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Project-Based Experiential Learning of Photovoltaic Systems

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Project-Based Experiential Teaching and Learning of Photovoltaic Systems

Abstract

As the demand for renewable energy professionals rises, there is an increasing need to cultivate a workforce that possesses both theoretical knowledge and hands-on technical skills. Project-based experiential learning (PBL), a student-centered instructional approach, engages learners in real-world projects that span the lifecycle of PV systems—from design and installation to performance analysis. This method not only facilitates a deeper understanding of solar energy principles and PV system architecture but also equips students with essential soft skills, including teamwork, critical thinking, and problem-solving, which are critical for success in the rapidly evolving energy sector.

This paper details the integration of project-based learning into PV education, illustrating its role in enhancing student motivation, knowledge retention, and practical competence. Several case studies are presented, highlighting student-led projects focused on small-scale PV system design and performance evaluations. The results indicate that students not only achieve higher levels of technical mastery but also exhibit improved creativity and innovation in problem-solving. Feedback from students suggests that PBL fosters practical readiness, essential for careers in photovoltaic engineering. The paper concludes that PBL is an effective pedagogical model for PV systems education, combining theoretical rigor with experiential learning to meet the needs of a growing renewable energy industry.

1. Introduction

The transition to renewable energy sources has become a global priority, driven by the urgent need to meet growing energy demands sustainably while reducing the environmental impact of carbon emissions [1]. This shift is crucial for ensuring a sustainable future and combating the impacts of climate change. Among the various renewable energy technologies available today, photovoltaic (PV) systems have gained significant prominence. They have emerged as one of the most effective and scalable solutions for harnessing solar energy, which is abundant, clean, and renewable. The rapid growth in the adoption of PV systems highlights the increasing demand for a skilled workforce capable of driving innovation and improving efficiency in this sector [2, 3].

To meet the rising demand for skilled professionals in PV technology and its applications, educational institutions worldwide must re-evaluate their pedagogical approaches. Traditional teaching methods, which often emphasize theoretical learning, are no longer sufficient to equip students with the practical knowledge and problem-solving skills required in the rapidly evolving renewable energy landscape [4].

Project-based experiential teaching and learning (PBTL) has emerged as a transformative approach to address this gap in PV education. By integrating theoretical instruction with hands-on experience, PBTL fosters a deeper understanding of PV systems' design, installation, and maintenance [5]. This approach not only helps students grasp complex concepts but also enables them to apply their knowledge in real-world scenarios, thereby preparing them for the multifaceted challenges of the renewable energy sector. Through collaborative projects, case studies, and practical experiments, students gain critical thinking, teamwork, and technical skills essential for their future careers. By embracing PBTL, educational institutions can play a pivotal role in shaping the next generation of professionals who will drive the global transition to renewable energy.

Due to the cost and time constraints associated with physical laboratory activities and projects, virtual laboratories and multimedia become appealing alternatives [6, 7, 8]. Paper [7] introduced a virtual PV power systems laboratory where students used the Cadence PSpice circuit simulator to design and implement simple stand-alone PV power systems. Paper [8] explored the use of multimedia in teaching renewable energy, with one of the six developed modules focusing on PV energy production. Students engage with the material through internal and external links, animations, and videos. A project-based learning approach to teaching PV electricity was presented in [9], where students designed PV systems using literature and online resources; however, these designs were not physically implemented. While virtual lab activities and simulations offer valuable learning experiences, they often do not account for real-world complexities such as inverter efficiency, battery charging discharging losses, cable losses, grounding, and balance of system considerations. A laboratory course on solar PV systems using low-cost equipment was discussed in [10], focusing primarily on power generation and shading effects rather than a complete PV system.

Recognizing the value of PBTL and addressing gaps in the literature, EGR657, a PV systems course at Grand Valley State University (GVSU), was redesigned to incorporate diverse group projects, case studies, and hands-on experiments. This enhancement aims to equip students with the practical and analytical skills required to excel in the rapidly evolving field of renewable energy.

This paper explores the integration of PBTL in PV systems education. It discusses the pedagogical framework, case studies, group projects, assessment and evaluation, providing an overview of how this method enhances students' understanding of PV technology and prepares them for careers in the energy industry.

