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Enhancing Pre-Service Science Teachers' Energy Literacy through SDG-Oriented Integrated STEM Learning: A Solar Energy Project

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Abstract: Energy literacy is a crucial competency for pre-service science teachers, who are expected to integrate renewable energy issues into school science instruction in line with the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 7 (Affordable and Clean Energy). This study examined changes in energy literacy among pre-service science teachers who took part in SDG-oriented integrated STEM learning built around a mini solar-panel (solar cell) project, and assessed the validity of the learning module and instruments and the practicality of the implementation. A pre-experimental one-group pretest-posttest design without a comparison group was used with 35 pre-service science teachers enrolled in the Matter and Energy course. Energy literacy was measured with an expert-validated instrument consisting of 20 knowledge items (cognitive dimension; true/false or multiple-choice), 9 attitude statements (affective dimension; 5-point Likert scale), and 7 self-reported energy behavior statements (behavioral dimension; 5-point Likert scale). The STEM-based Matter and Energy module and the energy literacy instrument were rated highly valid (84.2% and 90.2%), and the implementation across three consecutive meetings was in the practical category (77.6%, 77.6%, and 80.0%). The average energy literacy score increased from 62.97% (pretest) to 80.69% (posttest), with a normalized gain (N-gain) of 0.48 (medium category). The largest gain was in the cognitive dimension (N-gain 0.85; high), followed by the behavioral (0.50; medium) and affective (0.18; low) dimensions. Paired differences were statistically significant in all dimensions ($p < 0.001$), with large effect sizes. Participation in the learning was associated with an improvement in energy literacy, particularly in conceptual knowledge, whereas the smaller affective change suggests that attitudes may need longer and more sustained instruction. Because the design had no control group, the improvement cannot be attributed to the intervention alone, and the findings should be regarded as preliminary.

Keywords: Energy literacy; Project-based learning; Renewable energy; SDGs; STEM

Introduction

The global energy crisis and the urgency of transitioning toward renewable energy sources have become one of the multidimensional challenges of the 21st century that demand a serious response from the education sector (Owusu & Asumadu-Sarkodie, 2016). Heavy reliance on fossil fuels, in addition to causing environmental impacts such as climate change, also threatens the long-term energy security of many countries, including Indonesia, which possesses substantial renewable energy potential that remains underutilized. This condition underscores the importance of energy literacy as a fundamental competency that young people particularly pre service science teacher students who will become agents of change in instilling energy awareness in future students must possess (DeWaters & Powers, 2011).

Energy literacy is defined as a comprehensive understanding of the nature, use, and impact of energy on life, encompassing three main dimensions: cognitive (knowledge), affective (attitudes and values), and

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behavior (real world conduct and actions) (DeWaters et al., 2013; DeWaters & Powers, 2007). These three dimensions are interrelated; an energy-literate individual not only understands energy concepts scientifically but also holds genuine concern for energy issues and translates that concern into energy saving behavior and support for clean energy (Kalmi et al., 2021). Various studies indicate that students' cognitive achievement in energy literacy tends to be lower than their affective achievement, indicating a gap between concern and actual knowledge about energy (DeWaters & Powers, 2011).

Efforts to improve energy literacy require an instructional approach capable of integrating scientific concepts with real world, contextual problems. The Integrated Science, Technology, Engineering, and Mathematics (STEM) approach is regarded as an effective strategy because it emphasizes interdisciplinary connections in solving authentic problems (Kelley & Knowles, 2016). Sanders (2009) defines integrated STEM education as an approach that explores teaching and learning between or among two or more STEM subject areas, or between a STEM subject and one or more other school subjects. Bybee (2010) asserts that such an integrated curricular approach is relevant for addressing global challenges related to energy, health, and the environment.

A number of empirical studies have demonstrated the effectiveness of project-based learning (PjBL) integrated with STEM in improving students' science learning outcomes on renewable energy topics. Adriyawati et al. (2020) found that integrating STEAM-PjBL significantly improved elementary school students' scientific literacy on alternative energy material. A study by Syamra and Suryadi (2025) comparing conventional PjBL with STEM integrated PjBL in the context of renewable energy education in Indonesia showed that the PjBL-STEM group achieved significantly higher scientific creativity scores, particularly in generating original and technical solutions related to renewable energy. Similarly, Nazhifah et al. (2023) developed STEM-based e-learning on the renewable energy topic that was proven to improve high school students' creative thinking skills.

