Embedding Renewable Energy and Propulsion Design in Engineering Technology Education: A Solar–Electric Hybrid UAV Capstone Project

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1. Introduction

Project-based and experiential learning approaches have been widely shown to enhance student engagement, conceptual understanding, and retention in STEM education, particularly when students are exposed to authentic, open-ended engineering problems that integrate analysis, design, and experimentation [1], [2]. Long-term studies in engineering education further highlight the importance of multidisciplinary design experiences and the incorporation of real-world constraints in preparing graduates for modern engineering practice [5], [6]. In response, national initiatives led by the American Society for Engineering Education (ASEE) have emphasized the need for curricular innovation that integrates sustainability, systems thinking, and industry relevance into undergraduate engineering programs [3].

Within this context, unmanned aerial vehicles (UAVs) provide an effective educational platform due to their inherently multidisciplinary nature, combining aerodynamics, propulsion, structures, electronics, and control systems. Among these, solar–electric UAVs are of particular interest, as they incorporate renewable energy harvesting to enable extended endurance while reducing emissions, noise, and operational costs. From both educational and technical perspectives, solar–electric propulsion offers a compelling framework for exploring sustainable aerospace systems.

This paper presents a senior design capstone project focused on the design, implementation, and experimental validation of a solar–electric hybrid propulsion system for a micro-class UAV, using a 24-hour endurance target as a design benchmark. The project is embedded within the Engineering Technology curriculum and emphasizes applied, project-based learning aligned with ABET Engineering Technology Accreditation Commission (ETAC) outcomes [4]. At the time of submission, the project has completed design, modeling, and preliminary experimental validation, with results demonstrating the feasibility of subsystem integration and providing insight into energy balance and performance characteristics under representative operating conditions.

2. Educational Context and ABET Alignment

The project is conducted within a required two-semester senior design sequence for Engineering Technology students. All modeling, component trade studies, MPPT schematic development, propulsion sizing, and preliminary experimental testing presented in this manuscript were completed by a three-student capstone team as part of their formal coursework, under faculty mentorship and structured design-review milestones. Capstone projects in this sequence emphasize applied problem solving, system-level design, teamwork, documentation, and technical communication, consistent with established practices in engineering education [1], [5].

Student learning assessment is implemented through a multi-layered framework consisting of (1) rubric-based evaluation of analytical and modeling artifacts, (2) subsystem design review scoring aligned with ETAC outcomes, (3) pre- and post-project self-efficacy surveys, and (4) structured peer evaluation of team contributions. These instruments are defined prior to experimental implementation and are applied consistently throughout the project lifecycle.

The solar–electric UAV capstone project is explicitly aligned with ABET Engineering Technology Accreditation Commission (ETAC) baccalaureate student outcomes [4]. Outcome attainment is supported through direct assessment artifacts embedded across design, modeling, and preliminary validation activities.

- ETAC Student Outcome 1 (SO1) is addressed through analytical modeling, propulsion sizing, and energy-balance simulations using computational tools.
- ETAC Student Outcome 2 (SO2) is evaluated through structured Preliminary and Final Design Reviews (PDR/FDR), where students present and justify system architecture, component selection, and performance trade studies under realistic constraints.
- ETAC Student Outcome 3 (SO3) is assessed through written and oral communication, including the capstone report, technical presentations, and conference-style submissions.
- ETAC Student Outcome 4 (SO4) is supported through experimental planning and preliminary testing, including definition of test procedures, instrumentation, and data analysis for propulsion and power subsystems.
- ETAC Student Outcome 5 (SO5) is evaluated through peer assessment, task responsibility matrices, and faculty observation of teamwork and professional collaboration.

Students integrate prior coursework in thermodynamics, fluid mechanics, electrical systems, electronics, and control systems into a multidisciplinary design experience, reinforcing design-thinking principles described in [6]. Active learning strategies—including iterative design reviews, collaborative problem solving, and model-based trade studies—are incorporated throughout the project, consistent with evidence demonstrating improved student engagement and performance in engineering education [2].
Student learning outcomes are further assessed using pre- and post-project Likert-scale surveys aligned with ETAC outcomes (Table 2). Due to the small cohort size, results are analyzed using descriptive statistics. In addition, rubric-based evaluations and qualitative student reflections are used to assess system-level design quality, application of modern tools, and effectiveness of technical communication. These combined methods provide complementary evidence of student attainment of ETAC outcomes within the context of a solar–electric hybrid UAV capstone project.

