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Enhancing Physics Students' Learning Outcomes in Energy Concepts Through STEM Instructional Strategies Aligned with Sustainable Development Goals (SDGs)

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Abstract

This study examined the effectiveness of four STEM-based instructional strategies- Problem-Based Learning (PBL), Project-Based Learning (PjBL), Inquiry-Based Learning (IBL), and Interdisciplinary Approaches (IDA)- in enhancing senior high school students' conceptual understanding and engagement with physics energy concepts aligned with the Sustainable Development Goals (SDGs) in the Mampong Municipality of Ghana. Unlike most prior studies that examined single strategies or cognitive outcomes alone, this quasi-experimental research directly compared all four approaches within one design using 240 students from intact classes. One-way ANOVA results showed no statistically significant differences among the strategies in conceptual understanding ($F(3, 236) = 2.236$, $p = .085$). In contrast, significant differences emerged for student engagement ($F(3, 236) = 11.622$, $p < .001$, $\eta^2 = .129$), with PjBL producing significantly higher engagement than PBL, IBL, and IDA. These findings demonstrate that while the four STEM strategies yield comparable conceptual gains in SDG-aligned energy concepts, Project-Based Learning is distinctly more effective for fostering engagement in the Ghanaian senior high school context. This study provides empirical evidence to guide the selection of STEM pedagogies for sustainability-focused physics education in resource-constrained settings.

Keywords: STEM education, conceptual understanding, student engagement, physics energy concepts, Sustainable Development Goals (SDGs).

1. Introduction

Achieving quality education has become a global priority, with education systems expected to equip learners with both foundational academic knowledge and practical and adaptable skills (Almeida & Morais, 2025; González-Pérez & Ramírez-Montoya, 2022). The Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action), emphasise the need for education to foster

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sustainability awareness, critical thinking, and real-world problem-solving (Del Río Castro et al., 2021; Hoque et al., 2022). Physics education, particularly in energy-related topics, provides a natural context for integrating sustainability themes, as concepts such as energy transformation, conservation, and renewable sources are directly connected to global energy and climate challenges (Martínez-Borreguero et al., 2024; Wang, 2024).

However, physics instructional strategies in many developing countries, including Ghana, remain dominated by traditional lecture-based methods that encourage rote memorisation rather than deep conceptual understanding or active engagement (Coffie et al., 2020; Assem et al., 2023). Conversely, many Ghanaian teachers appear to use outmoded instructional strategies that do not support effective student learning outcomes (Appiah-Twumasi, 2019). Hence, students frequently struggle with abstract energy concepts, hold persistent misconceptions, and demonstrate low motivation (Appiah-Twumasi et al., 2021; Resbiantoro et al., 2022; Osei & Mensah, 2021). Again, national examination bodies, such as the West African Senior School Certificate Examination (WASSCE), consistently report poor performance and hold misconceptions in energy-related topics (WAEC, 2023, 2024). These challenges are heightened by inadequate teacher preparation, limited resources, and rigid curricula that leave little or no room for innovative instructional strategies (Gül et al., 2023; Megawati et al., 2025). Learners, on the other hand, acquire knowledge best when they collaborate with their peers with diverse learning abilities while teachers act as facilitators and guides (Osei & Appiah-Twumasi, 2018).

STEM-based instructional strategies, such as Problem-Based Learning (PBL), Project-Based Learning (PrBL), Inquiry-Based Learning (IBL), and Interdisciplinary Approaches (IDA), have gained traction as effective approaches for enhancing science learning outcomes (Fadillah et al., 2024; Hasanah, 2024). These strategies align with the constructivist principles by engaging students in active inquiry, collaboration, and real-world problem-solving skills (Bou Saad et al., 2025). Moreover, when explicitly aligned with the SDGs, STEM instruction can enhance both conceptual understanding and student engagement by demonstrating the relevance of physics to sustainability challenges (Kennedy & Odell, 2024; Prayogi & Verawati, 2024).

Previous studies have largely examined individual STEM strategies in isolation from one another. For example, Serevina et al. (2024) investigated the effects of PBL on critical thinking and conceptual understanding of renewable energy, while Bakirci et al. (2022) focused on STEM-supported IBL and its impact on the conceptual understanding of force and energy. Other studies have explored PrBL (Chasani & Sari, 2023; Makkonen et al., 2021) or hands-on inquiry approaches (Toli & Kallery, 2021), typically assessing only cognitive outcomes. Few studies have simultaneously compared four STEM instructional strategies (PBL, PrBL, IBL, and IDA) within a single design, and even fewer have done so while examining both conceptual understanding and student engagement in the context of SDG-aligned physics energy concepts. Empirical research of this comparative nature remains particularly scarce in Ghanaian senior high school settings and other resource-constrained contexts.

