Methodology

In this study, I used computational fluid dynamics (CFD) to investigate how wing-integrated wind turbines (WIWTs) influence the aerodynamics of electric aircraft. The analysis focused on understanding the effects of turbine placement along the wing and the role of different airfoil geometries on both aerodynamic performance and energy extraction. By simulating airflow, pressure distribution, and turbine power output, I was able to systematically evaluate how design variations impacted lift, drag, and potential electrical power recovery. This CFD-based approach allowed controlled testing of multiple configurations, enabling direct comparisons between turbine locations and airfoil types. The resulting data provided a basis for correlating aerodynamic outcomes with turbine positioning and wing design, which is critical for optimizing WIWT integration in electric aircraft.

This study began by constructing detailed 3D CAD models, following the structural and geometric modeling recommendations from Dr. Magedi Saad and colleagues, who evaluated six airfoils of varying aerodynamic qualities to study turbine interactions (Saad et al. 2021). Based on their framework, three airfoils - NACA 4412, CLARK Y, and a NACA 23015 - were selected to represent a range of camber and thickness distributions relevant to WIWT integration. Consistent with work from Esteben Valencia, and fellow professors at the National Polytechnic Institute, the CAD workflow used parametric modeling to allow rapid reconfiguration of chord length, turbine inlet geometry, and internal cavity structure, ensuring consistent geometry across turbine placements (Valencia et al. 2020). The turbine was placed at three different positions per airfoil - leading-edge, mid-chord, and near-tip - this decision was informed by Samuel Merryisha and Parvathy Rajendran, from the Engineering Campus at Universiti Sains Malaysia, whose advanced CFD research on lifting surfaces demonstrated how pressure gradients and surface

shear vary predictably along a wing (Merryisha & Rajendran 2019). The turbine rotor itself was represented using a simplified geometry consistent with actuator-disk-based CFD recommendations from Eric Lynch, School of Aerospace Engineering at Georgia Institute of Technology, who emphasized that reduced-order rotor representation maintains realistic momentum extraction while keeping computational cost manageable (Lynch, 2011). All final wing-turbine assemblies were exported as STEP files for meshing.

Computational meshes were generated using a hybrid strategy that reflected the meshing principles outlined by Saad et al., Valencia et al., and Lynch, all of whom stress the necessity of resolving high-shear regions, boundary layers, and wakes to ensure numerical accuracy. The external fluid domain extended ten chord lengths upstream, fifteen downstream, and ten chord lengths above and below the wing to avoid artificial recirculation caused by proximity to domain boundaries. Unstructured tetrahedral cells were applied in the far field, while structured prism inflation layers were used near walls and the turbine cavity. Eric Lynch emphasized the importance of accurately capturing surface shear and boundary-layer growth in turbine-airfoil interaction studies (Lynch, 2011). This guided the use of inflation layers targeting $y+ \approx 1$, enabling the SST k-ω turbulence model to resolve turbulence directly rather than rely on wall functions. Local refinement was applied near blade tips and at the turbine inlet region, to resolve tip vortices and steep velocity gradients. Mesh skewness was kept below 0.3, and grid independence was verified using coarse, medium, and fine meshes of the baseline NACA 4412 mid-chord configuration, with less than 2% variation in lift, drag, and torque between medium and fine grids (Lynch, 2011; Saad et al. 2021).

To accurately simulate airflow around the wing and through the embedded turbine, the SST k-ω turbulence model was implemented in accordance with the methodology of Chris

Kaminsky and companions. Their work demonstrated that the SST k-ω model provides superior performance in capturing boundary-layer behavior, flow separation, tip vortices, and transitional structures over a wide range of aerodynamic regimes (Kaminsky et al. 2012). Solver settings were derived from Dr. Magedi Saad and colleagues, who used a dynamic mesh and User Defined Functions (UDFs) to represent rotor motion and physical properties (Saad et al. 2021). Similarly, this study employed a dynamic mesh to simulate turbine rotation, with the UDF specifying rotor mass, rotational axis, and blade motion. The solver was configured as a pressure-based, three-dimensional, transient simulation using absolute velocity formulation. Residuals, lift and drag forces, and turbine torque were monitored continuously to verify steady-state convergence (Kaminsky et al. 2012). The combined turbulence-solver-actuator disk framework ensured that complex aerodynamic behaviors were fully resolved across all geometric configurations.