Table 1. Mapping of ABET ETAC Student Outcomes to Assessment Methods

ETAC Student Outcome	Primary Assessment Methods	Representative Evidence
SO1 – Application of knowledge and modern tools	Analytical modeling and simulation assignments	Computer-based energy-balance models; propulsion sizing calculations
SO2 – System and component design	Preliminary (Midterm) and Final Design Reviews (PDR/FDR)	Solar–electric propulsion architecture; component trade studies and design justification
SO3 – Technical communication	Written reports and oral presentations	Capstone report; design review slides; conference-style abstract
SO4 – Experimentation and data analysis	Planned bench-top propulsion and power-system testing	Defined test procedures; planned thrust, power, and battery state-of-charge data sets
SO5 – Teamwork and collaboration	Peer evaluation and faculty observation	Peer assessment forms; task responsibility matrix

Table 2. Self-Efficacy Survey Questions Aligned with ABET ETAC Student Outcomes

ETAC Student Outcome	Survey Question ID	Self-Efficacy Survey Statement
SO1 – Application of Knowledge and Modern Tools	SO1-Q1	I am confident in my ability to model and analyze energy balance in a solar–electric propulsion system for a UAV application.
	SO1-Q2	I am confident in my ability to use computational tools to evaluate propulsion performance and power requirements.
SO2 – System and Component Design	SO2-Q1	I am confident in my ability to design a solar–electric hybrid propulsion architecture that integrates energy harvesting, storage, and propulsion subsystems.
	SO2-Q2	I am confident in my ability to evaluate design trade-offs involving endurance, efficiency, and system constraints in UAV propulsion systems.
SO3 – Technical Communication	SO3-Q1	I am confident in my ability to document the design and analysis of a renewable-energy-based UAV system in a technical report.
	SO3-Q2	I am confident in my ability to explain solar–electric propulsion concepts and design decisions during technical presentations.

ETAC Student Outcome	Survey Question ID	Self-Efficacy Survey Statement
SO4 – Experimentation and Data Analysis	SO4-Q1	I am confident in my ability to plan experiments or validation procedures for evaluating propulsion and power-system performance.
	SO4-Q2	I am confident in my ability to interpret experimental or simulated data related to thrust, power consumption, and energy efficiency.
SO5 – Teamwork and Professional Collaboration	SO5-Q1	I am confident in my ability to work effectively with teammates on a multidisciplinary renewable-energy UAV project.
	SO5-Q2	I am confident in my ability to contribute responsibly to collaborative tasks such as system integration, documentation, and design reviews.

3. Problem Definition and Design Requirements

Achieving 24-hour endurance as a design benchmark in a micro-class unmanned aerial vehicle (UAV) presents a challenging energy-balance problem governed by aerodynamic efficiency, propulsion-system performance, and energy-conversion efficiency. Classical propulsion and thermodynamic principles indicate that propulsive efficiency, drag minimization, and effective energy management are critical factors in sustaining extended-duration flight [7], [8].

Previous studies on UAV propulsion and performance have demonstrated that propulsion efficiency and emissions considerations strongly influence vehicle sizing, mission feasibility, and operational sustainability [9]–[12]. These findings motivate the selection of solar–electric propulsion as a viable approach for exploring sustainable alternatives to conventional combustion-based UAV systems within an academic design context.

Based on a review of existing long-endurance solar-powered UAV platforms, the project adopts the following representative design requirements, which are used to guide analytical modeling and simulation studies:

- Maximum takeoff mass below 3.5 kg
- Cruise airspeed of approximately 9 m/s
- Thrust-to-weight ratio of approximately 0.3
- High-aspect-ratio wing geometry characteristic of solar-powered UAV configurations
- Lithium-ion battery energy density in the range of 200–300 Wh/kg

The primary technical objective of the project is to analytically close the daily energy balance, such that solar energy harvested during daylight hours is sufficient to sustain propulsion and recharge onboard batteries to support nighttime operation. This objective is evaluated through modeling and simulation, rather than through demonstrated flight performance at the current stage of the project.

4. Literature Context: Solar–Electric UAVs

Extensive research has demonstrated the theoretical and experimental feasibility of solar-powered unmanned aerial vehicles (UAVs) for extended-endurance missions through the integration of photovoltaic energy harvesting, battery energy storage, and high-efficiency propulsion systems [13]–[24]. These studies encompass a broad range of vehicle classes, including low-altitude micro-UAVs [18]–[20] and near-space or high-altitude platforms [14], [23], [24]. Recent sizing and configuration studies for small solar-powered UAVs further demonstrate how wingspan, mass distribution, and structural considerations directly influence achievable endurance and energy autonomy at the conceptual design stage [16].

Energy-autonomy modeling and power-system optimization have been shown to play a central role in sustaining long-duration operation, particularly under variable solar-irradiance and diurnal conditions [15], [17], [21], [22]. Optimization methods, including genetic-algorithm-based approaches, further underscore the importance of multidisciplinary, system-level design in the development of solar-powered UAVs [19].