A relevant and applicable renewable energy project context for STEM learning in Indonesia is the solar panel (solar cell), given Indonesia's equatorial geographic position with abundant solar radiation potential throughout the year. Purwaningsih et al. (2020) showed that the application of STEM-PjBL significantly improved students' problem solving ability compared to conventional discovery learning. Handayani et al. (2024) explored students' engineering design thinking on the renewable energy topic and found that the problem identification and idea-development stages were key to project success. Another study by Aspridanel et al. (2022) confirmed that a STEM-integrated flipped classroom model supported by an e-module was able to improve pre service teacher students' systems thinking ability.

The importance of integrating renewable energy education with the Sustainable Development Goals (SDGs) agenda is further reinforced by various international institutions. UNESCO (2015) emphasizes that investment in STEM education is one of the key strategies for achieving SDG 4 on quality education, while the United Nations (2015) positions education as the key to achieving all other SDGs, including SDG 7 on affordable and clean energy. UNESCO (2026), through its collaborative project, asserts that revitalizing STEM education contributes directly to achieving SDG 4 and SDG 9 (Industry, Innovation, and Infrastructure). SDG-oriented learning demands that students not only understand scientific concepts but also develop awareness of socio environmental responsibility and sustainable problem-solving skills (Ramulumo & Shabalala, 2024).

Ocetkiewicz et al. (2017), in their study in Poland, asserted that renewable energy education integrated into the school curriculum contributes significantly to shaping an energy conscious and sustainability oriented generation. Muhaimin et al. (2020) highlighted the importance of integrating digital resources into science learning, including in contexts with limited access, as part of a strategy to equalize science and energy literacy. Meanwhile, a systematic review by Nik Abdul Majid et al. (2025) of 30 studies related to the integration of energy literacy in science education concluded that interdisciplinary approaches, hands-on experiments, and STEM integration consistently proved effective in improving students' understanding of and attitudes toward energy, particularly renewable energy.

At the pre service teacher level, energy literacy competency carries a dual urgency: first, as personal knowledge capital, and second, as pedagogical capital for teaching energy concepts to future students. Putra and Kumano (2018), in a comparative study of pre service science teacher students in Japan and Indonesia, found significant differences in energy learning progression and STEM conceptualization, indicating the need to strengthen energy literacy from the pre service teacher education stage onward. Mirantika et al. (2026), through a teacher needs analysis, found that more than 80% of teachers experienced difficulty assessing students' collaborative problem-solving skills in STEAM-based renewable energy learning, underscoring the need for validated and well tested modules and assessment instruments.

Project-based learning also allows the assessment of learning processes and products authentically, rather

than relying solely on final outcomes, which makes it suitable for evaluating conceptual knowledge, engineering process skills, and attitudes toward energy sustainability issues (Kurniahtunnisa et al., 2023). A project performance assessment was part of the learning activities in the present study, but its scores are not analyzed in this article, which focuses on energy literacy outcomes.

The conceptual framework of this study links the stages of the solar-panel project to the three dimensions of energy literacy proposed by DeWaters and Powers (2011). First, the orientation and design stages require students to use concepts of energy conversion, electric circuits, and efficiency to plan a working device; this activity is expected to contribute mainly to the cognitive dimension, because energy is a concept that cuts across several disciplines (Braskén & Pörn, 2021; Kelley & Knowles, 2016). Second, assembly and testing give students direct experience of how much electrical output a renewable source can deliver under real conditions, which may shape attitudes toward renewable energy (affective dimension) while engaging them in the engineering design process (Handayani et al., 2024). Third, presentation and reflection that connect the project to SDG 7 and SDG 13 invite students to consider their own energy choices, which may relate to energy-saving behavior and support for clean energy (behavioral dimension) (Karpudewan et al., 2016). These pathways are theoretical expectations that guide the choice of outcome variables; because this study has no comparison group, they are not tested here as causal mechanisms.

Previous STEM-PjBL studies have mostly examined creativity (Athifah & Syafriani, 2019; Sriyansyah & Azhari, 2017), problem-solving (Purwaningsih et al., 2020), and 21st-century skills (Muttaqiin, 2023). These are generic learning outcomes and do not show whether a renewable energy project changes the knowledge, attitudes, and behavior that define energy literacy. Studies that do address energy or environmental literacy leave three specific gaps. First, Karpudewan et al. (2016) measured knowledge, attitudes, behavior, and beliefs after project-based energy learning, but with secondary school students rather than pre-service teachers. Second, Ramadhana et al. (2022) evaluated online PjBL-STEAM learning tools for environmental literacy, a broader construct that does not separate the cognitive, affective, and behavioral components of energy literacy within a solar-panel context. Third, studies involving pre-service science teachers have compared energy learning progression and STEM conceptualization across countries (Putra & Kumano, 2018) rather than evaluating a project-based STEM intervention, and, to the authors' knowledge, evidence from Indonesian teacher education programs is still scarce. Accordingly, this study differs from earlier work in that it (a) targets pre-service science teachers, who need energy literacy both for themselves and for their future teaching; (b) uses a solar-panel project that is explicitly oriented to SDG 7 and SDG 13 and organized around the engineering design process; and (c) reports the three energy literacy dimensions separately, using N-gain, paired difference tests, and effect sizes, together with evidence on the validity of the module and instrument and the practicality of the implementation.

