



Enhancing Students' Critical Thinking Skills through IMOREAR: An AR-Based Renewable Energy Module

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ABSTRACT

Critical thinking skills are essential competencies in renewable energy learning, requiring evidence-based analysis, evaluation, and informed decision-making. This study aimed to enhance students' critical thinking skills through an Interactive E-Module on Renewable Energy Using Augmented Reality (IMOREAR). The study employed a pre-experimental one-group pretest–posttest design involving 30 high school students (12 male and 18 female students aged 15–16 years) in Garut, West Java. The intervention was conducted over four meetings using project-based learning supported by AR-based visualization and renewable energy prototyping activities. The research instrument consisted of 15 contextual multiple-choice items developed based on domain-specific critical thinking indicators. Data was analyzed using Rasch modeling to estimate students' ability measures in logits. The results indicated a significant improvement ($p < 0.001$), with the average logit score increasing from -1.20 to 0.46 and an effect size of 1.64 (large). These findings suggest that IMOREAR enhances students' critical thinking skills, underscoring its value in fostering 21st-century skills.

Keywords: augmented reality, renewable energy, critical thinking skills, project-based learning, Rasch analysis

INTRODUCTION

The 21st century is marked by the accelerated development of science and technology, fundamentally changing students' characteristics and the demands for educational competencies. The Industrial Revolution 4.0 and digital transformation require individuals to possess higher-order thinking skills, technological literacy, and the capacity for evidence-based decision-making (Attarang, 2025; Nurdini et al., 2025; Rajaram, 2021). In this context, science education emphasizes not only the mastery of concepts but also the development of scientific reasoning and critical evaluation skills for navigating increasingly complex information. This challenge becomes even more significant when students face global issues such as climate change and the transition to renewable energy.

Global warming and the energy crisis are pressing socio-scientific issues globally. Increasing greenhouse gas emissions have led to serious ecological consequences, including melting polar ice caps, rising sea levels, and increasing extreme weather events (Kanna et al., 2024; Mikhaylov et al., 2020; Shen et al., 2020). The International Energy Agency (2023) reports a substantial increase in global renewable energy capacity, highlighting the growing international commitment to a clean energy transition. This issue is not only scientific but also involves social, economic, and public

policy considerations. Therefore, science education plays a strategic role in equipping students with critical thinking skills regarding scientific claims, environmental data, and energy technology solutions.

Critical thinking (CT) skills are widely recognized as essential competencies for the 21st century, equipping students to navigate complex information and make informed decisions in real-life situations (Aviyanti, Fratiwi, Gani, et al., 2025; Bara et al., 2025). An international panel of experts in the Delphi report defined CT as “*purposeful, self-regulatory judgment that results in interpretation, analysis, evaluation, and inference*” (Fountain, 2016; Vendrell-Morancho & Moya, 2025). This definition suggests that CT enables students not only to understand information but also to assess its validity, construct evidence-based arguments, and make rational and responsible decisions. However, recent research confirms that CT cannot be understood solely as a generic skill detached from the context of a particular discipline (Afandi et al., 2025). Tiruneh et al. (2018) argue that CT is more appropriately operationalized within specific domains through indicators such as reasoning, hypothesis testing, argument analysis, probability and uncertainty analysis, and problem-solving and decision-making. Therefore, its development must be embedded within the conceptual structure and epistemic practices of a particular discipline.

Although science curricula explicitly emphasize the development of higher-order thinking skills, school learning practices still exhibit significant discrepancies. Several studies report that learning about global warming and renewable energy issues tends to focus on mastering factual knowledge and procedural solutions, with limited attention to evidence evaluation, argument analysis, and data-based decision-making (Wang & Wang, 2023; Yulianti et al., 2023). Even when critical thinking skills are stated as learning objectives, they are often not systematically integrated into classroom activities (Cahyanto et al., 2025; Harris & De Bruin, 2018; Scoular et al., 2020). Research by Aviyanti, Fratiwi, Nurdini, et al. (2025) also shows that in the context of global warming and renewable energy, assessments are still dominated by measuring conceptual knowledge rather than evidence-based reasoning. This mismatch creates a gap between curriculum objectives that emphasize higher-order thinking and actual classroom learning practices. In many cases, students are exposed to renewable energy concepts passively, without meaningful opportunities to test hypotheses, interpret empirical evidence, or evaluate alternative solutions based on physical principles. Consequently, their capacity to draw scientific inferences and make rational decisions in complex environmental contexts remains underdeveloped.