Several landmark demonstrations, such as the AtlantikSolar UAV, validate analytical frameworks that integrate aerodynamics, propulsion, structural design, and energy-management strategies [23]. These academic efforts are complemented by industry-scale high-altitude pseudo-satellite (HAPS) platforms, including Airbus Zephyr and BAE Systems PHASA-35, which illustrate the operational relevance and scalability of solar–electric aircraft concepts [25]–[28].

Collectively, this body of work provides the theoretical foundation and design context for the modeling and simulation efforts undertaken in the present capstone project, informing subsystem selection, performance targets, and energy-balance analysis without implying direct replication of large-scale systems.

5. Engineering Methodology

At the time of submission, the student team has completed propulsion sizing calculations, diurnal solar energy availability modeling, battery state-of-charge (SoC) trajectory simulations, and MPPT schematic development. Bench-top testing has also been conducted to support initial validation of subsystem behavior.

Quantitative outputs include estimated cruise power requirements, thrust-to-power relationships, and solar energy availability profiles derived from NSRDB data, along with modeled overnight energy balance. Experimental results—including battery discharge performance and thrust variation—show reasonable agreement with analytical predictions, providing validation of the modeling framework while highlighting the effects of system losses and non-ideal component behavior.

These analytical and experimental results serve as measurable technical artifacts demonstrating engineering analysis, system integration, and model-based validation within the practical constraints of a senior capstone project.

5.1 System Architecture Overview

The system architecture developed for this project integrates four primary subsystems: electric propulsion, solar photovoltaic energy harvesting, lithium-ion battery energy storage, and a custom maximum power point tracker (MPPT).

Rather than constructing a complete airframe at this stage, the project emphasizes a ground-based propulsion and power-system demonstrator. This approach enables detailed evaluation of thrust requirements, subsystem efficiencies, and energy-flow interactions under controlled conditions prior to full flight integration.

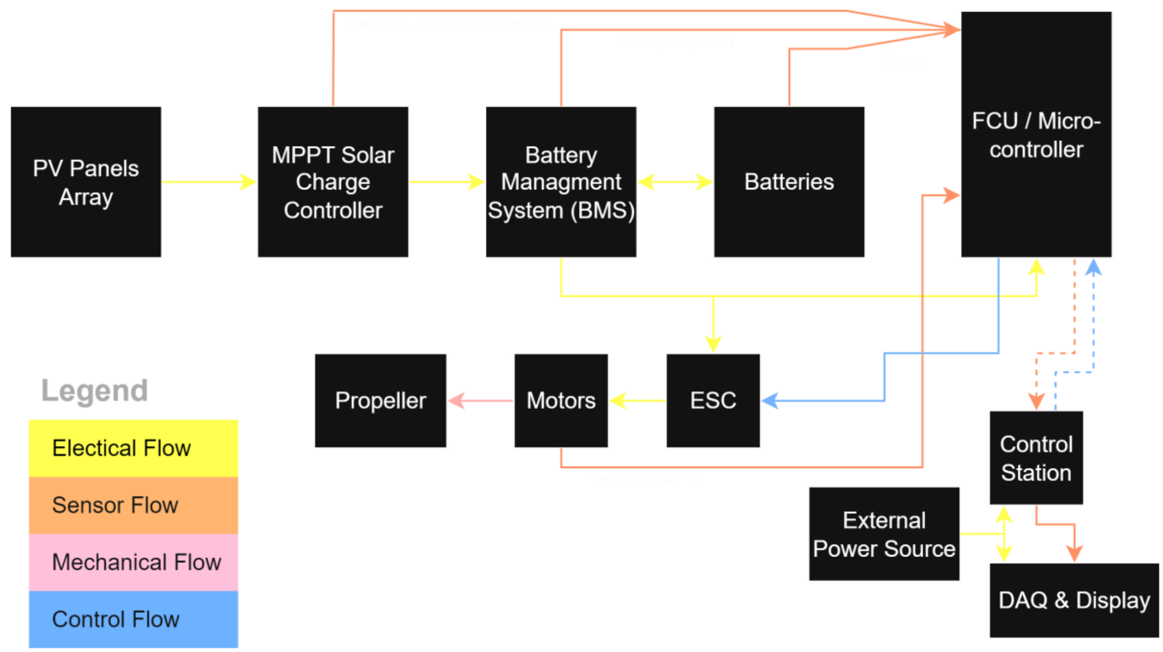

Figure 1. Conceptual system architecture of the solar–electric hybrid propulsion demonstrator.

Figure 1 illustrates the conceptual system architecture of the solar–electric hybrid propulsion demonstrator, including energy flow paths, control interfaces, and planned instrumentation. The architecture supports both analytical modeling and experimental validation, providing a structured framework for subsystem integration and performance assessment within the constraints of a senior design capstone project.

Fabrication and experimental implementation of the demonstrator are in progress, with integration and testing planned to further evaluate subsystem interactions and overall system performance..

