Development of an Integrated PhET and Augmented Reality Package in a Flipped Classroom to Improve Conceptual Understanding of Renewable Energy

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Abstract
Renewable energy is an abstract topic in junior high school science: its systems and energy conversions are difficult to visualize, and teacher-centered instruction often leaves students with fragile, fragmented conceptual understanding. This study developed and evaluated a learning package that integrates PhET virtual-laboratory simulations with augmented reality (AR) 3D visualizations, delivered through a flipped-classroom approach, and examined its feasibility, practicality, and effectiveness for Grade IX students' conceptual understanding of renewable energy. Following the ADDIE Research and Development model, PhET simulations and AR scenes (authored in Assemblr Edu) were integrated into a flipped lesson in which first exposure occurred before class and class time was used for manipulation and discussion. Feasibility was assessed by media, content, and language experts using the Gregory index; practicality by teacher and student response questionnaires; and effectiveness by a 25-item conceptual-understanding test (pretest–posttest, n = 34) analyzed with the Hake normalized gain (N-gain) after confirming item construct validity. The package was very valid (media Gregory index 0.89; content and language 1.00), highly practical (student 91% and 81%; teacher 93%), and, in a single-group pretest–posttest design, associated with a medium gain (mean N-gain 0.50; scores rose from 81.18 to 91.53). Pairing manipulable simulation and spatial AR within a flipped structure was designed to shift learning toward a student-centered, inquiry-oriented process. The package offers a feasible, smartphone-deliverable route to visualizing abstract renewable-energy concepts.

1. Introduction

Renewable energy is a curriculum priority and a topic on which abstract reasoning is unavoidable. Energy forms, conversions, and system behavior cannot be seen directly, and they are easily reduced to memorized definitions when taught through static text and diagrams (Hudha, Batlolona & Wartono, 2019). Renewable energy is conceptually demanding even at higher levels (Bhattacharya, 2001), and students' awareness and understanding of it are often limited (Çakirlar Altuntaş & Turan, 2018; Cholily et al., 2019; Hadiprayitno, Jufri & Nufus, 2020). Conceptual understanding, the ability to interpret, exemplify, classify, summarize, infer, compare, and explain a concept rather than merely recall it, is difficult to achieve, and teacher-centered instruction frequently leaves misconceptions intact. Improving conceptual understanding of energy requires representations that make the invisible manipulable and a pedagogy that gives students room to reason.

Two technologies address the representational problem in complementary ways. PhET interactive simulations provide a virtual laboratory in which learners change variables and immediately observe consequences, linking macroscopic, symbolic, and sub-microscopic representations; across science subjects, PhET has repeatedly strengthened students' conceptual understanding (Rahmawati et al., 2022; Pranata, 2023; Furqon, 2024; Doyan, Hadi & 'Ardhuha, 2023; Faour & Ayoubi, 2018; Salame & Makki, 2021; Kamila, Rahmawati & Jumadi, 2021; Yani & Widiyatmoko, 2023; Suherman, Kariadinata & Chusni, 2025). Augmented reality (AR) complements simulation by rendering systems and contexts as spatial 3D scenes on a smartphone, allowing learners to inspect renewable-energy components and their arrangement directly (Santos et al., 2014; Dunleavy, Dede & Mitchell, 2009; Kerawalla et al., 2006; Garzón, 2021; Thees et al., 2020; Yilmaz, 2021; Akçayır & Akçayır, 2017; Saputra et al., 2026). Used together, manipulation and spatial visualization can address what static text cannot.

Technology alone, however, is insufficient; its value depends on the surrounding pedagogy. The flipped classroom relocates first exposure to pre-class video and reserves class time for manipulation, discussion, and guided inquiry, making the lesson more student-centered (Bishop & Verleger, 2013; Abeysekera & Dawson,

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2014), an approach well matched to simulation-based discovery learning (de Jong & van Joolingen, 1998) and to teachers' willingness to use interactive simulations (Kriek & Stols, 2010). Flipped designs show small-to-moderate advantages over conventional instruction (van Alten et al., 2019; Yu & Yu, 2023; Zainuddin et al., 2019), reflecting the broader benefits of active learning (Freeman et al., 2014), although challenges such as pre-class procrastination can persist (AlJarrah, Thomas & Shehab, 2018); combining flipping with PhET has improved outcomes in junior high science (Jufriansah, Lering & Donuata, 2022), as has blended, video-based delivery in Indonesian settings (Huda et al., 2018). Integrating PhET and AR within a flipped lesson therefore aligns the technologies with a pedagogy designed to let students reason actively with them.