In response to this challenge, various instructional approaches have been implemented to strengthen students' critical thinking skills, including project-based learning and the integration of interactive digital technologies in science learning. Project-based learning is considered relevant because it encourages students to confront authentic problems, formulate goals, plan work steps, process information, and evaluate results based on specific criteria (Hussein, 2021; Sánchez-García & Reyes-de-Cózar, 2025). It is also supported by previous research, which shows that the experiential learning approach, supported by science tools, significantly improves all indicators of critical thinking skills in the context of basic science concepts (Syaodih et al., 2019). However, many classroom implementations lack sufficiently structured instructional tools to ensure that learning systematically activates critical thinking indicators. At this point, the use of learning modules becomes important because they can serve as instructional scaffolds that gradually guide the learning experience while maintaining consistent links between goals, activities, and assessments. Nevertheless, empirical research integrating structured modules with project-based learning to foster critical thinking skills in the context of renewable energy at the secondary school level is still limited.

On the other hand, the development of Augmented Reality (AR) technology opens new opportunities to strengthen science learning modules, particularly when the material requires visualizing abstract or complex phenomena. AR enables the integration of three-dimensional virtual objects with the real environment in real time, helping students build a stronger conceptual

understanding as a foundation for critical thinking (AlGerafi et al., 2023; İbili et al., 2020; Papanastasiou et al., 2019). Meta-analyses show that AR contributes to increased engagement, motivation, and conceptual understanding (Kaur et al., 2020; Nikou, 2025; Yoon et al., 2017), which is important because critical thinking requires an adequate conceptual understanding before students can evaluate evidence and make decisions. However, Demircioglu et al. (2023) emphasize that the integration of AR in science learning is often naive, presented as a mere technological feature rather than as part of a pedagogical design explicitly targeting the development of critical thinking skills. Therefore, a structured AR-integrated module embedded within a project-based learning framework is essential to ensure that visualization serves not merely as a representational tool, but as a driver of higher-order thinking, including interpreting contextual information, analyzing cause-and-effect relationships, evaluating evidence, and determining the most rational renewable energy solutions under specific constraints (Tiruneh et al., 2018).

Based on these issues, there is an urgent need to design learning interventions that explicitly integrate AR technology with higher-order cognitive processes in the context of renewable energy. Such interventions should not only enhance conceptual understanding but also engage students in analyzing causal relationships, testing data-driven hypotheses, evaluating scientific claims, and making evidence-based decisions. In response to this need, the present study develops and implements an Interactive E-Module on Renewable Energy Using Augmented Reality (IMOREAR), project-based learning, and renewable energy prototyping activities to activate domain-specific indicators of critical thinking. Accordingly, this study seeks to examine the effectiveness of IMOREAR in enhancing secondary students' critical thinking skills within renewable energy learning.

METHODOLOGY

This study employed a pre-experimental one-group pretest-posttest design to assess variations in students' critical thinking skills before and after the implementation of targeted learning interventions. The study was conducted in October 2025 at a public senior high school in Garut, West Java, in the context of renewable energy instruction implemented through the Project-Based Learning (PjBL) model. The participants comprised 30 students who completed both the pre-test and post-test. The sample included 12 male and 18 female students aged 15–16 years, representing heterogeneous academic abilities. Participants were selected through purposive sampling based on their readiness to use digital devices and the implementation of project-based learning in the classroom.

The research procedure commenced with a pretest to assess students' initial critical thinking skills in renewable energy. Subsequently, students participated in learning activities using the Interactive E-Module on Renewable Energy Using Augmented Reality (IMOREAR). The IMOREAR interface is presented in Figure 1.

