Harvesting the Sky:

The Effect of Wing-Integrated Wind Turbine Blade Design on Power Generation in Electric Aircraft

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The aviation industry is one of the most rapidly growing contributors to global pollution, releasing large amounts of carbon dioxide, nitrogen oxides, and other greenhouse gases into the atmosphere each year. Commercial aircraft burn fossil fuels at extremely high rates, and the emissions produced at cruising altitudes have especially strong environmental effects. As worldwide air travel increases, these emissions continue to rise, placing significant pressure on international efforts to reduce climate-changing pollutants. Because aviation relies heavily on long-distance transportation and high-power engines, it remains one of the most difficult sectors to decarbonize. This challenge makes the search for cleaner aviation technologies both urgent and essential for meeting global sustainability goals.

Electric aviation has often been proposed as a potential solution to this problem, but current electric aircraft face major limitations. Modern batteries are heavy, store limited energy, and cannot support the long ranges required for commercial flights. As a result, most electric aircraft prototypes are restricted to short-distance travel, slow speeds, or very small passenger loads. Without an additional source of in-flight energy, electric aviation remains restricted by existing battery technology. This limitation has created a need for new systems that can support electric aircraft while they remain in motion, reducing the burden placed entirely on stored battery power.

To address this challenge, this research project introduces a new concept: Wing-Integrated Wind Turbines (WIWTs). WIWTs are a proposed system in which small, aerodynamically efficient wind turbines are embedded directly into the wings of an aircraft. Unlike traditional turbines designed for stationary wind farms, WIWTs operate by capturing the fast, concentrated airflow naturally produced as an aircraft moves forward. Because the airflow over a wing accelerates due to the wing's airfoil shape, this motion provides a continuous and powerful stream of air that could, in theory, be converted into electrical energy. WIWTs were created for this investigation as a potential method of generating supplemental power during flight without relying on external fuel sources.

If effective, this system could significantly change the outlook of electric aviation. The additional in-flight energy produced by WIWTs could extend aircraft range, stabilize energy supply, and reduce the battery mass required for long trips. By decreasing reliance on fossil fuels and boosting the practicality of electric aircraft, WIWTs could contribute to lowering aviation-related emissions and slowing the environmental impact associated with air travel. In the long term, innovations such as this could help shift the aviation industry toward cleaner technology, making sustainable flight more achievable and reducing the sector's contribution to global pollution.

The independent variable in this experiment was the design of the WIWT. Four distinct designs were tested: a horizontal-axis wind turbine, a three-bladed H-Rotor vertical-axis turbine, a three-bladed Savonius vertical-axis turbine, and a six-bladed parallel-to-wind turbine. Each design possesses unique structural and aerodynamic characteristics that influence energy capture. Horizontal-axis turbines, commonly used in large-scale wind farms, perform well in consistent high-speed winds but are less effective in turbulent airflow, such as that found on aircraft wings. Vertical-axis turbines, including the H-Rotor and Savonius designs, capture wind from multiple directions, making them more adaptable to variable airflow. The parallel-to-wind turbine, a novel concept developed for this study, features a low-drag configuration aligned with airflow over the wing to maximize energy capture while minimizing aerodynamic resistance.

The dependent variable was the electrical power output of each turbine, measured in volts (V). This variable reflects each turbine’s efficiency in converting airflow into usable electrical energy under controlled conditions. Output was measured with a digital voltmeter connected to each turbine’s terminals, with readings recorded systematically during wind tunnel tests. Multiple trials were conducted to account for variability, and the average voltage output was used for analysis to ensure reliable comparisons across turbine designs.

The relationship between the independent and dependent variables is grounded in aerodynamic theory, which suggests that blade shape and orientation directly affect energy conversion efficiency. Designs that reduce drag while optimizing exposure to accelerated airflow, such as the parallel-to-wind turbine, exploit pressure differentials along the wing surface to enhance power generation. Previous research on small-scale and experimental turbines supports this relationship, demonstrating that blade geometry and alignment are critical determinants of energy output, particularly in turbulent or variable wind conditions.

The hypothesis used in this experiment was: if a Parallel-to-Wind Wind Turbine is integrated into an aircraft wing, then it will generate more electrical energy than other turbine designs because its orientation allows it to capture the accelerated airflow over the wing surface while theoretically minimizing drag. Superior performance from this design would demonstrate that WIWTs can function effectively in flight conditions, supporting the feasibility of WIWTs as a supplemental power source for electric aircraft.

