



Aviation Case-Based Learning for Energy Literacy among Middle School Students: A Mixed-Methods Study

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Abstract

This study investigated how aviation-based Case-Based Learning (CBL) relates to different dimensions associated with energy literacy development, including conceptual understanding, sustainability awareness, and evidence-based decision-making. Energy literacy is viewed as a multidimensional construct that integrates understanding of energy concepts, awareness of sustainability consequences, and the capacity to utilize evidence when making decisions. However, applying scientific knowledge to complex and authentic situations remains challenging for many students. An embedded mixed-methods design was conducted with 45 Grade VII and VIII students from an international school in Surabaya, Indonesia. The 180-minute intervention utilized an aviation fuel-efficiency scenario to explore students' conceptual understanding, sustainability awareness, and decision-making processes. Quantitative results showed a statistically significant improvement in the conceptual dimension of energy literacy from pre-intervention to post-intervention assessment scores (Wilcoxon $W = 105$, $p = .022$); however, this result should be interpreted cautiously due to the substantial ceiling effect observed. Qualitative findings indicated that students used quantitative evidence to revise their initial interpretations and relate aviation energy decisions to the Sustainable Development Goals (SDGs). Nevertheless, students experienced difficulties in balancing efficiency, safety, and reserve-fuel considerations. Integrated findings revealed a knowledge–awareness–application mismatch, suggesting that strong conceptual understanding and sustainability awareness do not always translate into effective evidence-based decision-making. These findings suggest that aviation-based CBL may serve as a pilot-scale instructional approach for bridging conceptual knowledge and evidence-informed application.

Keywords: Aviation education; Case-based learning; Energy literacy; Evidence-based decision-making; Sustainability awareness.

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INTRODUCTION

Energy production and consumption patterns play a fundamental role in shaping transportation systems, economic development, resource availability, environmental sustainability, and global responses to climate change. Consequently, energy-related decisions are closely associated with several Sustainable Development Goals (SDGs), particularly SDG 7, which emphasizes access to affordable and clean energy; SDG 12, which promotes responsible consumption and production practices; and SDG 13, which addresses climate action. Nevertheless, the Sustainable Development Goals Report 2024 highlights that global advancement toward these targets remains insufficient, requiring accelerated efforts across interconnected social, economic, and environmental dimensions (United Nations, 2024). In this context, science education needs to move beyond the delivery of factual information and

procedural calculations by cultivating students' capacity to interpret evidence, assess alternative options, and evaluate the implications of energy-related decisions.

This broader competency is represented through the concept of energy literacy. Individuals who demonstrate energy literacy are expected to possess knowledge of energy concepts and systems, understand the consequences associated with energy production and utilization, develop perspectives that support responsible energy practices, and make informed decisions regarding energy issues (DeWaters & Powers, 2011; Varghese & Chandrasenan, 2023). Recent scholarship further positions energy literacy as a multidimensional construct that involves cognitive understanding, affective awareness, and decision-making capabilities rather than being restricted to the acquisition of factual knowledge alone (Białynicki-Birula et al., 2022; Castañeda-Garza et al., 2025; Nik Abdul Majid et al., 2025). This multidimensional perspective becomes increasingly important when students are required to address complex situations in which energy efficiency, economic considerations, environmental consequences, and safety-related factors must be simultaneously evaluated.

Despite growing attention toward energy literacy education, enabling students to transform conceptual knowledge into informed decisions remains a significant challenge. Research involving Indonesian junior high school students revealed moderate levels of energy literacy, although students' cognitive performance remained relatively limited despite expressing concern about energy-related issues (Usman et al., 2021). Previous investigations have also demonstrated that possessing knowledge and favorable attitudes toward energy issues does not necessarily result in effective application, as decision-making processes are influenced by contextual conditions, perceived effectiveness, self-efficacy, and social norms (Heeren et al., 2016; Tolppanen et al., 2021; Zhou et al., 2022). Therefore, post-intervention measurements of awareness should not be interpreted as direct evidence of behavioral transformation. Instead, instructional approaches should provide opportunities for learners to apply knowledge, evaluate evidence, and make decisions within contexts involving meaningful consequences.

Scientific literacy frameworks provide a theoretical foundation for connecting conceptual understanding with evidence-based decision-making. These frameworks emphasize competencies such as evaluating scientific information, interpreting quantitative evidence, identifying relevant data, developing explanations, and supporting conclusions with appropriate justification (Gormally et al., 2012; OECD, 2023). Within the context of energy education, these competencies include interpreting data representations, estimating energy consumption, comparing efficiency strategies, considering environmental and economic consequences, accounting for uncertainty, and defending selected alternatives. Therefore, assessments embedded within authentic contexts can provide insight into whether students are capable of applying energy concepts through practical reasoning rather than simply reproducing scientific definitions.