Despite the promise of each component, few studies document the systematic development of an integrated PhET-and-AR package within a flipped design for renewable energy or evaluate its effect on conceptual understanding measured through a validated, indicator-based instrument. This study addresses that gap and asks: (1) Is the package feasible (valid) according to experts? (2) Is it practical according to teachers and students? (3) Is it effective in improving Grade IX students' conceptual understanding of renewable energy?

2. Method

2.1. Research Design

The package was developed with the ADDIE Research and Development model (Branch, 2009; Rachma, Iriani & Handoyo, 2023). Its five phases (analysis, design, development, implementation, and evaluation) were carried out sequentially, the output of each phase serving as the input to the next, and the cycle closed with an empirical test of the product's feasibility, practicality, and effectiveness. Figure 1 outlines the activities undertaken in each phase.

Figure 1. ADDIE Phases and Outputs in Developing the PhET-and-AR Package

In the Analysis stage, a needs analysis using observation and teacher interviews confirmed that renewable-energy concepts were experienced as abstract and that available technology was under-used; the curriculum was mapped to define target conceptual-understanding indicators. In the Design stage, the team selected and sequenced PhET simulations, storyboarded the AR scenes, and authored a flipped lesson plan together with the data-collection instruments. In the Development stage, the AR scenes were built in Assemblr Edu, the package was assembled, and media, content, and language experts validated it; a context-specific AR artifact ("Environmental Cases") was added in response to expert feedback. In the Implementation stage, the package was delivered through the flipped design (pre-class video followed by in-class manipulation and discussion), first in a small-scale trial and then in a limited field trial. The Evaluation stage then consolidated the practicality and effectiveness evidence and informed the final round of refinements.

2.2. Participants and Setting

The study was conducted in the 2025/2026 academic year with one Grade IX class. The characteristics of the participants we took were 9th grade students and had not received the topic of renewable energy at a state junior secondary school (IX-G; n = 34). Two science teachers acted as practitioner validators and as respondents to the practicality questionnaire. Students took part voluntarily, and all records were anonymized before analysis. The package was implemented over five sessions.

2.3. Instruments

Expert-validation sheets addressed media, content, and language aspects. Teacher and student response questionnaires were built on a four-point Likert scale covering usability, support for comprehension, and engagement, and were administered in both the small-scale and the limited field trials. Conceptual understanding was measured with a 25-item test mapped to seven indicators (interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining) drawn from the revised Bloom taxonomy; comparable indicator and two-tier-based instruments have been used to probe conceptual understanding in Indonesian science classes (Suryani, Rusilowati & Wardono, 2016). Item construct validity was confirmed against the product–moment critical value (critical value r = 0.339 at n = 34), with all items exceeding the threshold and retained for use.

2.4. Data Analysis

Inter-rater content validity was indexed with the Gregory coefficient, D/(A+B+C+D), and read against standard bands (≥0.80 very high). Practicality scores were reported as percentages and judged against the usual

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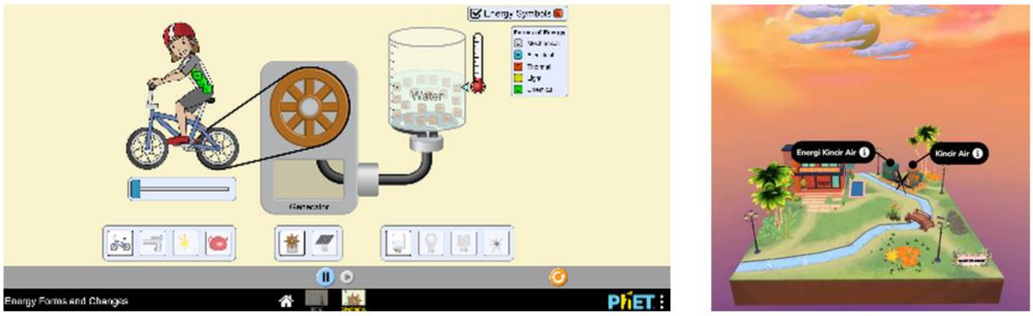
cut-offs (≥70% = practical/high). Learning effectiveness was gauged with Hake's normalized gain, g = (post − pre)/(100 − pre), and classified with the standard bands (high ≥ 0.70; medium 0.30–0.69; low < 0.30; Hake, 1998); all statistics were computed in SPSS 27.

