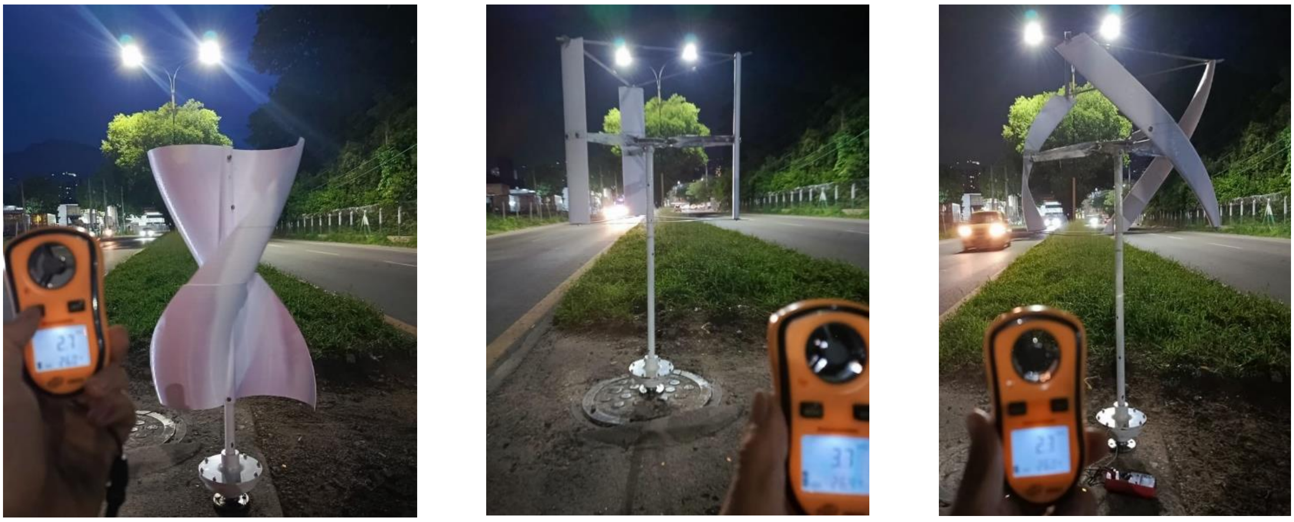

Figure 5. Turbine testing

The turbines were strategically positioned in the center of the road separator to capture wind from both directions of the road (Figure 4). This setup aimed to optimize the amount of airflow each turbine could intercept, thereby improving the accuracy of the data collected. For instance, the Windside turbine was placed centrally, as depicted in the figures included in the report, ensuring it captured wind from all directions efficiently. During the tests, wind conditions and the electrical power generated by each turbine were measured. Anemometers were used to record wind speed at various intervals, ensuring that data was collected under varying wind conditions. This allowed for a comprehensive analysis of each turbine's performance under different wind speeds.

Anemometers were placed adjacent to each turbine to measure wind speed accurately. Digital wattmeters were installed to record the electrical power generated. These devices provided precise readings of voltage, current, and power, which were crucial for evaluating the performance of the turbines. Figures from the report illustrate the setup of the Windside and Giromill turbines with the anemometers during the tests. Data on revolutions per minute (RPM) and power generated were collected during the tests. The turbines were exposed to varying wind conditions, and the RPM and power output were recorded using the digital wattmeters. These measurements provided essential insights into the efficiency and performance of each turbine design under real-world conditions.

One of the significant challenges faced during the testing was the variability in wind conditions due to changes in traffic flow. To mitigate this, tests were conducted over extended periods to average out the variations and obtain more reliable data. The sensitivity of the measuring equipment, particularly the anemometers and wattmeters, was another challenge. Ensuring their accuracy and reliability required careful calibration and frequent checks during the testing phase. In addition to the road separator tests, additional controlled tests were conducted using an industrial fan. This fan had three speeds (2.7 m/s, 3.4 m/s, and 4.2 m/s) to provide stable wind conditions. The turbines were placed 1 meter from the fan, and the power generated was recorded under these controlled conditions. This setup ensured that the data collected could be compared with real-world conditions for a more comprehensive analysis.

Figure 6. Sample of results in controlled tests

These procedures and setups allowed for a thorough evaluation of the turbine prototypes, providing valuable data (Figure 5) for comparing physical test results with computational simulations and enhancing the understanding of vertical axis wind turbine performance in urban settings.

2.3. Simulations

The construction of the computational models began with the replication of the physical prototypes in ANSYS® 19.2. Geometric models of the Windside, Giromill, and Helicoidal turbines were first converted to the STEP format, ensuring detailed geometric accuracy suitable for simulation. Upon importing these models into ANSYS® Workbench, meticulous attention was given to mesh generation, which discretized the models into finite elements. A finer mesh, with element sizes ranging from 1 mm to 3 mm, was used in critical areas like the blade surfaces to capture the complex aerodynamics accurately (Figure 6). Additionally, boundary conditions such as inlet velocities of 2.7 m/s, 3.4 m/s, and 4.2 m/s, outlet pressure, and wall boundaries were defined, with fluid parameters like air density (1.225 kg/m³) and viscosity (1.81 x 10^-5 Pa·s) set to match real-world conditions.