Based on the foregoing, this study aims to examine changes in the energy literacy of pre-service science teachers who took part in SDG-oriented integrated STEM learning using a mini solar-panel renewable energy project, and to document the quality of the learning materials used. Specifically, this study examines: (1) the validity of the STEM-based Matter and Energy learning module and the energy literacy instrument; (2) the practicality of the learning implementation across three meetings; and (3) the pre-post changes in students' energy literacy across the cognitive, affective, and behavioral dimensions, analyzed using normalized gain (N-gain) (Hake, 1998), paired difference tests, and effect sizes. Because the study uses a one-group pretest-posttest design, changes in scores are interpreted as being associated with participation in the learning rather than as proof of its causal effect. This study is expected to contribute theoretically by clarifying how the stages of an SDG-oriented STEM project may relate to the three dimensions of energy literacy, and practically as a reference for developing renewable energy project learning in pre-service science teacher education programs.

Method

This study used a quantitative approach with a pre-experimental, one-group pretest-posttest design, in which a single group receives the treatment and is measured before (pretest) and after (posttest) the treatment, without a comparison or control group (Creswell & Creswell, 2018). The design was chosen because the study was an initial investigation carried out within an existing course schedule, and because it also served to test the validity and practicality of the developed instructional materials. The design can be depicted as O1 X O2, where O1 is the energy literacy pretest, X is the SDG-oriented integrated STEM learning based on a mini solar-panel renewable energy project, and O2 is the energy literacy posttest. This design estimates the change in scores between the two measurements but cannot separate the contribution of the learning from other influences. The main threats to internal validity are the testing effect (familiarity with

the instrument), maturation, history (other courses or experiences between the measurements), instrumentation, and regression toward the mean (Shadish et al., 2002). To limit these threats, the interval between measurements was restricted to the three-meeting learning sequence and a single validated instrument was used at both measurements; nevertheless, the results are interpreted as pre-post change associated with the learning and not as a directly caused effect.

The target population was pre-service science teacher students enrolled in the Matter and Energy course. The accessible population was the intact Regular Class A, consisting of 35 students, and all of them were included as subjects (total sampling). This class was chosen because suitability between lecture topics in sample groups and modules.. The participants were 18-20 years old students in second semester and have previous experience with STEM or project-based learning.. Because a single intact class of limited size was used, without random selection or random assignment, the findings apply to this group and should not be generalized to other pre-service science teachers without further evidence.

Participation was part of regular coursework and was voluntary with respect to the use of data for research. Students were informed about the purpose of the study and assured that their data would be anonymized and used for research purposes only.

The treatment consisted of SDG-oriented integrated STEM learning using a mini solar-panel (solar cell) construction and testing project as a concrete representation of renewable energy utilization. The learning was implemented across three meetings, covering the following stages: (1) orientation to energy problems and their linkage to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action); (2) design and assembly of the mini solar-panel project using an engineering design process approach; and (3) testing, product presentation, and reflection on project achievement. The learning was supported by a STEM-based Matter and Energy module that was developed and validated prior to implementation, in line with the recommendation of Mirantika et al. (2026) regarding the importance of well structured instructional materials to support collaborative and problem-solving skills in STEAM-based renewable energy learning.

Energy literacy was measured with an energy literacy test and questionnaire based on the framework of DeWaters and Powers (2011) and DeWaters et al. (2013), covering three dimensions (Table 1). The cognitive dimension consisted of 20 items on conceptual knowledge of energy and renewable energy in a true/false or multiple-choice format, scored 0 for an incorrect and 1 for a correct answer (maximum score 20). The affective dimension consisted of 9 attitude statements toward energy issues on a 1–5 Likert scale (maximum score 45). The behavioral dimension consisted of 7 statements on energy-saving behavior and support for renewable energy on a 1–5 Likert scale (maximum score 35). Behavior was therefore measured through self-reported questionnaire statements and not by observing what students actually did; the behavioral scores describe self-reported behavior and willingness to act and are treated as such throughout this article. The sum of the raw scores of the three dimensions gives the total energy literacy score (maximum 100 = 20 + 45 + 35).