2. Project-based Experiential Teaching and Learning (PBTL)

PBTL is an educational methodology that seamlessly integrates hands-on, real-world projects into the curriculum, providing a dynamic and interactive alternative to traditional teaching methods [11]. Unlike conventional instruction, where students often passively absorb information through lectures and textbooks, PBTL fosters active engagement, collaboration, and problem-solving. This approach is built on the understanding that students learn most effectively when they are directly involved in practical tasks that simulate real-world scenarios, allowing them to bridge the gap between theoretical concepts and their applications.

Experiential learning immerses students in real-world environments where they are required to make decisions, solve complex problems, and interact with dynamic variables. By stepping beyond the confines of textbooks and lectures, students gain hands-on experience that fosters not only knowledge retention but also the development of critical skills essential for their professional growth. Experiential learning empowers students to adapt to the challenges of real-world scenarios and think creatively to address them [12].

In the context of PV systems, PBTL employs a combination of collaborative projects, case studies, and practical experiments. These activities are carefully designed to provide students with a comprehensive understanding of PV systems while cultivating critical thinking, teamwork, and technical skills that are essential for their future careers. Through hands-on projects, students gain exposure to the entire lifecycle of a PV system, starting with the conceptual stages of system design and planning, followed by the installation, testing, troubleshooting, and performance analysis,

Working in teams to address practical, real-world challenges, students not only deepen their technical expertise but also develop key soft skills such as communication, adaptability, and leadership. For instance, they might collaborate to design and install a PV system for a specific application, analyze its performance under varying environmental conditions, or devise strategies for optimizing its efficiency. These tasks encourage creativity and innovation while providing a safe space for students to experiment, learn from mistakes, and refine their approaches. Experiential learning transforms students into proactive, skilled professionals who are prepared to make meaningful contributions to the renewable energy sector and drive the global transition toward sustainable energy solutions.

3. Course Description

EGR657 Photovoltaic Systems is a three-credit course designed for graduate and selected undergraduate students in electrical engineering, offering a detailed introduction to the rapidly evolving field of photovoltaics. The course aims to equip students with an understanding of the principles, technologies, and applications of PV systems, preparing them to address the growing demand for sustainable energy solutions. The course covers various PV system architectures, ranging from standalone system and grid-connected configurations to hybrid systems incorporating energy storage. Students gain a deep understanding of system components, including solar panels, batteries, charge controllers, DC/DC converters, inverters, as well as their roles in ensuring the optimal operation of PV systems. In addition to the technical aspects, the course also covers the practical and economic considerations essential for designing efficient and cost-effective PV systems. Students are introduced to key concepts such as component sizing, system optimization, and cost assessment. The textbook for this course is *Photovoltaics: Fundamentals, Technology, and Practice* by K. Mertens [13].

Some of the objectives of the course are listed below:

- Students will be able to calculate the power output of a PV panel based on its tilt and azimuth angle.

- Students will be able to describe the basic components and main performance parameters of a PV system.
- Students will be able to design, troubleshoot, and test PV systems.
- Students will be able to effectively communicate technical concepts.

Through a combination of theoretical instruction, case studies, practical experiments, and group projects, students will develop a comprehensive understanding of PV systems, enabling them to contribute to the renewable energy industry upon graduation.

4. Course Topics

Lectures of EGR657 are delivered with PowerPoint and examples on the white board. The topics presented are:

- Solar radiation and sun path
- Basic semiconductor physics including pn junction diodes, optical absorption and photon emission
- Solar cell operation and technologies
- PV systems basics and design
- PV systems components: PV module and array, energy storage, charge controllers and MPPT, Inverters
- PV metrology
- Economic consideration and environmental impacts
- Standalone PV systems and grid-connected PV plants

Simulation software is used to complement the lecture. Examples are described below.

- MATLAB Simulink is a widely used simulation platform for electronic circuits and power systems in both industry and academia. In recent years, research on modeling solar panels and PV systems using MATLAB Simulink has expanded significantly [14, 15]. Its application in academic settings for solar cell and panel modeling has also been reported [16]. In this course, students utilize MATLAB Simulink to build a silicon solar cell model and analyze the effects of key parameters—such as series resistance, shunt resistance, light intensity, and temperature—on the current-voltage (I-V) and power-voltage (P-V) characteristics. Figure 1a illustrates the Simulink setup for characterizing a silicon solar cell, with solar irradiance as the input and current, voltage, and power as the outputs. A variable resistor serves as a load to adjust the extracted power. Figure 1b depicts the I-V curve of the solar cell under different series resistance values. As the series resistance increases, both the short-circuit current and the maximum power decrease. Similarly, Figure 1c demonstrates how temperature variations affect the I-V curve. In addition to running the simulation, students analyzed the generated graphs to extract key PV parameters such as open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power (P_{mp}), and fill factor (F). They then analyzed and summarized how these parameters vary with series resistance, shunt resistance, temperature, and illumination intensity.

