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Transforming Engineering Education through Project-Based Learning: A Solar Water Heater Case Study for Teaching Thermodynamics

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Abstract*– Engineering education faces the challenge of promoting a meaningful understanding of thermodynamic principles while engaging students in sustainability-focused learning; in response, this study presents a Project-Based Learning (PBL) intervention centered on the design and construction of a solar water heater, implemented over five weeks with 45 first-year engineering students at a higher education institution in Mexico. The experience followed a structured methodology that integrated literature review, analytical heat transfer modeling, prototype construction, experimental testing, and computational simulation, and was evaluated through a mixed-methods approach combining quantitative data from a 23-item Likert-scale questionnaire with qualitative feedback from open-ended questions, with instrument reliability confirmed using Cronbach's alpha ($\alpha = 0.925$). Results show high levels of student engagement and satisfaction, with over 90% of responses indicating agreement or strong agreement regarding the effectiveness of the PBL approach, alongside reported improvements in understanding thermodynamic concepts, particularly heat transfer, and the development of key engineering competencies such as problem-solving, teamwork, and technical communication. Overall, the findings suggest that hands-on, sustainability-oriented PBL experiences can significantly enhance learning outcomes in early engineering education, offering a replicable pedagogical framework that integrates thermodynamics, sustainability, and active learning within limited academic timeframes while helping bridge the gap between theory and real-world application.

Keywords-- ***Project-Based Learning (PBL), Higher Education, Educational Innovation, STEM Education, Global Sustainability Challenge.***

I. Introduction

In recent years, the significance of sustainable development and its impact on society have become central themes in higher education, particularly within science, technology, engineering, and mathematics (STEM) disciplines. Engineering education plays a critical role in preparing future professionals to address global challenges related to energy efficiency, renewable resources, and environmental sustainability. Within this context, fostering a solid understanding of thermodynamic principles is essential, as these concepts underpin many real-world engineering systems associated with energy generation and transfer.

Despite the fundamental importance of thermodynamics in engineering and physical sciences, traditional lecture-based teaching approaches often fail to effectively connect theoretical concepts with practical applications, leaving students underprepared to address complex, real-world problems [1], [2], [3]. Research in engineering and physics education has consistently shown that students experience conceptual difficulties when thermodynamic principles are presented in abstract or mathematical forms, without opportunities to observe and apply these concepts in authentic contexts [4], [5]. As a result, there is a growing need for instructional strategies that promote meaningful learning by bridging the gap between theory and practice.

Project-Based Learning (PBL) has emerged as a promising pedagogical approach to address these challenges. PBL emphasizes active student engagement through the investigation and solution of real-world problems, promoting deeper conceptual understanding and the development of professional competencies. Prior studies have demonstrated that implementing PBL in engineering courses can improve student's self-efficacy, motivation, and problem-solving abilities, particularly when projects are designed to reflect realistic engineering scenarios [2], [3], [6]. Moreover, sustainability-oriented projects provide a powerful context for learning, as they allow students to explore socially relevant challenges while applying core engineering principles [7], [8].

Recent research suggests that PBL interventions involving renewable energy systems, such as solar thermal technologies, enable students to engage directly with thermodynamic processes while developing technical and collaborative skills [9], [10], [11]. Structured activities focused on the design and construction of solar water heaters have been shown to deepen conceptual understanding, connect theoretical knowledge to experimental observations, and foster teamwork and technical communication skills essential for engineering practice [12]-[15]. These experiential learning opportunities align with international frameworks that emphasize the integration of sustainability and active learning in engineering education [16].

In early engineering education, Project-Based Learning (PBL) has been shown to be particularly effective when implemented through short, guided interventions closely aligned with real-world problems. In first-year courses, several studies report improvements in student performance, motivation, design skills, and teamwork, especially when projects incorporate sustainability or renewable energy contexts [17], [18], [19]. In thermodynamics and physics education, evidence indicates that combining PBL with experimental activities, computational simulation, and structured scaffolding enhances conceptual understanding, reasoning, and problem-solving abilities [20], [21]. These findings support the implementation of short, structured PBL interventions during the early stages of the engineering curriculum [17].

Despite the growing body of literature highlighting the benefits of PBL and sustainability-focused learning experiences, there remains limited empirical evidence on the implementation of short-term, structured PBL interventions explicitly designed to support the learning of thermodynamics during the early stages of engineering education. Many reported studies focus on advanced engineering courses or long-term curricular reforms, leaving a gap in understanding how hands-on, sustainability-oriented projects can effectively enhance conceptual understanding, motivation, and skill development among first-year engineering students within constrained academic timelines.

