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PROBLEM-SOLVING IN STEM LEARNING THROUGH SOLAR CELL PROJECTS: STUDENTS' PRIOR KNOWLEDGE TO SUPPORT SUSTAINABLE DEVELOPMENT GOALS (SDGs)

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Abstract

The study investigated students' prior knowledge of problem-solving in STEM through a solar cell project. A quantitative descriptive approach was used with an essay-based instrument aligned to Osborne's problem-solving indicators, and students' responses were scored and compared between groups using an independent t-test. Results showed that prior knowledge was generally low across all indicators and that performance did not differ significantly between the comparison groups. Students struggled to link physics principles with technological design, to plan feasible solutions, and to justify choices with quantitative reasoning. They also had difficulty interpreting current–voltage and power–voltage relationships. These findings suggest that learners enter project work with fragile conceptual frameworks because foundational ideas about energy, efficiency, and system constraints have not been integrated with real contexts. Integrating a solar cell project within STEM is recommended, as it provides authentic tasks that connect concepts to practice, strengthen scientific reasoning, and support the development of problem-solving competencies. This study supports sustainable development goals (SDGs).

Keywords: Prior knowledge, Problem-solving, Project, Solar cell, STEM.

1. Introduction

Problem-solving is widely recognized as a core 21st-century skill, encompassing cognitive processes that extend beyond rote memorization toward constructing new knowledge and adapting existing understanding to unfamiliar situations [1, 2]. Within STEM education, prior knowledge serves as a foundational entry point for learning, allowing students to meaningfully connect science, technology, engineering, and mathematics with their personal experiences and contextual understanding [3].

In addition to its relevance in education, problem-solving is essential in the development of renewable energy systems, such as solar cells, where integrated, innovative, and systems-based thinking is required to address technical, economic, and environmental constraints [4]. Because of this complexity, structured learning programs that promote critical thinking about sustainable development are needed to prepare students to solve multifaceted challenges [5].

As a key component of science, engineering, and medical education, problem-solving has been the focus of numerous studies and frameworks [3]. The organization for economic cooperation and development (OECD) outlines competencies for scientific problem-solving, while Osborne and colleagues identify five indicators that characterize scientific approaches to diverse problems. From an engineering perspective, effective problem-solving is central to improving renewable energy systems, particularly those supported by real-time supervisory control and data acquisition (SCADA) systems for monitoring and troubleshooting hybrid systems [6].

Sustainable design requires not only technical efficiency but also environmental awareness, such as optimizing the integration of photovoltaic systems in buildings to increase energy yields while reducing dependency on fossil sources [7]. Because renewable energy issues span multiple disciplines, including engineering, environmental science, and policy, they demand collaborative and adaptive solutions [8, 9]. These considerations affirm the relevance of embedding STEM approaches into physics instruction at the secondary level.

According to the 2012 programme for international student assessment (PISA) assessment, approximately one-fifth of 15-year-old students in OECD countries could only solve simple, familiar problems, while fewer than 12% could systematically address complex ones [10]. The assessment also reported significant global and intra-national disparities in problem-solving proficiency [10].

Many high school graduates continue to encounter difficulties in solving real-world problems, largely due to two unresolved issues: the challenge of accurately assessing problem-solving skills and the lack of effective instructional designs that foster them [3]. However, research shows that incorporating authentic, context-rich problems into classroom practice can improve students' problem-solving abilities and deepen their conceptual reasoning and decision-making [11, 12]. These tasks mirror the complexity and unpredictability of real-life demands.

This study aims to investigate students' prior knowledge of problem-solving skills within a STEM framework using a solar cell project. Conducted with 67 tenth-grade students in Banjarmasin, the study employed a quantitative descriptive approach and used an essay-based problem-solving test containing three contextual items. The novelty of this research lies in applying Osborne's problem-solving indicators to assess students' initial abilities in understanding physics concepts through engineering-based renewable energy applications. Unlike earlier studies, this research emphasizes prior knowledge not merely as a predictor of success but as a vital component in designing effective STEM learning, particularly in project-based settings.

The findings offer a practical reference for teachers to create meaningful instructional activities focused on solar energy, with the hypothesis that STEM-based project learning, when supported by contextual relevance, can improve students' problem-solving capacities. However, before introducing such interventions, it is necessary to assess students' prior understanding to tailor instructional materials and scaffold learning appropriately. This study, therefore, explores students' cognitive readiness in physics problem-solving related to solar cells, with the intention of informing strategies that foster higher-order thinking and prepare students to address real-world energy challenges as active, solution-oriented citizens. This study supports sustainable development goals (SDGs).