5.2 Propulsion Subsystem Design

The propulsion subsystem consists of a high-efficiency brushless DC motor, a fixed-pitch propeller optimized for low Reynolds number operation, and a programmable electronic speed controller (ESC). Proper matching of the motor–propeller combination is critical for solar–electric UAV endurance, as propeller efficiency strongly influences power consumption under cruise conditions [29].

Propulsion sizing and efficiency trade studies are guided by classical propulsion theory [7], [8], with UAV-specific considerations informed by prior research on electric and hybrid propulsion systems [9]–[12]. Initial performance evaluation was conducted using analytical calculations and simulation models, including MATLAB-based energy-balance analysis and

spreadsheet-based sizing tools. These models incorporate published propeller performance data [29] and solar resource inputs derived from NSRDB datasets.
Preliminary bench-top testing has been performed to assess propulsion behavior under controlled conditions. Measured thrust trends show qualitative agreement with analytical predictions, particularly in the relationship between available electrical power and thrust output. These results provide initial validation of the propulsion sizing methodology and highlight the impact of voltage-dependent performance under battery discharge.

5.3 Solar Energy Harvesting and Storage

Solar energy harvesting is modeled using high-efficiency monocrystalline photovoltaic cell characteristics representative of lightweight aerial applications. Prior studies have shown that photovoltaic efficiency, array placement, and operational conditions significantly influence harvested energy and overall system performance [13], [14], [17]. These factors are incorporated into system-level simulations using site-specific irradiance data from the NSRDB to estimate available solar input under representative conditions.
Energy storage is provided by a lithium-ion battery pack, which serves as the primary energy buffer during transient operation and nighttime conditions. Lithium-ion batteries are widely used in UAV applications due to their high gravimetric energy density, cycle life, and reliability [15], [18]. Battery behavior is modeled to capture state-of-charge variation, charge–discharge efficiency, and nonlinear discharge characteristics.
Preliminary bench-level testing included electrical characterization of photovoltaic modules and validation of ESC–motor integration. In addition, controlled battery discharge testing was conducted to evaluate system-level energy performance. These results were used to verify manufacturer specifications, refine model parameters, and support validation of the energy-balance analysis.

5.4 Custom MPPT and Power Management

Commercial maximum power point tracker (MPPT) solutions suitable for lightweight solar–electric UAV platforms are limited. Accordingly, a custom MPPT architecture was developed at the conceptual and schematic levels, optimized for low-voltage photovoltaic input and lithium-ion battery charging.
Effective power management is essential for maintaining energy balance in long-endurance solar-powered UAVs. Strategies such as state-of-charge (SoC) trajectory management and power-flow regulation are incorporated into the system design to improve overall efficiency and operational stability [15], [21], [22].
Figure 2 illustrates the conceptual architecture of the custom MPPT, including photovoltaic input, sensing and control elements, power conversion stages, and battery charging interfaces. The design is informed by established analytical and experimental frameworks for solar-powered UAV systems [23], [24], while integrating modern sensing and control components appropriate for instructional implementation.
At the time of submission, the MPPT design has been completed at the schematic level, and prototype hardware has been developed. Initial subsystem integration has been initiated; however, full functional validation under solar input conditions is ongoing and will be completed in future testing.