Case-Based Learning (CBL) represents an instructional approach that corresponds with these requirements by involving students in authentic or simulated situations containing problems, evidence, alternative interpretations, and competing solutions. A systematic review conducted by Dewi & Rahayu (2023) identified 52 CBL studies in science education published between 2012 and 2022. The review showed that CBL research has predominantly focused on health-related disciplines and chemistry, whereas applications within physics and school-level science contexts remain comparatively limited. This concentration indicates that findings from professional education settings should not automatically be generalized to secondary science learning environments. Although recent research has demonstrated that CBL integrated with virtual laboratory activities can support creative thinking in secondary physics education (Muhyi et al., 2024), differences remain in learner characteristics and targeted outcomes compared with the present focus on energy literacy development among middle school students. Evidence from medical and nursing education provides valuable insights regarding

scaffolding and collaborative reasoning; however, its transferability to lower secondary science contexts requires careful consideration (Besche et al., 2025; Xiang et al., 2025).

Aviation provides a particularly relevant context for exploring energy literacy because aircraft fuel consumption is determined by the interaction of multiple variables, including aircraft mass, travel distance, altitude, weather conditions, flight phase, route selection, and operational procedures. Efforts to improve fuel efficiency may contribute to reduced operating costs and emissions; however, such improvements must be balanced with safety obligations and reserve fuel requirements. Current sustainable aviation strategies therefore incorporate technological innovation, sustainable fuel development, regulatory approaches, air traffic management, and operational efficiency improvements (International Civil Aviation Organization, 2025; Raihan, 2025). Studies examining trajectory-based fuel estimation further demonstrate that climb, cruise, descent, altitude, and speed profiles significantly influence aircraft fuel consumption patterns (Zhang et al., 2025). Because these variables interact dynamically, aviation offers an authentic setting in which students must evaluate trade-offs among competing considerations rather than identify a single predetermined solution.

The instructional intervention investigated in this study was adapted from Mathematically Modeling Aircraft Fuel Consumption, an aviation-focused case developed by Pyatt & Coomes (2012). Unlike many environmental education approaches that employ locally situated contexts (Rudyshyn et al., 2021; Sunyono et al., 2025), this study utilized a standardized, data-intensive global aviation scenario involving a Boeing 737 flight from Los Angeles to Denver. The purpose of adopting this scenario was not to introduce aviation as an isolated content area, but to establish an authentic quantitative environment where Indonesian middle school students could analyze complex information, compare possible fuel-reduction strategies, and examine the relationship between energy efficiency and operational safety. To align the original case with the instructional context, modifications were made through metric conversion, simplification of performance data tables, and restructuring of questions around energy efficiency, operational risk, and Sustainable Development Goals.

Although energy literacy has been extensively investigated, an important theoretical issue remains regarding the relationship among students' conceptual understanding, sustainability awareness, and their ability to apply evidence when making decisions in authentic situations. Recent perspectives in science education conceptualize sustainability awareness as a multidimensional component of energy literacy, involving students' recognition of sustainability challenges, understanding of environmental consequences, and awareness of responsible practices (Koçulu, 2025; Andriansyah et al., 2025; Puspita et al., 2026). Previous research indicates that knowledge and positive attitudes alone do not necessarily lead to competent and responsible application (Heeren et al., 2016; Tolppanen et al., 2021; Zhou et al., 2022). However, limited attention has been given to how this transition occurs when middle school students are required to evaluate energy efficiency while simultaneously considering uncertainty, operational constraints, and potential risks. In this study, the knowledge–awareness–application mismatch refers to the condition in which students demonstrate adequate conceptual understanding and sustainability awareness but experience difficulties transferring these competencies into evidence-based decision-making practices. Therefore, the contribution of this study extends beyond the application of CBL within an aviation setting. This research specifically examines the knowledge–awareness–application mismatch in energy literacy development by investigating the relationship between students' conceptual understanding, sustainability awareness, and their capacity to utilize evidence in decision-making.

By combining multiple forms of evidence, including changes in conceptual achievement, category transitions, sustainability awareness, performance-based decision-making, and students' written reasoning, this study offers insight into why learners who demonstrate strong conceptual knowledge and sustainability awareness may nevertheless encounter difficulties in

developing evidence-based decisions. Previous research has explored energy literacy from several perspectives, such as conceptual understanding, sustainability awareness, and behavioral intentions; however, these dimensions have commonly been examined independently rather than as interconnected elements within authentic decision-making situations (Białynicki-Birula et al., 2022; DeWaters & Powers, 2011; Heeren et al., 2016). Although students may possess adequate knowledge and favorable sustainability orientations, transforming such understanding into evidence-informed decisions remains challenging, particularly when decision-making requires consideration of competing factors, including efficiency, uncertainty, and risk (Tolppanen et al., 2021; Zhou et al., 2022). Accordingly, this study uses aviation not only as an instructional context but also as an authentic scenario for examining how energy literacy dimensions are expressed when students engage with complex decision-making situations. Through the integration of conceptual assessment, sustainability awareness measures, performance-based tasks, and qualitative reasoning, this study examines whether students' conceptual understanding and sustainability awareness are reflected in their ability to formulate evidence-informed decisions. The study was guided by the following research questions:

- 1) How is aviation-based Case-Based Learning (CBL) associated with changes in specific dimensions of energy literacy, particularly students' conceptual understanding and ability to interpret energy consumption data?
- 2) How do students demonstrate sustainability awareness and evidence-based decision-making related to energy efficiency, environmental responsibility, and safety considerations, and how do their written responses contribute to the interpretation and contextualization of quantitative findings?

