Literature Review

As a result of the persistent challenge of low battery density, researchers are now exploring onboard energy-harvesting systems to supplement stored power and extend the limited range of electric aircraft. Dr. Magedi Saad, an academic researcher at Tun Hussein Onn University of Malaysia, and colleagues note that "the Ram Air Turbine (RAT) is used as an emergency power source to feed vital apparatuses required for aircraft in case of main systems failure," emphasizing its value as a "wind harvesting technology for aircraft and its advantages as [an] auxiliary power generator during landing process" (Saad et al., 2021). Their observation demonstrates that wind-based energy generation is already a functional concept in aviation, even when confined to short-term emergency operations. Expanding on this, Matthew Dowling and Mark Costello from the Georgia Institute of Technology observe that "only large-scale systems typically achieve a power coefficient of over 50%. At smaller scales, power coefficients usually drop dramatically due to the aerodynamic characteristics of airfoils at low Reynolds numbers" (Dowling & Costello, 2018). The Reynolds number measures how air behaves around a blade, indicating whether the airflow stays attached or becomes weak and prone to separation. Showing thattThis decline mirrors the aerodynamic constraints that limit RAT performance, revealing a shared efficiency challenge rooted in scale rather than principle. Adding a practical dimension, Dale Walter-Robinson, CEO of ElectronAir LLC, patented an *Energy cell Regenerative System for Electrically Powered Aircraft,* in which, "at least one fan generator [is] mounted on an aircraft… near a propeller… to harness the kinetic energy of the propeller blast," so it doesn't affect the flight characteristics of an aircraft (Walter-Robinson, 2014). This system demonstrates how continuous, drag-neutral energy harvesting can be structurally integrated into existing aircraft designs. Together, these studies show that the main challenge to effective airborne wind harvesting lies in engineering efficiency rather than conceptual feasibility. Overcoming small-scale aerodynamic losses through integrated turbine design could transform wind systems from emergency backups into fully embedded energy sources that extend the range of electric aircraft.

Building upon the foundational understanding of RAT operation, recent research has shifted toward refining aerodynamic geometry and flow interaction to enhance overall power output. Dr. Magedi Saad and his research team conducted a Computational Fluid Dynamics (CFD) investigation that found "the counter-rotating [RAT] improved the performance of the conventional… RAT by increasing efficiency up to 45%, with power outputs reaching 113.26 kW compared to 62.36 kW" (Saad et al., 2021). While this study centers on RATs, the findings highlight how flow symmetry and wake control, key aspects of aerodynamic efficiency, could be applied in distributed turbine systems across aircraft to reduce drag and improve overall energy capture. Further supporting this potential, Aeronautical and Astronautical Engineering researcher, Miguel Bolaños-Vera and colleagues developed a CFD-based model of a commercial RAT featuring "a 1.016 m diameter rotor and three aerodynamic blade sections… [achieving] power generation within a 5–60 kW range by combining high-lift and low-drag airfoils" (Bolaños-Vera et al., 2024). Their segmented blade design, which tailors the geometry to local airflow conditions, mirrors the principles required for distributed wind systems integrated along wing structures, where dynamic wind-circulation regions demand adaptive airfoil design. Extending these findings, Francesco Trevisi, European Academy of Wind Energy PhD Award Winner, and colleagues explored the aerodynamic co-design of wings and turbines, reporting that "placing the turbines at the wing tips and rotating them inboard down lead to higher power production… [with] a maximum power coefficient CP = 0.95 at $\alpha = 9°$" (Trevisi et al., 2025).

Their work underscores how turbine-wing interaction can enhance, rather than hinder, aerodynamic efficiency, suggesting that energy-harvesting wings could become structural assets rather than performance liabilities. Collectively, these studies shift the discussion from stand-alone turbine efficiency to aerodynamic synergy, showing that WIWTs can transform aircraft into hybrid energy-generating systems that sustain longer, more efficient flights.

As ideas advance toward integration into aircraft structures, optimizing the geometry, materials, and control systems of small-scale turbines is critical for maintaining efficiency and stability under variable conditions. Chris Kaminsky and fellow professors, from the Department of Engineering at Grand Valley State University, revealed that “increasing the attack angle of the airfoil created larger regions of separation causing what is known as the stall effect… [having] large separation regions would prove to be very inefficient because of the large amounts of drag that would exist” (Kaminsky et al., 2012). This study demonstrates that excessive flow separation (when airflow separates from a surface) at higher angles of attack drastically reduces aerodynamic efficiency by increasing turbulence and drag. In the context of WIWTs, such inefficiencies could offset energy gains if not properly managed, emphasizing the need for designs that balance lift generation with flow stability. Shifting from aerodynamic performance to structural composition, Antonio Rosato and his team from the Department of Architecture and Industrial Design at the University of Campania Luigi Vanvitelli, report that “fibreglass is the most used material for blade manufacturing... [while] aluminium dominates vertical-axis models” (Rosato et al., 2024). As demonstrated by the quote, these materials are favored in small-scale designs due to their ability to minimize excess loss and create consistent energy generation. Extending beyond design and materials, Barzegar-Kalashani et al. from Swinburne University of Technology emphasized that “in wind turbines, the aerodynamic power can be increased or decreased by pitching the airfoil distributed across the blade" (Barzegar-Kalashani et al., 2023). This adaptive mechanism allows turbines to automatically adjust to fluctuating wind conditions, ensuring efficient operation and protecting the structure from overload. Together, these studies reveal that successful WIWT implementation depends on the convergence of aerodynamic geometry, lightweight materials, and intelligent control, which collectively enable steady power generation under the dynamic conditions of flight.