In response to this gap, the present study examines the educational impact of a five-week Project-Based Learning intervention centered on the design and construction of a solar water heater, implemented in a first-year engineering course. The study seeks to provide empirical evidence on how this approach supports students' understanding of thermodynamic principles while fostering motivation, engagement, and the development of essential engineering competencies. By integrating experimental work, analytical modeling, and computational simulations, this research contributes a replicable pedagogical framework for incorporating sustainability-driven PBL experiences into early engineering education.

A. *Objective of the Study*

The objective of this study is to analyze the impact of a Project-Based Learning (PBL) strategy focused on the design and construction of a solar water heater on first-year engineering students' understanding of thermodynamic principles, motivation toward learning physics, and development of essential engineering competencies.

B. *Research Questions*

To achieve this objective, the study is guided by the following research questions:

- RQ1: How does a Project-Based Learning approach centered on the construction of a solar water heater influence first-year engineering students' understanding of fundamental thermodynamic concepts?
- RQ2: How does participation in this hands-on, sustainability-oriented project affect students' motivation and engagement in learning thermodynamics?
- RQ3: What engineering skills and competencies do students perceive as most developed through the implementation of this Project-Based Learning experience?

II. METHODOLOGY

This methodology combines Project-Based Learning (PBL) with STEM education principles, centering on the design and building of solar water heaters to enhance the understanding of thermodynamics concepts and address real-world problems.

A. Research Design

This study adopted a mixed-methods research design with a descriptive and exploratory approach, suitable for evaluating educational innovations implemented in authentic classroom contexts. The intervention was non-experimental, as it was conducted within a regular academic course without the use of a control group. The mixed-methods approach allowed for the integration of quantitative data on student perceptions with qualitative insights derived from open-ended responses, providing a comprehensive understanding of the educational impact of the Project-Based Learning (PBL) experience.

B. Participants and Context

The study was conducted at a higher education institution in Mexico, within the course *Application of Thermodynamics in Engineering Systems*. The participants consisted of 45 first-year engineering students, selected through convenience sampling, as they were enrolled in the course during the semester in which the intervention took place.

The course is part of the early engineering curriculum and aims to introduce students to fundamental thermodynamic concepts and their application in real-world engineering systems. The PBL intervention was implemented during a five-week academic period, aligned with the institutional challenge-based learning framework.

C. Educational Intervention and Procedure

The educational intervention consisted of a Project-Based Learning experience centered on the design, construction, and evaluation of a solar water heater prototype. The project was structured into six sequential stages, designed to progressively integrate theoretical knowledge, experimental practice, and computational analysis.

Stage 1: Research and Material Selection.

Students conducted a literature review on solar thermal systems, focusing on sustainability, solar energy principles, and heat transfer mechanisms. Guidance was provided on academic writing, source evaluation, and citation practices. At the end of this stage, students submitted an initial project report outlining the theoretical framework and proposed design.

Stage 2: Solar Collector and Fluid Circuit Design.

During this stage, student teams developed the technical design of the solar collector and fluid circuit, including material selection, cost estimation, and workflow planning. Emphasis was placed on engineering decision-making and feasibility analysis.

Stage 3: Prototype Construction.

Students assembled the solar water heater prototype, developing hands-on skills related to measurement, cutting, assembly, wiring, and system integration. Collaborative work was encouraged to promote teamwork and communication.

Figure 1 illustrates students using the tool room for necessary cuts and assemblies.

Fig. 1. Solar Water Heater Assembling.

Upon completion of this stage, students submitted the second draft of their written report, which includes evidence from the building process.

Stage 4: Experimentation and Analytical Modeling.

Experimental testing was conducted to collect temperature data over time under solar exposure. Figure 2 shows students working on their prototypes and measuring the temperature.

Fig. 2. Experimental Stage.

Students studied heat transfer through conduction and convection by examining temperature–time relationships, heat transfer rates, and the effects of solar radiation on system performance.

Stage 5: Computational Simulation.

A computational model was developed to simulate the thermodynamic behavior of the prototype, allowing students to compare theoretical predictions with experimental data and assess system performance.

Stage 6: Results Discussion and Prototype Competition.

Students analyzed their results, prepared a project poster, and presented their findings. Figure 3 shows the poster's presentation activity.