2. Literature Review

2.1. Problem-solving

Problem-solving skills encompass cognitive, metacognitive, and affective abilities that allow individuals to identify, analyse, and resolve various types of problems. These skills extend beyond routine tasks and involve handling complex, real-world, and ill-structured problems through reasoning, creativity, and decision-making processes [13]. In physics education, problem-solving involves applying core physics principles, constructing reasoning strategies, and integrating prior knowledge to solve both structured and unstructured tasks [14].

Students' ability to solve problems typically follows a multi-stage cognitive process: understanding known and unknown elements, devising a strategy, implementing the solution, and reflecting on outcomes. This process demands the activation of prior knowledge, logical reasoning, and continuous metacognitive monitoring. Furthermore, affective aspects such as motivation, confidence, and perseverance significantly influence how students engage in problem-solving [15].

At the beginning of this discussion, Table 1 outlines key aspects involved in problem-solving, emphasizing the interplay between cognition, metacognition, prior knowledge, and affective domains.

In the context of solar cell projects, students are expected to develop a wide range of problem-solving skills. These include:

(i) problem identification, such as recognizing inefficiencies in light-to-electricity conversion.

(ii) conceptual understanding, which involves connecting physics concepts (energy, power, photons, electricity) with engineering contexts and understanding the relationship between light intensity, surface area, and electrical output.

(iii) solution planning, including determining experimental methods, tools, materials, and prototypes.

(iv) reasoning and decision-making, such as selecting optimal materials or panel tilt angles under given constraints.

(v) experimentation and innovation, through trials and refinements to improve system efficiency.

(vi) monitoring and reflection, involving metacognitive evaluations of system performance and necessary corrections.

(vii) collaboration and communication, working in teams to collect and present findings; and

(viii) creativity and critical thinking, which are demonstrated by designing new solar configurations and interpreting experimental data with scientific accuracy.

Table 1. Problem-solving aspect.

No.	Aspects	Description
1	Cognitive processes	Recognizing what is given, what is asked, selecting or devising a strategy, executing steps, and verifying or reviewing the solutions.
2	Use of prior knowledge & reasoning	Students bring in what they already know (concepts, procedures) to understand and plan solutions.
3	Metacognitive monitoring	Being aware of whether their plan is working, checking mistakes, and revising the strategy if needed.
4	Problem-solving steps	(1) Understand the problem, (2) devise a plan, (3) carry out the plan, (4) look back (review).
5	Non-routine / real-world / higher-order problems	Problems that require modelling, interpretation, or strategy-building, rather than simple formulaic application.
6	Affective and motivational factors	Confidence, persistence, ability to overcome difficulties, emotional and attitudinal engagement with the problem-solving process.

2.2. Science, technology, engineering, and mathematics (STEM)

STEM education is an integrative instructional approach that combines science, technology, engineering, and mathematics through problem-based and context-driven learning. It emphasizes inquiry, design thinking, and real-world applications to promote critical thinking, creativity, collaboration, and problem-solving. The core objective of STEM education is to build STEM literacy, enabling learners not only to pursue careers in science and technology but also to function as informed citizens in a rapidly advancing society [16].

Rather than presenting each discipline separately, STEM often adopts interdisciplinary or transdisciplinary approaches where students apply integrated knowledge across fields. Learning is grounded in real-world problems and authentic tasks, fostering student exploration, design, experimentation, and reflection. Many reports regarding STEM have been well-documented [17, 18]. As demonstrated in Table 2, extensive studies have examined the efficacy of STEM learning across educational contexts and learning outcomes.

Table 2. Previous studies about STEM.

No.	Title	Ref.
1	Enhancing student communication competencies in STEM using virtual global collaboration PjBL	[19]
2	Evidence of STEM enactment effectiveness in Asian student learning outcomes	[20]
3	Equity-Oriented Conceptual Framework for K-12 STEM literacy	[21]
4	Indonesian preservice STEM teachers' experiences in STEM-TPACK design-based learning.	[22]
5	Concepts of creativity in design-based STEM education	[23]
6	High school teachers' beliefs and practices of STEM integration in complex design systems	[24]
7	A Framework for Epistemological Discussion on Integrated STEM Education	[25]
8	Profiling self-regulation behaviours in STEM engineering design learning	[26]
9	Infusing the engineering design process into STEM PjBL for preservice technology teachers	[27]
10	Web-based vs. classroom-based STEM learning on collaborative problem-solving in junior high school	[28]
11	Impact of STEM teaching approach on creative thinking and mathematical achievement	[29]

In this study, STEM learning is implemented through project-based physics instruction involving solar cells. The project requires students to integrate knowledge from all four STEM domains:

(i) Science: Students explore core physics concepts such as energy, power, light intensity, photons, and electricity. They investigate the photovoltaic effect and how voltage, current, and surface area influence electrical output.