METHOD

Research Design

This study adopted an embedded mixed-methods framework implemented within a pre-experimental one-group pretest–posttest structure. The quantitative component functioned as the primary analytical strand and focused on examining changes in students' conceptual understanding of energy-related concepts, score transitions across achievement categories, post-intervention sustainability awareness, and performance-based decision-making outcomes. The qualitative component was embedded to provide deeper insight into students' written explanations, numerical reasoning processes, selection of strategies, evaluation of risks, and sustainability-related interpretations during the learning process. The quantitative and qualitative components were not interpreted as separate bodies of evidence; rather, qualitative findings were integrated into the analytical interpretation to explain, contextualize, and refine the quantitative patterns, thereby contributing to the formulation of meta-inferences (Bazeley, 2024; Fàbregues et al., 2024). The study design is expressed as:

$$O_1 \rightarrow X \rightarrow O_2 + QN + QL$$

O_1 represents the energy literacy pretest, X refers to the aviation CBL intervention, and O_2 represents the posttest. QN indicates the quantitative evidence obtained from the questionnaire and decision-making rubric, whereas QL refers to students' qualitative written responses.

Participants and Research Setting

The study was conducted at an international school located in Surabaya, East Java, Indonesia. To ensure institutional confidentiality, the school's identity was not disclosed in either the research dataset or the manuscript. The initial sample consisted of 55 students from four classes, including two Grade VII classes and two Grade VIII classes. For the matched analysis, only students who completed all required research components were included. These components consisted of the pretest, participation in the instructional intervention, posttest, sustainability awareness questionnaire, and assessed worksheet activities. Ten students were

excluded due to incomplete data records, resulting in a final analytical sample of 45 students, comprising 20 Grade VII students and 25 Grade VIII students. Anonymous identification codes were applied throughout data management and reporting procedures to maintain participant confidentiality.

Aviation Case-Based Learning Intervention

The instructional intervention was developed using an aviation-oriented Case-Based Learning (CBL) approach that positioned energy efficiency and decision-making within an authentic aviation scenario. Each participating class engaged in three instructional sessions, with each session lasting 60 minutes, resulting in a total learning duration of 180 minutes. The learning activity was presented through a simulated case involving an airline seeking recommendations to improve the fuel efficiency of a Boeing 737-400 flight route between Los Angeles and Denver. During the learning process, students worked individually and collaboratively to identify the problem, predict fuel consumption patterns, interpret aircraft performance data, conduct relevant calculations, compare alternative operational strategies, and formulate recommendations supported by evidence.

Table 1. Structure of the aviation CBL intervention

Meeting	Principal Learning Activities
Case orientation and energy concepts	Determine the aircraft's energy source; categorize jet fuel as renewable or non renewable; differentiate energy conservation from energy efficiency; explain the importance of responsible use; and predict which flight phase consumes the most fuel.
Fuel consumption data analysis	Interpret data for the climb, cruise, and descent phases; calculate cruise distance; identify fuel use per kilometer; and determine fuel consumption by phase, total consumption, and estimated financial cost.
Strategy evaluation and recommendation	Evaluate continuous descent, optimum cruise altitude, and reduced reserve fuel; consider efficiency, uncertainty, operational risk, environmental consequences, and safety; and formulate a recommendation supported by evidence.

Worksheet Adaptation

The instructional worksheet was adapted from the aviation-based case Mathematically Modeling Aircraft Fuel Consumption developed by Pyatt & Coomes (2012). The original activity involved mathematical modeling processes, including function development, interpolation procedures, aircraft weight analysis, and comparisons among alternative fuel reduction strategies. To ensure suitability for junior high school science learning, several adjustments were implemented. These modifications included converting imperial measurement units into kilograms and kilometers, reducing the complexity of aircraft performance tables, and removing advanced mathematical modeling components. Additional questions were incorporated to establish connections between numerical analysis and broader concepts, including non-renewable energy resources, energy efficiency, economic considerations, environmental responsibility, Sustainable Development Goals (SDGs), and aviation safety.

For classroom calculations, the flight distance was established at approximately 1,340 km, the average combined mass of one passenger and accompanying luggage was defined as 80 kg, and the contextual fuel price was fixed at IDR 15,000 per kilogram. A reserve fuel quantity of 1,800 kg was incorporated as a simplified pedagogical assumption for comparing classroom scenarios rather than as an actual aviation operational requirement. In real-world aviation practice, reserve fuel calculations are influenced by regulatory requirements, weather conditions, alternate airport availability, anticipated delays, route characteristics, and

operational flight planning considerations. The adapted worksheet was reviewed by the research supervisor to evaluate its content relevance, linguistic clarity, alignment with instructional objectives, and appropriateness for Grade VII and VIII students.

Research Instruments

Four complementary instruments were used to examine three dimensions associated with energy literacy: conceptual understanding, sustainability awareness, and evidence-based decision-making. The instruments were developed based on established conceptualizations of energy literacy, scientific literacy, contextualized assessment, and evidence evaluation frameworks (DeWaters & Powers, 2011; Gormally et al., 2012; OECD, 2023; Varghese & Chandrasenan, 2023).