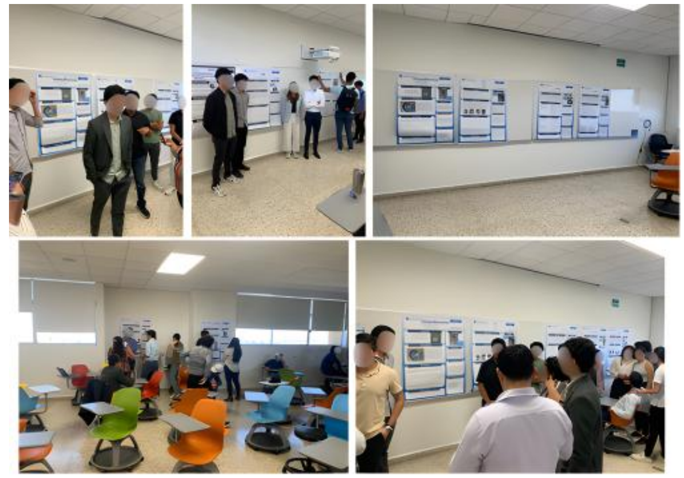

Fig. 3. Students Presenting the Results.

A final prototype competition was held to evaluate performance under predefined criteria, fostering reflection, self-evaluation, and peer feedback. Figure 4 shows some of the prototypes presented for the final competition.

Fig. 4. Solar Water Heaters Prototypes.

D. Instruments and Data Collection

Data was collected using a 23-item online questionnaire based on a four-point Likert scale (1 = Strongly disagree, 2 = Disagree, 3 = Agree, 4 = Strongly agree), complemented by three open-ended questions designed to capture students' qualitative perceptions of the learning experience.

The questionnaire assessed three main dimensions:

1. Students' perceived understanding of thermodynamic principles.
2. Evaluation of the Project-Based Learning methodology.
3. Motivation, satisfaction, and perceived development of engineering competencies.

E. Data Analysis

Likert-scale items were grouped according to their corresponding research questions and underlying constructs.

Items related to conceptual understanding of thermodynamics (RQ1), student motivation and satisfaction (RQ2), and development of engineering skills and competencies (RQ3) were aggregated by dimension.

For each dimension, response frequencies were calculated across all corresponding items and participants. These frequencies were then converted into percentage distributions and represented using pie charts to illustrate overall trends in student perceptions. This approach allowed for a clear and concise visualization of the distribution of responses without altering the ordinal nature of the Likert-scale data.

Quantitative data were analyzed using descriptive statistics to determine response distributions and overall trends. The internal consistency and reliability of the questionnaire were assessed using Cronbach's alpha coefficient, yielding a value of $\alpha = 0.925$, which indicates high reliability [22].

Qualitative data from open-ended responses were evaluated using thematic analysis, allowing for the identification of recurring themes related to challenges encountered, perceived learning gains, and recommendations for improvement.

The integration of quantitative and qualitative findings supported triangulation and enhanced the validity of the results.

III. RESULTS

The results are presented in alignment with the three research questions guiding this study, integrating quantitative survey data and qualitative student feedback to provide a comprehensive analysis of the Project-Based Learning (PBL) intervention.

A. RQ1: Impact of the PBL Intervention on the Understanding of Thermodynamic Principles

To address RQ1, student perceptions related to learning outcomes in thermodynamics were analyzed using survey items focused on heat transfer principles, application of theoretical concepts, and analysis of real thermal systems.

As shown in Figure 5 based on the data summarized in Table I, the distribution of responses indicates a strongly positive perception of learning outcomes, with 94.2% of responses falling within the categories of agree (54.2%) and strongly agree (40.0%). Only 5.8% of responses reflected disagreement, and no responses were recorded in the strongly disagree category.

This pattern suggests that the hands-on construction and testing of the solar water heater significantly supported students' conceptual understanding of thermodynamic processes, particularly conduction and convection. The experimental component allowed students to directly observe temperature variations and validate theoretical models, reinforcing abstract concepts through practical application.

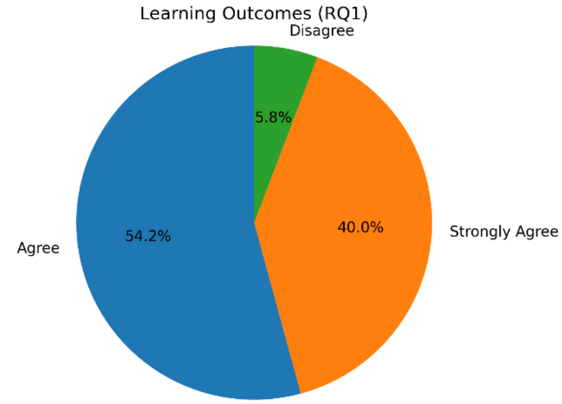

Fig. 5. Distribution of student perceptions regarding learning outcomes in thermodynamics.

