

INTEGRATING SOLAR ENERGY EXPERIMENTS INTO STEM EDUCATION FOR SUSTAINABILITY

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Abstract: This article presents a STEM-based educational model focused on the utilization of solar energy through experimental and inquiry-based learning. The model integrates the theoretical foundations of photovoltaic and solar thermal systems with hands-on experimental activities. This approach enables students to investigate key factors influencing solar energy efficiency, including light intensity, temperature, material composition, and panel orientation. The transition toward sustainable energy systems is one of the most pressing challenges of the twenty-first century. Solar energy, as a renewable and widely accessible resource, plays a crucial role in reducing dependence on fossil fuels and mitigating climate change. Higher education institutions have a strategic responsibility to prepare future professionals capable of understanding, applying, and advancing solar technologies. Through structured experiments and interdisciplinary learning, students develop scientific, technological, and analytical competencies while gaining a deeper understanding of sustainable energy solutions. The findings highlight the educational value of experimental STEM environments in fostering environmental awareness, problem-solving skills, and readiness for sustainable innovation.

Keywords: solar energy education, STEM learning, photovoltaics, renewable energy, experimental learning, sustainability

1. INTRODUCTION

The rapidly increasing global demand for energy, together with the significant environmental and climatic impacts associated with fossil fuel consumption, has intensified the need for a transition toward clean and renewable energy sources. Conventional energy systems based on coal, oil, and natural gas contribute substantially to greenhouse gas emissions, air pollution, and resource depletion, prompting international efforts to promote sustainable energy solutions (International Energy Agency, 2021). Within this context, solar energy - derived from the sun's radiant light and heat - has emerged as one of the most promising alternatives due to its abundance, renewability, and minimal environmental footprint (Maka & Alabid, 2022). Unlike finite fossil resources, solar energy is widely available and can be harnessed in diverse geographic regions, offering long-term potential for energy security and environmental sustainability (Arias et al. 2021, Nunes, 2023).

Recent advances in photovoltaic and solar thermal technologies have led to significant improvements in the efficiency, reliability, and affordability of solar energy systems (Goswami, 2022). Technological developments in semiconductor materials, system design, and energy storage have expanded the applicability of solar energy across residential, commercial, and industrial sectors. As a result, solar technologies are increasingly integrated into modern energy infrastructures, contributing to reduced carbon emissions and supporting global climate mitigation strategies. However, the effective deployment and continued advancement of solar energy systems require a workforce equipped with strong scientific knowledge, technical skills, and an understanding of sustainability principles.

In this context, education - and particularly STEM education (Science, Technology, Engineering, and Mathematics) - plays a critical role in supporting the transition toward sustainable energy systems (English, 2023). Higher education institutions are uniquely positioned to bridge the gap between scientific theory and practical application by providing learning environments that encourage experimentation, innovation, and problem-solving. Through STEM-based instruction, universities can prepare students to understand the fundamental principles of solar energy technologies while also developing the competencies necessary to design, evaluate, and optimize renewable energy solutions.

Integrating solar energy topics into STEM curricula enables students to connect abstract scientific concepts, such as energy conversion, semiconductor physics, and thermodynamics, with real-world technological applications and global sustainability challenges. Experimental and inquiry-based learning approaches allow students to actively engage with solar energy systems, fostering critical thinking, interdisciplinary understanding, and data-driven decision-making. Within this educational framework, students are encouraged to explore the performance of solar technologies under varying conditions, analyze efficiency-related parameters, and assess the environmental and societal implications of renewable energy adoption.

This article presents an educational framework for utilizing solar energy in a STEM learning environment, with a particular emphasis on experimental activities that support inquiry, critical thinking, and interdisciplinary learning.

By integrating theoretical foundations with hands-on experimentation, the proposed model aims to enhance students' scientific and technological competencies while promoting awareness of sustainable energy solutions and their role in addressing contemporary energy and environmental challenges.

2. EDUCATIONAL FRAMEWORK FOR SOLAR ENERGY IN STEM

STEM education is based on pedagogical approaches that emphasize learning through exploration, experimentation, and systematic problem-solving (Margot & Kettler, 2019). Rather than relying solely on theoretical instruction, STEM learning environments encourage students to actively engage with scientific phenomena, test hypotheses, and analyze empirical data (Hebecci & Usta, 2022). When applied to renewable energy topics, this approach enables learners to investigate complex energy systems and to evaluate technological solutions based on measurable performance indicators and real-world constraints. Such an experiential learning process is particularly important in the context of sustainability, where understanding the interaction between technology, environment, and society is essential (UNESCO, 2020).

