Project-Based Learning through Renewable Energy: A Wind-to-Heat Energy Conversion

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Project-Based Learning with Renewable Energy: A Wind-to-Heat Capstone Case Study

Abstract

This paper presents a senior design capstone project where mechanical engineering students created a wind-powered thermal energy system for greenhouses. The students applied concepts from thermodynamics, heat transfer, fluid mechanics, and machine design to build a working prototype. The project included defining requirements, following engineering standards, choosing concepts with decision matrices, analytical modeling, prototyping, and experimental testing. While the prototype did not reach its target thermal output, the differences between predicted and actual results gave students valuable lessons about modeling assumptions, electromagnetic losses, and design choices made late in the process. This paper describes the project structure, teaching goals, student learning outcomes, and key lessons, and offers a model for adding renewable energy projects to mechanical engineering capstone courses.

1. Introduction

Project-based learning plays a central role in mechanical engineering education by providing students with opportunities to integrate technical knowledge, teamwork, and professional judgment in the solution of open-ended problems. Senior capstone design courses, in particular, are intended to prepare students for engineering practice by requiring students to address realistic constraints, justify design decisions, and evaluate system performance through analysis and experimentation.

In recent years, renewable energy has emerged as a compelling context for capstone design projects due to its interdisciplinary nature and societal relevance. Renewable energy systems naturally require the application of core mechanical engineering principles while also introducing considerations related to sustainability, cost, safety, and system integration. As a result, such projects provide an effective means of engaging students while reinforcing program-level learning objectives and accreditation outcomes.

This paper presents a senior design project in which mechanical engineering students designed and evaluated a wind-to-heat energy conversion system within a two-semester capstone sequence. Students defined system requirements, researched applicable engineering standards, evaluated alternative concepts using decision matrices, developed analytical models, fabricated a prototype, and conducted experimental testing. Emphasis was placed on engineering judgment, assumption awareness, and iterative refinement rather than on achieving a predetermined performance target.

Although the prototype did not achieve the thermal output predicted by steady-state analysis, discrepancies between analytical predictions and experimental observations became a central component of the learning experience. The contribution of this paper is not the presentation of a novel wind-powered heating device, but rather the documentation of a practice-based educational case study intended to provide a transferable framework for integrating renewable energy and sustainability into mechanical engineering capstone design courses. The broader context motivating this work is discussed in the following section.

In addition to describing the technical development of the system, this work also evaluates the effectiveness of the project in supporting student learning and engagement and identifies opportunities for improvement in future implementations.

2. Background

Global food production has increasingly relied on greenhouse farming, particularly in highly populated regions. However, heating greenhouses requires substantial energy and can become expensive when electricity or fossil fuels are used [1]. To address this challenge, alternative approaches that utilize renewable energy sources have gained interest, particularly for off-grid or remote applications. One such approach is wind-powered heat generation, sometimes referred to as "green heat," which converts mechanical energy from wind directly into thermal energy without electrical power generation.

Previously developed wind-powered heating systems often face limitations such as high upfront costs, unreliable heat delivery, and complex system integration. In response to these challenges, the present project was conducted under a limited budget with the goal of exploring a low-cost, mechanically driven heating concept suitable for instructional and proof-of-concept purposes. Achieving reliable heat delivery under these constraints required the system to operate at relatively low wind speeds while remaining adaptable for potential integration with existing heating or energy storage systems.

From an educational perspective, renewable energy systems provide an effective context for senior capstone design projects because they require students to integrate principles from thermodynamics, fluid mechanics, heat transfer, dynamics, and materials. In addition to technical considerations, such projects introduce professional constraints related to cost, safety, manufacturability, and sustainability. As a result, renewable energy–focused projects align well with mechanical engineering program objectives and accreditation outcomes.