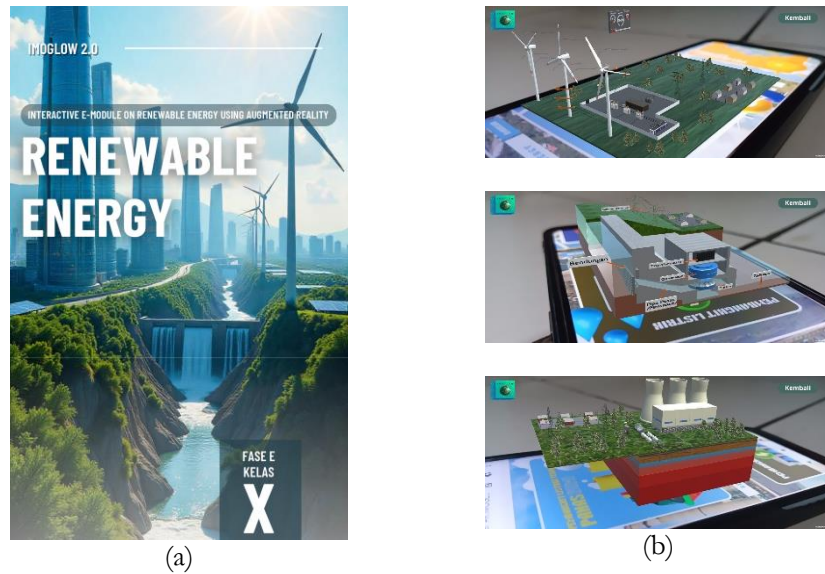


Figure 1. (a) Cover of the Renewable Energy E-Module; (b) Augmented Reality 3D Visualizations

The learning intervention was conducted over four sessions, each lasting 45 minutes. Students explored renewable energy concepts through AR-based visualization to understand the operational principles of various systems, including hydroelectric power plants (PLTA), solar power plants (PLTS), wind power plants (PLTB), geothermal power plants (PLTP), and gas-fired power plants (PLTBG). Subsequently, students worked collaboratively in groups to design, construct, and test simple renewable energy prototypes as part of the project-based learning activities. At the end of the learning series, students presented their project outcomes and completed a posttest to assess changes in their critical thinking skills following the intervention.

The research instrument consisted of 15 multiple-choice questions, developed by researchers, based on domain-specific indicators of critical thinking skills, namely reasoning, hypothesis testing, argument analysis, likelihood and uncertainty analysis, and problem-solving and decision-making (Tiruneh et al., 2018). The Rasch analysis results indicated that the instrument was valid and reliable (Aviyanti, Fratiwi, Nurdini, et al., 2025). Item validity was indicated by the Point Measure Correlation (Pt-Measure Corr.) value of > 0.20 with the support of Outfit MNSQ and ZSTD values within an acceptable range, so that the retained items met the model fit criteria. In terms of reliability, person reliability was obtained at 0.73 (moderate category), item reliability at 0.94 (very high), and Cronbach's alpha (KR-20) at 0.74 (high), which indicated adequate internal consistency and item calibration stability for measuring critical thinking skills.

The primary data consisted of students' critical thinking skill scores collected through pretests administered prior to IMOREAR and posttests administered after IMOREAR. In addition to analyzing overall critical thinking performance, students' achievement across each domain-specific indicator was also examined. Assessment was conducted by assigning a score to each correct answer. The score for each aspect was calculated by summing the item scores corresponding to that indicator. The resulting scores were subsequently converted into percentages using Equation (1).

$$P_{CT} = \left(\frac{R_1 + R_2 + \dots + R_n}{S + S + \dots + S} \right) \times 100\% \quad (1)$$

(Kubiszyn & Borich, 2013)

The description:

P_{CT} : Percentage of critical thinking skill scores (%)

R_1 : Total score of the first respondent in one critical thinking aspect

R_2 : Total score of the second respondent in one critical thinking aspect

- R_n : Total score of the nth respondent in one critical thinking aspect
- S : Maximum score in one critical thinking aspect
- N : Number of respondents

Furthermore, raw scores were analyzed using Rasch modeling and converted into logit measures of ability. Changes in individual ability were examined using the Rasch stacking technique to compare pretest and posttest logit scores for each student. The interpretation of logit score gains followed the criteria presented in Table 1, which classifies the magnitude of improvement ranging from very high to decreasing.

Table 1. Criteria for Logit Gain Interpretation

Logit Gain Value	Interpretation
$\text{logit} > 2.97$	Very High
$1.98 < \text{logit} \leq 2.97$	High
$0.99 < \text{logit} \leq 1.98$	Moderate
$0 < \text{logit} \leq 0.99$	Low
$\text{logit} = 0$	No Improvement
$\text{logit} < 0$	Decrease

Prior to hypothesis testing, the assumption of normality was examined using the Shapiro–Wilk test. Differences between the mean pretest and posttest logit scores were analyzed using a paired-samples t-test at a significance level of 0.05. The hypotheses were formulated as follows:

Ho: There is no significant difference between the mean pretest and post-test logit scores.