Table 2. Research instruments and measurement characteristics

Instrument	Description	Scoring and psychometric evidence
Energy literacy assessment	A 15-item multiple-choice test administered before and after the intervention to assess energy concepts, transformations, renewable and non-renewable resources, energy efficiency, SDGs, quantitative interpretation, and evidence-based reasoning.	Dichotomous scoring (0 = incorrect, 1 = correct), transformed into a 0–100 scale. Reliability was examined using KR-20, resulting in coefficients of .723 (pretest) and .841 (posttest). Content validity: Aiken's $V = .867$. Item difficulty and discrimination analyses were conducted.
Sustainability awareness questionnaire	A 15-item Likert-scale questionnaire administered after the intervention to assess awareness of energy resources, efficiency, environmental responsibility, and SDGs.	Five-point scale (1–5). Reliability: Cronbach's $\alpha = .910$; indicator coefficients ranged from .667–.890. Content validity: Aiken's $V = .933$.
Evidence-based decision-making rubric	An analytic rubric assessing students' interpretation of fuel data, efficiency reasoning, alternative selection, risk evaluation, and recommendation synthesis.	Four-level scale (0–3), maximum score 15, adapted from scientific evidence evaluation principles in TOSLS (Gormally et al., 2012). Weighted Cohen's $\kappa = .791$.
Written responses	Students' predictions, explanations, calculations, strategy comparisons, and reflections generated during CBL activities.	Used for thematic analysis and mixed-method integration.

Content validity of the instruments was evaluated by ten validators using a seven-point rating scale based on four criteria: alignment with learning objectives, content representation, item clarity, and linguistic appropriateness for junior high school students. The validity evidence was examined using Aiken's V coefficient. Both instruments exceeded the critical threshold of .683 for ten validators using seven response categories at $\alpha = .05$, indicating acceptable content validity (Kania et al., 2024).

Score Classification and Quantitative Analysis

The pretest and posttest results were examined using criterion-referenced categories that separated student scores into three levels, namely low, medium, and high. The category definitions were informed by the student model-state classification framework introduced by Ferrarelli & Iocchi (2021), with uniform score cutoffs applied to both assessment points to enable consistent comparison. The classification was used as an analytical grouping strategy rather than as a standardized diagnostic threshold. The specific criteria and corresponding score

ranges for each category are reported in Table 3.

Table 3. Score classification procedures

Classification Approach	Criterion	Classification
Criterion referenced	$0 \leq \text{score} < 50$	Low
	$50 \leq \text{score} < 75$	Medium
	$75 \leq \text{score} \leq 100$	High

Descriptive statistics comprised the mean, median, standard deviation, minimum, and maximum. Changes at the individual level were categorized as improvement, stability, or decline. Because scores from the 15 item test were discrete and bounded and the observed pretest distribution was strongly concentrated near the maximum score, normality required for parametric analysis was not assumed. Differences between paired pretest and posttest scores were therefore examined with the Wilcoxon signed rank test at a two tailed α level of .05 (Garrocho-Rangel et al., 2024; Schober & Vetter, 2020). The direction and magnitude of the observed change were represented using the matched pairs rank biserial correlation (Fiel Peres, 2026). Individual normalized gain and normalized loss were calculated as supplementary descriptive measures but were treated cautiously because high initial scores and ceiling effects may distort normalized indices (Nissen et al., 2018). Questionnaire findings were summarized using item and indicator means, standard deviations, proportions of positive responses, and Cronbach's α . Since the five indicator scores represented repeated measures derived from ordinal responses, differences across indicators were analyzed with the Friedman test, followed by Bonferroni adjusted pairwise Wilcoxon tests. Rubric outcomes were summarized in terms of means, standard deviations, frequencies, percentages, and confidence intervals.

Qualitative Analysis and Mixed Methods Integration

Thematic analysis of students' written responses was conducted by the first, third, and fourth researchers following the systematic procedures described by Naeem et al. (2023). The analytical process involved repeated reading of responses, identification of meaningful units, extraction of relevant expressions and keywords, generation of preliminary codes, organization of related codes, development and refinement of themes, selection of representative quotations, and interpretation of themes in relation to the research questions. The third and fourth researchers independently coded the qualitative responses, after which the coding results were compared to identify areas of agreement and disagreement. Any discrepancies in interpretation were subsequently reviewed through an adjudication process conducted by the first researcher, who examined the differences and determined the final coding decisions. An audit table was developed to maintain transparency throughout the analytical process by documenting connections among original responses, codes, categories, themes, and interpretive notes. All quotations reported in the findings were anonymized to protect participant identities.

Integration of quantitative and qualitative evidence was performed through a joint display approach. For constructs represented in both analytical strands, quantitative findings were presented alongside corresponding qualitative evidence. The relationship between the two forms of evidence was interpreted as convergence, expansion, or partial inconsistency, followed by the development of meta-inferences and educational implications. The joint display was considered an analytical component rather than merely a mechanism for presenting results (Haynes-Brown & Fetters, 2021). The procedures used to align constructs and generate meta-inferences followed recent recommendations for ensuring rigor and quality in mixed-methods integration (DeJonckheere et al., 2024; Fàbregues et al., 2024).