Materials used included a large cardboard box (cut into two panels measuring 160 cm × 60 cm), duct tape, a hot glue gun with approximately twenty glue sticks, a digital anemometer, a leaf blower, balsa wood or 3D-printed plastic for wing supports, two wooden dowels (0.8 cm and

1.4 cm diameters), foam board sheets (45 cm × 35 cm), two DC motors, a multimeter, and multiple wind turbine blade sets (two blades per design). Additional tools included a marker, ruler, and utility knife.

The wind tunnel was constructed by cutting the cardboard box into two panels, each measuring 120 cm × 55 cm. Panels were scored every 30 cm to facilitate bending and were then formed into a rectangular tunnel. Seams and scored areas were secured with duct tape and reinforced with hot glue to prevent air leakage. A mounting system for the leaf blower was created by cutting a gap in a separate cardboard panel to fit the blower's nose. The blower was inserted, secured with tape and glue, and supported with a small cardboard stool to maintain clearance for airflow. After construction, the wind tunnel airflow was tested using the digital anemometer, and the leaf blower was adjusted to produce a wind speed of approximately 55 kph.

The wing structure was built using thin wood or foam board to replicate a NACA 6412 airfoil, scaled to a length of 40 cm. Four internal supports were created, each drilled with four holes at the front, middle, and back to reduce weight and allow for wire routing. Additional foam board or wood pieces were glued between supports to strengthen the structure. Two foam board sheets (41 cm × 20 cm) were scored at 0.25 cm intervals along the first 4 cm and 1.5 cm intervals for the remainder to allow them to bend around the airfoil. The scored sheets were glued to the supports, leaving 4 cm between each support and a 12 cm gap at the center. Excess material was trimmed, and edges were smoothed with sanding.

Openings were cut into the wing to install each turbine type. For the Savonius configuration, a 7 cm × 6 cm opening was cut at the bottom of the wing and a round hole was drilled to accommodate the DC motor shaft. The motor was inserted with the shaft facing outward, and wires were routed through the support holes and connected to the multimeter. The turbine blades were attached, and preliminary tests were conducted. The H-Rotor and Horizontal-Axis turbines were installed using similar procedures, with corresponding openings cut in the wing and motors and blades mounted according to their orientation. For the Parallel-to-Wind turbine, a 5 cm × 2.5 cm slot was cut on top of the wing, the motor was mounted sideways with the shaft facing inward, and the turbine was attached and tested.

The completed wing was mounted inside the wind tunnel using wooden dowels through the farthest forward and rear holes in the supports. The wing was positioned in the center of the tunnel to maximize airflow exposure, and the multimeter was set to the 20V DC setting. The leaf blower was activated, and wind speed was confirmed at approximately 55 kph using the anemometer. If a turbine did not spin automatically, it was manually started before taking readings. Electrical output from each turbine was recorded for five trials per design, and the data were analyzed to determine power generation efficiency. All procedures were repeated consistently to ensure reliable comparisons between turbine designs.

The data collected from the trials revealed clear and consistent differences in energy generation among the four wing-integrated wind turbine (WIWT) designs. The Parallel-to-Wind turbine produced the highest power output, with a mean output of 0.258 volts and a narrow range of 0.02 volts. This consistent performance demonstrates the reliability and efficiency of the Parallel-to-Wind design in capturing airflow energy when integrated into a wing structure. The Savonius turbine generated moderate power, averaging 0.164 volts with a range of 0.03 volts, indicating some variability in performance. Both the H-Rotor and Horizontal-Axis turbines produced negligible energy, with mean outputs of 0.004 volts and 0.002 volts, respectively, confirming their limited suitability for wing integration under the tested conditions.

Figure 1: Data Gathered

Type of Wind Turbine	Energy Generated (20V)						
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Range
Savonius	0.18	0.16	0.17	0.15	0.16	0.164	0.03
H-Rotor	0.01	0	0.01	0	0	0.004	0.01
Parallel to Wind	0.25	0.26	0.26	0.27	0.25	0.258	0.02
Horizontal-Axis	0	0.01	0	0	0	0.002	0.01

The null hypothesis for this experiment stated that the Parallel-to-Wind turbine would not generate more energy than the other WIWT designs. To test this, a one-way analysis of variance (ANOVA) was conducted to evaluate whether the differences in mean energy output among the four turbine types were statistically significant. The ANOVA results revealed a p-value of less than 0.01, indicating extremely strong confidence that the differences observed were not due to random variation but were instead attributable to the turbine design itself. The F-statistic of 1800 further supports this conclusion, demonstrating a clear separation in mean energy output between at least some of the groups. This analysis confirmed that the choice of turbine type had a substantial and measurable effect on power generation, validating the need to investigate specific designs for WIWT implementation.