Wind-to-heat energy conversion systems are particularly well-suited for instructional settings because they remove the added complexity of electrical generation and power electronics. By focusing on mechanical and thermal energy conversion, students are able to concentrate on fundamental engineering principles while still addressing a realistic and socially relevant problem. Furthermore, wind-to-heat systems naturally expose students to the limitations of idealized analysis and the challenges associated with real-world operating conditions, making them effective platforms for learning about uncertainty, iteration, and trade-off analysis.

While prior work has explored renewable energy technologies and project-based learning independently, fewer studies document the implementation of wind-powered thermal systems as practice-based educational case studies. Related renewable-energy capstone projects and project-based learning implementations have been reported in the engineering education literature, highlighting the value of sustainability-focused design problems in supporting systems thinking, student engagement, and professional skill development [2], [3], [4]. Accordingly, the present work focuses on the educational value of a wind-to-heat senior design project, emphasizing project structure, design decision-making, engagement with engineering standards, and learning from non-ideal experimental outcomes.

3. Project Description, Requirements, and Standards

This section defines the scope, objectives, and constraints of the wind-to-heat senior design project. The requirements established here guided subsequent design decisions and served as both a technical and instructional framework for the capstone experience.

3.1. Project Objectives and Constraints

The primary objective of the project was to design a device capable of converting mechanical energy from wind into thermal energy. The system was intended as a proof-of-concept design suitable for instructional purposes and potential application in small-scale, off-grid heating contexts. To maintain focus on mechanical energy conversion, the system was required to operate without electrical power generation or chemical reactions.

An initial target thermal output of 1.5 kW was established at the beginning of the project. Subsequent analysis demonstrated that this target was not feasible within the available time, budget, and environmental constraints. As a result, the objective was revised to emphasize maximizing achievable thermal output while maintaining system feasibility. This revision allowed students to reassess project goals based on analytical results and practical limitations.

The system was required to operate under average wind-speed conditions representative of the Southern Kentucky region [5] and to demonstrate proof of concept through analytical calculations, numerical simulations, and experimental testing. A budget constraint of approximately $2,000 was imposed to reinforce cost awareness and manufacturability considerations typical of professional engineering practice.

3.2. Functional Requirements

Based on the revised objectives, the following requirements guided the design process:

1. The system shall convert mechanical energy from wind into thermal energy without electricity.
2. The system shall operate under low to moderate wind-speed conditions representative of the local environment.
3. The design shall prioritize simplicity, robustness, and ease of fabrication using commercially available components.

4. The system shall demonstrate proof of concept through documented analysis, simulation, and physical prototype.
5. The total project cost shall remain within the established budget constraint.

These requirements were intentionally broad to allow multiple viable design approaches while maintaining sufficient structure for evaluation.

3.3. Professional Requirements and Engineering Standards

In addition to technical requirements, students were required to research and apply relevant engineering standards associated with rotating machinery, thermal exposure, and mechanical power transmission. Engagement with standards was incorporated into the requirement definition and concept evaluation phases to support professional skill development and alignment with ABET Criterion 5.

Standards related to machinery safety and risk assessment (ANSI/AMCA 12100:2010), human response to contact with heated surfaces (ANSI/AMCA 13732-1), aerodynamic performance testing (ANSI/AMCA 210-16), and transmission shaft design (ANSI/AMCA B106.1M-1985) informed decisions related to allowable surface temperatures, shaft sizing, structural integrity, and testing methodology. This process provided students with experience interpreting professional standards and translating them into actionable design constraints.

4. Design Methodology and Final Design

This section describes the design methodology used to develop the wind-to-heat system and the evolution of the final design. The intent of this section is to document how students translated project requirements to a feasible system-level design through structured decision-making, iteration, and integration of subsystems.

During the first semester of the capstone sequence, students were organized into three teams, each tasked with developing a distinct concept for the wind-to-heat system. This structure allowed multiple design approaches to be explored in parallel, with each team focusing on different configurations for the turbine, frame, and heating mechanism.