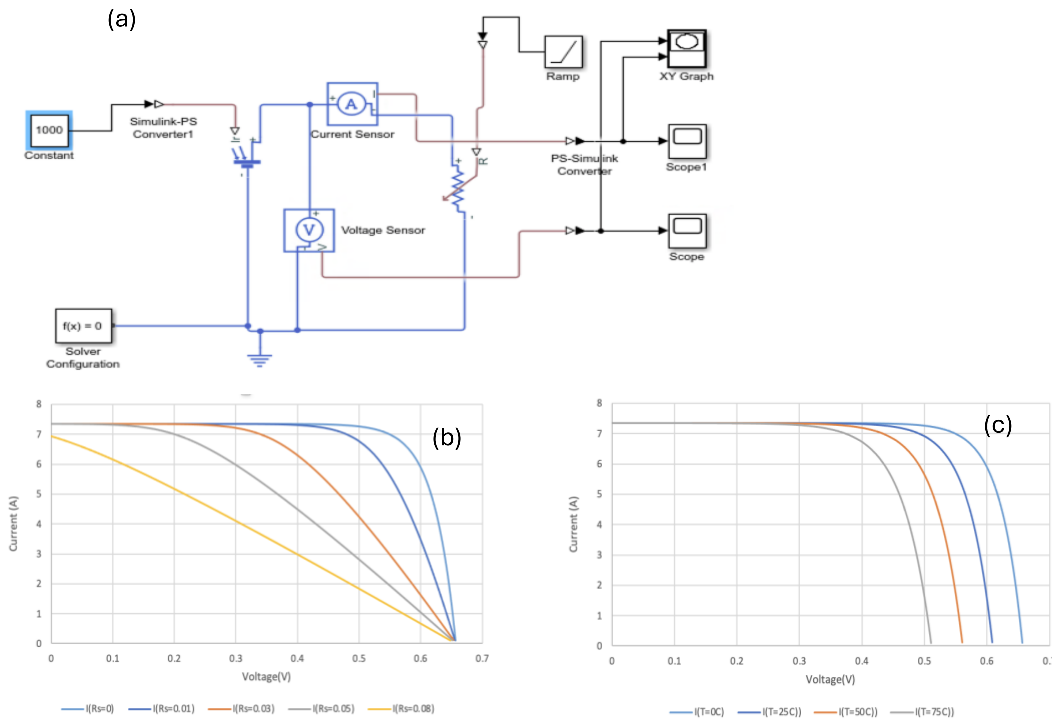


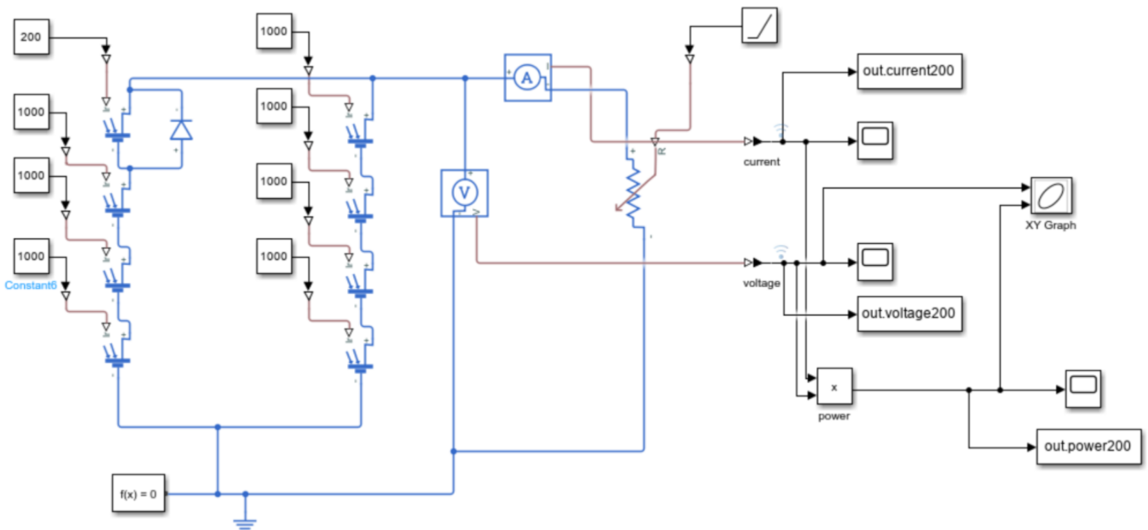
Figure 1The effect of series resistance and temperature on the performance of solar cell. (a) MATLAB Simulink setup (b) The I-V curve of the solar cell as series resistance changes from 0 to 0.08Ω (c) The I-V curve as temperature changes from 0°C to 75°C