Each airfoil-turbine configuration was simulated under controlled boundary conditions that matched the domain-sizing and inflow recommendations of Esteban Valencia and fellow professors. They emphasized that consistent boundary conditions and sufficiently large flow domains are essential for avoiding numerical interference and enabling realistic flow development (Valencia et al. 2020). Thus, a uniform inlet velocity was applied at the upstream boundary, a pressure-outlet condition was enforced downstream, and all wing and turbine surfaces were assigned no-slip wall conditions. These settings prevented artificial acceleration or recirculation near the boundaries and ensured meaningful flow distribution. Domain sizing was maintained based on Valencia et al. to prevent the outer flow from constraining wake growth; while the dynamic mesh and UDF-driven rotor motion followed Saad et al.'s method for representing rotating machinery in a transient, pressure-based solver environment (Saad et al.

2021; Valencia et al. 2020). Each configuration was run until aerodynamic forces and rotor torque stabilized within 1-2% over successive time steps, indicating steady-state behavior.

After simulation completion, data was post-processed to determine the aerodynamic effects of turbine placement and airfoil geometry on wing performance and energy extraction. Lift, drag, pressure contours, velocity fields, and turbine torque were extracted for every configuration and compared across the three placement locations and three airfoils. Additionally, Kaminsky et al. emphasized the importance of evaluating turbine efficiency using aerodynamic penalties alongside torque production, informing how these metrics were correlated to estimate the net aerodynamic cost of turbine integration (Kaminsky et al. 2012). Turbine-induced wake structures and inflow velocity deficits were examined using actuator-disk theory and momentum methods (Lynch, 2011). Finally, velocity-field comparisons and surface-pressure differences across airfoils incorporated principles regarding surface modification effects and interpretation of WIWT-induced aerodynamic modifications (Merryisha & Rajendran, 2019). Together, these analyses provided a comprehensive assessment of how WIWT placement and airfoil design influence aerodynamic efficiency and potential electric-flight energy recovery.

The methodologies described above provided a clear framework for investigating the effects of WIWTs on electric aircraft aerodynamics. Data was collected entirely through CFD simulations, systematically testing combinations of three airfoil types and three turbine placements to measure lift, drag, pressure distribution, and turbine power output. The outlined approaches from the sources were invaluable in shaping this study, allowing for a systematic and controlled evaluation of turbine placement and airfoil geometry. The resulting datasets will continue to support analysis of flight range and turbine efficiency, demonstrating how careful application of research can make a complex engineering problem manageable.

Works Cited:

Akagi, R. (n.d.-b). RAM Air-Turbine of minimum drag. DigitalCommons@CalPoly.
https://doi.org/10.15368/theses.2021.11

Barzegar-Kalashani, M., Seyedmahmoudian, M., Mekhilef, S., Stojcevski, A., & Horan, B.
(2023). Small-scale wind turbine control in high-speed wind conditions: A review.
Sustainable Energy Technologies and Assessments, 60, 103577.
https://doi.org/10.1016/j.seta.2023.103577

Bhattacharya, S., Anagnostou, D., Schwane, P., Bauer, C., Kallo, J., & Willich, C. (2022, July
29). *A flexible DC–DC converter with multi-directional power flow capabilities for
power management and delivery module in a hybrid electric aircraft.*
https://oparu.uni-ulm.de/items/5cf1f523-cab7-4a7f-9a70-aba3d9b1e98e

Bolaños-Vera, M. A., Ortiz-Pérez, A., Durazo-Romero, E., Pérez-Mota, J., González-Uribe, L.,
& Pérez-Reyes, I. (2024). Numerical analysis of aerodynamic performance of the Ram
Air Turbine in an aircraft. *Heliyon*, *10*(11), e32039.
https://doi.org/10.1016/j.heliyon.2024.e32039