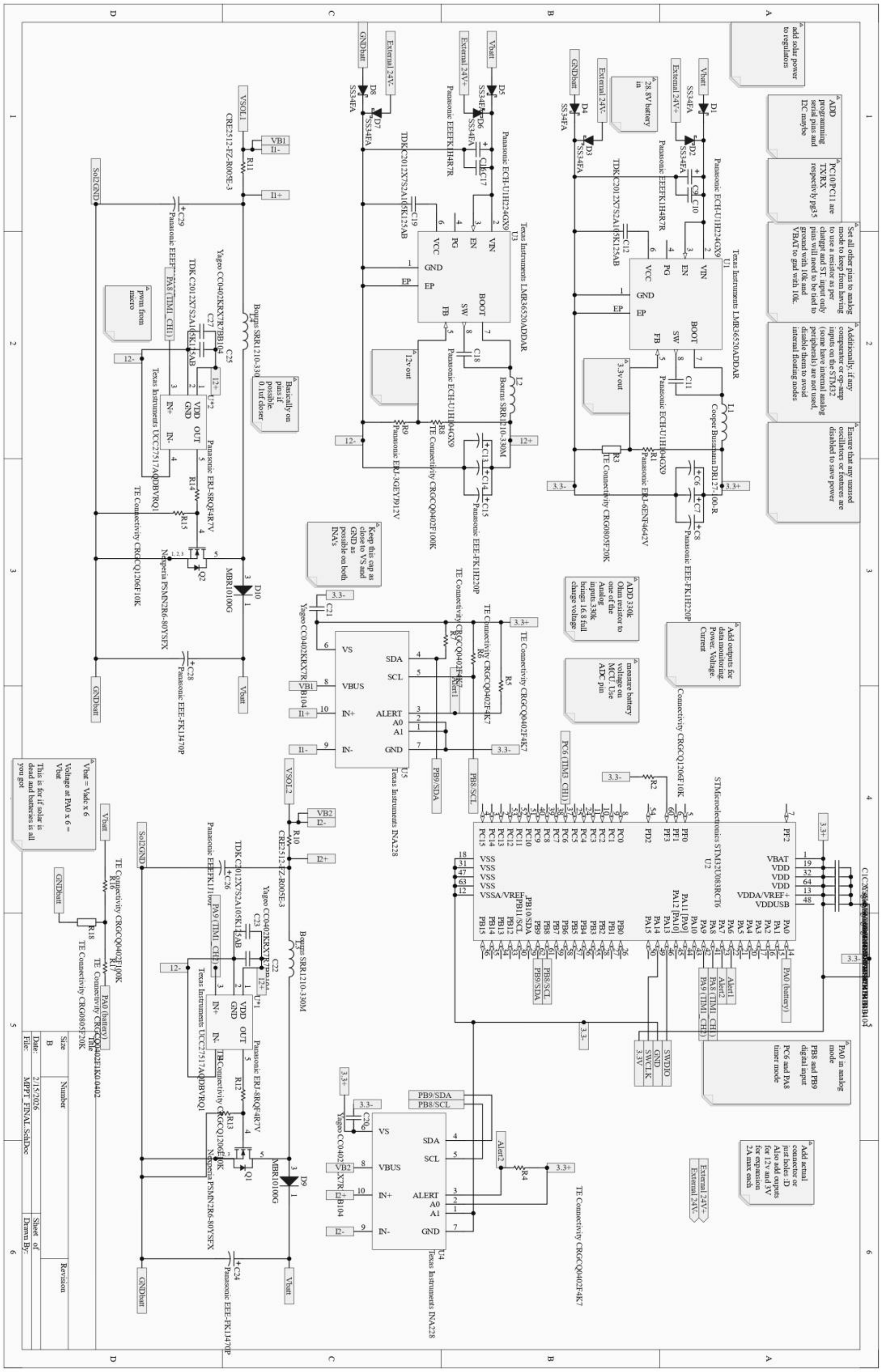

Figure 2. Conceptual block diagram of the custom maximum power point tracker (MPPT)

5.5 Instrumentation and Data Acquisition

A data acquisition and instrumentation framework has been developed to support experimental validation of the propulsion and power subsystems. Measurements include thrust using a load-cell-based system, electrical power flow, battery voltage and current, and overall system efficiency metrics. Data are collected and logged for time-resolved analysis to enable comparison with analytical and simulation results. The use of modern data acquisition and instrumentation tools reinforces experiential learning objectives and aligns with best practices in engineering education [1], [6].

5.6 Preliminary Analytical and Simulation Results

To support performance prediction prior to fabrication, the student team conducted propulsion sizing, energy-balance modeling, and solar resource analysis using measured irradiance data. Based on estimated aerodynamic drag and cruise conditions (9 m/s), the required steady-cruise thrust was calculated to be approximately 3.43 N, corresponding to an estimated electrical power demand of 20 W. Continuous 24-hour operation at this power level requires:

$$20\ \text{W} \times 24\ \text{h} = 480\ \text{Wh/day}.$$

Hourly Global Horizontal Irradiance (GHI) data were obtained from the National Renewable Energy Laboratory (NREL) National Solar Radiation Database (NSRDB) Typical Meteorological Year (TMY) dataset for Houston, Texas [30]. Monthly and daily solar energy availability were computed through Excel-based integration of hourly GHI values.

For December conditions, the average daily solar availability was approximately 2,578 $\text{Wh/m}^2\text{/day}$. A reduced-irradiance sensitivity analysis (60% of the monthly average) was also performed to evaluate system robustness under moderately cloudy conditions. However, analysis of daily data revealed that the worst recorded December day (December 24) exhibited only 473 Wh/m^2, indicating that actual variability due to cloud cover can be more severe than simplified reduction assumptions.

Applying photovoltaic efficiency (22.5%), MPPT efficiency (97%), and battery charge efficiency (95%), December-average energy neutrality would require approximately 1.5 m^2 of photovoltaic area. In contrast, worst-case winter days would require substantially larger collection area and therefore do not guarantee continuous operation under extreme low-irradiance conditions.

Experimental validation is scheduled for March–April, when solar availability in Houston is significantly higher than winter values. NSRDB seasonal trends indicate that spring irradiance levels are approximately twice those of December, enabling energy-neutral operation with reduced photovoltaic area. Accordingly, due to capstone budget constraints and airframe weight limitations, a 0.75 m^2 photovoltaic area was selected for prototype fabrication and spring testing.