This study contributes by directly comparing the effectiveness of four STEM-based instructional strategies on both conceptual understanding and student engagement within a single quasi-experimental design, while explicitly aligning the instruction of physics energy concepts

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with SDG 7 and SDG 13 in Ghanaian senior high schools. The specific objectives of this study were to compare the effectiveness of PBL, PrBL, IBL, and IDA in enhancing student learning outcomes (engagement and conceptual understanding). These include:

1. How do different STEM-based instructional strategies compare in enhancing SHS students' conceptual understanding of physics energy concepts aligned with the SDGs?
2. How do different STEM-based instructional strategies compare in enhancing SHS students' engagement with physics energy concepts in alignment with the SDGs?

1.1 Theoretical Review

This study is grounded in two complementary theories. Constructivist Learning Theory (Piaget, 1976; Vygotsky, 1978) of the view that learners actively construct knowledge through experience, social interaction in their mediated environment, and reflection rather than rote memorisation or merely passively receiving information. In STEM-based instructional strategies, students engage in inquiry, experimentation, and collaborative problem-solving, which facilitates conceptual change and deeper understanding in the learning process (Banihashem et al., 2022). Self-Determination Theory (Deci & Ryan, 1985, 2000) emphasises that intrinsic motivation and sustained engagement are fostered when three basic psychological needs, namely autonomy, competence, and relatedness, are satisfied in the learning environment. STEM strategies that offer choice, meaningful challenges, and collaborative learning environments support these needs, thereby enhancing student engagement (Bureau et al., 2022). Together, these theories provide a comprehensive lens for understanding how instructional strategies influence both cognitive and affective learning outcomes in SDG-aligned physics education.

1.2 Conceptual Framework

The conceptual framework (Figure 1) positions STEM-based instructional strategies (PBL, PrBL, IBL, IDA) as the independent variable. The integration of SDG themes (particularly SDG 7 and SDG 13) mediates the relationship between instructional strategies and student learning outcomes. The dependent variables are conceptual understanding and student engagement. The framework hypothesises that all four strategies improve outcomes relative to traditional instruction, but that they may differ in their effectiveness, with IBL expected to be most effective for conceptual understanding and PrBL for engagement.

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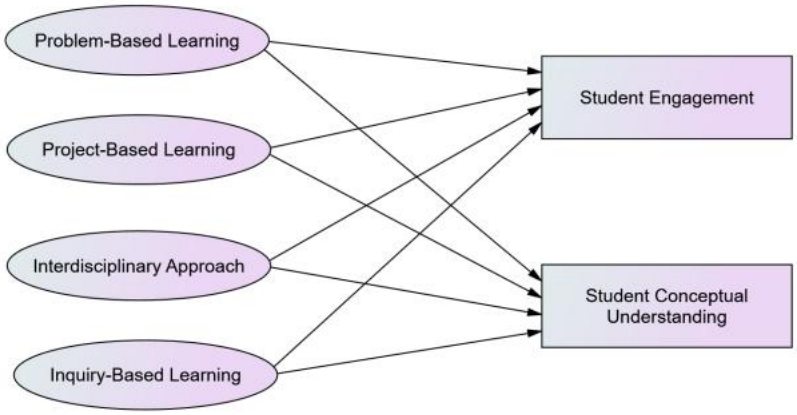


Figure 1: Conceptual Framework of the Study

1.3 Empirical Review

Previous studies have examined the effectiveness of individual STEM strategies in physics education. Serevina et al. (2024) found that PBL significantly improved students' critical thinking and conceptual understanding of renewable energy topics. Bakirci et al. (2022) reported that STEM-supported IBL produced moderate to large effect sizes ($\eta^2 > 0.14$) on conceptual understanding of force and energy. Chasani and Sari (2023) also demonstrated that PrBL improved students' conceptual understanding on assisted e-learning, with N-gain values in the high category (0.44–0.46). Again, Toli and Kallery (2021) posit that hands-on inquiry-based interventions positively enhanced student interest and learning outcomes in energy concepts (Cohen's d = 1.75). Moreover, Makkonen et al. (2021) reported that PrBL fostered high engagement among gifted students, particularly through autonomy and challenge. However, few studies have directly compared multiple STEM strategies within a single design, and even fewer have done so in the context of SDG-aligned physics instruction in sub-Saharan Africa. This study addresses this gap.