Ha: There is a significant difference between the mean pretest and post-test logit scores.

To determine the magnitude of the intervention effect, Cohen’s *d* was calculated and interpreted according to the criteria presented in Table 2.

Table 2. Effect Size Categories

Effect Size (<i>d</i>)	Interpretation
$0.20 < d \leq 0.50$	Small
$0.50 < d \leq 0.80$	Medium
$d > 0.80$	Large

(Kallojeri & Piccirillo, 2023)

RESULT AND DISCUSSION

This study employs the Interactive E-Module on Renewable Energy Using Augmented Reality (IMOREAR) within a Project-Based Learning (PjBL) framework to enhance students’ critical thinking skills. The intervention was conducted over four meetings encompassing stages of concept exploration through Augmented Reality visualization, renewable energy prototype design and construction, system testing, and project presentation and reflection. This instructional design was systematically structured to integrate AR-based conceptual representations with authentic epistemic activities through projects, ensuring that each learning stage explicitly activates domain-specific indicators of critical thinking.

From an instructional design viewpoint, IMOREAR may be regarded as a systematic epistemic framework in which each phase of learning is intentionally aligned with specific cognitive processes. This alignment ensures that students are not only exposed to content but are also actively engaged in reasoning, evaluating evidence, and making decisions. Such a design reflects a shift from content-oriented instruction to process-oriented learning, where knowledge construction becomes central to the learning experience.

Each phase of the IMOREAR implementation was deliberately aligned with specific dimensions of critical thinking. The AR-based exploration stage mainly promoted thinking by enabling students to visualize cause-and-effect relationships within energy systems. The project design and construction phase supported hypothesis testing through iterative experimentation and variable manipulation. Meanwhile, the presentation and reflection stages fostered analysis of arguments and decision-making, as students were required to justify their design choices with empirical evidence. This structured alignment implies that the development of critical thinking skills is expected to be systematically embedded within the instructional sequence, rather than emerging as a by-product of learning activities (Golden, 2023; Radulović & Stančić, 2017).

The implementation of critical thinking skills using IMOREAR can be further understood as a structured progression of cognitive engagement throughout learning phases. During the AR-based exploration stage, students practice thinking by identifying causal relationships within energy systems. Hypothesis testing occurs in the design and experimentation phase, where students evaluate system performance through iterative testing and modifications. In the presentation and reflection stage, students participate in argumentation and decision-making by justifying their design choices using empirical evidence. This progression suggests that critical thinking is not considered a separate outcome, but rather a systematically embedded part of the learning process through interconnected cognitive activities.

In practice, students explore concepts through Augmented Reality media, which present interactive simulations of the operational mechanisms underlying various renewable energy systems, including hydroelectric power plants (PLTA), solar power plants (PLTS), wind power plants (PLTB), geothermal power plants (PLTP), and gas-fired power plants (PLTBG), as illustrated in Figure 2. This dynamic visualization enables students to observe energy transformation processes in real time and to construct a meaningful understanding of the cause-and-effect relationships among system components. Throughout this exploratory phase, students engage in active collaborative discussions concerning the working principles of each system, energy efficiency, and the key variables that influence overall technology performance.



Figure 2. Students using IMOREAR

The subsequent stage involves project-based activities, in which students collaborate in groups to design, construct, and systematically test a simple renewable energy prototype. Throughout this process, students engage in variable identification, hypothesis formulation and testing, iterative design revision, and evaluation of experimental outcomes. Some groups make design modifications after discovering that their initial prototype failed to produce optimal output, indicating a data-driven reflective process. In the presentation stage, students articulate their system design, provide reasoned justifications for their design choices, and defend their arguments using prototype testing results. This activity demonstrates strong epistemic engagement and serves as an early indication of the development of critical thinking skills within the learning process. Figure 3 presents an illustrative example of a student-constructed wind turbine prototype.



Figure 3. PLTB Prototype Results

Essentially, the iterative nature of the project-based activities enables students to engage in real-world scientific processes, including hypothesis testing, result interpretation, and explanation revision. This iterative cycle is crucial for fostering higher-order thinking, as it requires students to continuously evaluate the validity of their ideas and make evidence-based judgments. These processes directly contribute to the observed improvements in problem-solving and decision-making indicators.