Solar energy education is especially well suited to STEM-based instruction due to its interdisciplinary nature. The study of solar energy draws upon fundamental principles from:

- physics, including the behavior of light, electrical circuits, and thermodynamic processes;
- chemistry, particularly the properties and behavior of semiconductor materials used in photovoltaic cells;
- engineering, involving system design, optimization, and efficiency analysis;
- information technologies, which support data collection, monitoring, modeling, and visualization.

This interdisciplinary integration allows students to develop a holistic understanding of how solar energy systems function and how they can be improved for greater efficiency and sustainability (Margot & Kettler, 2019; English, 2023).

The educational model presented in this study integrates solar energy topics into a structured learning sequence designed to progressively build knowledge and skills. The framework begins with the development of a conceptual understanding of solar energy systems, including photovoltaic and solar thermal technologies, their operating principles, and their role in modern energy systems. This theoretical foundation is supported by experimental investigations, in which students examine performance-related parameters such as light intensity, temperature, material composition, and panel orientation under controlled conditions (Zhang et al., 2020). According to Margot & Kettler, 2019 through hands-on experimentation, learners gain practical experience in measurement techniques and develop an appreciation for the variability and limitations inherent in real-world energy systems.

A key component of the framework is data analysis and interpretation. Students are guided to collect quantitative data, organize results, and identify patterns and relationships that influence system performance. This process strengthens analytical reasoning and reinforces the importance of evidence-based conclusions in scientific and engineering practice. Finally, the framework emphasizes the application of experimental findings to real-world sustainability challenges. Students consider how their results can inform the design of more efficient solar energy systems, support energy conservation strategies, or contribute to broader efforts aimed at reducing environmental impacts.

Through this comprehensive model, students are not only introduced to solar energy technologies but are actively involved in the scientific and engineering processes used to evaluate, optimize, and apply renewable energy systems. As a result, STEM education becomes a powerful tool for developing technical competence, critical thinking, and sustainability-oriented perspectives essential for addressing contemporary and future energy challenges.

3. METHODOLOGY: EXPERIMENTAL STEM DESIGN

The methodological approach is about integrating the inquiry-based and project-oriented learning, which positions students as active participants in the educational process. Instead of passively receiving information, learners are encouraged to engage directly with scientific questions related to solar energy systems through the formulation of hypotheses, the design of experiments, the systematic collection of data, and the development of evidence-based conclusions. This pedagogical method reflects the core principles of STEM education by emphasizing experiential learning, analytical thinking, and the integration of knowledge across scientific and technological disciplines.

The experimental activities are implemented within laboratory or STEM classroom environments equipped with basic measurement instruments and renewable energy kits, such as photovoltaic cells, light sources, temperature sensors, and multimeters. The structure of the activities allows for flexibility and scalability, making them suitable for adaptation to different educational levels, institutional contexts, and resource availability. This adaptability ensures that the experimental model can be applied across diverse higher education settings without requiring highly specialized infrastructure.

Students work in small collaborative teams, a format that supports both independent inquiry and cooperative learning. Collaborative work fosters peer interaction, communication, and shared problem-solving, while individual responsibilities ensure active participation and accountability throughout the experimental process (Scager et al., 2016). Through this balanced approach, students not only develop technical and analytical skills but also enhance their ability to communicate scientific ideas and collaborate effectively - competencies that are essential for professional practice in renewable energy and sustainability-related fields.

4. LEARNING OBJECTIVES

The primary objectives of the experimental activities are aligned with both cognitive and skill-based learning outcomes. First, the activities aim to develop a solid understanding of the fundamental principles of solar energy conversion, including the operation of solar photovoltaic cells and solar thermal systems. Students explore how solar radiation is transformed into electrical or thermal energy and examine the physical and chemical mechanisms underlying these processes.

Second, the methodology focuses on investigating the key factors that affect solar cell efficiency. Through systematic experimentation, students analyze how variables such as light intensity, temperature, material composition, and panel orientation influence energy output. This enables learners to understand performance variability and to recognize the practical constraints associated with solar energy systems in real-world conditions.

Third, the experimental design supports the development of essential scientific skills, including accurate measurement, data recording, statistical analysis, and scientific reporting. Students are guided to use appropriate instruments, interpret quantitative results, and communicate findings using structured laboratory reports and presentations. These activities strengthen analytical thinking and reinforce the importance of methodological rigor in scientific research.

Finally, the methodology aims to promote awareness of renewable energy applications and sustainability. By linking experimental findings to broader environmental and societal challenges, students are encouraged to reflect on the role of solar energy in reducing carbon emissions and supporting sustainable development. Through this integrated approach, the experimental STEM design not only enhances technical competence but also fosters responsible attitudes toward renewable energy and environmental concern.