TABLE I
SURVEY RESPONSES DISTRIBUTION ON THE LIKERT SCALE

Variable	Value	%
Strongly Disagree	1	0
Disagree	2	5.8
Agree	3	54.2
Strongly Agree	4	40

B. RQ2: Effects of the PBL Experience on Student Motivation and Engagement

Regarding RQ2, survey items related to motivation, satisfaction, and engagement revealed highly favorable outcomes.

Survey results shown in Figure 6 indicate high levels of motivation and satisfaction associated with the project-based approach. A substantial proportion of students reported that the experience was more engaging than traditional lecture-based instruction, highlighting the relevance of sustainability-focused challenges and teamwork dynamics. Notably, 74% of participants expressed a clear preference for learning physics through experimental or project-based activities, reinforcing the affective benefits of the intervention.

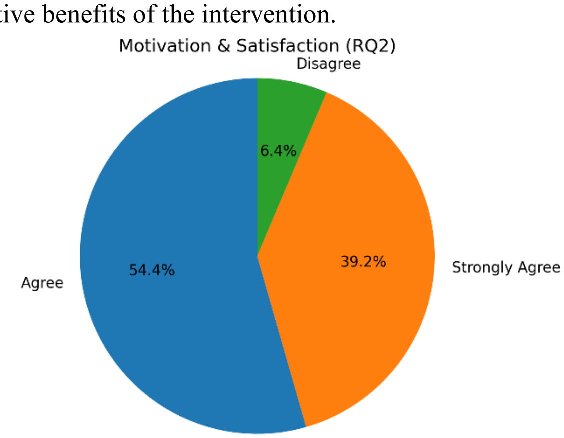

Fig. 6. Distribution of Likert responses related to student motivation, satisfaction, and perceived relevance of the PBL Experience.

Qualitative responses further support these findings, with students describing the project as "more dynamic," "motivating," and "meaningful" compared to conventional classes. The integration of real-world sustainability challenges contributed to increased interest and perceived relevance of thermodynamics within an engineering context.

C. RQ3: Development of Engineering Skills and Competencies

To address RQ3, the analysis focused on student's perceived development of engineering skills such as problem-solving, teamwork, communication, and logical reasoning.

The data collected and represented in Figure 7 reveal that most students perceived significant growth in key engineering competencies because of participating in the PBL intervention. Survey responses indicate that more than 88% of participants agreed or strongly agreed that the project enhanced their ability to solve problems collaboratively, communicate technical ideas, and apply logical reasoning to real engineering challenges.

Qualitative analysis identified three recurring themes:

1. Technical and organizational challenges, including material availability and time management.
2. Meaningful learning through collaboration, emphasizing teamwork and peer interaction.
3. Recommendations for improvement, such as extending project duration and providing additional institutional support.

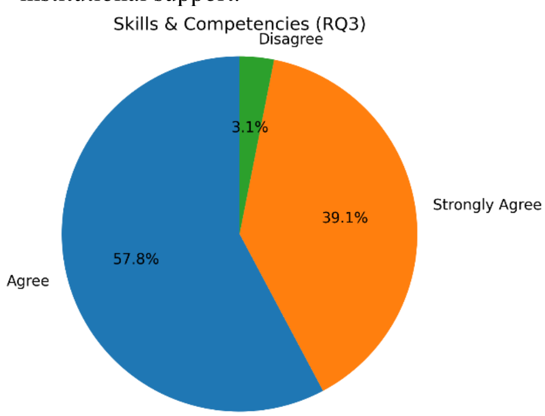

Fig. 7. Distribution of Likert responses regarding the development of technical skills and engineering competencies through the PBL intervention.

These findings highlight that, beyond conceptual learning, the PBL experience effectively supported the development of professional skills essential for engineering practice.

D. Reliability of the Measurement Instrument

The internal consistency of the Likert-scale questionnaire was assessed using Cronbach's alpha, a widely accepted reliability coefficient for instruments measuring perceptions and attitudes in educational research. The questionnaire included items addressing students' perceived learning outcomes, motivation, and development of engineering competencies, which are conceptually related constructs within the context of Project-Based Learning.

The analysis yielded a Cronbach's alpha value of $\alpha = 0.925$, indicating excellent internal consistency according to commonly accepted thresholds in educational measurement. This high coefficient suggests that the items included in the instrument consistently measure the intended constructs and that the responses exhibit a strong level of coherence.