2. Methods

2.1 Research Design and Setting

A quasi-experimental pretest–posttest non-equivalent group design was used for this study. This design was adopted because the research was conducted in four distinct intact senior high school physics classrooms within normal educational settings, where random assignment of individual students was not feasible due to administrative constraints, school timetables, and ethical considerations regarding the disruption of existing class structures. Quasi-experimental designs are

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widely recommended in educational research when true experimental control is impractical, as they permit comparison of interventions while maintaining the ecological structure of the school settings (Cohen et al., 2018; Creswell, 2014). The use of intact classes also reflects the practical realities of implementing instructional interventions in Ghanaian public senior high schools.

This study was conducted in four public senior high schools in the Mampong Municipality of the Ashanti Region, Ghana. The municipality has 96 primary schools, 62 junior high schools, and five public senior high schools (Ghana Statistical Service, 2021). These schools in the municipality have provided an appropriate context for examining STEM-based instructional strategies aligned with the SDGs, given the documented challenges of traditional physics instruction and limited resources in the area.

2.2 Participants and Sampling

A multistage sampling technique was used for this study. First, all SHSs offering physics were purposively selected. Second, four schools were randomly selected from the total population. Third, SHS 2 physics intact classes were selected from each school. Fourth, energy-related physics concepts (work, power, energy conservation, and renewable sources) were purposively selected as they align with SDGs 7 and 13. Fifth, each intact class was randomly assigned to one of four STEM strategies (PBL, PrBL, IBL and IDA), respectively. The sample comprised 240 students: School A (PBL, n=61), School B (PrBL, n=59), School C (IBL, n=52), and School D (IDA, n=68). Ages ranged from 15 to 20 years.

2.3 Instrumentation

Five instruments were adapted in this study and used to collect data on students' conceptual understanding and engagement. Questionnaires and achievement tests were used in this study because they provide standardised, efficient, and quantifiable measures of both cognitive and affective learning outcomes across multiple groups, allowing for consistent statistical comparisons. The questionnaires were self-reported data, particularly suitable for assessing student engagement, which encompasses behavioural, emotional, and cognitive dimensions that are best captured through learners' own perceptions. The Energy Conceptual Understanding Achievement Test (ECUAT) was a 20-item instrument comprising 15 multiple-choice questions and five theory questions designed to assess students' knowledge and application of energy concepts (work, power, energy conservation, and renewable energy sources) aligned with SDGs 7 and 13. The Student Engagement Questionnaire (SEQ) was a 10-item Likert-scale instrument measuring behavioural, emotional, and cognitive engagement in learning physics energy concepts through the assigned STEM strategies. The Student Conceptual Understanding Questionnaire (SCUQ) was a 10-item Likert-scale instrument that captured students' self-reported depth of understanding and confidence in applying energy concepts. In addition, four parallel strategy-specific questionnaires (PBLQ, PrBLQ, IBLQ, and IDAQ), each containing 15 items, were developed and tailored to the pedagogical features of Problem-Based Learning, Project-Based Learning, Inquiry-Based

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Learning, and Interdisciplinary Approaches, respectively; these instruments assessed students' experiences, perceived effectiveness, and engagement with the specific strategy used in their class. All instruments were administered as pretests and posttests to enable comparison of changes attributable to the instructional interventions.

2.4 Implementation Fidelity

To ensure consistent delivery of the four STEM strategies, one qualified physics teacher (B.Ed. Physics, with a minimum of five years of teaching experience) was assigned to each of the four intact classes. All teachers participated in a two-week standardised training workshop that covered the pedagogical principles, scripted lesson plans, and SDG integration protocols for each of their assigned strategies. To monitor implementation, three scheduled classroom observations per teacher were conducted using a validated observation checklist; observers were trained to achieve inter-rater reliability above 90% prior to the main data collection. In addition, teachers completed weekly self-report fidelity logs, and student work artifacts were reviewed to confirm alignment with the prescribed lesson structures. Teacher qualifications and experience were comparable across groups. The study protocol also included procedures to systematically track adherence and minimize instructor-related variability, ensuring that the interventions were delivered as designed.

2.5 Validity and Reliability of the Instrument

Content validity was established using Lawshe's Content Validity Ratio (CVR) with six expert raters. The CVR values ranged from 0.933 to 0.967, exceeding the minimum threshold. Reliability was confirmed using Cronbach's alpha (α=0.79–0.90) and Cohen's kappa (κ=0.81–0.86) for inter-rater agreement.