Taken together, the alignment between instructional phases and cognitive processes, combined with the iterative and inquiry-based nature of the activities, positions IMOREAR as a learning design that actively engages students in higher-order thinking practices. Furthermore, the findings revealed a statistically significant improvement in students' critical thinking skills following the implementation of the proposed learning intervention, as illustrated in Figure 4.

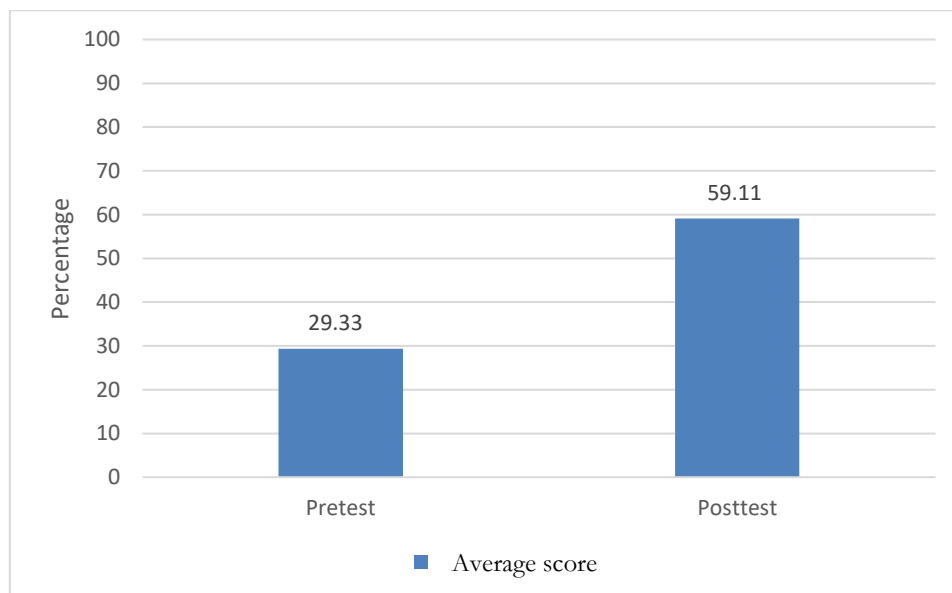


Figure 4. Pre-Test and Post-Test Results of Students' Critical Thinking Skills

Figure 4 presents a comparative overview of students' critical thinking skills based on pre-test and post-test assessments. Prior to the intervention, the mean percentage of students' critical thinking skills was 29.33%, placing the cohort within the low category. Following the implementation of IMOREAR, the mean percentage increased to 59.11% in the post-test, indicating a substantial improvement of nearly 30 percentage points in students' overall critical thinking performance.

This improvement reflects not only a quantitative gain but also a qualitative change in students' ability to engage in analytical thinking, evaluation, and evidence-based decision-making within the context of renewable energy learning. The extent of change indicates that the intervention promoted the growth of higher-order thinking processes rather than just enhancing factual understanding.

This improvement can be further interpreted as the cumulative effect of integrating conceptual visualization and epistemic practice. Rather than functioning as separate instructional components, Augmented Reality (AR) and Project-Based Learning (PjBL) in IMOREAR operate synergistically. AR promotes conceptual understanding by enabling students to visualize abstract processes, while project-based learning provides opportunities to apply, test, and refine that understanding through real-world work. This integration creates a learning environment in which students actively construct, evaluate, and revise knowledge, encouraging deeper critical thinking. This synergy enables students to progress from merely recognizing concepts to actively constructing and evaluating knowledge. This process is crucial for developing critical thinking skills specific to their field of study.