(ii) Technology: Learners use tools such as multimeters, lux meters, and light sensors to gather experimental data. Digital platforms (e.g., Excel, PhET simulations, Arduino) support data analysis and performance simulations of solar panels.

(iii) Engineering: Students design and construct simple solar cell prototypes using materials like semiconductors or natural dye-sensitized cells. They refine their designs through iterative testing of angles, circuits, and materials to enhance performance.

(iv) Mathematics: Students are required to calculate electrical power and to compare efficiency. They also interpret graphs (e.g., light intensity vs. power, surface area vs. voltage) and use equations to predict system performance under different conditions.

By integrating these disciplines into a cohesive project, STEM learning enables students to address complex problems, make data-informed decisions, and deepen their understanding of renewable energy technologies.

2.3. Solar cell

Figure 1 illustrates the fundamental structure of a solar cell and the process by which incoming light is converted into electrical energy. A solar cell, also known as a photovoltaic cell, is a semiconductor device that transforms photon energy into electricity through the photovoltaic effect. It typically consists of a p–n junction that separates photo-generated charge carriers (electrons and holes), resulting in a current when the terminals are connected to an external circuit [30].

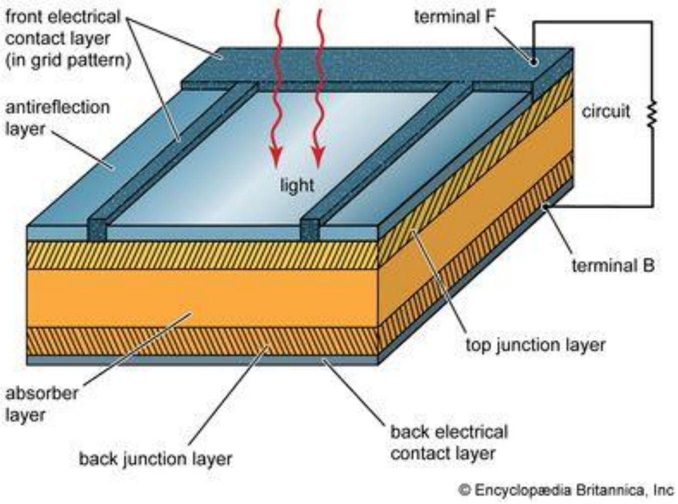

Fig. 1. Solar cell component [31].

The global photovoltaic market is dominated by crystalline silicon solar cells, valued for their high reliability and moderate efficiency. Commercially available models typically achieve efficiencies in the range of 15% to 22%, with laboratory versions reaching higher benchmarks due to architectural advancements such as passivated emitter rear cell (PERC) technology [32, 33]. Meanwhile, perovskite solar cells (PSCs) are emerging rapidly, offering high efficiency with lower production costs [34]. Organic photovoltaics have also gained traction, with material innovations such as π-extended nonfullerene acceptors enabling considerable performance gains [35].

Historically, photovoltaic technologies have progressed through three main generations. The first generation utilized crystalline silicon, offering high performance but demanding significant material resources [36]. The second generation introduced thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), which enhanced flexibility and reduced material use, though issues like toxicity and material scarcity remain [37]. The third generation includes dye-sensitized solar cells (DSSCs) and PSCs, which employ organic–inorganic hybrid structures. DSSCs achieve modest efficiency but suffer from poor long-term stability, while PSCs offer superior light absorption and efficient charge transport, positioning them as promising candidates for next-generation photovoltaics [38, 39].

The step-by-step energy transformation process in a solar cell is summarized in Table 3, which explains how sunlight initiates electrical generation. When light photons with sufficient energy strike the semiconductor surface, they are absorbed and generate electron–hole pairs. These carriers are then separated by the electric field at the p–n junction and collected at the electrodes, resulting in an external current.

Table 3. Description of the process energy transformation in a solar cell.

Process/Component	Description
Photon absorption	Sunlight photons with energy equal to or greater than the band gap excite electrons from the valence to the conduction band, creating holes.
Generation of electron-hole pairs	Each absorbed photon forms an electron-hole pair, unless energy is lost via heat (thermalization).
Built-in electric field / p-n junction	The junction creates an internal field that drives electrons toward the n-side and holes toward the p-side, ensuring charge separation.
Charge collection	Electrodes on both sides collect charges and allow current to flow through an external circuit, generating usable electricity.

Figure 2 presents the idealized current–voltage (I–V) curve of a solar cell. At zero voltage, the current reaches its peak, while the voltage reaches its maximum (open-circuit voltage) when no current flows. This behaviour illustrates the nonlinear nature of photovoltaic output and helps identify operating conditions.