3. Results and Discussion

3.1. The Developed Product

The package integrates PhET virtual-laboratory simulations of energy forms and conversions with AR 3D scenes authored in Assemblr Edu, including a context-specific artifact that situates renewable-energy concepts in real environmental situations. In the flipped design, students engage with introductory video before class and use class time to manipulate the simulation, explore the AR scenes, and discuss their reasoning with the teacher and peers. The design intent is to couple variable manipulation (PhET) with spatial visualization (AR) inside a structure that frees class time for sense-making. Figure 2 shows the PhET interface and a representative AR scene.



(a) (b)

Figure 2. PhET Interface and a Representative AR Scene. (a) PhET Virtual Laboratory; (b) 3D AR Scene of Renewable-Energy Systems

3.2. Feasibility (Expert Validation)

Expert validation was very high: the media-aspect Gregory index was 0.89 (16 of 18 item pairs rated relevant by both validators; very high), while the content and language aspects reached 1.00, indicating very high agreement among validators on accuracy, curriculum alignment, and clarity. Reviewers recommended refinements to navigation cues and to the realism of certain 3D objects, after which the package was deemed highly valid for trial. High expert validity for well-structured simulation- and AR-based media is consistent with prior development studies (Saputra et al., 2026; Rahmawati et al., 2022).

3.3. Practicality (User Response)

Practicality was strong across trials: student responses were 91% in the small-scale trial and 81% in the limited field trial, and the teacher response was 93%. Students described the package as user-friendly and engaging, and teachers regarded it as feasible to implement within a normal schedule. The slight decrease from the small-scale to the limited field trial is consistent with the more variable conditions of a full-class setting and does not alter the high overall rating. These results align with evidence that flipped, technology-supported designs are well received when the materials are clear and accessible (Jufriansah et al., 2022; van Alten et al., 2019; Papakostas et al., 2021), and, because the package runs on students' own smartphones with free tools, they speak to adoptability in resource-constrained schools (Alalwan et al., 2020).

3.4. Effectiveness (Conceptual Understanding)

Conceptual understanding improved from pretest to posttest, with a mean N-gain of 0.50 (*SD* 0.57; range −2.00 to 1.00), in the medium category (Figure 3, Table 1); the mean score rose from 81.18 (*SD* 16.38) to 91.53 (*SD* 8.51), and two of the 34 students recorded a negative individual gain, indicating that most students advanced toward mastery following the flipped, manipulation-oriented design. The improvement is in line with PhET studies that report gains in students' conceptual understanding across science subjects (Rahmawati et al., 2022; Pranata, 2023; Furqon, 2024; Suherman, Kariadinata & Chusni, 2025).

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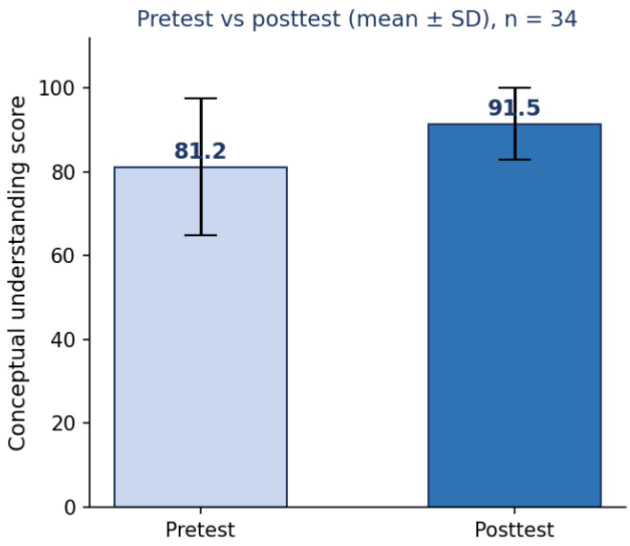