Table 1. Blueprint of the Energy Literacy Instrument

Dimension	Items	Response format and scoring	Aspect measured	Indicators and item numbers
Cognitive	20	True/false or multiple choice; 0–1 per item; maximum score 20	Conceptual knowledge about energy and renewable energy	Basic understanding of the concept, sources, properties, types, and role of energy in everyday life (1-20)
Affective	9	1–5 Likert scale; maximum score 45	Attitudes toward energy issues	A person's perspective or concern regarding energy, climate change, and sustainability issues. (21-29)
Behavioral	7	1–5 Likert scale; maximum score 35	Self-reported energy-saving behavior and support for renewable energy	Real applications in everyday life, such as the habit of turning off electrical appliances that are not in use. (30-36)
Total	36	Sum of raw scores; maximum score 100	Energy literacy	

Content validity of the instrument was established by three expert validators using a 15-item validation sheet on a 1–5 scale (results in Table 2). There was no empirical try-out in this study. Scores were interpreted as the percentage of the maximum score of each dimension and of the total, and the gain in scores was categorized with the N-gain criteria described below.

In addition to the energy literacy instrument, this study used a validation sheet for the STEM-based Matter and Energy module (22 items, 1–5 scale, three validators) and a learning-implementation observation sheet (practicality) on a 1–5 scale. Implementation at each of the three meetings was observed by 2 observers, namely science education lecturers who are members of the research team. Observers observe, record, and document behavior, events, or research objects objectively, accurately, and systematically in accordance with research guidelines or objectives. The implementation score for each meeting was calculated from the mean of the observers' scores relative to the maximum score.

Module and instrument validity data were analyzed by calculating the average percentage score from all validators relative to the ideal maximum score, both for the whole sheet and for each aspect (content, construction, and language), then categorized according to the following criteria: highly valid (81–100%), valid (61–80%), moderately valid (41–60%), less valid (21–40%), and invalid (0–20%), consistent with the content-validity approach based on expert judgment commonly used in Indonesian educational instrument development (Kania et al., 2024). Practicality data were analyzed by calculating the percentage of learning implementation at each meeting based on the average observer score relative to the maximum score, with a practical category assigned when the score reached ≥61%.

Pretest and posttest energy literacy data were analyzed in several stages. First, raw scores on each dimension were converted into percentages relative to the ideal maximum score (cognitive, 20; affective, 45; behavioral, 35). The total energy literacy score was obtained by summing the raw scores of the three dimensions (maximum 100) and expressing the result as a percentage, so each dimension contributes in proportion to its number of items and score range rather than being weighted equally. Means and standard deviations (SD) in the tables are expressed in percentage points of the maximum score. Second, the improvement was calculated using the normalized gain (N-gain) formula of Hake (1998): $\langle g \rangle = (S_{post} - S_{pre}) / (S_{max} - S_{pre})$, where Spost is the posttest score, Spre is the pretest score, and Smax is the ideal maximum score. The formula was applied to the class mean percentages of each dimension and of the total, and individual N-gain values were also calculated to classify each student. N-gain values were categorized as high ($g \geq 0.7$), medium ($0.3 \leq g < 0.7$), and low ($g < 0.3$). Because N-gain depends on the starting level of the group (Meltzer, 2002), it is interpreted together with the raw changes. Third, the significance of the difference between pretest and posttest scores was tested with a paired-sample t-test, supported by the nonparametric Wilcoxon signed-rank test as a confirmatory test given the relatively small sample size ($n = 35$), with a significance level of $\alpha = 0.05$ (Sudjana, 2005). For each dimension, the mean difference, the SD of the differences, the 95% confidence interval (CI) of the mean difference, and the standardized effect size for paired data (Cohen's $d_z = t/\sqrt{n}$) are reported; d_z values of about 0.2, 0.5, and 0.8 are conventionally regarded as small, medium, and large (Cohen, 1988). Statistical significance and effect size describe the size of the pre-post change and are not evidence that the learning was its only cause.

Result and Discussion

Validity of the Module and the Energy Literacy Instrument

The expert validation results for the STEM-based Matter and Energy module from three validators showed total scores of 88.85, 84.95, and 94 out of an ideal maximum score of 110 (22 items × 5), yielding an average validity percentage of 84.2%, which falls into the highly valid category. Meanwhile, the energy literacy instrument obtained validation scores of 90.67, 85.33, and 94.67 out of an ideal maximum score of 75 (15 items × 5), with an average validity percentage of 90.22%, also falling into the highly valid category. The overall results and the results for each aspect (content, construction, and language) are summarized in Table 2.