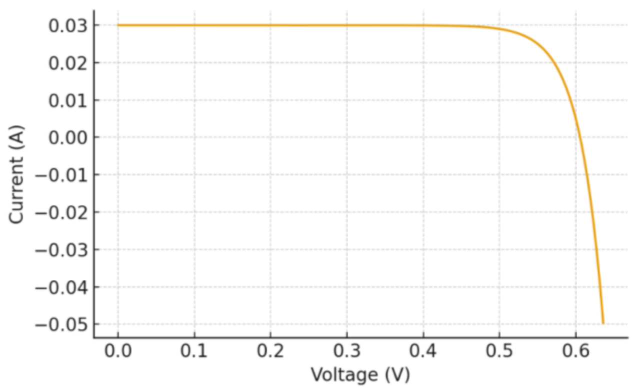

Fig. 2. Idealized solar cell I-V curve [40].

Despite technological progress, large-scale adoption faces persistent challenges. Material toxicity (such as cadmium in CdTe and lead in PSCs) raises environmental concerns, prompting researchers to seek safer alternatives [36]. Production scalability and long-term durability, particularly in PSCs and organic photovoltaics, remain unresolved [41]. Environmental factors such as heat, moisture, and prolonged sunlight exposure can accelerate degradation, compromising performance stability [38]. Moreover, the integration of solar cells into infrastructure-for example, in building-integrated photovoltaics (BIPV) and electric vehicle systems-requires careful attention to mechanical resilience and design optimization [42].

Figure 3 shows the power-voltage (P-V) curve, which identifies the maximum power point (MPP) (a critical value where a solar cell achieves peak efficiency). Because irradiance and temperature vary in real-world conditions, photovoltaic systems often implement Maximum Power Point Tracking (MPPT) algorithms to ensure continuous operation near the MPP [43].

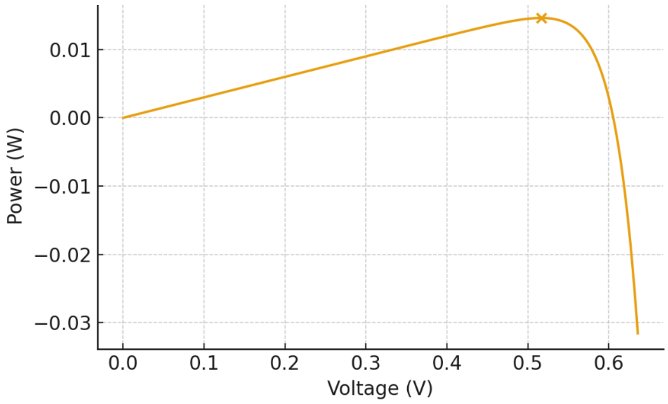

Fig. 3. P-V curve and maximum power point [40].

2.4. Prior knowledge

Prior knowledge refers to the information and understandings that learners possess before encountering new content. This includes not only facts and concepts, but also procedures, schemas, experiences, and personal beliefs [44]. The effectiveness of prior knowledge depends not merely on its presence, but on how well it is structured, how easily it can be retrieved, and how it integrates with new learning. When this knowledge is coherent and well-organized, it supports inference-making, comprehension, and long-term retention [45].

Table 4 highlights several prior studies that explore the influence of prior knowledge on learning outcomes, reasoning ability, and student engagement. These studies consistently show that students with well-developed prior knowledge (accompanied by coherent epistemic beliefs) are more likely to construct high-quality, evidence-based arguments, while those with limited knowledge often rely on simplistic or opinion-based reasoning.

Table 4. Previous studies about prior knowledge.

No.	Title	Ref.
1	Epistemic beliefs and prior knowledge as predictors of the construction of different types of arguments on socioscientific issues	[46]
2	How Does Prior Knowledge Influence Learning Engagement? The Mediating Roles of Cognitive Load and Help-Seeking	[47]
3	Can Students without Prior Knowledge Use ChatGPT to Answer Test Questions? An Empirical Study	[48]
4	The Rich-Get-Richer Effect: Prior Knowledge Predicts New Learning of Domain-Relevant Information	[49]
5	Propagating Facial Prior Knowledge for Multitask Learning in Face Super-Resolution	[50]
6	Mathematical Flexibility: Aspects of a Continuum and the Role of Prior Knowledge	[51]
7	The mediating effects of needs satisfaction on the relationships between prior knowledge and self-regulated learning through AI chatbot	[52]
8	Which Prior Mathematical Knowledge Is Necessary for Study Success in the University Study Entrance Phase?	[53]
9	The perceived effectiveness regarding Immersive Virtual Reality learning environments changes by the prior knowledge of learners	[54]

Importantly, prior knowledge can either support or hinder learning, depending on its accuracy and relevance. Misconceptions or fragmented knowledge can lead to misunderstandings that persist over time. Therefore, educators must not only identify what students know but also investigate how they conceptualize and apply that knowledge, including any misconceptions or flawed beliefs they may hold.