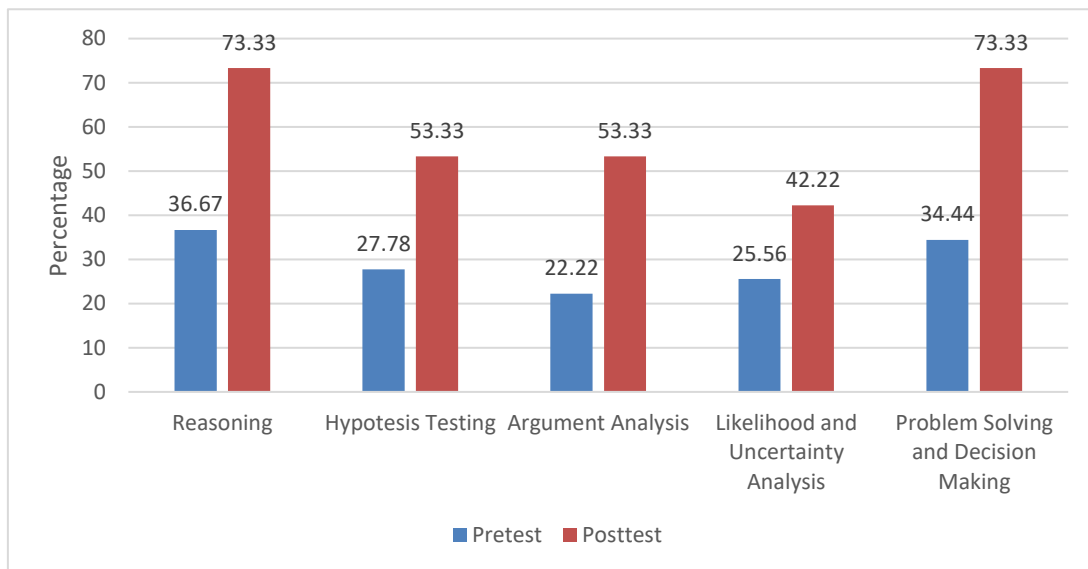


Figure 5. Pre-Test and Post-Test Results of Students' Critical Thinking Skills Across Five Domain-Specific Aspects

In the pre-test, the scores across the five indicators were as follows: reasoning (36.67%), hypothesis testing (27.78%), argument analysis (22.22%), likelihood and uncertainty analysis (25.56%), and problem-solving and decision-making (34.44%). Following the intervention, all aspects improved. Reasoning increased to 73.33%, hypothesis testing to 53.33%, argument analysis to 53.33%, likelihood and uncertainty analysis to 42.22%, and problem-solving and decision-making to 73.33%. The greatest improvement occurred in reasoning, problem-solving, and decision-making. In contrast, the lowest improvement was observed in likelihood and uncertainty analysis, although it still showed a meaningful increase relative to baseline performance.

However, the differential improvement across indicators implies that not all aspects of critical thinking respond to short-term interventions in the same way. While reasoning and decision-making showed substantial gains, the relatively lower improvement in likelihood and uncertainty analysis indicates that probabilistic reasoning requires more explicit and sustained instructional support. This finding highlights the importance of designing targeted scaffolds for certain aspects of critical thinking, rather than assuming uniform development across all indicators.

These findings align with a growing body of literature showing that critical thinking skills are best enhanced when learning is designed contextually and integrated systematically with higher-

order cognitive activities. Significant improvements in reasoning align with the findings of Lin et al. (2023), Latipah et al. (2021), and Bhakti et al. (2019), who demonstrated that augmented reality-based visualizations help students build more stable mental models of complex scientific phenomena. Complementing these findings, meta-analyses conducted by Papanastasiou et al. (2019) and Lai et al. (2019) established that AR contributes meaningfully to enhanced conceptual understanding and learning engagement, which are foundational to the development of higher-order reasoning. Improvements in problem-solving and decision-making support the findings of Loyens et al. (2023) and Sasson et al. (2018), who emphasized that Project-Based Learning is effective in fostering higher-order thinking skills through iterative cycles of planning, testing, and evaluating solutions. In this regard, the integration of AR and PjBL offers a complementary combination of conceptual representation and authentic scientific inquiry. This finding is also consistent with research showing that systematically designed experiential learning involving empirical analysis activities can improve domain-specific indicators of critical thinking skills in the context of science learning (Syaodih et al., 2019).

The current findings not only support earlier research but also expand on the existing literature. They show that combining Augmented Reality (AR) and Project-based Learning (PjBL) contributes to learning outcomes within a unified instructional system. In this system, conceptual visualization and epistemic practices work together synergistically. This integration enables students to actively construct, test, and refine their understanding, thereby strengthening multiple dimensions of critical thinking simultaneously rather than in isolation.