Through this exercise, students gained a deeper understanding of the concepts covered in lectures. By analyzing Figure 1b, they reinforced key ideas, including:

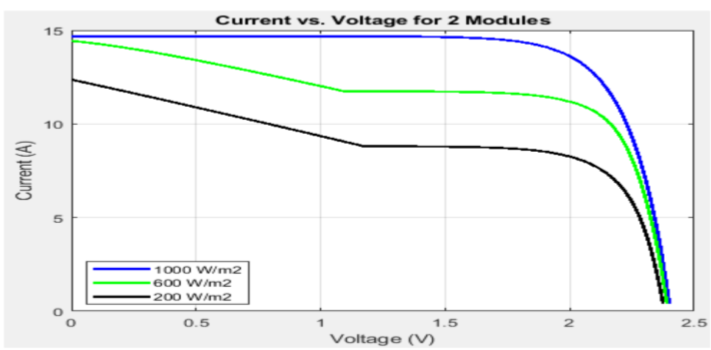
- Solar cells with the same V_{oc} and I_{sc} may not produce the same P_{mp}, highlighting the importance of the fill factor, F, where $F = \frac{P_{mp}}{V_{oc}I_{sc}}$.
- Parasitic series resistance influences the slope of the I-V curve near the V_{oc} but not affect the I_{sc}.
- Parasitic shunt resistance affects the slope of the I-V curve near the I_{sc} but not the V_{oc}. These effects are not directly apparent from the I-V equation.

Additionally, temperature is a significant environmental factor in semiconductor performance. Students observed how temperature variations impact the cell voltage, consequently, the maximum output power. Later, they will compare these simulation results with experimental measurements from their solar projects.

MATLAB Simulink is also employed to study the impact of partial shading on the performance of PV systems. Figure 2a illustrates an example of partial shading in a configuration with two solar panels connected in parallel, where the top solar cell of the left panel experiences partial shading. Figure 2b demonstrates that as the solar irradiance on the shaded solar cell decreases, both the current and power output are significantly reduced. A common misconception is that partial shading only impacts the shaded portion of a solar panel. However, as seen in figure 2b, students observed that shading reduces the current across all solar cells, leading to a significant decrease in overall output power.



(a)



(b)

Figure 2 The effect of partial shading on the performance of PV panels. (a) MATLAB Simulink setup (b) The I-V curve of the PV panels as the light intensity on one of the solar cells changes from 1000W/m^2 to 200W/m^2

- PV-FChart is a comprehensive software tool for the analysis and design of PV systems [17]. It provides monthly average performance estimates for each hour of the day and supports three types of systems: standalone systems, battery storage systems, and utility interface systems. The software offers both fixed and tracking configuration options. Simulation results from PV-FChart provide valuable insights, including the percentage of the load met by the system, the excess daily electrical energy generated by the solar cells that can be used for battery charging, and the additional daily energy required to compensate for power insufficiency from the PV cells. An example of PV-FChart's application in this course is presented in the case studies section.

5. Case Studies

Students gain hands-on experience with the design process through various practical case studies, including standalone systems such as a water-pumping system, a parking-lot lighting system, and a critical-need refrigeration system. Starting with the provided system design requirements, students work through essential stages: load determination, battery sizing, array sizing (comparing fixed and tracking arrays), selection of balance-of-system components, and overall system design.

An example of a grid-connected PV system is the 3 MW Consumers Energy Solar Garden located on our campus. This Solar Garden consists of 11,200 fixed-mount solar panels oriented southward. To analyze system performance, students use PV-FChart software. By incorporating local weather data, they can estimate the daily or monthly electrical energy output of the solar plant for various panel tilt angles. The analysis also determines the optimal tilt angle and calculates the number of panels connected in series and parallel.