Clarke, M. A., Erhard, R. M., Smart, J. T., & Alonso, J. (2021). Aerodynamic optimization of
Wing-Mounted propeller configurations for distributed electric propulsion architectures.
AIAA Aviation 2019 Forum. https://doi.org/10.2514/6.2021-2471

Deere, K. A., Viken, J. K., Viken, S. A., Carter, M. B., NASA Langley Research Center, Wiese, M. R., Norma Farr, & Craig Technologies. (2017). Computational analysis of a wing designed for the X-57 distributed electric propulsion aircraft. AIAA Aviation Forum, 1–2. https://ntrs.nasa.gov/api/citations/20170005883/downloads/20170005883.pdf

Dowling, M., & Costello, M. (2018b). Feasibility Study of embedded wind energy harvesting system for Parafoil-Payload Aircraft. *Journal of Aircraft*, *55*(5), 2127–2136. https://doi.org/10.2514/1.c034832

Kaminsky, C., Filush, A., Kasprzak, P., & Mokhtar, W. (2012). A CFD study of wind turbine aerodynamics. In American Society for Engineering Education & Grand Valley State University, *Proceedings of the 2012 ASEE North Central Section Conference*. https://asee-ncs.org/proceedings/2012/Full%20Papers/Kaminsky.pdf

Li, S., Gu, C., Xu, M., Li, J., Zhao, P., & Cheng, S. (2021). Optimal power system design and energy management for more electric aircraft. *Journal of Power Sources*, *512*, 230473. https://doi.org/10.1016/j.jpowsour.2021.230473

Lynch, C. E. (2011). Advanced CFD methods for wind turbine analysis. In *SMARTech Repository (Georgia Institute of Technology)*. http://hdl.handle.net/1853/39491

Merryisha, S., & Rajendran, P. (2019). *Experimental and CFD analysis of surface modifiers on Aircraft wing: a review*. https://akademiabaru.com/submit/index.php/cfdl/article/view/3516

Praça, L. C. G. F. &. M. G. S. &. P. P. (2023). Power Electronics Converters for On-Board
electric power systems. *ideas.repec.org*.
https://ideas.repec.org/a/gam/jeners/v16y2023i9p3771-d1135273.html

Rosato, A., Perrotta, A., & Maffei, L. (2024). Commercial Small-Scale Horizontal and Vertical
Wind Turbines: A Comprehensive Review of geometry, materials, costs and performance.
Energies, 17(13), 3125. https://doi.org/10.3390/en17133125

Saad, M., Mohd, S. B., & Zulkafli, M. F. (2017). A survey on the use of ram air turbine in
aircraft. AIP Conference Proceedings. https://doi.org/10.1063/1.4981189

Saad, M. M. M., Mohd, S., Zulkafli, M. F., Samiran, N. A., & Didane, D. H. (2021). CFD
simulation study on the performance of a modified RAM air turbine (RAT) for power
generation in aircraft. Fluids, 6(11), 391. https://doi.org/10.3390/fluids6110391

Trevisi, F., Cassoni, G., Gaunaa, M., & Fagiano, L. M. (2025). Concurrent aerodynamic design
of the wing and the turbines of airborne wind energy systems. *European Academy of
Wind Energy*. https://doi.org/10.5194/wes-2025-134

Valencia, E. A., Berrazueta, M., Leines, D., Lema, H., Rodriguez, D. A., & Hidalgo, V. (2020).
Aerodynamic design and testing of a Ram Air Turbine for Small Fixed-Wing UAVs.
AIAA Propulsion and Energy 2020 Forum. https://doi.org/10.2514/6.2020-3957

Walter-Robinson, D. M., & Llc, E. (2014, June 20). WO2015195856A1 - Energy cell
regenerative system for electrically powered aircraft - Google Patents.
https://patents.google.com/patent/WO2015195856A1/en