RESULTS AND DISCUSSION

Conceptual Development of Energy Literacy Under Ceiling Constraints

The matched dataset consisted of 45 students who successfully completed all components required for the analysis. The mean of the energy literacy conceptual assessment increased

from 86.67 ($SD = 15.24$) before the intervention to 90.81 ($SD = 15.13$) after the intervention. A corresponding increase was also observed in the median value, which shifted from 86.67 to 93.33, with an average paired-score difference of 4.15 points ($SD = 13.43$). The observed scores at both measurement points covered a range from 20 to the highest possible score of 100, reflecting variation in students' initial and subsequent performance levels (Table 4).

Table 4. Descriptive statistics for energy literacy test scores

Measure	<i>N</i>	Mean	<i>SD</i>	Median	Minimum	Maximum
Pretest	45	86.67	15.24	86.67	20.00	100.00
Posttest	45	90.81	15.13	93.33	20.00	100.00
Paired difference	45	4.15	13.43	0.00	-26.67	60.00

The Wilcoxon signed-rank test demonstrated a statistically significant positive difference between students' pretest and posttest conceptual assessment scores ($W = 105, p = .022$). The matched-pairs rank biserial correlation coefficient ($r_{tb} = .483$) indicated a moderate magnitude of change favoring post-intervention performance. Given that the assessment scores were discrete, bounded, and characterized by a concentration of observations near the upper score limit, a non-parametric approach was considered more appropriate than parametric testing (Garrocho-Rangel et al., 2024; Schober & Vetter, 2020). In addition, normalized gain and normalized loss values were interpreted carefully because ceiling effects can influence the accuracy of improvement estimates when participants begin with relatively high baseline achievement (Nissen et al., 2018).

Table 5. Item difficulty and discrimination indices of the energy literacy assessment

Item	Difficulty Index		Discrimination Index	
	Pretest	Posttest	Pretest	Posttest
Q1	.933	.978	.167	.083
Q2	.800	.933	.500	.250
Q3	.933	.956	.083	.167
Q4	.933	.978	.167	.083
Q5	.911	.956	.333	.167
Q6	.911	.911	.333	.250
Q7	.978	.978	.083	.083
Q8	.933	.956	.250	.167
Q9	.933	.911	.167	.250
Q10	.956	.956	.167	.167
Q11	.800	.844	.250	.500
Q12	.867	.978	.167	.083
Q13	.622	.644	.917	.833
Q14	.556	.689	.833	.833
Q15	.933	.956	.250	.167

Additional item-level analysis further clarified the identified ceiling effect and the sensitivity of individual items in differentiating student performance (Table 5). Most items showed high difficulty index values in both assessments, indicating that many students had already demonstrated proficiency in fundamental energy concepts before the intervention. Discrimination indices varied across items, with Q13 and Q14 showing the highest values in both assessment phases, suggesting stronger capacity to distinguish differences in students' conceptual understanding. Conversely, items with very high difficulty index values tended to show lower discrimination capacity, reflecting the limited sensitivity of some items under conditions of high baseline achievement.

Although the statistical analysis indicated a positive change, interpretation of the practical significance requires consideration of students' initial performance characteristics. Before the intervention, 13 students (28.89%) had already achieved the maximum possible

score, while this number increased to 22 students (48.89%) after the intervention. Moreover, the median paired difference remained at 0.00, indicating that the significant statistical result primarily reflected a greater tendency toward positive score movement rather than consistent improvement among every participant. Therefore, the observed change is more appropriately interpreted as evidence of conceptual refinement among students rather than a uniform improvement pattern across the entire sample. The analysis of individual category transitions provides further insight into this pattern. The category transitions were further examined to establish whether the increase in mean scores represented widespread improvement among students or was primarily attributable to shifts occurring within specific performance groups.

Table 6. Pretest to posttest category transition matrix

Category Pretest	Parameter	Posttest Category			Total
		Low	Medium	High	
Low	Count	1	0	1	2
	% within row	50.000%	0.000%	50.000%	100.000%
	% within column	100.000%	0.000%	2.381%	4.444%
	% of total	2.222%	0.000%	2.222%	4.444%
Medium	Count	0	1	3	4
	% within row	0.000%	25.000%	75.000%	100.000%
	% within column	0.000%	50.000%	7.143%	8.889%
	% of total	0.000%	2.222%	6.667%	8.889%
High	Count	0	1	38	39
	% within row	0.000%	2.564%	97.436%	100.000%
	% within column	0.000%	50.000%	90.476%	86.667%
	% of total	0.000%	2.222%	84.444%	86.667%
Total	Count	1	2	42	45
	% within row	2.222%	4.444%	93.333%	100.000%
	% within column	100.000%	100.000%	100.000%	100.000%
	% of total	2.222%	4.444%	93.333%	100.000%

Of the 39 students who were initially classified within the high-performance category, 38 remained in the same category after the intervention, whereas one student moved to the medium category. Among the four students initially categorized as medium, three advanced to the high category while one remained unchanged. These transitions resulted in an increase in the proportion of students classified as high performers, from 86.67% before the intervention to 93.33% afterward. Nevertheless, persistence within the high category should not be interpreted as evidence that no learning occurred, as several students had already reached the maximum score threshold before participating in the intervention.