Figure 2: ANOVA (One-Way) Summary

Effect	**Degrees of Freedom (df)**	**F-statistic (MS / MS residual)**	**P-value**	**Interpretation of P-value Explain**

Turbines	3	1800	<0.01	A P-value of <0.01 means extremely strong confidence that the groups are different.		
Residual	19	-	-	-	-	-

Following the ANOVA, post hoc pairwise comparisons were performed to determine which turbine types differed significantly from one another. The Parallel-to-Wind turbine generated significantly more energy than the H-Rotor, Horizontal-Axis, and Savonius turbines, with mean differences of 0.255, 0.257, and 0.0943 volts, respectively, and p-values below 0.01. The Savonius turbine also produced significantly more energy than both the H-Rotor and Horizontal-Axis turbines, with mean differences of 0.161 and 0.162 volts, respectively. In contrast, no significant difference was observed between the H-Rotor and Horizontal-Axis turbines, as indicated by a mean difference of -0.00167 volts and a p-value of 0.98. These post hoc results demonstrate that turbine orientation and blade design are primary factors affecting energy generation and provide strong statistical support for the conclusion that the Parallel-to-Wind design is the most effective among the turbines tested.

Figure 3: Post-Hoc Comparisons

Pair	**Mean diff**	**P-value**	**Interpretation of P (Auto)**	**Interpretation of P (Manual)**
Horizontal-Axis + H-Rotor	-0.00167	0.98	Means: no evidence that the groups might be different	Parallel-to-Wind significantly higher
Parallel to Wind + H-Rotor	0.255	<0.01	Means: extremely strong confidence that the groups are different	Parallel-to-Wind significantly higher
Savonius + H-Rotor	0.161	<0.01	Means: extremely strong confidence that the groups are different	Parallel-to-Wind significantly higher
Parallel to Wind + Horizontal-Axis	0.257	<0.01	Means: extremely strong confidence that the groups are different	Savonius significantly higher
Savonius +	0.162	<0.01	Means: extremely strong confidence	Savonius significantly higher

Horizontal-Axis			that the groups are different	
Savonius + Parallel to Wind	-0.0943	<0.01	Means: extremely strong confidence that the groups are different	No significant difference

The results clearly supported the experimental hypothesis, showing that the Parallel-to-Wind turbine consistently generated the highest energy among all tested designs. Its alignment with the airflow and streamlined integration into the wing structure allowed it to harness accelerated wind effectively, resulting in both high power output and consistent performance across trials. The Savonius turbine produced moderate energy but was limited by its vertical-axis design, which is less suited to the predominantly laminar airflow over a wing, leading to slightly more variability between trials. The H-Rotor and Horizontal-Axis turbines demonstrated minimal energy generation, underscoring the limitations of conventional turbine configurations when applied to wing-mounted applications.

Examining both the mean outputs and trial-to-trial variation provided additional insight into the reliability of each design. The Parallel-to-Wind turbine's narrow range confirmed predictable performance, while the Savonius turbine showed modest fluctuations that may affect continuous energy generation in practical aviation scenarios. These observations emphasize that consistent output is as critical as maximum energy generation when evaluating turbine designs for integration into aircraft wings.

Collectively, the findings highlight the importance of blade design and orientation in WIWT performance. The Parallel-to-Wind turbine effectively captures high-speed airflow over the wing while theoretically minimizing drag, demonstrating the potential for WIWTs to serve as a dependable supplementary power source in electric aviation. This study underscores the need to optimize aerodynamic compatibility in turbine design to achieve both efficiency and reliability, reinforcing the feasibility of WIWTs for advancing sustainable aviation technology.

In conclusion, by integrating wind turbines into aircraft wings, the potential exists to create a quasi-closed energy loop, where the motion of the aircraft generates airflow that the turbines convert into electrical energy to supplement onboard systems. While this system does not achieve perpetual motion due to energy losses inherent in mechanical systems, it represents a significant advancement in improving energy efficiency for electric aviation. This innovative approach aligns with broader research into renewable energy integration, where onboard harvesting technologies reduce reliance on external energy sources while enhancing operational sustainability. The aerodynamic optimization of turbine designs further supports the practicality of such systems by improving energy capture during flight conditions.

Overall, this study successfully identified the parallel-to-wind turbine as the most effective design for wing-mounted applications in electric aircraft. By aligning the blades with airflow to minimize drag and maximize energy capture, this design significantly outperformed traditional turbine configurations. These findings contribute valuable insights into the development of sustainable aviation technologies and underscore the importance of aerodynamic optimization in energy harvesting systems. Future research should explore the integration of energy storage solutions and real-flight testing to further validate the practical applications of these findings.

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