Table 2. Summary of Expert Validation Results for the Module and Energy Literacy Instrument

Aspect Validated	Number of Items	Validator 1 Score	Validator 2 Score	Validator 3 Score	Average (%)	Category
STEM-Based Matter and Energy Module	22	88,85	84.95	94	84.2	Highly Valid
Content aspect	15	88.57	82.86	90	87.14	Highly Valid
Construction aspect	5	88	92	92	90.67	Highly Valid
Language aspect	2	90	80	100	90	Highly Valid
Energy Literacy Instrument	15	90.67	85.33	94.67	90.22	Highly Valid
Content aspect	11	89.09	83.64	97.73	88.45	Highly Valid
Construction aspect	2	100	100	100	100	Highly Valid
Language aspect	2	90	80	100	90	Highly Valid

The highly valid category for both the module and the instrument indicates that, according to the experts, the developed instructional materials met the content, construction, and language criteria and are suitable for use in the learning process. This result is consistent with Kania et al. (2024), who emphasized that expert validation is a crucial stage in the development of educational instruments to ensure content validity before an instrument is used on a wider scale. The high validity score of the module is also in line with the recommendation of Mirantika et al. (2026) on the importance of systematically designed STEAM-based renewable energy materials to support collaborative and problem-solving skills.

The validators considered the STEM-based Matter and Energy module to be feasible for use, with several suggestions for improvement. In terms of content, validators recommended strengthening the link between the solar-panel project stages and the energy concepts targeted in each meeting, and making the connection to SDG 7 and SDG 13 more explicit in the student worksheets. In terms of construction, they suggested clarifying the sequence of the engineering design steps and adding clearer assessment criteria for the project product. In terms of language, they advised simplifying several long instructions and standardizing technical terms (e.g., energy conversion and efficiency). These suggestions were addressed by revising the activity descriptions, worksheet instructions, and terminology before implementation.

For the energy literacy instrument, validators judged that the items represented the cognitive, affective, and behavioral dimensions adequately. Their suggestions concerned (a) rewording a few knowledge items that contained ambiguous options or more than one plausible answer, (b) rephrasing attitude statements that were double-barreled so that each statement addressed one idea, and (c) making behavioral statements more specific to everyday energy-saving actions. The items were revised accordingly before the pretest.

Practicality of the Learning Implementation

The practicality of the SDG-oriented integrated STEM learning based on the renewable energy project was measured through implementation observations across three meetings by 17 observers (see the Method section for the observation procedure). The mean observer scores gave an implementation percentage of 77.6% at the first meeting, 77.6% at the second meeting, and 80.0% at the third meeting, with an overall average of 78.4%, which falls into the practical category (Figure 1). The slightly higher score at the third meeting may reflect growing familiarity of students and the lecturer with the STEM project-based learning syntax, although the three scores are close and the differences between meetings were not tested.

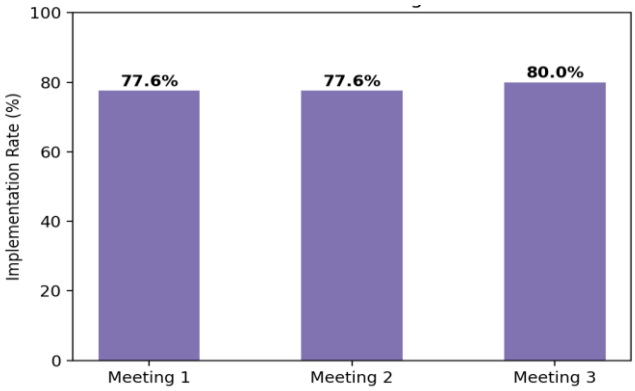

Figure 1. Percentage of Learning Implementation (Practicality) Across Three Meetings

These practicality findings are in line with Aykan and Yıldırım (2022), who showed that well-structured STEM learning implementation, despite field-level challenges, can still reach the practical category when supported by well-prepared lesson design. The small increase at the third meeting is also compatible with the iterative nature of project-based learning, in which students and facilitators become more familiar with the stages of the engineering design process as the project progresses (Handayani et al., 2024). Practicality here refers to how fully the planned learning steps were carried out as seen by observers; it does not show that the learning caused the changes in energy literacy reported below.

Improvement in Students' Energy Literacy

Descriptive analysis of the pretest and posttest energy literacy scores of the 35 students showed higher mean scores at posttest in all dimensions. The cognitive dimension increased from an average of 8.66 (43.3%) at pretest to 18.37 (91.9%) at posttest. The affective dimension increased from 29.77 (66.2%) to 32.54 (72.3%). The behavioral dimension increased from 24.54 (70.1%) to 29.77 (85.1%). The total score, obtained by summing the raw scores of the three dimensions (maximum 100), increased from an average of 62.97 (62.97%) at pretest to 80.69 (80.69%) at posttest. A summary of the descriptive statistics is presented in Table 3, in which means and SDs are expressed as percentages of the maximum score (SD in percentage points). A visual comparison of pretest and posttest means is presented in Figure 2, and the N-gain per dimension is shown in Figure 3.