The qualitative evidence provides further clarification of the quantitative findings. Students frequently modified their initial interpretations after working with numerical information related to aircraft fuel consumption. Several participants initially assumed that the climb phase required the greatest amount of fuel because of the substantial energy demands associated with gaining altitude. However, after examining the provided data, many students revised their explanations and identified the cruise phase as the largest contributor to fuel consumption. This pattern suggests that aviation-based CBL supported evidence-informed conceptual reconstruction by encouraging students to evaluate quantitative information rather than depend exclusively on intuitive explanations.

This interpretation is consistent with scientific literacy perspectives that emphasize the importance of interpreting evidence, constructing reasoning, and developing justified conclusions (Gormally et al., 2012; OECD, 2023). However, considering that the study employed a one-group pretest–posttest design, individual decreases in performance should be interpreted cautiously, as the observed changes cannot be attributed solely to the intervention itself (Dewi & Rahayu, 2023; Xiang et al., 2025).

Sustainability Awareness as a Post-Intervention Outcome

Following participation in the aviation-based CBL activity, students reported favorable sustainability awareness after participating in the aviation-based CBL activity. The overall mean score obtained from the questionnaire was 4.618 on a five-point Likert scale, with 92.89% of responses indicating positive perceptions through the categories of agree and strongly agree. The questionnaire also demonstrated strong internal reliability, as reflected by Cronbach's $\alpha = .910$.

Table 7. Sustainability awareness questionnaire results

No.	Indicator	Items	Mean	SD	Positive responses (%)	Cronbach's α
1	Energy source awareness	1-3	4.711	.412	97.04	.676
2	Energy efficiency awareness	4-6	4.785	.356	99.26	.765
3	Environmental responsibility	7-9	4.652	.564	94.07	.667
4	SDG 7, 12, and 13 awareness	10-12	4.504	.618	91.11	.890
5	Perceived contribution of CBL and data	13-15	4.437	.706	82.96	.735
Overall questionnaire		1-15	4.618	-	92.89	.910

Analysis across the five measured indicators showed that energy efficiency awareness achieved the highest mean score ($M = 4.785$, $SD = .356$). In contrast, students' perceptions regarding the contribution of CBL and data-based learning produced the lowest mean score, although the value remained favorable ($M = 4.437$, $SD = .706$). The Friedman test revealed statistically significant differences among the five indicators, $\chi^2(4) = 21.416$, $p < .001$. Further pairwise comparisons using Bonferroni adjustment indicated that energy efficiency awareness was significantly higher than both SDG awareness and perceptions of CBL contribution.

These findings suggest that students developed a strong understanding of energy efficiency and sustainability-related concepts within the aviation learning context. Nevertheless, the results should be interpreted as representing students' post-intervention awareness and perceptions rather than evidence of changes in sustainability-related behavior. Since sustainability awareness was assessed only after the intervention, the study does not provide a baseline comparison to determine whether students' awareness increased as a result of the learning experience.

The qualitative responses provided additional insight into the nature of students' sustainability reasoning. Many students associated reduced aviation fuel consumption with decreased emissions, responsible resource utilization, and climate action. However, variations were identified in the depth and quality of their explanations. While some students constructed evidence-supported arguments connecting aviation efficiency with broader sustainability objectives, others were able to identify relevant sustainability concepts but provided limited explanation of the underlying relationships.

This finding corresponds with previous energy literacy research demonstrating that possessing knowledge and favorable attitudes toward energy-related issues does not necessarily result in consistent behavioral choices or effective actions (DeWaters & Powers, 2011). Recent reviews of energy literacy development further highlight that energy literacy encompasses more than conceptual understanding, requiring individuals to evaluate consequences, interpret information, and make informed decisions regarding energy use (Santillán & Cedano, 2023).

Evidence-Based Application and Risk-Oriented Decision-Making

The evidence-based decision-making rubric was used to examine students' ability to integrate quantitative evidence, compare alternative solutions, and construct justified recommendations within an aviation fuel-efficiency context. The overall performance score obtained from the rubric was 76.89 ($SD = 16.79$). Based on the established achievement

categories, 30 students (66.67%) were classified as high performers, 10 students (22.22%) were categorized at the medium level, and five students (11.11%) were placed within the low-performance category.

Table 8. Evidence-based decision-making rubric results

Rubric dimension	Mean raw score (0-3)	SD	Mean percentage (%)
Interpretation of fuel consumption data	2.42	1.10	80.74
Operational efficiency reasoning	2.18	.94	72.59
Evidence-based selection among alternatives	2.60	.69	86.67
Risk and reserve fuel evaluation	1.69	.79	56.30
Synthesis in the mini report	2.64	.53	88.15
Overall rubric score	11.53	2.52	76.89

Analysis of the individual rubric dimensions showed that students obtained the strongest performance in the synthesis component of the mini report ($M = 2.64/3$, $SD = .53$) and evidence-based selection among available alternatives ($M = 2.60/3$, $SD = .69$). Conversely, the lowest achievement was observed in risk and reserve fuel evaluation ($M = 1.69/3$, $SD = 0.79$), followed by operational efficiency reasoning ($M = 2.18/3$, $SD = 0.94$). This pattern suggests that students were relatively proficient in identifying efficient alternatives and supporting their choices with available evidence, but experienced greater difficulty when decisions required the simultaneous consideration of efficiency, uncertainty, and safety constraints.