Preliminary experimental results (Section 6) provide partial validation of the analytical model. A controlled battery discharge test under a constant 20 W load demonstrated approximately 16.5 hours of operation, compared to a predicted endurance of approximately 18.9 hours. This level of agreement is considered reasonable given system losses and battery non-idealities, and supports the validity of the modeling approach.

Overall, December-based modeling serves as a conservative design benchmark, while March–April field validation represents the practical operational scenario for this capstone implementation. This seasonal trade study directly informed photovoltaic sizing, battery-capacity selection, and MPPT architecture decisions, and highlights the importance of site-specific and time-dependent solar resource analysis in long-endurance UAV design.

6. Testing and Validation

Planned experimental activities include static thrust testing, electrical power consumption characterization, solar input and maximum power point tracker (MPPT) efficiency evaluation, and battery state-of-charge (SOC) tracking under representative duty cycles. These measurements are intended to validate analytical and simulation-based models developed during the design phase and to assess the feasibility of closing the daily energy balance associated with a 24-hour endurance design benchmark.

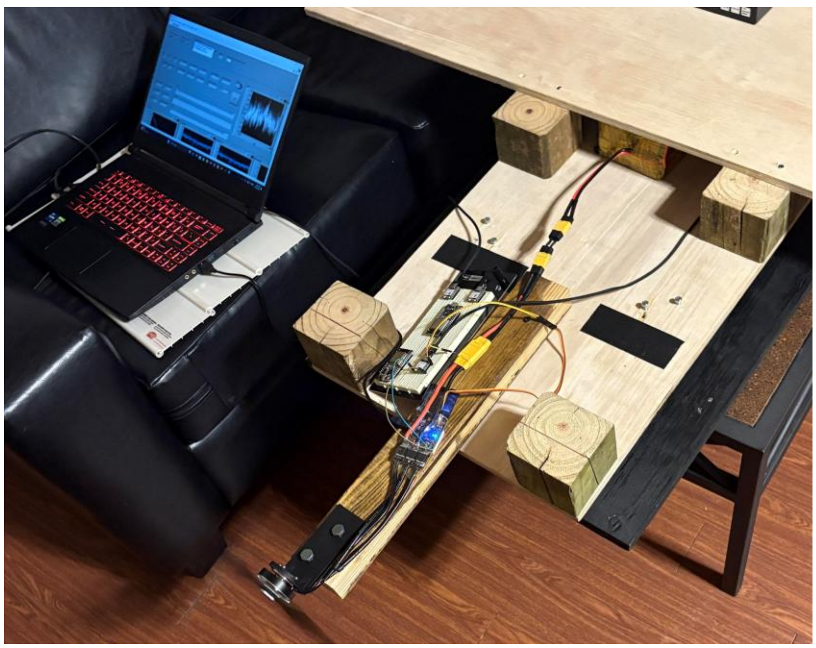

Figure 3. Test setup

At the time of submission, limited preliminary testing has been completed to support initial validation of subsystem performance. A bench-top propulsion and energy testing setup was developed to measure thrust and monitor electrical behavior under controlled laboratory conditions, as shown in Fig. 3. The setup integrates the propulsion unit, battery system, measurement instrumentation, and data acquisition components to enable repeatable testing. Additional subsystem development is illustrated in Fig. 4, including (a) installation of photovoltaic panels and (b) the custom MPPT prototype. These components form the basis for future integrated solar–electric system testing.

(a) (b)

Figure 4. (a) Installation of solar panels, (b) MPPT prototype

A nighttime discharge test was performed using a fully charged lithium-ion battery (~400 Wh) under a constant 20 W load, without solar input. The system operated for approximately 16.5 hours, compared to an ideal estimate of 18.9 hours, with the difference attributable to conversion losses and non-ideal battery behavior (Figure 5).