At the end of the first semester, the concepts developed by the three teams were evaluated based on performance potential, feasibility, cost, and alignment with the project requirements. In the second semester, students combined into a single team and worked collaboratively to develop a final design that incorporated the most effective elements from the initial concepts.

This two-phase approach supported early-stage exploration followed by collective refinement, allowing students to engage in both independent design thinking and collaborative decision-making.

4.1 Preliminary Concepts

The concepts developed during the first semester were evaluated using structured decision-making tools, as described below.

In developing the final design, it was essential to systematically evaluate and compare available components. Decision matrices were employed as a structured tool to facilitate this evaluation. By assigning criteria, weights, and scores, these matrices enable an objective comparison of options based on performance, cost, reliability, and other relevant factors. This approach ensured that the selection process was transparent, consistent, and aligned with the overall design requirements in Section 3.

Based on the design decision matrices, the wooden frame concept was selected for the frame, the vertical-axis wind turbine (VAWT) for the turbine, and Concept B for the heater design. Figures 1-3 summarize the initial designs considered for the frame, turbine, and heater subsystems.

The evaluation of design alternatives using decision matrices highlighted the relative strengths of each option and provided a clear rationale for selecting the final design components. While multiple configurations could have satisfied the project requirements, the selected concepts demonstrated a favorable balance among expected performance, ease of fabrication, and cost.

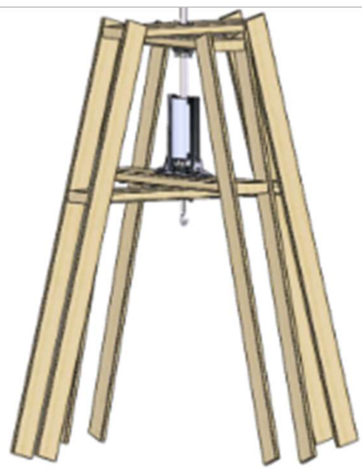
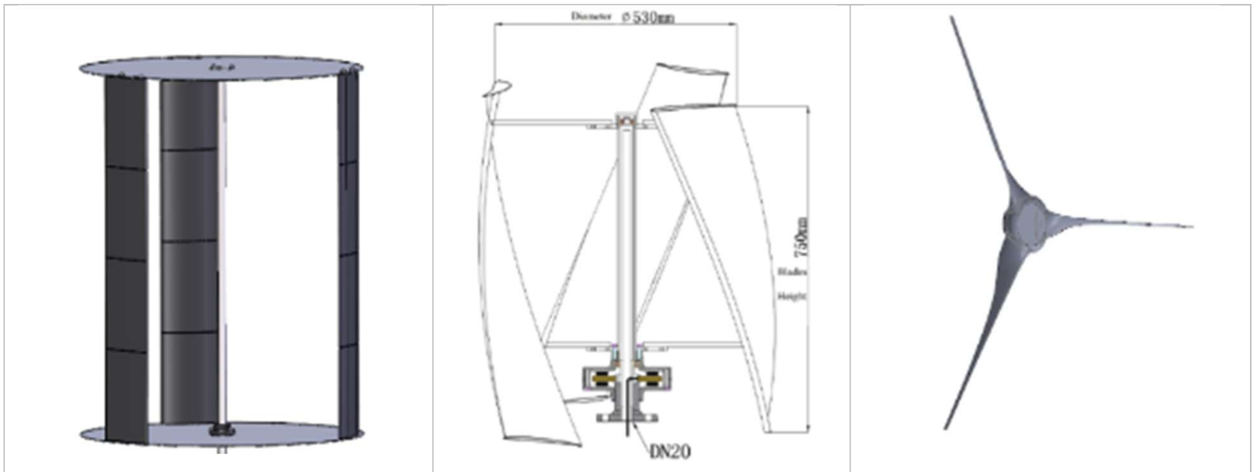
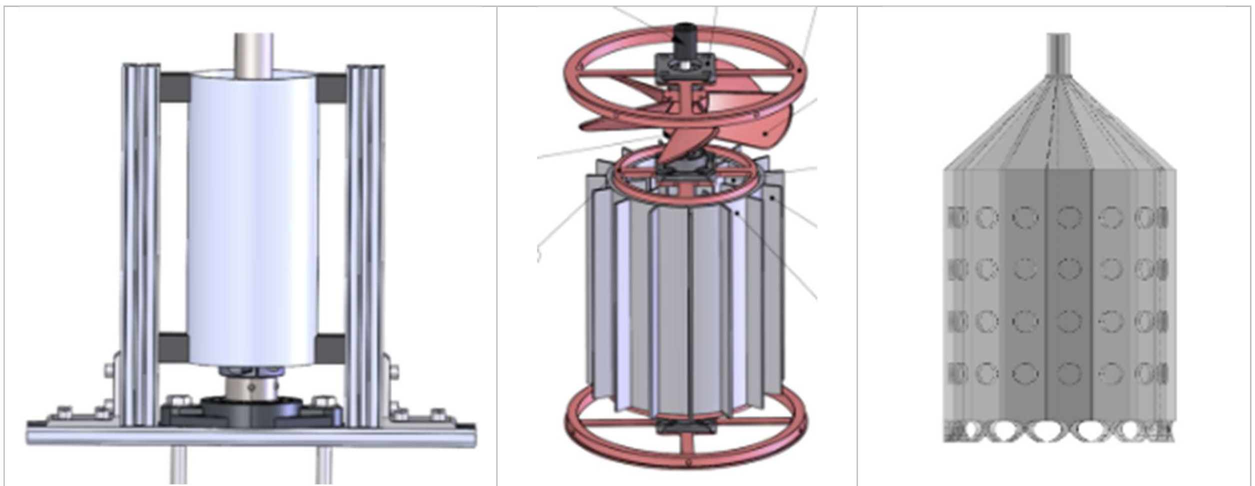
		