These results indicate that many students were capable of interpreting numerical information and developing recommendations supported by available evidence. However, the process of applying conceptual understanding within situations involving uncertainty, competing objectives, and operational limitations remained more demanding. Several students tended to prioritize strategies associated with greater fuel reduction while providing insufficient consideration of reserve fuel requirements, changing weather conditions, potential delays, route adjustments, and emergency-related constraints.

Your answer:

According to my research, the "cruising" phase of flight uses about 48% of total fuel. Calculations show that:

$$\frac{\text{Cruise Fuel}}{\text{Total Fuel}} \times 100\% = \frac{2495.7}{5556.7} \times 100\%$$

$$= 44.91\% (2 \text{ dp})$$

This shows that the plane should fly at a higher flight altitude, of around 40,000 ft, to reduce drag and save more fuel efficiently.

Strategy B should be the best strategy as it both efficiently save fuel but still ensuring safety by having a little bit of reserve fuel. Therefore, strategy B should be directly adopted.

Figure 1. An example of a student's evidence-based reasoning in the aviation fuel efficiency worksheet

The example presented in Figure 1 provides an illustration of how students incorporated quantitative information into their decision-making process by using fuel-related calculations to support recommendations while simultaneously considering efficiency and safety aspects. Nevertheless, differences among rubric dimensions demonstrate that possessing conceptual knowledge does not necessarily guarantee effective transfer into practical decision-making performance.

This finding reinforces broader perspectives of scientific literacy, which define scientific competence as the ability to interpret evidence, construct explanations, evaluate alternatives,

and justify decisions rather than simply recall scientific information (Gormally et al., 2012). Consequently, the development of such competence requires learning environments that provide students with structured opportunities to engage with complex problems, analyze evidence, and reason through uncertainty and competing considerations (Dawson & Venville, 2022; Dvir & Tsybulsky, 2025).

Knowledge–Awareness–Application Mismatch

Taken together, the findings indicate that students' learning outcomes were not uniformly distributed across the investigated dimensions. The integration of quantitative and qualitative findings identified a distinctive pattern in which conceptual knowledge, sustainability awareness, and evidence-based application developed at different levels rather than progressing in parallel. The combined evidence indicates that improvements in one dimension were not necessarily accompanied by equivalent advancement in the others.

Table 9. Joint display integrating quantitative and qualitative findings

Focus	Quantitative finding	Qualitative evidence	Relationship	Meta inference and implication
Knowledge change	<i>M</i> increased from 86.67 to 90.81, <i>W</i> = 105, <i>p</i> = 0.022; <i>r</i> _{tb} = 0.483, 20 gain, 17 stable, 8 loss.	FT3 showed that calculations redirected students from intuitive climb predictions to cruise based conclusions.	Convergence + expansion	CBL was associated with modest achievement growth, while qualitative evidence identified numerical analysis as a mechanism of conceptual revision.
Ceiling and depth	42/45 were high at posttest, 13/45 had already obtained 100 at pretest.	FT1 and FT2 revealed sound foundations but continuing imprecision in distinguishing efficiency from conservation.	Expansion	High totals did not always reflect equally precise understanding, more advanced transfer tasks are needed.
Sustainability and SDGs	Overall awareness <i>M</i> = 4.618, IQ3 = 4.652, IQ4 = 4.504.	FT5 connected efficiency with emissions, responsible consumption, and climate action, although some responses only named an SDG.	Convergence + nuance	Awareness was favorable, but evidential quality differed, SDG tasks should require explanation.
Perceived CBL contribution	IQ5 <i>M</i> = 4.437, 82.96% positive responses.	FT6 identified the authentic context, numerical activities, and discussion as mutually supportive.	Convergence + expansion	Students valued the combined contribution of context, calculation, and collaboration.
Applied decisions	Rubric <i>M</i> = 76.89, synthesis = 2.64/3, evidence-based selection = 2.60/3.	FT4 included recommendations that balanced efficiency, cost, feasibility, and safety.	Convergence	Final reports and strategic choices provided authentic evidence of applied energy literacy.
Risk	Risk or reserve	FT7 documented	Convergence	Evaluation of uncertainty

Focus	Quantitative finding	Qualitative evidence	Relationship	Meta inference and implication
reasoning	dimension = 1.69/3, the lowest dimension.	unsafe or insufficiently justified recommendations and persisting errors concerning flight phases.	+ expansion	and risk requires explicit scaffolding involving weather, delays, routing, and reserve scenarios.
Cross construct alignment	28/45 were high in knowledge, awareness, and skills. Ten were high in knowledge and awareness but not skills.	Several students with strong conceptual and awareness profiles nevertheless produced weak evidence or decisions.	Partial inconsistency	Knowledge and awareness are necessary but do not ensure application, multidimensional assessment should be maintained.

The joint display demonstrated convergence between the quantitative improvement in energy literacy performance and qualitative evidence showing that students revised their initial interpretations after engaging with numerical analysis. Nevertheless, the integrated findings also revealed partial divergence, as strong conceptual understanding and favorable sustainability orientations were not consistently reflected in equally strong decision-making outcomes. The overall meta-inference suggests that aviation-based CBL facilitated a transition from intuitive reasoning toward evidence-informed judgment among many students. Through engagement with quantitative data, students were able to reconsider assumptions and construct more justified explanations. However, the process of transforming acquired knowledge into decisions that require balancing uncertainty, safety considerations, and competing objectives remained substantially more challenging.