Understanding students' prior knowledge is essential for three main reasons. First, it has a strong impact on learning outcomes: students with richer and more relevant background knowledge tend to acquire new material more efficiently, demonstrate better comprehension, and engage in deeper reasoning [55]. Second, it influences learning engagement: familiar knowledge structures reduce cognitive load, allowing students to participate more actively in learning tasks [47]. Third, it informs instructional design: by assessing and building upon learners' prior understanding, teachers can avoid redundancy, target misconceptions, and design learning sequences that are more meaningful and effective [45].

3. Method

This study employed a quantitative descriptive design involving 67 tenth-grade students from a public high school in Banjarmasin, Indonesia. Detailed information regarding this method is explained elsewhere [56]. Participants were assigned to either an experimental group or a control group. Before engaging in STEM-based project activities, students completed a test designed to assess their prior knowledge in problem-solving. The research instrument consisted of an essay-based problem-solving test comprising three items contextualized within the domain of renewable energy, specifically focusing on solar cell projects. The test was constructed based on Osborne's five indicators of problem-solving skills, which include fact finding, problem finding, idea finding, solution finding, and acceptance finding. All items were reviewed by content experts and were determined to meet criteria for both validity and reliability.

Data obtained from student responses were evaluated using a structured scoring rubric, and results were presented in categorical form according to performance levels. To compare the level of prior knowledge between the two groups, the researchers conducted an independent samples t-test, enabling the identification of any statistically significant differences in students' problem-solving readiness before the intervention. We analysed statistics to get a better understanding of the results. Detailed information on how to analyse using statistical analysis is reported elsewhere [57].

4. Results and Discussion

4.1. Overview of students' prior knowledge in problem-solving

Table 5 presents the mean scores for each of the five problem-solving indicators in both experimental and control groups. These results reveal that students demonstrated low levels of problem-solving skills across all indicators. The assessment focused on fact finding, problem finding, idea finding, solution finding, and acceptance finding. These indicators were used to evaluate students' prior knowledge before the implementation of STEM-based project learning on solar cell technology.

The overall low performance indicates that students from both groups entered the STEM learning process with limited prior understanding of the problem-solving process, particularly in applying physical concepts to real-world scenarios. This finding emphasizes the need to design instructional scaffolding that addresses these conceptual gaps.

Table 5. Means score of students' prior knowledge.

Indicators	Experiment Group	Category	Control Group	Category
Fact Finding	1.28	Low	1.36	Low
Problem Finding	0.57	Low	0.90	Low
Idea Finding	0.86	Low	1.10	Low
Solution Finding	0.57	Low	0.82	Low
Acceptance Finding	0.44	Low	0.79	Low

4.2. Analysis of problem-solving indicators

Figure 4 provides an example of the problem-solving question administered to students. The item was constructed to cover all five indicators and involved a real-world challenge related to solar cell implementation.

Case description:

"In a remote village far from the city center, access to electricity from the state electricity company (PLN) is very limited. Power outages are frequent, and electricity is sometimes available for only a few hours a day. To meet their energy needs, most residents rely on fuel-powered generators. However, the use of these generators poses several challenges.

First, operational costs are very high due to rising fuel prices. Residents must spend a considerable portion of their income just to turn on the lights at night or operate basic electronic devices. Second, fuel availability is often delayed because of distribution difficulties. The road to the village is rocky and muddy, especially during the rainy season, making fuel supplies unstable. As a result, residents often live in darkness for several days.

Furthermore, smoke emissions from the generators cause air pollution and noise, both of which negatively affect health and comfort. Children struggle to study at night due to limited lighting and generator noise, while small vendors face difficulties in keeping their goods fresh because of the lack of stable electricity for refrigeration.

In fact, the village's geographical location offers considerable potential for harnessing alternative energy sources. The village receives sunlight almost year-round, with an average of 5–6 hours of effective sunlight per day. The residents' rooftops are sufficiently large to accommodate solar panels, and the open land surrounding the settlement can be utilized for small-scale solar power installations.

Given these conditions, the student team was tasked with designing a simple, affordable, and environmentally friendly solar-based energy solution. The system is expected to provide sufficient electricity to power household lighting and support children's evening study activities."

Problems:

a) What are the key facts regarding the electricity crisis in a remote area that depends solely on fossil fuels?

b) What challenges would the community face if they continue to rely on fossil fuels?

c) What alternative energy solutions could be implemented in the area to promote environmental sustainability? Select the most appropriate option (e.g., solar panels) and explain the reason for your choice.

d) Develop a solution based on the selected alternative energy source.

e) What are the potential advantages and disadvantages of the proposed solution?

Fig. 4. Excerpt of problem-solving item exam.