Wooden Frame Concept	Cart Frame Concept	Steel Tubing Frame Concept

Figure 1. Preliminary frame design concepts were evaluated using a decision matrix.



Concept A	Concept B (VAWT)	Concept C

Figure 2. Initial turbine design concepts were considered for the project.



Concept A	Concept B	Concept C

Figure 3. Initial heater design concepts were evaluated for thermal generation performance.

4.2 Final Design Concept

The systematic evaluation of frame, turbine, and heater concepts using decision matrices provided a transparent and objective basis for selecting the components incorporated into the final wind heater design. Each matrix allowed potential options to be compared against weighted criteria such as performance, cost, manufacturability, and reliability, revealing clear distinctions in how effectively each concept met the project requirements.

Across these evaluations, the wooden frame, the VAWT turbine, and Heater Concept B consistently demonstrated superior alignment with the design goals through ease of construction and versatility, aerodynamic efficiency, and optimal heat-generation characteristics. Together, these results establish a well-supported foundation for the final design. The integrated final design concept is shown in Figure 4.

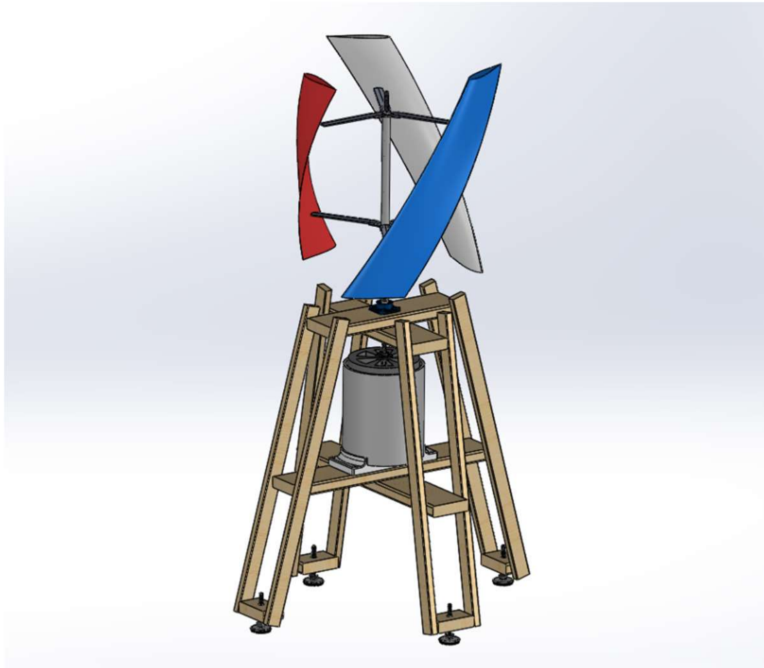


Figure 4. Final Concept SolidWorks Assembly

Several adjustments were made to improve efficiency and stability. The heater design was modified to use 30 cylindrical magnets in a shell configuration, and a second aluminum tube was added around the magnet core to enhance the heat generation. Heat sink fins included in early concepts were removed, and the outer aluminum pipe was insulated to better control heat dissipation. Frame dimensions were adjusted to accommodate the revised heater geometry, and adjustable feet and a leveling feature were added to improve stability during testing on uneven surfaces. These changes reflect the iterative nature of the design process and the need to balance analytical predictions with practical fabrication and assembly considerations.

4.3 Design Calculations

To verify the selected design concepts, calculations were performed to estimate turbine power, shaft torque, heater power output, and core temperature. Wind power from the turbine was used to determine the angular velocity of the heater apparatus, which was then used to estimate eddy current generation and the resulting heat output [6], [7].

The calculations were used primarily as decision-support tools to establish feasible operating ranges and to compare design alternatives. Simplifying assumptions, including steady-state operation and idealized boundary conditions, were documented and discussed. While these assumptions allowed tractable analysis, students recognized that experimental operation would likely deviate from idealized predictions.

4.4 Simulation Results

ANSYS simulations were conducted to complement the analytical calculations and to visualize temperature distributions within the heater core under idealized conditions. The same boundary conditions used in the analytical analysis were applied in the simulation, including a constant temperature, an insulated outer surface, convection at the inner surface, and internal heat generation.

The simulation yielded a maximum temperature that closely matched the analytical prediction, as shown in Figure 5. This agreement reinforced the internal consistency of the modeling approach while also highlighting the distinction between idealized analysis and real-world system behavior.