This integrated pattern highlights a knowledge–awareness–application mismatch within energy literacy development. Although students demonstrated relatively strong conceptual understanding and positive sustainability awareness, these strengths were not consistently transferred into evidence-based decision-making practices. Previous energy literacy studies have similarly reported that knowledge and favorable attitudes toward energy issues do not automatically result in effective actions or informed behavioral choices, indicating the importance of providing learners with opportunities to apply knowledge within authentic decision-making contexts (DeWaters & Powers, 2011; Santillán & Cedano, 2023).

Nevertheless, the findings suggest that a single short-term intervention is unlikely to generate comprehensive development across all dimensions associated with energy literacy. Future implementations should therefore involve repeated CBL cycles incorporating progressively more complex cases, explicit prompts for risk evaluation, and reflective activities that encourage students to examine the consequences of their decisions.

Limitations and Educational Implications

The findings of this study should be considered in light of several methodological limitations. First, the application of a one-group pretest–posttest design restricts the ability to establish causal relationships because potential influences, including maturation, testing effects, and external factors, were not controlled. Accordingly, the observed differences should be interpreted as changes occurring in association with the intervention rather than as definitive evidence of causal impact. Second, the study was conducted with a relatively limited sample drawn from a single international school.

Although incomplete datasets were excluded based on predetermined completeness criteria, the possibility of attrition-related bias cannot be entirely eliminated. Third, the interpretation of the energy literacy assessment was influenced by a ceiling effect, which

reduced the instrument's capacity to identify additional gains among students who demonstrated high initial performance. Fourth, sustainability awareness was assessed only following the intervention; therefore, the study does not provide evidence regarding changes compared with students' pre-existing awareness levels. Finally, the 180-minute instructional sequence represented a pilot implementation involving a single aviation-based CBL scenario and was not intended to evaluate long-term behavioral changes or sustained development of energy literacy competencies. In addition, the fixed reserve fuel condition included in the learning task functioned only as a pedagogical simplification and should not be considered a representation of actual aviation operational procedures.

Despite these limitations, this study presents a feasible instructional framework for integrating energy concepts, quantitative reasoning, sustainability perspectives, and evidence-based decision-making in middle school science education. The findings demonstrate that CBL activities can reveal students' reasoning processes and create opportunities for conceptual understanding to be reconstructed through engagement with evidence. Therefore, future learning designs should provide explicit scaffolding that connects conceptual knowledge and sustainability awareness with application-oriented reasoning, particularly in contexts requiring students to evaluate uncertainty, risk, and competing priorities.

CONCLUSION

Aviation-based Case-Based Learning (CBL) was found to contribute to the advancement of students' conceptual understanding as a specific dimension of energy literacy, particularly in their capacity to interpret energy consumption information within an aviation-related setting. The findings indicate that engagement with quantitative evidence enabled students to reconsider and refine their initial interpretations; however, such conceptual development should be interpreted cautiously by considering the characteristics of the assessment and the limitations of the research design.

The integration of quantitative and qualitative findings revealed that students exhibited favorable sustainability awareness following the intervention and were able to incorporate considerations of energy efficiency, environmental responsibility, and safety into their decision-making processes. Nevertheless, the extent to which conceptual understanding and sustainability awareness were transformed into evidence-based decision-making abilities differed among students. These findings demonstrate that energy literacy outcomes cannot be determined solely by examining conceptual knowledge or sustainability awareness, as the development of application-oriented reasoning may vary across individual learners.

Aviation-based CBL provides a feasible instructional framework for linking scientific concepts with authentic energy-related decision-making contexts in middle school science education. The findings emphasize the need for learning designs that deliberately facilitate students' movement from conceptual comprehension and recognition of sustainability challenges toward the practical application of knowledge in situations characterized by uncertainty, competing considerations, and real-world constraints.

RECOMMENDATION

Future research should consider employing more robust methodological designs, such as studies incorporating comparison groups or quasi-experimental approaches, along with larger samples drawn from multiple educational settings and delayed assessments to evaluate the persistence of learning outcomes. Subsequent investigations may also examine repeated implementations of CBL across diverse energy-related contexts to determine whether sustained engagement can enhance students' ability to transfer knowledge into evidence-based decision-making practices. Further refinement of measurement instruments should involve broader reliability evaluations, expert-based validation procedures, and pre-post assessments of sustainability awareness to enable more comprehensive analysis of developmental changes. In classroom applications, educators should provide structured guidance in quantitative

interpretation, uncertainty evaluation, risk assessment, and evidence-based justification to support students in applying scientific knowledge to authentic decision-making contexts.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Mahdiannur														
Erman				✓						✓		✓		

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

INFORMED CONSENT

This study involved middle school students in a normal educational setting and was exempt from ethical review. Participation was voluntary, with parental consent and student assent obtained, and all data were anonymized to maintain confidentiality.

ETHICAL APPROVAL

This study involved middle school students in a normal educational setting and was exempt from ethical review. Participation was voluntary, with parental consent and student assent obtained, and all data were anonymized to maintain confidentiality.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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