4.2.1. Fact finding

Figure 5 shows a sample of student responses addressing the fact-finding indicator. At this stage, students were expected to extract at least two relevant pieces of information from the problem and identify the central issue. However, most students failed to recognize key physical parameters such as solar irradiance, surface area, conversion efficiency, and household energy consumption, quantities that are essential in understanding solar energy systems.

In physics, energy received from sunlight on a surface can be calculated. To estimate power output, the efficiency of the system must also be considered [58]. The inability to recall or relate these concepts suggests that students were unfamiliar with applying the law of conservation of energy and the concept of power in practical, context-driven tasks.

Answer:

a. Fact finding:

1. The majority of residents rely on oil-fired generators for electricity.
2. Remote villages located far from city centers have limited access to PLN electricity, often resulting in frequent blackouts.

Selected main information 1

Fig. 5. Excerpt student answers on fact finding indicators.

4.2.2. Problem finding

Figure 6 presents excerpt of student responses for the problem-finding indicator. This stage required students to formulate a specific scientific problem based on the given information and explain its root causes. However, most students failed to articulate the core issue in scientific terms.

In the scenario provided, students were expected to identify the central challenge: insufficient electricity production by solar panels to meet household needs. From a physics standpoint, this involves comparing energy demand with the energy supplied by the solar panels. Many students could not construct such comparisons, indicating a lack of understanding in applying quantitative reasoning or the principle of energy balance to real-life energy challenges.

Answer:

b. Problem finding:

How can people's dependence on oil-fired generators for electricity be reduced in an environmentally friendly way

Fig. 6. Excerpt student answers on problem finding indicators.

4.2.3. Idea finding

Figure 7 shows responses to the idea-finding indicator, which evaluates students' ability to generate diverse and relevant solutions. Ideally, students should propose multiple alternatives, support them with logical reasoning, and identify the most viable option. However, only a few responses demonstrated this level of cognitive engagement.

Common ideas included basic suggestions like installing solar panels, but students rarely accounted for technical aspects such as optimal panel orientation, tilt angle, or energy storage mechanisms. Effective problem-solving in this context requires considering physical variables that influence output-such as solar radiation fluctuation, light angle of incidence, and temperature coefficient-factors that directly affect solar cell efficiency [58]. A well-reasoned idea would involve solutions like incorporating batteries for nighttime use or applying maximum power point tracking (MPPT) to maintain output under variable sunlight conditions [43].

Answer:
c. idea finding:

1. Household-scale solar panels for providing electricity for lighting and small appliances.
2. Small wind turbines installed along the coast or in villages.
   Main idea no. 1

Fig. 7. Excerpt student answers on idea finding indicators.

4.2.4. Solution finding

Figure 8 presents examples of student responses for the solution-finding indicator. This component measures students' capacity to identify the most appropriate solutions while considering their advantages, limitations, and practical feasibility. The results indicate that only a small number of students from both groups were able to propose technically relevant solutions, highlighting a limited ability to critically evaluate alternatives and a need for improved instructional guidance.

Most student responses were limited to general actions such as connecting a solar panel to a charge controller, then to a battery, and finally to an LED lamp. These answers lacked quantitative analysis or consideration of real-world constraints such as panel capacity, load demands, or total daily energy requirements. From a physics standpoint, effective solution planning must align with the law of conservation of energy. Electrical output can be estimated, as well as the energy produced over a given time period. In addition, system design should include components like battery storage, account for internal resistance, and evaluate energy losses across conversion and distribution pathways [58]. The inability of students to integrate these variables reflects a superficial understanding of energy systems and a lack of experience in applying physics principles in engineering contexts.

Answer:
d. Solution finding:
Panel → charge controller → battery → fuse → LED light

Fig. 8. Excerpt student answers on solution finding indicators.

4.2.5. Acceptance finding

Figure 9 illustrates the acceptance-finding indicator, which assesses students' ability to evaluate the strengths and weaknesses of proposed solutions and justify their choices with logical reasoning. The data show that only a few students were able to articulate the benefits of alternative energy systems, especially those involving solar technologies, indicating underdeveloped evaluative reasoning.

Answer:
e. acceptance finding:
Advantages: clean energy, low maintenance, and significantly lower electricity bills.

Fig. 9. Excerpt student answers on acceptance finding indicators.

Students' low performance in this indicator reflects a limited grasp of the technical constraints of photovoltaic systems. Although third-generation solar technologies such as dye-sensitized solar cells (DSSCs) and perovskite solar cells (PSCs)) have achieved notable efficiency gains exceeding 25% in laboratory settings [59, 60], they are also susceptible to performance losses due to thermal effects. For example, studies report that for every one-degree Celsius increase in temperature, solar panel efficiency may decrease by 0.4% to 0.65% [61, 62]. Designing efficient solar systems, therefore, requires students to consider thermodynamic constraints and adopt strategies like passive or active cooling systems. However, most student responses remained descriptive and failed to reflect an understanding of such environmental and technical considerations [63].