2.6 Sampling Procedures

The intervention lasted for eight weeks. In Week 1, students were oriented to their assigned strategy. Weeks 2–4 focused on problem identification, project planning, experimentation, and data collection. Weeks 5–6 involved solution development, refinement, and presentations. Weeks 7–8 focused on real-world applications and reflection. All activities were explicitly aligned with SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action). A pretest (ECUAT, SEQ, SCUQ) was administered before the intervention, and a posttest was administered after eight weeks.

2.7 Data Analysis

Quantitative data were analysed using SPSS version 27 and AMOS version 23. Descriptive statistics (means, standard deviations) and inferential statistics (one-way ANOVA, Welch test,

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Games-Howell post-hoc, and structural equation modelling) were used. Effect sizes (η^2, Cohen's d) were reported in this study.

2.8 Ethical Considerations

Ethical clearance was obtained from the university's Institutional Review Board and the Ghana Education Service. Informed consent was obtained from the students and teachers. Participation was voluntary, anonymity was guaranteed, and participants could withdraw at any time.

3. Results

Research question one sought to compare the effectiveness of the four STEM instructional strategies in enhancing conceptual understanding using the post-test scores from the physics energy concepts test. The result is presented in Table1.

Table 1 One-Way ANOVA Results of the Posttest Scores for the Conceptual Understanding by the STEM Strategy

	SS	df	MS	F	Sig.
Between Groups	1849.87	3	616.62	2.236	0.085
Within Groups	65076.62	236	275.75		
Total	66926.49	239			

As shown in Table 1, a one-way ANOVA was conducted to compare posttest scores on the energy concepts test across the four STEM instructional strategies. Levene's test indicated a violation of the homogeneity of variance assumption ($p < .001$). Therefore, the Welch robust test of equality of means was examined and yielded a significant result ($p = .026$). However, the standard one-way ANOVA result was not statistically significant ($F_{(3, 236)} = 2.236$, $p = 0.085$, $\eta^2 \approx 0.028$). The results suggest that the four strategies (PBL, PrBL, IBL, and IDA) produced comparable levels of conceptual understanding of physics energy.

Research question 2 investigated the differences in students' self-reported engagement with physics energy concepts across the same four schools, each applying one STEM instructional strategy. This was also analysed using one-way ANOVA, and the results are presented in Tables 2 and 3.

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Table 2: One-Way ANOVA Results for Student Engagement Scores

	SS	df	MS	F	Sig.
Between Groups	12.06	3	4.02	11.622	.000
Within Groups	81.63	236	0.35		
Total	93.69	239			

Table 3: Games-Howell Post-Hoc Comparisons for Student Engagement Scores

Comparison (I – J)	Mean Difference	SE	p	95% CI Lower	95% CI Upper
PrBL – PBL	0.496*	0.089	0.001	0.264	0.728
PrBL – IBL	0.577*	0.106	0.001	0.300	0.854
PrBL – IDA	0.483*	0.097	0.001	0.229	0.737
PBL – IBL	–0.081	0.117	0.899	–0.387	0.224
PBL – IDA	–0.013	0.110	0.999	–0.298	0.273
IBL – IDA	–0.094	0.123	0.871	–0.416	0.228

As shown in Table 2, one-way ANOVA on posttest Student Engagement scores revealed a statistically significant difference among the four groups, $F_{(3,236)} = 11.622$, $p<0.001$, $\eta^2=0.129$. Games-Howell post-hoc comparisons as indicated in Table 3 showed that Project-Based Learning (PrBL) produced significantly higher engagement than PBL, IBL, and IDA (mean differences 0.483–0.577, all $p<0.001$).

4. Discussion

4.1 Discussion of findings

This study examined the effectiveness of four STEM-based instructional strategies (PBL, PrBL, IBL, and IDA) in enhancing senior high school students' conceptual understanding and engagement with physics energy concepts aligned with the SDGs. The principal findings are threefold. First, no statistically significant differences were found among the four strategies in promoting conceptual understanding ($F_{(3,236)} = 2.236$, $p=0.085$). Second, Project-Based Learning produced significantly higher student engagement than the other three strategies ($F_{(3,236)} = 11.622$, $p<0.001$, $\eta^2=0.129$).

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The finding that all four STEM strategies produced comparable levels of conceptual understanding (RQ1) aligns with constructivist learning theory, which posits that any active, experiential approach can foster conceptual change (Piaget, 1976; Vygotsky, 1978). Students in all four groups engaged in meaning-making through problem-solving, inquiry, or project work, which likely contributed to similar gains. The non-significant differences may also reflect contextual constraints in Ghanaian SHSs, such as large class sizes, limited resources, and examination pressures, which could have weakened the potential advantages of specific strategies (Osei & Mensah, 2021). This finding is consistent with previous meta-analyses reporting that active learning strategies generally outperform traditional instruction but often do not differ substantially from one another.