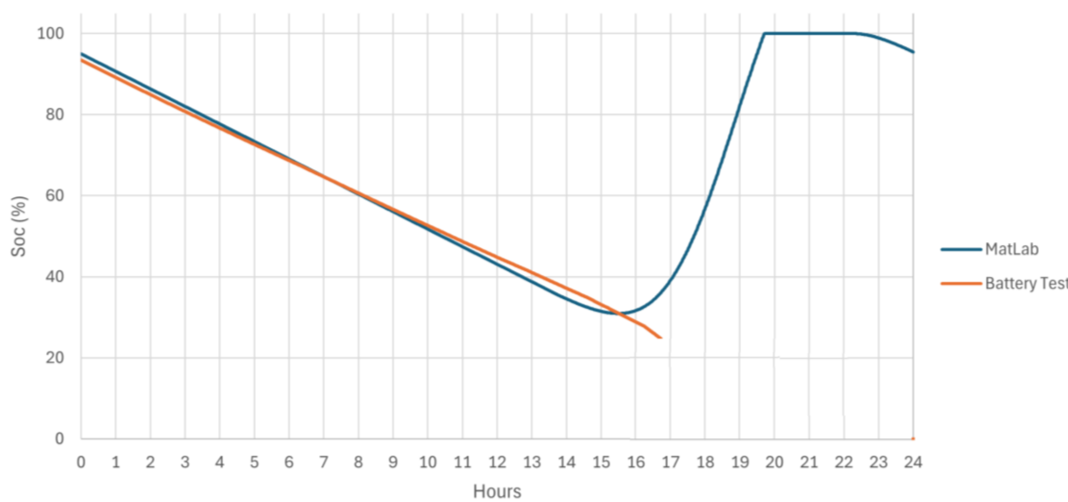

Figure 5. SoC prediction vs. Test

Figure 5 compares predicted (Matlab simulation) and measured battery SoC over time. The results show a smooth decrease with good agreement over most of the discharge period. Deviations near the end are attributed to nonlinear battery characteristics and the absence of solar input for recharging. These results provide initial validation of the energy consumption model and battery sizing assumptions.

Preliminary thrust measurements were also obtained during operation. After filtering high-frequency noise, the thrust data were locally averaged to highlight the overall trend, and the resulting values (in Newtons) show a gradual decrease as battery voltage and available power decline (Fig. 6).

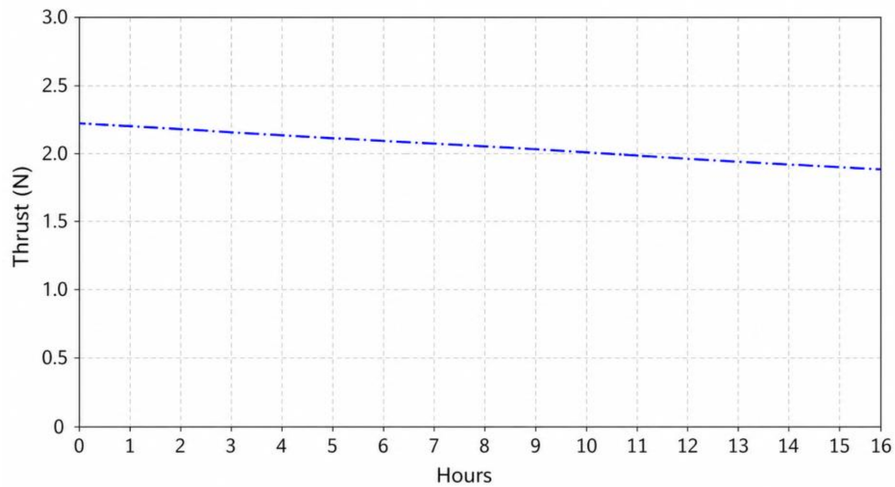

Figure 6. Thrust vs. time during discharge test (filtered data showing overall trend).

As shown in Fig. 6, thrust decreases with time during discharge, confirming the expected coupling between energy availability and propulsion performance. Reduced battery voltage leads to lower motor speed and corresponding thrust reduction, consistent with the propulsion model described in Section 5.

Fully integrated system testing—including simultaneous solar input, MPPT operation, and closed-loop energy management—has not yet been completed. Fabrication and testing of the integrated solar–electric system are ongoing. Future work will focus on validating daytime energy harvesting, MPPT efficiency, and full diurnal energy balance under representative environmental conditions.

7. Educational Outcomes and Broader Impact

By engaging students in a multidisciplinary, renewable-energy-focused capstone project, this work reinforces design thinking, active learning, and system-level integration skills that have been shown to improve student engagement and learning outcomes in engineering education [2], [6]. Through the integration of analytical modeling, simulation-based design, and system-level trade studies, students develop practical competencies directly applicable to modern engineering technology practice.

Student learning outcomes were evaluated using a combination of rubric-based assessments, peer evaluations, and a pre- and post-project self-efficacy survey aligned with ABET ETAC outcomes. Survey results indicate a consistent and measurable improvement in student confidence across all outcome areas, with the average Likert-scale score increasing from approximately 3.07 (pre-project) to 4.20 (post-project) on a 5-point scale (Figure 7).