Conversely, the likelihood and uncertainty analysis aspects showed relatively lower improvements. This outcome is consistent with Kuhn (2019) explained that the capacity to evaluate uncertainty and probability develops gradually and requires explicit practice in interpreting risk and variability. Differential patterns of improvement across indicators have similarly been reported in prior studies, which suggest that the development of critical thinking skills does not always occur uniformly in each dimension, but is influenced by the cognitive complexity associated with each indicator (Bhakti et al., 2019). These findings suggest that although IMOREAR proves effective in strengthening causal reasoning and decision-making, enhancing the probabilistic dimension of critical thinking may require more focused instructional interventions and longer learning duration.

To further examine the consistency of these improvements across individual students, a Rasch stacking analysis was conducted to compare students' ability levels before and after the intervention, expressed in log-odd units (logits), as presented in Table 3.

Table 3. Summary of Students' Critical Thinking Improvement Based on Rasch Analysis

Category of Improvement	Number of Students	Percentage (%)
Very High	4	13.33%
High	6	20.00%
Moderate	12	40.00%
Low	8	26.67%
Total	30	100%

Table 3 reveals that the majority of students experienced moderate to great improvement in their critical thinking skills following the intervention. Specifically, 40.00% of students were categorized as moderate improvement, while 33.33% were categorized as high or very high. This distribution indicates that most students benefited meaningfully from the intervention, with a considerable proportion demonstrating substantial gains in their ability levels. At the same time, 26.67% of students were classified in the low improvement category, suggesting that although positive gains were observed across all participants, the magnitude of improvement varied among individuals. The Rasch analysis further indicates that the mean logit score increased from -1.20 in the pre-test to 0.46 in the post-test, with an average gain of 1.66, placing it in the moderate improvement category. The standard deviation decreased from 1.37 to 0.99, indicating a more

homogenous distribution of students' skills after the intervention. This decrease in variability suggests that the learning intervention not only enhanced overall performance but also promoted a more equitable development of critical thinking skills across students with varying initial ability levels.

In terms of individual performance, the overall positive shift across all categories reflects a consistent upward trend in students' abilities. The presence of students in the high and very high improvement categories indicates that the intervention was particularly effective for certain learners, possibly due to stronger prior knowledge, higher engagement, or more effective use of learning strategies. Conversely, the existence of students in the low improvement category suggests that not all learners responded equally to the instructional design, highlighting the role of individual differences in shaping learning outcomes. Such variation is commonly observed in learning environments that emphasize inquiry and active engagement, where students progress at different rates depending on their readiness and participation.

In the Rasch measurement framework, the changes in logit scores show how students' abilities relate to the difficulty of test items. This approach provides a clearer, step-by-step understanding of students' learning progress. Unlike raw scores, which test characteristics may influence, Rasch-based estimates account for both student ability and item difficulty, allowing for a more robust evaluation of learning gains. Therefore, the observed increase in logit scores reflects not only improved performance but also a meaningful advancement in students' underlying critical thinking competence.

Taken together, the distribution of improvement and the shift in logit scores suggest that the intervention was effective in promoting both individual progression and overall consistency in learning outcomes. The dominance of moderate improvement, accompanied by reductions in variability, indicates that the instructional design scaffolded learning in a way accessible to a broad range of students, while still allowing higher levels of achievement among more advanced learners. This pattern highlights the potential of integrated AR and project-based learning environments to support both equitable and meaningful development of domain-specific critical thinking skills.

To further validate these findings statistically, an inferential analysis was conducted. Further statistical analysis confirmed that the observed differences between pre-test and post-test scores were statistically significant. The results of the Shapiro–Wilk normality test indicated that both pre-test ($p = 0.153$) and post-test ($p = 0.099$) data met the assumption of normality. Based on these conditions, a paired-samples t-test was conducted, yielding a p-value of $p < 0.001$, indicating a statistically significant difference between pretest and post-test scores. In addition, the effect size analysis using Cohen's d yielded a value of 1.643, which is categorized as large. This finding suggests that the intervention not only produced statistically significant gains but also had a substantial practical impact on students' critical thinking skills.

These findings reinforce the robustness of the results from both descriptive and Rasch analyses, indicating that integrating Augmented Reality, structured learning modules, and Project-Based Learning (PjBL) within a single instructional framework can yield meaningful and impactful improvements in higher-order thinking skills. Rather than functioning as isolated instructional components, these elements appear to operate synergistically to support deeper cognitive engagement and sustained learning development. This interpretation aligns with previous research suggesting that interventions explicitly designed to target domain-specific dimensions of critical thinking tend to yield stronger and more consistent learning gains compared to more general instructional approaches (Tiruneh et al., 2018).