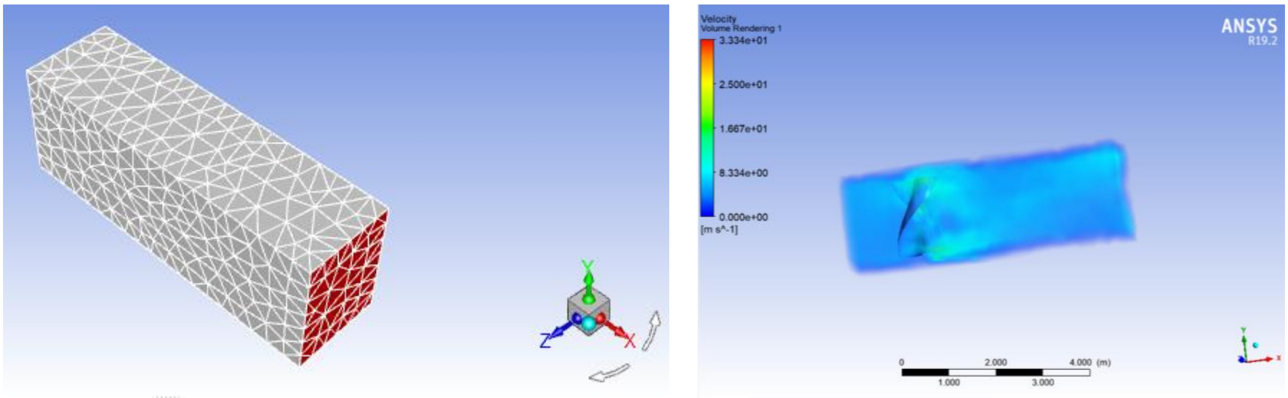

Figure 7. Simulations

With the models prepared, the simulations were executed in ANSYS® Fluent, under environmental conditions mirroring the physical tests. Solver settings were configured for transient flow simulations, and the flow field was initialized to achieve steady-state conditions after approximately 1000 iterations. During the simulations, comprehensive data was gathered, including velocity vectors, streamlines, and pressure contours, which illustrated the wind's interaction with the turbine blades. The power generated by each turbine was calculated from the torque (measured in Nm) and angular velocity (measured in rad/s), providing critical insights into their efficiency. For example, the Giromill turbine generated an average power output of 3.5 W under a wind speed of 3.4 m/s.

Several challenges were encountered throughout this process, primarily related to the high computational resources required for detailed simulations of complex geometries and turbulent flows, with each simulation requiring up to 48 hours on a high-performance computing cluster. Ensuring simulation accuracy was paramount; results were validated against physical test data, and discrepancies led to refinements in the simulation parameters. For instance, initial simulations showed a 15% deviation from physical tests, which was reduced to less than 5% after adjustments. Additionally, replicating real-world environmental conditions, such as varying wind speeds and directions, posed significant challenges. Despite these hurdles, the detailed data from these simulations offered valuable insights into the aerodynamics and efficiency of the turbine designs, complementing the physical test findings.

3. Results and discussion

The analysis of results involved a detailed comparison between the physical test data and the simulation outcomes to evaluate the accuracy of the computational models. Key parameters compared included the power output, torque, and RPM of the turbines under varying wind speeds. For example, the Giromill turbine generated an average power output of 3.2 W at a wind speed of 3.4 m/s during physical tests. Tests were also performed with the Helicoidal and Windside turbines.