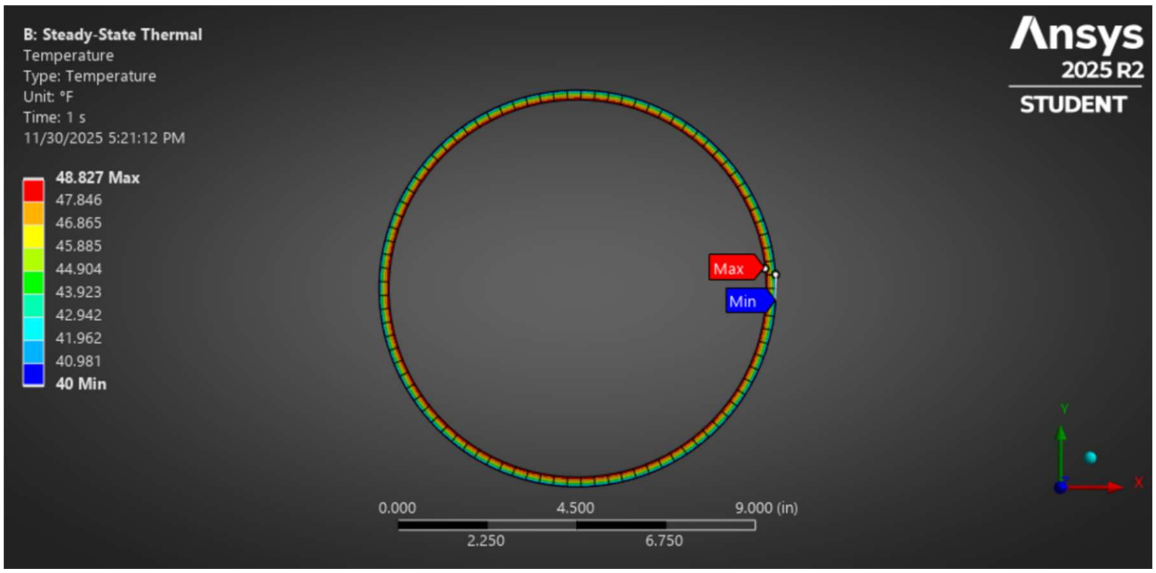


Figure 5. ANSYS Simulation of Core

In addition, a functional block diagram (as shown in Figure 6) was developed to illustrate the flow of energy through the system and the interaction between major components, supporting system-level understanding.

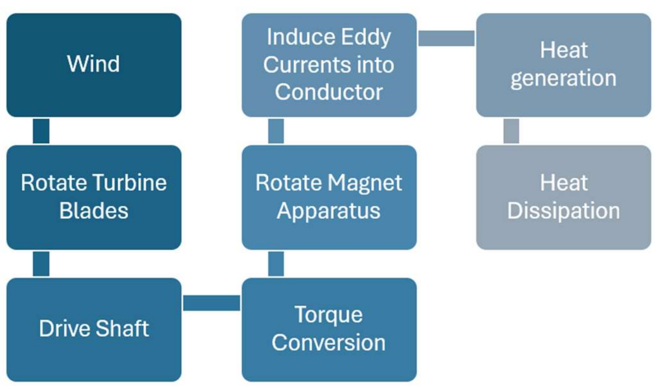


Figure 6. Functional Block Diagram

5. Results and Discussion

Initial testing was performed in mid-November with the goal of validating the turbine tip-speed ratio assumptions, turbine-to-heater power transmission, and internal surface temperature of the heating core. Multiple stages of testing were conducted as the team experienced difficulty replicating the required design wind speed of 3.5 m/s under laboratory conditions.

To obtain data, a pitot tube was placed in the airflow to measure wind speed [8]. A small piece of tape was used as a marker to determine each full rotation of the turbine, which was counted over one minute to obtain RPM. For temperature measurements, a thermocouple was used to measure the internal surface temperature of the outer aluminum core. These readings were validated using a temperature gun.

The first round of testing was conducted using a box fan, which produced an average freestream velocity of 1.4 m/s and 2.1 m/s on fan levels two and three, respectively. The resulting turbine RPM and temperature change relative to ambient air are shown in Table 1. At these wind speeds, the system did not initiate rotation, and no measurable temperature increase was observed. These results indicate that the available wind energy was insufficient to overcome the combined inertial and resistive effects of the turbine-shaft heater assembly.

Table 1. *Box Fan Test Results*

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Fan Speed	2	2	2	3	3	3
Freestream Velocity (m/s)	1.372	1.422	1.524	2.286	2.134	1.981
Measured RPM	0	0	0	0	0	0
Measured Change (°F)	0	0	0	0	0	0

To achieve higher wind velocities, a second round of testing was conducted using a battery-powered leaf blower. Wind speed, turbine rotational speed, and temperature change were recorded using the same methods as in the initial test. The results of this testing are presented in Table 2. Although wind velocities exceeded the design value of 3.5 m/s, the measured turbine speeds and temperature increases remained significantly lower than predicted by analytical calculations.