5. EXPERIMENTAL ACTIVITIES

The experimental activities are designed to support inquiry-based learning by allowing students to systematically explore the physical and technological factors influencing solar energy performance. Each experiment focuses on a specific parameter affecting photovoltaic efficiency and is structured to promote hypothesis formulation, controlled experimentation, data collection, and analytical interpretation. Together, the experiments provide a comprehensive understanding of how solar energy systems operate under varying environmental and technical conditions. The study was conducted with undergraduate students enrolled in STEM-related programs, including physics and chemistry. The participants were from courses that integrate renewable energy or sustainability-related content into their curricula. Participation in the experimental activities was embedded within regular coursework, ensuring authentic engagement and alignment with learning objectives.

Prior to the experimental phase, participants were introduced to the basic theoretical concepts of solar energy systems and received instructions on the safe use of measurement instruments and experimental equipment. This ensured a common foundational knowledge level and minimized procedural variability during experimentation.

The diverse academic background of the participants supported interdisciplinary interaction and collaborative problem-solving. Such diversity enabled students to approach solar energy challenges from multiple perspectives, reflecting real-world professional contexts in which renewable energy solutions require cooperation among specialists from different fields.

Experiment 1: Effect of Light Intensity on Photovoltaic Output

In the first experiment, students investigate the relationship between incident light intensity and the electrical output of a solar photovoltaic cell. A controlled artificial light source is positioned at varying distances from the solar cell to simulate different illumination levels. Light intensity is measured using a lux meter, while the resulting voltage and current generated by the solar cell are recorded with a multimeter.

By systematically varying light intensity and recording the corresponding electrical output, students observe a direct correlation between the amount of incident radiation and electricity generation. This experiment reinforces fundamental photovoltaic principles, including photon absorption and charge carrier generation. In addition, students learn to control experimental variables and to distinguish between dependent and independent parameters, strengthening their understanding of experimental design and measurement accuracy.

Experiment 2: Influence of Temperature on Solar Cell Efficiency

The second experiment focuses on the impact of temperature on the performance of solar photovoltaic cells. Students expose the solar cell to controlled heating or cooling conditions using a heat source (such as a lamp or warm air) or cooling elements (such as an ice pack). Throughout the experiment, the surface temperature of the solar cell is continuously monitored using a thermometer or temperature sensor, while voltage and current output are measured at each temperature level.

The collected data allow students to analyze how increasing temperature typically leads to a decrease in electrical efficiency, despite constant light conditions. This experiment highlights an important practical challenge in solar energy system design, as elevated operating temperatures can reduce performance in real-world installations. Students are encouraged to discuss potential engineering solutions, such as ventilation or material selection, to mitigate thermal losses.

Experiment 3: Comparison of Semiconductor Materials

In the third experiment, students compare the performance of photovoltaic cells constructed from different semiconductor materials, such as silicon, gallium arsenide, or cadmium telluride. All cells are tested under identical lighting conditions to ensure comparability of results. Voltage and current outputs are measured, and efficiency is calculated based on the recorded values.

Through this comparative analysis, students gain insight into how material properties influence photovoltaic performance, cost, durability, and environmental impact. The experiment fosters critical evaluation of technological trade-offs, encouraging students to consider not only efficiency but also sustainability and resource availability. This activity strengthens interdisciplinary connections between chemistry, physics, and engineering while promoting informed decision-making in renewable energy technology selection.

Experiment 4: Angle Dependence of Solar Panels

The fourth experiment examines how the orientation of a solar panel affects its energy output. Students mount a solar panel on an adjustable stand and vary its tilt angle relative to the light source, testing multiple orientations (e.g., 0°, 30°, and 60°). For each angle, voltage and current are measured after a fixed exposure period to ensure consistent conditions.

The results demonstrate that solar panel orientation significantly influences energy capture, with an optimal angle producing maximum electrical output. This experiment links scientific observation with practical application, as students relate their findings to real-world considerations such as geographic location, seasonal variation, and installation design. By interpreting the results, students develop an applied understanding of how experimental data inform effective solar energy deployment.

6. RESULTS AND EDUCATIONAL IMPACT

The results of the experimental activities indicate that students develop a significantly deeper and more coherent understanding of solar energy systems when learning is grounded in hands-on investigation. Through direct engagement with photovoltaic and solar thermal experiments, students demonstrate improved ability to interpret quantitative data, identify performance trends, and understand the relationships between environmental variables and system efficiency. The systematic collection and analysis of voltage, current, temperature, and light intensity data enable students to move beyond theoretical descriptions and to construct evidence-based explanations of solar energy behavior.

Students show increased proficiency in applying scientific methods, including hypothesis formulation, variable control, and data interpretation. The experimental design encourages learners to critically evaluate their results, recognize sources of measurement uncertainty, and compare outcomes across different experimental conditions. As a result, students gain a more realistic understanding of how solar energy systems perform in real-world settings, where efficiency is influenced by multiple interacting factors. This experiential learning process supports the development of analytical reasoning and reinforces the importance of empirical evidence in energy-related decision-making.