Table 3. Descriptive Statistics and N-Gain of Student Energy Literacy

Dimension	Pretest Mean (%)	Pretest SD	Posttest Mean (%)	Posttest SD	N-Gain	N-Gain Category
Cognitive	43.3	6.29	91.9	8.41	0.85	High
Affective	66.2	5.20	72.3	5.61	0.18	Low
Behavior	70.1	4.67	85.1	6.20	0.50	Medium
Total Energy Literacy	63.0	3.49	80.7	3.59	0.48	Medium

Note. n = 35. Means and SDs are percentages of the maximum score (SD in percentage points). Total = sum of the raw scores of the three dimensions (maximum 100). N-gain was computed from the class mean percentages with the formula of Hake (1998). Total means are rounded to one decimal here (62.97% and 80.69% in the text).

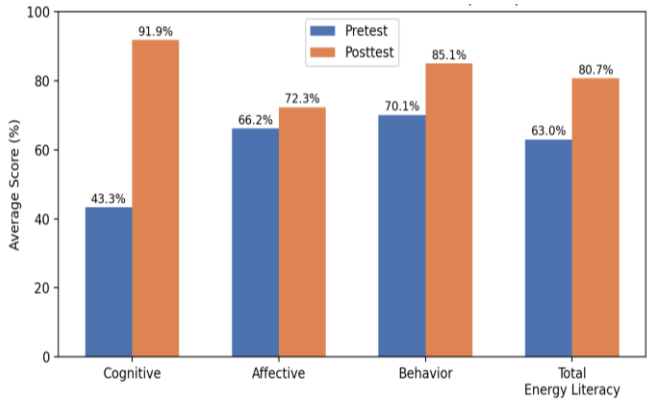

Figure 2. Comparison of Average Pretest and Posttest Energy Literacy Scores per Dimension

The paired-sample t-test showed that posttest scores were significantly higher than pretest scores in all dimensions: cognitive ($t(34) = 27.08$; $p < 0.001$), affective ($t(34) = 6.97$; $p < 0.001$), behavioral ($t(34) = 12.75$; $p < 0.001$), and total ($t(34) = 22.91$; $p < 0.001$). The Wilcoxon signed-rank test led to the same conclusion for each of the three dimensions ($p < 0.001$). Table 4 adds the size of the changes. The mean differences were 48.6 percentage points (95% CI [44.9, 52.2]) for the cognitive dimension, 6.2 [4.4, 8.0] for the affective dimension, 14.9 [12.6, 17.3] for the behavioral dimension, and 17.7 [16.1, 19.3] for the total score, with Cohen's dz values of 4.58, 1.18, 2.16, and 3.87, respectively, all above the conventional threshold for a large effect. These very large effects, particularly in the cognitive dimension, should be read with caution because the design had no control group and the same instrument was used at both measurements. The results show that scores were higher after the learning, not that the learning was the only cause of the difference.

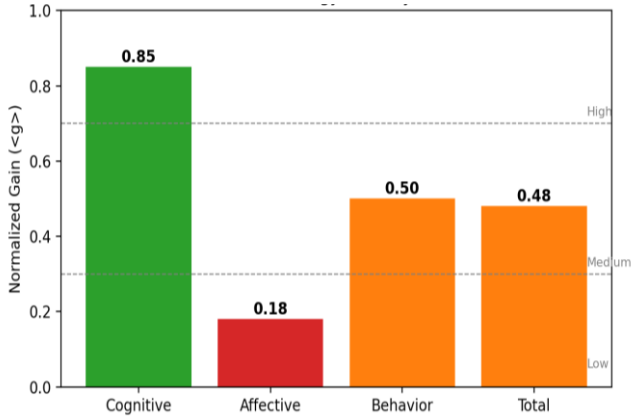

Figure 3. Average Normalized Gain per Dimension of Energy Literacy

Table 4. Paired Difference Statistics, Effect Sizes, and Significance Tests for Energy Literacy Improvement (Paired t-test and Wilcoxon Signed-Rank Test)

Dimension	Mean diff.	SD diff.	95% CI	t(34)	p (t-test)	dz	W	p (W)
Cognitive	48.6	10.6	[44.9, 52.2]	27.08	<0.001	4.58	0.0	<0.001
Affective	6.2	5.2	[4.4, 8.0]	6.97	<0.001	1.18	14.0	<0.001
Behavioral	14.9	6.9	[12.6, 17.3]	12.75	<0.001	2.16	0.0	<0.001
Total	17.7	4.6	[16.1, 19.3]	22.91	<0.001	3.87	–	–

Note. Mean diff. = posttest minus pretest, in percentage points of the maximum score; SD diff. = SD of the differences; CI = confidence interval of the mean difference; df = 34; dz = Cohen's dz = $t/\sqrt{n}$; W = Wilcoxon signed-rank statistic. A Wilcoxon test was not reported for the total score.