The discrepancy between theoretical predictions and experimental results highlights several important considerations. First, the analytical modeling assumed steady-state operation, which would require sustained wind speeds over extended periods. Due to testing constraints, all experimental measurements were conducted under transient conditions, limiting the ability of the system to reach steady-state thermal behavior. As a result, the measured temperature changes were substantially lower than steady-state predictions.

Table 2. *Single Battery Powered Leaf Blower Test Results*

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Freestream Velocity (m/s)	12.353	11.527	14.693	21.488	26.238	22.352
Measured RPM	7	7	8	13	16	14
Measured Change (°F)	0	0	0	-.1	0	-.1

Second, late-stage design modifications contributed to increased mechanical and electromagnetic loading. In particular, the magnet holder was redesigned using a heavier configuration and stronger magnets without revisiting the original torque and power calculations. The increased mass raised the moment of inertia of the rotating assembly, while the stronger magnetic field introduced additional resistive forces within the aluminum core. The combined effects exceeded the mechanical power available from the turbine-shaft system, limiting rotational speed and thermal output.

While the system did not achieve the targeted thermal performance, the results provided valuable learning opportunities. Students were required to revisit their assumptions, evaluate the impact of design changes, and understand why the system behaved differently from predictions.

From an instructional perspective, these challenges played a central role in student learning. Rather than following a fixed solution path, students had to interpret unexpected results and adjust their approach accordingly. This reinforced the importance of validation, iteration, and engineering judgment in real-world design.

5.1 Assessment of Student Learning and Engagement

In addition to system performance, the project was evaluated based on its impact on student learning and engagement. Evidence was gathered from student reports, presentations, design reviews, and instructor observations throughout the project.

Students actively participated during the design and testing phases, especially when addressing the gap between analytical predictions and test results. Troubleshooting these issues required them to reassess assumptions, rethink design choices, and suggest modifications based on observed behavior.

The project also supported the development of key engineering skills, such as system-level integration of thermodynamics, fluid mechanics, and heat transfer, along with applying engineering standards.

Although the system did not meet the original thermal performance goal, it successfully achieved its educational objectives by encouraging critical thinking, iterative problem-solving, and understanding of real-world engineering challenges.

6. Lessons Learned and Recommendations

This project provided several insights that can improve future implementations. One key finding was the importance of structured design validation. Late-stage changes were made without reviewing earlier calculations, which contributed to differences between predicted and actual system performance.

Future projects should incorporate checkpoints to verify consistency between analysis and design modifications. Students initially relied heavily on steady-state assumptions. Providing early instruction on transient behavior and real-world variability would enhance modeling accuracy. Finally, adding simple assessment tools would offer more direct evidence of learning and support project refinement in future iterations.

7. Conclusions

This paper presented a senior design project in which mechanical engineering students designed and evaluated a wind-to-heat energy conversion system within a project-based learning framework [9]. The project integrated concepts from thermodynamics, fluid mechanics, heat transfer, dynamics, and electromagnetics while requiring students to address realistic constraints related to cost, safety, manufacturability, and applicable engineering standards.

Although the final prototype did not achieve the thermal output predicted by steady-state analysis, the discrepancy between analytical predictions and experimental results served as a central learning outcome. Students were required to examine the limitations of modeling assumptions, assess the impact of late-stage design changes, and reconcile theoretical expectations with transient real-world operating conditions. This experience reinforced the importance of validation, iteration, and trade-off analysis in engineering design.

The project structure encouraged systematic decision-making through the use of requirements definition, decision matrices, analytical modeling, simulation, prototyping, and testing. Engagement with professional standards further supported alignment with ABET outcomes and provided students with experience translating abstract guidelines into concrete design constraints.

Rather than proposing a novel wind-powered heating technology, this work contributes a transparent, practice-based educational case study. The project demonstrates how renewable energy systems can be effectively incorporated into mechanical engineering capstone design to support student learning, systems thinking, and professional skill development. The framework described in this paper is transferable to other mechanical engineering programs seeking to integrate sustainability and renewable energy into capstone design curricula.

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