Furthermore, students' inability to weigh the trade-offs of energy solutions-such as cost, efficiency, material sustainability, and environmental impact-suggests their reasoning has not yet matured into scientific evaluation. Scientific reasoning requires learners to challenge idealized solutions using quantitative data and validated models [64]. This is particularly critical in the field of renewable energy, where the feasibility of solutions must balance environmental responsibility, technical practicality, and resource availability [8]. Embedding such trade-offs into classroom scenarios can help students develop deeper analytical skills and real-world problem-solving competence.

4.3. Interpretation and physics reasoning

The findings of this study further reveal that students lacked the foundational skills to analyse solar energy problems quantitatively. For instance, designing a solar cell system to meet the energy demands of a typical household (approximately 1 kWh per day) requires understanding the mismatch between available solar energy and consumption. Assuming an 18% efficient solar panel and an average solar irradiance of 4 kWh/m²/day, one 100 Wp panel would only produce about 720 Wh per day. This is insufficient to meet demand, leading to inequality [64]. Most students failed to conduct such estimations or relate energy output to daily household needs, indicating that core concepts like energy conversion, power calculation, and system optimization had not been internalized.

The analysis of solar panel performance requires interpreting current-voltage (I-V) and power–voltage (P-V) curves. Many students demonstrated confusion in this area, unable to describe how maximum power is obtained or how environmental factors influence output. The I–V curve shows the relationship between current and voltage in a solar cell, while the P–V curve illustrates power as a function of voltage. Maximum power does not occur at the extremes of voltage or current but at an optimal point called the maximum power point (MPP) [65].

Environmental variables play a critical role: increased light intensity raises current, while elevated temperatures reduce voltage, shifting the MPP and altering system efficiency. Without this understanding, students cannot predict or adjust system behaviour under variable conditions [66, 67]. In practical applications, engineers use maximum power point tracking (MPPT) technologies to maintain performance by adjusting system parameters in real time. These systems have been shown to significantly improve energy conversion under fluctuating irradiance levels [43, 67]. The limited ability of students to engage with these concepts suggests a need to strengthen instruction on scientific modelling, data interpretation, and the physical laws governing energy systems.

4.4. Interpretation of findings and implications for STEM learning

Students' limited ability to consider relevant variables (such as light intensity, surface area, voltage, and temperature) when designing energy solutions reflects weak competencies in interpreting physical graphs. As shown in the earlier indicators, students struggled to relate physics concepts to graphical representations, especially in reading and analysing current–voltage (I–V) and power–voltage (P–V) curves. Yet, this competency is a crucial dimension of scientific literacy, as it enables learners to understand the dynamic relationships among key physical variables and evaluate system performance under varying environmental conditions [68, 69]. Effective photovoltaic system design requires real-time analysis of current, voltage, and power, particularly for identifying the operating point that delivers maximum energy output [70].

The inability to interpret such graphs hinders students from connecting physics learning to real-world problem-solving. Therefore, graph interpretation should be explicitly embedded within STEM education as a targeted learning objective [71]. Technological tools can be used to strengthen this process. For example, IoT-integrated MPPT systems enable students to observe how solar panels respond to changing light conditions and learn to maintain optimal output [72]. In addition, automatic tracking systems that align solar panels with the sun's movement offer concrete applications of physics principles in engineering design [73]. Mastery of I-V and P-V curves is thus not only theoretically relevant but also essential for preparing students to engage with emerging challenges in renewable energy engineering.

These findings are consistent with models of scientific thinking, where cognitive processing begins with identifying and organizing information, followed by reasoning and concluding [13, 14]. In this context, students must first identify key details in the problem scenario by rereading and integrating prior knowledge with the given information [15]. However, the data reveal that students performed poorly in the solution-finding and acceptance-finding indicators. Most were unable to generate appropriate strategies or evaluate solutions systematically. This suggests a lack of flexibility in problem-solving (a trait associated with the capacity to construct and apply diverse strategies) [11]. Problem-solving, by definition, involves identifying solutions through the acquisition and organization of relevant information [12], a process in which knowledge is constructed through the cognitive integration of existing and new concepts [1, 11].

To validate the observed performance, a statistical comparison was conducted between the experimental and control groups. The results of the prior knowledge test showed no statistically significant difference between the groups: the experimental group had a mean score of 11.19, while the control group scored 14.94. The independent samples t-test yielded a t-value of –1.942 with a significance level of $p = 0.056$, which exceeds the 0.05 threshold for significance. This finding confirms that the two groups possessed comparable levels of prior knowledge before the instructional intervention, enabling a more objective assessment of the learning treatment's effectiveness.