The distribution of individual N-gain categories shows that, of the 35 students, 33 students (94.3%) fell into the medium category, 1 student (2.9%) into the high category, and 1 student (2.9%) into the low category (Figure 4). Most students therefore showed a gain of similar magnitude, which suggests that the average pattern was not driven by a few individuals. The distribution itself does not indicate why the gains occurred.

The largest pre-post change occurred in the cognitive dimension (N-gain 0.85; high category). This pattern is consistent with the view that hands-on design and testing of a mini solar panel gives students a concrete context in which to apply concepts of energy conversion and renewable energy, in line with the constructivist principles underlying project-based learning (Adriyawati et al., 2020), and it is similar in direction to the report that STEM-PjBL produced better

learning outcomes than conventional discovery learning (Purwaningsih et al., 2020). However, several features of this study make the size of the cognitive change difficult to attribute to the project alone. The pretest mean was low (43.3%), leaving much room for gain, in line with earlier findings that students' knowledge about energy is limited (DeWaters & Powers, 2011) and that students often hold fragmented conceptions of energy (Lancor, 2014). The knowledge items were also closely linked to the content of the module, so the posttest may reflect recently taught material more than broader understanding. In addition, the same instrument was used twice, which can raise posttest scores through familiarity, and no delayed posttest was given, so retention is unknown.

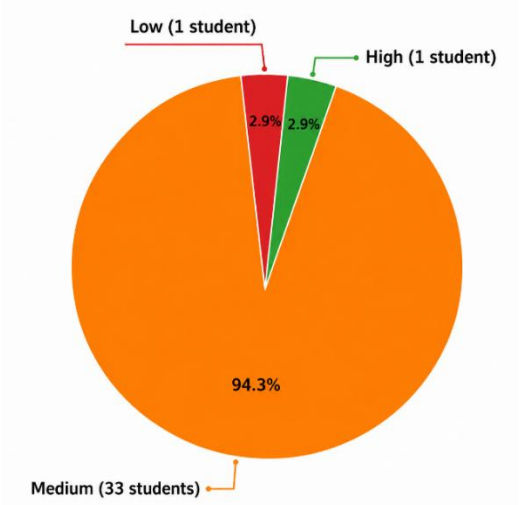

Figure 4. Distribution of N-Gain Categories for Student Energy Literacy

Comparison with earlier studies is possible only in part. Karpudewan et al. (2016) used a quasi-experimental design with a control class and reported significant differences favoring project-based energy learning in knowledge, attitudes, behavior, and beliefs. The present study also found significant pre-post changes in all three dimensions, but it cannot show whether they exceed what would have occurred without the intervention. DeWaters and Powers (2011) described secondary students with relatively favorable attitudes but weaker knowledge; the pretest profile of the pre-service teachers here (cognitive 43.3%, affective 66.2%, behavioral 70.1%) shows the same ordering, which means that the dimensions started from very different levels and had unequal room to improve. Studies on STEM-PjBL with other outcomes, such as scientific creativity (Syamra & Suryadi, 2025), compared groups and measured different constructs, so their effect sizes cannot be compared directly with the N-gain values reported here.

The affective dimension changed least (N-gain 0.18; low category), although the difference was statistically significant and the paired effect size was large (dz = 1.18). Four explanations should be considered. First, the pretest level was already fairly high (66.2%), so the possible gain was smaller than in the cognitive dimension, and N-gain values are sensitive to the starting level of students (Meltzer, 2002); a starting level of 66.2% is not a ceiling in the strict sense, however, since about a third of the scale remained unused. Second, Likert-type attitude statements are generally less sensitive to short instruction than right-or-wrong knowledge items, and responses may be affected by social desirability, particularly among students who are being trained as science teachers. Third, three meetings may be too short for attitudes and values to change (Ocetkiewicz et al., 2017), which points to the need for more sustained strategies such as reflective habituation or values-clarification discussions (Ramulumo & Shabalala, 2024). Fourth, the cognitive items were scored 0–1 and the affective statements 1–5, so N-gain values are not strictly comparable across the two dimensions. Concern for energy issues also appears to be a relatively stable disposition that is already present before instruction, as DeWaters and Powers (2011) observed.

The behavioral dimension showed a medium N-gain (0.50). This dimension was measured with self-reported statements on energy-saving behavior and support for renewable energy, not through observation of actual behavior over time. Self-report measures of pro-environmental behavior can be inflated by social desirability and by the wish to be consistent with what has just been taught (Kormos & Gifford, 2014), and stated intentions often do not translate into action (Kollmuss & Agyeman, 2002). The result therefore indicates that students reported more energy-conscious behavior and stronger support for renewable energy after the project, which is in line with the emphasis of Handayani et al. (2024) on active engagement in the engineering design process for renewable energy topics. It should not be read as evidence that students' actual energy-use behavior changed, nor that the learning closed the gap between knowledge and action. Whether any change lasts beyond the course would require follow-up measurement and observation- or record-based data.