6. Group Projects

The course project is carried out in teams of two, with any remaining student forming a team of three. All team members actively participate in every aspect of the project. Each team is responsible for identifying a problem and designing a system that meets specific requirements. Project topics vary with each course offering.

System design requirements:

- System power is generated by solar panel(s) and stored in batteries.
- Battery charging and discharging need to be managed.
- Depend on the load types, system may or may not include inverters.
- Current and voltage of the solar panel and the energy storage unit need to be monitored.
- Hourly data need to be logged.
- System needs to be assembled and installed for use in an application.

The first step of the project involves identifying a problem, followed by creating a requirements document and a test plan for the system. Students must meet several milestones to ensure steady progress. These milestones include:

- Problem statement and solution description (week 7): Each team will draft a brief problem statement and outline their proposed solution. A 15-minute meeting with the instructor will be scheduled to assess the feasibility and scope of the project.
- Requirements document (week 8): Teams will develop a comprehensive requirements document detailing system specifications and validation methods. Another 15-minute

meeting will be held to review the document and ensure all necessary requirements are addressed.
- System design review (week 11): Teams will present their project designs to the class, receiving feedback and critiques from both the instructor and their peers.
- Procurement of system components
- System assembly, testing, and troubleshooting (week 13)
- Demonstration of completed system (week 15)

Examples of projects undertaken include the following: a one-axis solar tracking system, real-time PV system monitor and data logger with automated internet and SD card uploading, a PV system for pedestrian crosswalk sign, an outdoor solar powered charging station, investigate solar cell encapsulation along with maximum power output and shadowing effects for the university solar car racing team.

6.1 Example Project: A PV system for pedestrian crosswalk sign

The following shows the detailed milestone achievement of the project: a PV system for pedestrian crosswalk sign.

- Problem statement:

In multiple locations on the campuses of GVSU, pedestrian crosswalks are positioned mid-road or at intersections that are not 4-way stops. At these crosswalks, it is not intuitive for drivers to stop for pedestrians. To enhance pedestrian safety and promote sustainable energy solutions within the university, we propose to design and build a standalone solar PV system for a pedestrian crosswalk.

- System requirements

The system requirements and functional specifications are listed below:

1. The cost of the project must be within the approved budget.
2. The system designed must follow the local laws and regulations.
3. The system must use the solar panel as the main power source
4. The system must have the pedestrian crosswalk sign with the LED attached around the edge.
5. The system must have a backup source (battery) to ensure continuous operation.
6. The system must have the charge controller to prevent overcharge and over-discharge.
7. The system must have a push-button for a pedestrian to initiate the flashing.
8. The system must have a controller unit to:
    a. Collect the signal-input from the push-button to activate the flashing.
    b. Adjust the flashing time
    c. Adjust flashing speed

The system block diagram is illustrated in Figure 3.

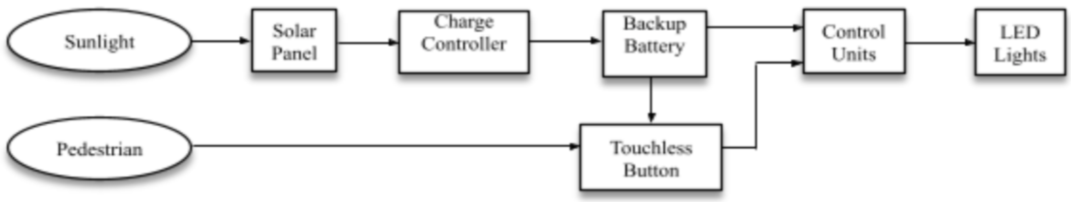


Figure 3 The block diagram of the PV system for a pedestrian crosswalk

- System design: Students went through the following key stages: energy requirement of loads (LED lights), battery sizing, solar panel sizing, charge controller sizing, selection of relay timer and balance-of-system components, and overall system design. Figure 4a depicts the designed system and figure 4b shows the photo of the completed system.

- System validation:

The system was tested against the system requirements and functional specifications. When the button is triggered, the relay timer initiates LED flashing for 30 seconds. If the button is triggered again before the 30-second time is up, the timer starts over. A flash time of 0.5s on and 0.5s off was set for the prototype. All other requirements were successfully met.