Given the equivalence in baseline abilities, the low level of problem-solving skills across both groups highlights the urgency of designing instructional environments that intentionally cultivate students' cognitive and reasoning abilities. Prior studies affirm that structured learning supports, and innovative pedagogies are essential in guiding learners through complex problems [74, 75]. Approaches such as STEM-based learning and blended learning models have demonstrated positive effects on students' higher-order thinking and problem-solving skills [76, 77]. These methods encourage conceptual exploration and provide authentic learning experiences that connect classroom instruction to real-life issues [78, 79].

In this context, solar cell project-based learning offers a powerful STEM strategy. It enables students to identify physical variables (e.g., irradiance, voltage, current, efficiency), perform quantitative analysis, and interpret I–V and P–V graphs as part of solving real-world energy problems. The absence of significant differences in students' initial knowledge reinforces the need to implement these instructional models (not as remedial efforts, but as proactive strategies to foster deep conceptual learning and future-ready problem-solving abilities). Embedding the context of solar energy into physics education strengthens the link between theory and application, supporting both 21st-century learning competencies and global efforts toward sustainable energy transitions.

4.5. Relevance to sustainable development goals (SDGs)

This study contributes directly to the achievement of several SDGs by aligning educational innovation with renewable energy awareness and action. First, it supports SDG 4: quality education by promoting inquiry-based and interdisciplinary learning through STEM, which enhances students' scientific literacy, critical thinking, and problem-solving competencies. These are essential skills for lifelong learning and active global citizenship.

Second, the integration of a solar cell project aligns with SDG 7: affordable and clean energy. By engaging students with real-world energy issues, the study fosters awareness of renewable energy technologies, particularly photovoltaics, and cultivates the knowledge necessary for developing and maintaining clean energy solutions. The instructional design encourages learners to quantify energy production, evaluate efficiency, and design small-scale systems—practical applications that support a transition toward sustainable energy use at the community level.

Third, the project-based learning model also addresses SDG 13: climate action, as it encourages students to reflect on the environmental implications of energy consumption and to consider cleaner, more sustainable alternatives. Through exploring the performance, limitations, and environmental impact of solar technologies, students are empowered to make informed decisions and contribute to climate resilience efforts.

Embedding SDGs into the curriculum not only reinforces the relevance of science education but also prepares students to participate meaningfully in solving complex global challenges. In this study, the solar cell project serves as a context in which students can connect local learning with global sustainability goals, making physics instruction more impactful and socially responsive. This study adds new information regarding SDGs, as reported elsewhere in Table 6.

Table 6. Previous studies on SDGs.

No.	Title	Ref.
1	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	[80]
2	Sustainable packaging: Bioplastics as a low-carbon future step for the SDGs	[81]
3	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation, supporting SDGs	[82]
4	HIRADC for workplace safety in manufacturing: A risk-control framework and bibliometric review to support SDGs	[83]
5	Techno-economic analysis of production ecobrick from plastic waste to support SDGs	[84]
6	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia’s green tourism policy and the SDGs	[85]
7	Definition and role of sustainable materials in reaching global SDGs completed with bibliometric analysis	[86]
8	Bibliometric insight into materials research trends and innovation to support SDGs	[87]
9	Physical adaptation of college students in high-altitude training to support SDGs	[88]
10	Enhancing job satisfaction through HRIS and communication: A commitment-based approach to SDGs	[89]
11	Enhancing innovative thinking through theory-based instructional model to support SDGs	[90]
12	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving SDGs	[91]
13	Enhancing occupational identity and self-efficacy through self-education in art/design aligned with SDGs	[92]
14	Integrating generative AI-based multimodal learning in education to enhance literacy aligned with SDGs	[93]
15	Dataset on Sulawesi schools and cultural implications to support SDGs	[94]
16	Enhancing professional readiness in vocational education aligned with SDGs	[95]
17	School feeding program and SDGs in education: Linking food security to learning outcomes	[96]
18	Influence of eco-friendly packaging on consumer interest to meet SDGs	[97]
19	SDG 12 implementation through lemon commodities and waste reduction	[98]
20	Mediterranean diet patterns and sustainability to support SDGs	[99]

5. Conclusions

This study revealed that students demonstrated low levels of problem-solving skills across all indicators of prior knowledge in the context of a solar cell project. Their limited ability to analyse, design, and justify energy-related solutions highlights the need for targeted instructional strategies. Integrating STEM-based, project-oriented learning within physics education offers a promising approach to enhance students' scientific reasoning and real-world application skills. The findings support the design of future instructional models that embed renewable energy contexts and promote critical engagement with sustainability challenges aligned with the SDGs.

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