As WIWTs become feasible, establishing reliable electrical management and energy distribution systems is essential to utilize the harvested power. Shuangqi Li and colleagues, from the Department of Electronic and Electrical Engineering at the University of Bath, explain that by adding a small battery that uses just 5% of its capacity, more than 23% of the times the fuel cell was producing over 40 kW (high power) can instead be shifted to a more efficient range of 10–40 kW, helping the system run closer to its best performance (Li et al., 2021). This demonstrates how adaptive battery sizing and intelligent energy management can stabilize fluctuating power inputs, a principle directly applicable to storing and distributing variable wind energy from WIWTs. Sumantra Bhattacharya, Faculty of Engineering at Universität Ulm, and professors note that "the converter is divided into two separate stages…the resonant converter stage and the voltage-balancing stage," the resonant converter stage can transfer electricity both ways between the high- and low-voltage systems, while the voltage-balancing stage adjusts the voltage so it reaches the proper level for the aircraft's main power network (Bhattacharya et al., 2022). This two-stage converter framework enables multi-directional energy flow between propulsion, storage, and auxiliary systems, ensuring power is delivered efficiently and safely throughout the aircraft. Luís Praça, a researcher at the Federal University of Ceara, and colleagues state that "[smart power electronics converters] make it possible to keep the on-board microgrid stable and reliable as more energy resources and electronic loads are connected" (Praça et al., 2023). Praça emphasizes that advanced converters and energy management strategies are critical for maintaining stability and reliability in aircraft microgrids, ensuring that variable energy output can be effectively integrated without disrupting the system. Together, these sources illustrate that successful WIWT integration relies on the convergence of adaptive energy storage, multi-directional conversion, and advanced microgrid control, ensuring wind-generated energy is efficiently stored, conditioned, and distributed across aircraft electrical systems.

Recent advances in aerodynamic modeling have shown that careful integration of propulsion and energy-harvesting systems into wing structures can transform aerodynamic interference into performance gains. Raymond Akagi, from California Polytechnic State University, shows that to reduce the effects of swirl and maximize efficiency, the actuator disk's diameter and rotation speed should be set to achieve a tip speed ratio just below 5, since increasing it beyond that adds very little extra power (Akagi, 2021). In this sentence, actuator disk refers to the section of the turbine interacting with the airflow, and tip speed ratio refers to the speed of the turbine blade in comparison to the airflow surrounding it. Thus, this relationship between swirl control and power efficiency shows that WIWTs must manage wake behavior to minimize drag while maintaining smooth, efficient airflow across the wing. Building on this, Matthew Clarke, Aerospace Professor at Stanford University, and fellow professors, identify that "on the wing section outboard of the propeller… the local wing section experiences an increase in the effective angle of attack due to the induced upwash from the blades," and the opposite is seen in the wing section inboard from the propeller (Clarke et al., 2021). These findings show that airflow around rotating systems can boost or reduce lift depending on placement, suggesting turbines in upwash zones could enhance wing performance and energy generation. Complementing this, Karen Deere, from NASA Langley Research Center, and colleagues, found that at a small angle of attack (0.6°), the cruise propulsors at the wingtip lower the wing's total drag by 7.5%, with the drag coefficient dropping to 0.0301 when powered (Deere et al., 2017). This measurable drag reduction demonstrates that aerodynamic coupling between propulsion and lift systems can be leveraged to achieve mutual benefit. Collectively, these studies illustrate how design precision - through controlled swirl, optimized placement, and wingtip interaction - lays the groundwork for successful WIWT integration, transforming aerodynamic challenges into energy-producing opportunities for next-generation electric aircraft.

Across the reviewed studies, the literature collectively demonstrates that advancements in sustainable aviation hinge on balancing aerodynamic performance, structural integrity, and energy regeneration. Research on small-scale wind systems, turbine geometry, materials, and control technologies has shown that energy capture can be efficiently achieved under variable aerodynamic conditions. Meanwhile, studies on distributed propulsion and aerodynamic integration emphasize that embedding energy systems within lifting surfaces can reduce drag and enhance stability. Together, these findings establish a foundation for combining aerodynamic efficiency with renewable energy recovery. Yet a critical research gap persists: WIWTs have never been directly examined in the academic literature, and no existing study investigates how a turbine system embedded within a lifting surface could influence both energy regeneration and aerodynamic performance. This study addresses that gap by asking: To what extent will WIWTs affect the flight range of electric aviation? It is hypothesized that properly designed WIWTs will enhance the operational range of electric aircraft by continuously supplementing onboard power with minimal aerodynamic penalty.

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