Overall, the total N-gain of 0.48 (medium category) and the large paired effect sizes indicate a substantial rise in scores from before to after the learning. Because there was no control group, this rise cannot be separated from testing effects, maturation, or other learning experiences between the two measurements, and the N-gain should be treated as descriptive. The high validity of the module and instrument and the practical category of implementation indicate that the materials were

judged suitable by experts and that the learning was carried out largely as planned; this supports the interpretability of the pre-post results but does not substitute for a comparison group.

The findings may be relevant for pre-service science teacher education. As future educators, students need not only adequate energy literacy for themselves but also the pedagogical competence to teach it. Taking part in a STEM-based, SDG-oriented solar-panel project may give them a concrete instructional model that they can adapt in their own classrooms, in line with the call of Putra and Kumano (2018) to strengthen STEM conceptualization from the pre-service stage onward. This study did not evaluate whether students later transferred the model to their own teaching, so this remains a possibility to be tested. Project performance assessment was part of the learning, consistent with Kurniahtunnisa et al. (2023), but its results were not analyzed here.

Several limitations should be noted. First, the one-group pretest-posttest design without a control group does not allow causal conclusions: testing effects, maturation, history, instrumentation, and regression toward the mean could each have contributed to the score changes. Second, only one intact class of 35 students, chosen without random sampling, was studied, which limits generalization. Third, the behavioral dimension relied on self-report, the same instrument was used at both measurements, and no delayed posttest was administered, so retention is unknown. Fourth, the three-meeting duration may not have been sufficient to produce substantial affective change, given that attitudes and values are generally formed through a longer-term learning process (Ocetkiewicz et al., 2017). Fifth, the reliability of the research instruments was not formally examined; therefore, the internal consistency and measurement stability of the instruments cannot be fully established. Sixth, inter-observer agreement was not assessed, limiting the ability to determine the extent to which different observers would produce consistent judgments when applying the same assessment criteria. These limitations should be considered when interpreting the findings, as potential measurement inconsistencies may have influenced the results. Future studies are encouraged to conduct appropriate instrument reliability testing, such as Cronbach's alpha for multi-item scales where applicable, and to assess inter-observer agreement using suitable statistical measures, such as Cohen's kappa or the intraclass correlation coefficient, depending on the nature of the data and assessment procedures. Such measures would strengthen the methodological rigor and credibility of subsequent research.

Future research should use a quasi-experimental or randomized design with a comparison group, include a delayed posttest, add observation- or record-based measures of energy behavior, and examine the contribution of each project stage and of the performance assessment to each energy literacy dimension.

Conclusion

This study found that pre-service science teacher students had higher energy literacy scores after SDG-oriented integrated STEM learning through a mini solar-panel renewable energy project, in a pre-experimental one-group pretest-posttest design. The developed STEM-based Matter and Energy module and the energy literacy instrument were both rated highly valid, with validity percentages of 84.2% and 90.2%, respectively. The learning implementation across three meetings reached the practical category, with an average implementation rate of 78.4%. The average energy literacy score increased significantly, from 62.97% (pretest) to 80.69% (posttest), with a total N-gain of 0.48 (medium category). The largest change occurred in the cognitive dimension (N-gain 0.85; high category), followed by the behavioral dimension (N-gain 0.50; medium category; self-reported), while the affective dimension showed a change in the low category (N-gain 0.18), although it remained statistically significant.

These findings suggest that a real-world, contextual, project-based STEM approach with an orientation toward the Sustainable Development Goals (SDGs) is associated with improved energy literacy, especially conceptual knowledge, but they do not establish that the learning caused the improvement. Because the study had no control group, was limited to one intact class, and measured behavior by self-report, its findings are preliminary. Strengthening the affective dimension probably requires more intensive and sustained instruction. Further research is recommended using a quasi-experimental or randomized design with a control group, a longer intervention, a delayed posttest, and observed behavioral measures, in order to test whether the improvements can be attributed to the intervention and whether they last across all three dimensions of energy literacy.

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Author Contributions

Conceptualization, S.A. and A.R.; methodology, S.A.; software, S.A.; validation, R.N.H.A., and H.; formal analysis, S.A.; investigation, S.A. and A.R.; resources, S.A. and J; data curation, S.A.; writing—original draft preparation, S.A.;

writing—review and editing, S.A.; visualization, S.A.; supervision, R.N.H.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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