Conceptually, the primary contribution of this research lies in the systematic integration of AR-based visual representations, a directed module structure, and authentic project-based activities to foster domain-specific critical thinking skills. Unlike most AR-focused studies, which tend to prioritize motivation or general conceptual understanding, the present study explicitly targets and

measures critical thinking indicators through a Rasch stacking approach, thereby providing a more comprehensive methodological and pedagogical contribution. In terms of practical implications, the findings suggest that science teachers can utilize AR as a cognitive scaffold placed within a project-based assignment framework, rather than simply as a demonstration medium. This integration is particularly relevant for teaching socio-scientific issues such as renewable energy, which inherently require multi-criteria evaluation, evidence-based reasoning, and informed decision-making in complex and uncertain contexts. This distinguishes the present study from prior research by not only demonstrating the effectiveness of AR and project-based learning, but also explicitly revealing the instructional mechanism through which domain-specific critical thinking is systematically developed.

However, when evaluating the results of this research, it is important to recognize several limitations. First, the use of a pre-experimental one-group pretest–posttest design without a control or comparison group limits the ability to draw strong causal inferences about the intervention's effectiveness. While the observed improvements in students' critical thinking skills are substantial, alternative explanations, such as testing effects, maturation, or classroom context, cannot be entirely ruled out. Second, the relatively small sample size ($n = 30$), drawn from a single school context, may limit the external validity and generalizability of the findings across different educational settings, student characteristics, and levels of prior knowledge. Third, the intervention's duration of four meetings may not be sufficient to fully capture the development of higher-order cognitive processes, particularly for more complex dimensions of critical thinking, such as likelihood and uncertainty analysis, which typically require prolonged and repeated engagement with probabilistic reasoning tasks.

In addition, although the study employed Rasch modeling to obtain a more robust measurement of students' ability, the assessment relied primarily on multiple-choice items, which may not fully capture the depth of students' reasoning processes, argument construction, or epistemic decision-making. The absence of qualitative data, such as students' written explanations, interviews, or discourse analysis during project activities, also limits the extent to which the underlying cognitive mechanisms of critical thinking development can be interpreted in detail.

Future research is therefore strongly recommended to employ more rigorous experimental or quasi-experimental designs involving control or comparison groups to strengthen causal inference and provide more robust evidence of effectiveness. Expanding the study across multiple schools and involving more diverse student populations would enhance the generalizability and ecological validity of the findings. Longitudinal research designs are also needed to examine the sustainability and transferability of critical thinking skills over time, particularly across different scientific domains and learning contexts.

Furthermore, future research should include more explicit instructional scaffolds focused on probabilistic reasoning and uncertainty analysis, as these aspects showed significantly lower progress than other indicators. Integrating mixed-method approaches, including qualitative data such as student explanations, reflective journals, or classroom discourse, would provide deeper insights into how critical thinking skills are constructed and enacted during learning activities. Finally, the integration of Augmented Reality and Project-Based Learning can be extended to other socio-scientific domains, such as climate change, environmental sustainability, and energy policy, to explore further its potential to foster complex reasoning and 21st-century competencies across broader educational contexts.

CONCLUSION

The implementation of the Interactive E-Module on Renewable Energy Using Augmented Reality (IMOREAR) within a Project-Based Learning has proven effective in enhancing students'

domain-specific critical thinking skills in renewable energy. This effectiveness is supported by a substantial increase in students' average critical thinking scores from 29.33% in the pre-test to 59.11% in the post-test, as well as a significant improvement in Rasch logit measures from -1.20 to 0.46, with a large effect size ($d = 1.64$). Consistent improvements were observed across all critical thinking indicators, including reasoning, hypothesis testing, argument analysis, likelihood and uncertainty analysis, and problem-solving and decision-making. Notably, the highest gains were identified in reasoning and problem-solving aspects, indicating stronger development in causal understanding and decision-making processes, while relatively lower gains in likelihood and uncertainty analysis suggest the need for more explicit instructional support in this area. The integration of Augmented Reality visualizations, structured modules, and authentic project activities encouraged students to develop deeper conceptual understanding while simultaneously fostering analytical reasoning, evidence evaluation, and reflective decision-making. These findings highlight the importance of integrated pedagogical design in promoting critical thinking within science or physics learning contexts.

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