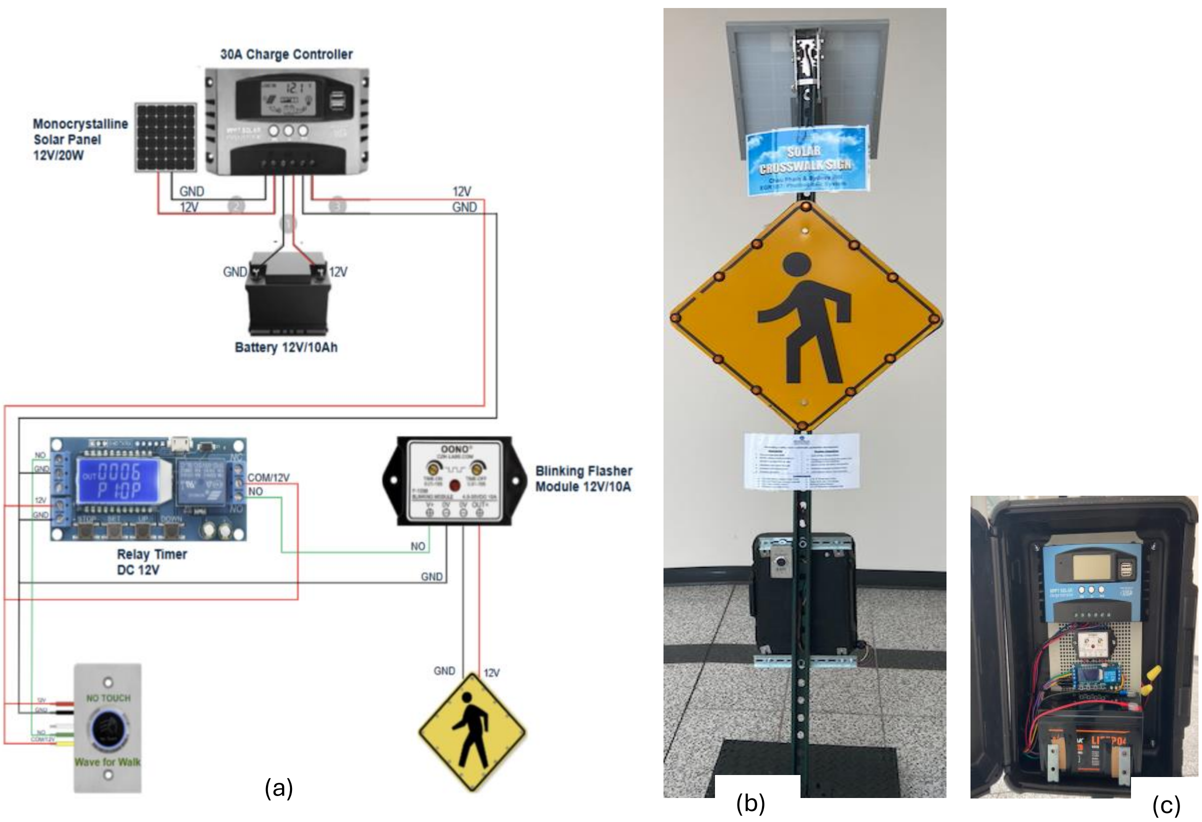


Figure 4 (a) The schematic of the PV system for a pedestrian crosswalk with each designed component identified (b) The complete system (c) inside of the control box

Another successfully completed project - a one-axis solar tracking system - is shown in Figure 5.

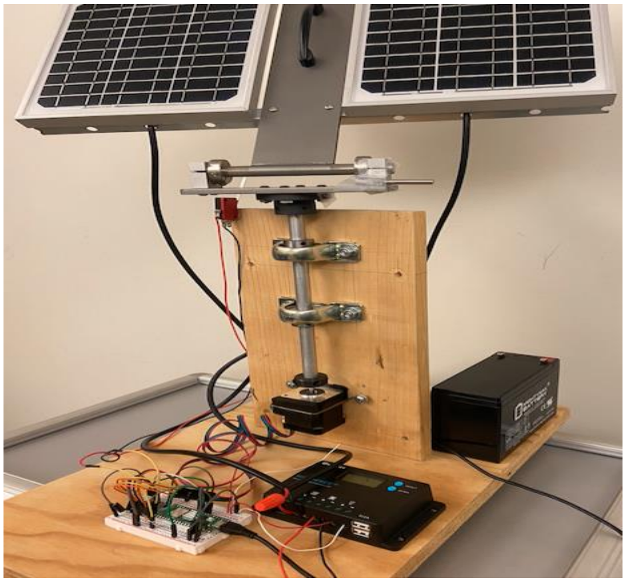


Figure 5 The completed project – one-axis solar tracking system

7. Course Assessments

Both formative and summative assessments were utilized to evaluate students' ability to apply the concepts and knowledge acquired during the course. Formative assessment involved ongoing evaluation and feedback throughout the project, enabling students to refine their approach and address any gaps in understanding. This included regular check-ins, peer reviews, and instructor guidance during critical phases such as system requirements generation and system design.