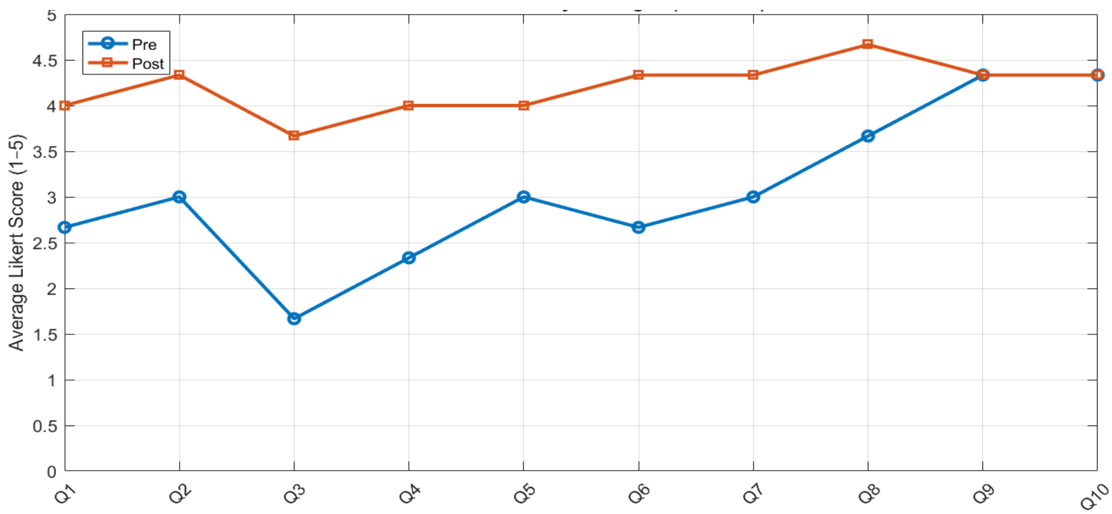

Figure 7. Pre- and Post-Project Self-Efficacy Scores

Figure 7 presents the mean pre- and post-project Likert-scale scores for each survey item (Q1–Q10). The results show a clear upward trend across all questions, indicating improved student confidence following completion of the project. The most significant gains are observed in Q3, Q4, and Q6–Q8, which correspond to competencies related to system-level design, energy modeling, and experimental planning—primarily aligned with ETAC Student Outcomes 1 and 2.

In contrast, items associated with communication and teamwork (e.g., Q9–Q10) show smaller or zero relative changes, which is consistent with higher initial baseline scores and suggests a ceiling effect. Overall, the results demonstrate that the project had the strongest impact on technical confidence areas directly tied to modeling, analysis, and system integration.

Given the small cohort size (n = 3), these findings are presented as preliminary; however, they provide quantitative evidence that the solar–electric UAV capstone framework supports measurable improvements in student self-efficacy, particularly in areas related to multidisciplinary integration and applied engineering analysis.

The project aligns with ASEE recommendations for transforming undergraduate engineering education by emphasizing sustainability, systems thinking, and industry relevance [3], [5]. As a scalable capstone framework, this work provides a model for incorporating renewable energy and hybrid propulsion concepts into Engineering Technology curricula, thereby supporting broader educational objectives related to workforce preparation and sustainable aerospace systems.

7.1 Representative Student Work and Contributions

To provide concrete evidence of student engagement, representative artifacts include propulsion sizing spreadsheets, MATLAB-based energy-balance simulations, MPPT schematic development, and subsystem trade-study matrices comparing photovoltaic area and battery mass fractions. Students independently developed simulation scripts to model diurnal solar irradiance and battery state-of-charge trajectories, and iteratively refined propulsion sizing based on cruise thrust requirements. These artifacts were evaluated during structured design reviews using faculty rubrics aligned with ETAC outcomes.

Student contributions were distributed using a task responsibility matrix (RACI format) and milestone-based deliverables assigned to individual team members. Each student was responsible for a primary subsystem—propulsion modeling, solar-energy modeling, and MPPT/power electronics architecture—while integration tasks were conducted collaboratively. Peer evaluation forms were administered at midterm and final review stages to assess individual participation, accountability, and technical contribution. These evaluations contributed to individual grading and ensured balanced engagement across the team.

The combination of independently developed analytical models, subsystem-level design ownership, and collaborative system integration provides direct evidence of student attainment of ETAC outcomes related to problem solving, system design, and teamwork within a multidisciplinary engineering context.

8. Conclusions and Future Work

This paper presents a solar–electric hybrid UAV capstone project that integrates renewable energy concepts, propulsion system design, and power electronics within an Engineering Technology curriculum. The project establishes a comprehensive engineering and educational framework aligned with ABET Engineering Technology Accreditation Commission (ETAC) outcomes [4], incorporating system-level modeling, energy-balance analysis, and experimental validation.

Bench-top testing was conducted to evaluate key subsystem behaviors, including battery discharge performance and propulsion characteristics. Experimental results demonstrate reasonable agreement with analytical predictions, supporting the validity of the modeling approach while highlighting the effects of real-world losses and non-ideal component behavior.

Future work will focus on continued system integration and expanded testing under representative operating conditions, including validation of solar energy harvesting, MPPT efficiency, and full diurnal energy balance. In addition, analytical and simulation models will be further refined using experimentally obtained data.

The overall approach is scalable and transferable to other Engineering Technology programs seeking to incorporate sustainable aerospace systems and renewable-energy integration into senior capstone design experiences.

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