The superior performance of Project-Based Learning on student engagement (Research Question 2) is explained by Self-Determination Theory (Deci & Ryan, 2000). PrBL provides high levels of autonomy (students design and execute projects), competence (mastery through hands-on construction), and relatedness (collaborative teamwork), which collectively foster intrinsic motivation and sustained engagement (Makkonen et al., 2021). The practical, tangible outcomes of PrBL, such as building a solar-powered device, likely made the SDG relevance more concrete and personally meaningful to students compared to the more abstract problem scenarios in PBL or the guided investigations in IBL.

4.2 Theoretical and Practical Implications

The finding that the four STEM strategies produced comparable gains in conceptual understanding extends Constructivist Learning Theory by suggesting that the process of active knowledge construction itself, rather than the specific form of instructional strategy, may be the primary driver of conceptual change in SDG-aligned physics education. The superior engagement observed under PrBL further supports Self-Determination Theory, indicating that strategies offering high levels of autonomy, competence, and relatedness are particularly effective in sustaining student motivation within this context.

Practically, the results point to several considerations for physics education in Ghana and similar settings. Project-Based Learning appears especially promising for enhancing student engagement with energy concepts linked to sustainability, while the comparable conceptual outcomes across strategies suggest that teachers may select among PBL, PrBL, IBL, and IDA according to available resources and classroom conditions without sacrificing understanding. The findings also highlight the value of embedding SDG themes in ways that connect abstract physics content to local, tangible issues. At the system level, the study underscores the potential benefits of providing basic instructional resources and professional development opportunities that support the implementation of active STEM pedagogies aligned with national curriculum goals and the Sustainable Development Goals.

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4.3 Recommendations

Physics teachers should design structured inquiry activities on energy efficiency and renewable sources, and implement short, collaborative project-based tasks such as building simple solar devices linked to local SDG issues. Teachers should form learning communities to share low-cost resources and lesson plans. Curriculum developers should revise the SHS physics syllabus to explicitly embed SDG 7 and 13 themes, reduce content overload, and allocate dedicated time for inquiry and project work. Policymakers should supply basic lab kits (solar cells, simple circuits, thermometers), digital simulations, and SDG-aligned teaching guides, prioritising under-resourced districts, and mandate national professional development on SDG-aligned STEM pedagogy. Teacher training institutions must integrate SDG modules into pre-service programmes and establish mentorship schemes where experienced teachers guide novices.

4.4 Limitations of the Study

Several limitations should be acknowledged. The quasi-experimental design used intact classes without random assignment, which may introduce selection bias. The study was confined to one municipality in Ghana, limiting generalisability. Self-report engagement measures may be subject to social desirability bias. The eight-week intervention may not fully capture long-term conceptual change. Teacher variability in implementing the assigned strategies, despite standardised lesson plans, could have influenced outcomes.

4.5 Suggestions for Future Research

Future research should address these limitations by employing randomised controlled trials or longitudinal designs to establish causal relationships and examine long-term retention of conceptual understanding and engagement. Replication studies in multiple regions of Ghana and other sub-Saharan African countries would enhance generalisability. Mixed-methods studies that incorporate classroom observations and student focus groups could provide richer insights into the mechanisms driving engagement and conceptual change. Intervention studies that explicitly test strategies for overcoming the identified challenges, such as resource provision packages, professional development programmes, or curriculum adjustments, would provide actionable evidence for policymakers. Finally, future research could examine how student characteristics (e.g., prior knowledge, gender, socio-economic status) moderate the effectiveness of different STEM strategies in SDG-aligned physics instruction.

5. Conclusion

This study examined four STEM-based instructional strategies, Problem-Based Learning, Project-Based Learning, Inquiry-Based Learning, and Interdisciplinary Approaches, for teaching

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physics energy concepts aligned with the SDGs in Ghanaian senior high schools. All four strategies comparably enhanced students' conceptual understanding. However, Project-Based Learning proved superior for fostering student engagement, while Inquiry-Based Learning was the most effective strategy for simultaneously promoting both conceptual understanding and engagement. Addressing these barriers through curriculum reform, resource provision, and targeted teacher development is essential to realising STEM education's potential to advance SDG 4 (Quality Education) and SDG 7 (Affordable and Clean Energy) in Ghanaian physics classrooms.

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