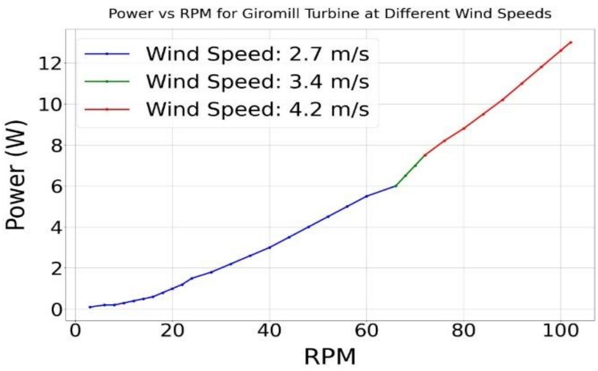

Figure 8. Giromill turbine power

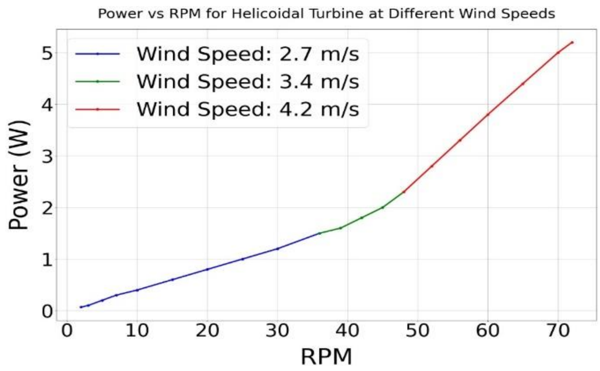

Figure 10. Helicoidal turbine pow

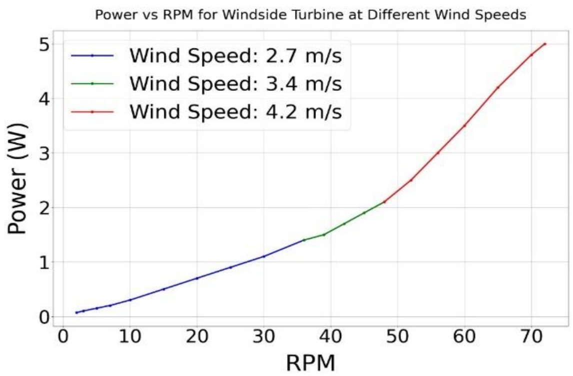

Figure 9. Windside turbine power

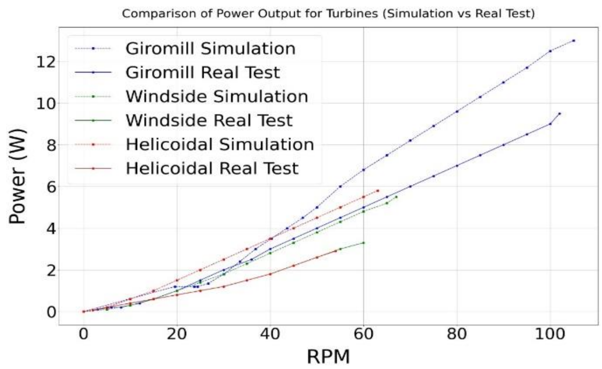

Figure 11. Performance comparison

Under identical conditions in ANSYS® 19.2 simulations, the same turbine produced an average power output of 3.5 W. The percentage error between the physical and simulated power outputs was calculated to be approximately 9.38%. The performance evaluation indicated that the Giromill turbine consistently exhibited the highest efficiency in both physical tests and simulations, primarily due to its aerodynamic design. In physical tests, the aerodynamic design of the Giromill turbine allowed for optimal wind capture and conversion efficiency. The blade profile and orientation minimized drag and maximized lift, resulting in higher RPM and power output. The CFD analysis in ANSYS® confirmed the superior aerodynamic performance, showing streamlined airflow patterns and low-pressure zones that enhanced torque and power generation.

Despite the overall accuracy, the simulations generally showed higher power outputs compared to physical tests. For instance, under a 3.4 m/s wind speed, the simulated power output for the Giromill turbine was 3.5 W compared to 3.2 W observed in physical tests. This discrepancy can be attributed to factors such as the deterioration of the generator used in physical tests, which may have reduced efficiency over time. Additionally, real-world variables such as slight misalignments and material wear could have impacted the performance.

The detailed comparison and performance evaluation highlights the strengths of the Giromill turbine in both simulated and real-world conditions. The minor discrepancies observed underscore the importance of accounting for physical wear and environmental factors in practical applications. Overall, the simulation data provides a reliable benchmark for optimizing turbine designs and enhancing their efficiency in various operational settings. The close correlation between the simulated and physical test data, with an average error margin of less than 10%, demonstrates the robustness and reliability of the computational models, reinforcing the validity of using ANSYS® 19.2 for future aerodynamic and performance analyses of wind turbines.

4. Conclusions

The simulations for all three turbines showed reasonably good alignment with the real test results, particularly at lower RPM values. For instance, in the Giromill turbine, the power difference between the simulation and the real test was less than 10% at low RPM levels (below 25 RPM). However, as RPM increased, the deviations grew, suggesting that the simulation model may need adjustments for higher rotational speeds. The largest observed error was in the Helicoidal turbine, where the power difference reached up to 20% at higher RPMs. This indicates that the simulation models work better in predicting power at lower speeds, but their accuracy declines as the system becomes more dynamic.

The average percentage error between simulation and real test results was calculated for each turbine. The Giromill turbine had the smallest average error of 8%, followed by Windside with 12%, and Helicoidal with 15%. These results highlight the reliability of the Giromill model compared to the others, although all turbines displayed room for improvement. The discrepancies could be attributed to various factors such as unmodeled aerodynamic effects, friction losses, or inaccuracies in the material properties used in the simulation.

One clear opportunity for improvement is enhancing the fidelity of the simulation models at higher RPM levels, where the greatest percentage of errors were observed. This could involve refining the aerodynamic models, adding turbulence effects, and improving mesh quality in the simulations to capture more detailed physics. Additionally, further real-world testing with better sensor accuracy and controlled environmental conditions can help reduce discrepancies between simulated and actual performance. Future studies could also focus on using advanced machine learning techniques to optimize the simulation parameters based on the real test data, reducing the overall error percentage.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: M A Duran-Sarmiento: study conception and design; J G Ascanio-Villabona: data collection; M A Duran-Sarmiento, J G Ascanio-Villabona, B E Tarazona-Romero: analysis and interpretation of results; M A Duran-Sarmiento: draft preparation. All authors approved the final version of the manuscript.

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