Summative assessment was conducted at the conclusion of the project to measure students' overall performance and mastery of the course objectives. This evaluation considered the quality of the final system design, the effectiveness of the test plan, and the ability to address the identified problem. Students were also assessed on their ability to work collaboratively within their teams, meet project milestones, and demonstrate a clear understanding of how the system met the defined requirements. All five projects were successfully completed, and three project teams participated in Project Day to showcase their work.

In the end-of-semester (EOS) evaluation, all students expressed that the class was effectively taught, and they enjoyed the course projects. Some of the comments were:

- The class effectively challenged my thinking through engaging content, interactive discussions, and challenging assignments.
- The professor's approach encouraged inquiry and critical thinking, making the learning experience both enjoyable and intellectually rewarding.
- There was a good combination of mathematical problem solving and hands-on project work.

Table 1 presents three representative questions from the EOS evaluation, while Figure 6 illustrates the responses from 13 students. All students expressed a great appreciation for the PV field as a result of this course. For the other two questions, 75% of students rated their response as (7), while 25% selected (6).

Table 1Three representative questions on the EOS evaluation

How would you describe your progress in this course with regards to:	Great (7)	(6)	(5)	Average (4)	(3)	(2)	None (1)
1. Developing an appreciation for the PV field	(7)	(6)	(5)	(4)	(3)	(2)	(1)
2. Understanding and solving problems in this field	(7)	(6)	(5)	(4)	(3)	(2)	(1)
3. Applying the material to real world issues	(7)	(6)	(5)	(4)	(3)	(2)	(1)

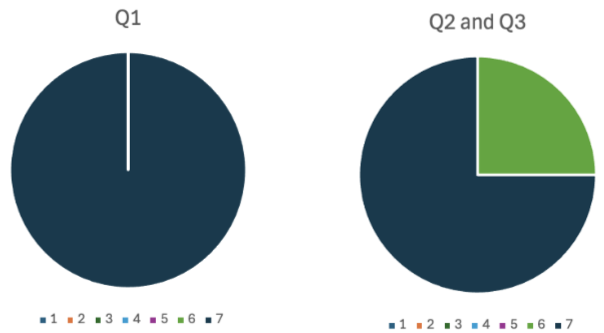


Figure 6 Students responses to the three survey questions

The data indicates that the course was highly effective in enhancing student appreciation and engagement in the PV field. This implies that the course design, which includes project-based learning, case studies, and hands-on experiments, successfully enhanced student understanding and enthusiasm for PV systems.

This class met once per week for three hours. Based on student feedback, a suggestion was made to split the course into two sessions per week to improve focus and reduce distractions. This change has been implemented in this winter term, and the feedback from current students has been positive.

PBTL in PV education offers numerous benefits but also presents several limitations and challenges:

- Time-intensive structure: PBTL requires substantial time for students to grasp theoretical concepts, design, and implement course projects. Instructors must also invest additional time in mentoring, evaluations, and project oversight.
- Resource constraints: Simulation tools, measurement equipment, and project components can be expensive. A single-user license for PV-FChart costs $400. In this course, project funding was supported by both the School of Engineering and a grant. Material and part costs varied across teams, ranging from $50 to $280.
- Assessment and evaluation: Assessing student performance in PBTL can be challenging, as projects often involve subjective elements. Developing clear rubrics that evaluate technical

skills, problem-solving abilities, and collaboration can help ensure fair and comprehensive assessment.

8. Conclusions

Project-based experiential teaching and learning provides an effective framework for PV systems education. By immersing students in hands-on projects, this approach bridges the gap between theory concepts and practical applications, enabling students to acquire both technical knowledge and practical skills essential for careers in the renewable energy sector. Throughout the course, students applied classroom knowledge to address real-world challenges. They refined system requirements, developed system specifications, and produced design documents while gaining valuable hands-on experience. All student teams successfully completed their projects, demonstrating proficiency in designing and implementing PV systems. The course outcomes confirmed that its objectives were successfully achieved.

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