Consequently, the high reliability of the instrument supports the robustness of the quantitative findings and strengthens confidence in the interpretation of students' perceptions regarding the effectiveness of the PBL intervention. This level of internal consistency provides a solid methodological foundation for the analysis of results and their subsequent discussion.

IV. Discussion

The findings of this study provide empirical evidence supporting the effectiveness of Project-Based Learning (PBL) as a pedagogical strategy for teaching thermodynamics in early engineering education, particularly when framed around sustainability-oriented, real-world challenges. By integrating analytical modeling, experimental testing, and prototype construction within a five-week intervention, the results demonstrate meaningful gains in student learning, motivation, and skills development.

In relation to RQ1, the high percentage of positive responses regarding learning outcomes suggests that hands-on engagement significantly enhances students' understanding of thermodynamic principles. These findings are consistent with previous research in physics and thermodynamics education, which reports that active and experimental learning strategies help students overcome conceptual difficulties by linking abstract models to observable phenomena [4], [5]. The direct measurement of temperature variations and the comparison between theoretical predictions and experimental data appear to play a critical role in consolidating students' understanding of heat transfer mechanisms, particularly conduction and convection.

Regarding RQ2, the results indicate that the PBL intervention positively influenced student motivation and engagement. Similar motivational effects of inductive and project-based learning strategies have been widely reported in engineering education literature, particularly in first-year courses where student engagement is critical [3]. The sustainability focus of the project, centered on solar energy applications, further contributed to students' perceived relevance of thermodynamics, reinforcing the idea that contextualized, socially relevant challenges can enhance affective dimensions of learning.

The findings addressing RQ3 reveal that the PBL experience supported the development of essential engineering competencies, including problem-solving, teamwork, and technical communication. The development of collaborative problem-solving and communication skills observed in this study aligns with prior findings in sustainability-oriented engineering education, which emphasize the role of real-world projects in fostering professional competencies and systems thinking [7], [8]. Students' reflections on teamwork, troubleshooting, and decision-making suggest that the project environment simulated authentic engineering scenarios, thereby preparing students for future academic and professional challenges.

From an educational innovation perspective, this study contributes a structured and replicable PBL framework that can be implemented within constrained academic timelines, such as five-week modules commonly used in challenge-based curricula. Unlike many reported experiences that require extended semesters or advanced coursework, this intervention demonstrates that meaningful learning gains can be achieved in early-stage engineering courses through carefully designed, sustainability-focused projects.

Nevertheless, the study presents certain limitations that should be considered when interpreting the results. The use of convenience sampling and the absence of a control group limit the generalizability of the findings. Additionally, the results are based primarily on self-reported data, which may be influenced by student perceptions and contextual factors. Future research should explore longitudinal implementations, incorporate comparative control groups, and include objective performance measures to further validate the impact of PBL interventions in thermodynamics education.

V. Conclusions

This study examined the implementation of a Project-Based Learning (PBL) intervention centered on the design and construction of a solar water heater as a strategy to enhance the teaching and learning of thermodynamics in early engineering education. The findings provide evidence that integrating hands-on, sustainability-focused projects within a structured pedagogical framework can significantly improve students' learning experiences and perceived outcomes.

The results indicate that the PBL approach effectively supported students' understanding of fundamental thermodynamic principles, particularly those related to heat transfer and energy systems. By engaging in experimental measurement, analytical modeling, and prototype construction, students were able to connect theoretical concepts with real-world applications, thereby reinforcing meaningful learning.

In addition to cognitive gains, the intervention positively influenced student motivation and engagement, as evidenced by a strong preference for experimental and project-based learning over traditional instructional methods. The sustainability context of the project, focused on solar energy applications, further enhanced the perceived relevance of thermodynamics to students' future professional practice.

Furthermore, the study highlights the development of essential engineering competencies, including problem-solving, teamwork, technical communication, and logical reasoning. These skills, which are fundamental to engineering practice, were fostered through collaborative project work and authentic design challenges, reinforcing the value of PBL as a comprehensive educational strategy.

From an educational innovation perspective, this research contributes a replicable and scalable PBL framework that can be implemented within short academic periods, such as five-week modules, making it particularly suitable for challenge-based curricula in engineering programs. While the study is limited by its reliance on self-reported data and the absence of a control group, the high reliability of the measurement instrument and the consistency of the results provide a solid foundation for the conclusions drawn.

Future work should explore longitudinal implementations, comparative studies with traditional instructional approaches, and the inclusion of objective performance indicators to further validate and extend the findings. Overall, this study supports the integration of sustainability-driven, project-based learning experiences as an effective approach to enhancing thermodynamics education and preparing engineering students to address complex real-world challenges.

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