Beyond technical and scientific knowledge, the STEM-based approach has a measurable impact on students' cognitive and collaborative skills. Working in small teams, students engage in discussion, negotiate experimental procedures, and collectively interpret results, which strengthens communication and collaboration skills. Problem-solving abilities are enhanced as students are challenged to optimize system performance, address experimental limitations, and propose practical improvements based on their findings. These competencies are essential for professional practice in engineering, science, and sustainability-related fields.

Furthermore, the interdisciplinary nature of the experimental activities supports integrated learning across physics, chemistry, engineering, and environmental science. Students develop an appreciation for the interconnectedness of scientific disciplines and recognize how combined knowledge is required to address complex sustainability challenges. By engaging with authentic renewable energy problems, learners gain insight into the broader societal

and environmental implications of energy choices. This holistic perspective fosters environmental awareness and encourages students to view solar energy not only as a technical solution but also as a critical component of sustainable development and climate mitigation strategies.

7. DISCUSSION

The findings of this study confirm that experimental STEM education represents an effective and pedagogically sound strategy for teaching renewable energy concepts, particularly in the context of solar energy. By embedding hands-on experimentation within the learning process, abstract scientific principles related to energy conversion, material properties, and system efficiency become tangible and accessible to students. This experiential approach enhances conceptual understanding by allowing learners to directly observe cause-effect relationships, thereby bridging the gap between theoretical knowledge and practical application.

Solar energy experiments provide an authentic context in which students can explore complex phenomena such as variability in energy output, efficiency losses, and environmental influences on system performance. Such real-world relevance increases student engagement and supports deeper learning, as students are more likely to adopt concepts when they can observe and measure their effects directly. In addition, the experimental focus encourages iterative learning, where students refine hypotheses, adjust parameters, and reassess outcomes - an approach that closely mirrors scientific and engineering practice.

The emphasis on sustainability within the experimental STEM framework further strengthens its educational impact. By working with renewable energy systems, students are encouraged to reflect critically on environmental responsibility, resource management, and the long-term consequences of energy-related decisions. This reflective dimension supports the development of sustainability-oriented values and ethical awareness, which are increasingly recognized as essential components of higher education. Rather than treating sustainability as a theoretical concept, the experimental approach situates it within concrete technological and societal contexts.

Moreover, integrating solar energy topics into STEM education contributes to the preparation of future professionals capable of supporting green innovation and sustainable development. The combination of theoretical foundations with experimental competencies equips students with transferable skills that are highly relevant to careers in renewable energy, engineering, environmental management, and related fields. Through data analysis, system optimization, and problem-solving activities, students develop professional practices aligned with the demands of a rapidly evolving green economy.

From an educational perspective, the interdisciplinary nature of the experimental activities reinforces the value of integrated STEM learning. Addressing solar energy challenges requires the application of knowledge from physics, chemistry, engineering, and environmental science, highlighting the necessity of cross-disciplinary thinking. This integrated approach prepares students to address complex, real-world problems that cannot be solved within the boundaries of a single discipline. Overall, the findings suggest that experimental STEM education not only improves learning outcomes but also plays a critical role in fostering scientifically literate, environmentally responsible, and innovation-oriented graduates.

8. CONCLUSION

Utilizing solar energy within a STEM educational framework offers substantial benefits for both student learning outcomes and the development of sustainability awareness. The experimental model presented in this article demonstrates that hands-on investigations of photovoltaic and solar thermal systems provide an effective means of deepening students' scientific understanding while simultaneously strengthening their technical and analytical skills. Through direct interaction with solar energy technologies, students are able to explore complex energy conversion processes, evaluate system performance under varying conditions, and interpret quantitative data in a meaningful way.

The integration of experimental learning into STEM education also fosters greater engagement and motivation among students. By addressing real-world challenges related to renewable energy, learners gain a clearer understanding of the relevance of scientific knowledge to contemporary environmental and societal issues. This approach supports the development of critical thinking, problem-solving, and interdisciplinary reasoning, which are essential competencies for addressing the multifaceted nature of sustainability challenges.

Moreover, engaging students in data-driven experimentation encourages evidence-based decision-making and reinforces the importance of scientific rigor in the design and evaluation of energy systems. The emphasis on sustainability throughout the learning process contributes to the formation of environmentally responsible attitudes and a deeper appreciation of the role of renewable energy in mitigating climate change.

In this context, higher education institutions play a vital role in preparing future professionals capable of contributing to the global transition toward sustainable and resilient energy systems. By integrating solar energy

experimentation into STEM curricula, universities can support the development of a skilled and sustainability-oriented workforce equipped to drive innovation and support long-term environmental and energy goals.

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