Figure 3. Conceptual-Understanding Scores Before and After Instruction (Mean ± *SD*, *n* = 34)

Table 1. Summary of Feasibility, Practicality, and Effectiveness

Indicator	Result
Feasibility, media (Gregory)	0.89 (very high)
Feasibility, content & language (Gregory)	1.00 (very high)
Practicality, students (small / limited)	91% / 81%
Practicality, teacher	93%
Effectiveness, mean N-gain	0.50 (medium)

3.5. Conceptual Understanding by Indicator

Because the instrument was mapped to seven indicators of conceptual understanding, Table 2 records which component of the package most directly supported each indicator. The manipulation-oriented PhET simulation was linked to the reasoning indicators (explaining, interpreting, and inferring): students varied light intensity on a photovoltaic panel or wind speed on a turbine generator and read the resulting voltage or current. The AR scenes were linked to the representational indicators (classifying and exemplifying) through concrete 3D instances of renewable-energy systems, while the context-specific “Environmental Cases” scene supported comparing by juxtaposing a renewable-energy environment with a fossil-emission one. Class discussion in the flipped lesson supported summarizing.

Table 2. How the Package Supported the Seven Conceptual-Understanding Indicators

Indicator	Primary support	Illustration
Explaining	PhET	Manipulating light/wind and observing voltage/current trains causal reasoning about energy conversion
Interpreting	PhET	Translating between manipulated values and graphical/numerical output
Inferring	PhET	Detecting patterns across repeated variable changes
Exemplifying	AR	Concrete 3D instances of renewable-energy systems
Classifying	AR	Grouping energy sources/types within the 3D scenes
Comparing	AR (Environmental Cases)	Juxtaposing a green renewable-energy environment with a degraded fossil-emission one
Summarizing	Flipped discussion	Consolidating observations during in-class discussion

3.6. Discussion

The package achieved its aims (a valid, practical, and effective learning environment) through the complementary and non-redundant roles of its three components. PhET let students manipulate variables and observe the consequences for energy conversion, turning abstract relationships into testable ones; the AR scenes made renewable-energy systems and their real-world context spatially concrete; and the flipped structure relocated first exposure to the material out of class, so that classroom time could be spent on the manipulation, discussion, and guided inference that consolidate understanding (de Jong & van Joolingen, 1998; van Alten et al., 2019; Bishop & Verleger, 2013). The high practicality scores (91% at small scale and 81% in the wider field trial) indicate that students experienced this integration as a single coherent activity rather than three separate tools, that usability did not degrade as the sample grew, an important precondition for classroom adoption (Jufriansah et al., 2022; Freeman et al., 2014).

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The pattern across the seven indicators (Section 3.5) points to a division of representational labor that explains why the package worked. The manipulable PhET simulations were the primary driver of the reasoning indicators (explaining, inferring, and interpreting) because varying light intensity on a photovoltaic panel or wind speed on a turbine generator and reading the resulting voltage or current gives students direct causal feedback (Banda & Nzabahimana, 2021; Faour & Ayoubi, 2018). The AR scenes were the primary driver of the representational indicators (classifying and exemplifying) by supplying concrete 3D instances of renewable-energy systems, while the contrastive "Environmental Cases" scene, which juxtaposes a renewable-energy environment with a fossil-degraded one, supported comparing by staging a form of cognitive conflict that prompts learners to reason about difference rather than memorize it (Suryani, Rusilowati & Wardono, 2016; Garzón, 2021). Summarizing, the highest-order indicator, emerged in the synchronous class discussion that the flipped format protected. This mapping is consistent with multimedia and cognitive-load accounts in which pairing dynamic symbolic representation with concrete spatial representation lowers extraneous load and frees capacity for schema construction (Abeysekera & Dawson, 2014; Thees et al., 2020).

The medium rather than large magnitude of the gain (N-gain 0.50) is unsurprising and largely attributable to a ceiling effect: the class entered with a high mean pretest score of 81.18, leaving limited headroom before the posttest mean of 91.53. Under such conditions a medium normalized gain still represents a substantial move toward mastery, and it was achieved against the backdrop of a demanding pedagogical transition, with students shifting from teacher-dependent reception to self-regulated pre-class preparation, an adjustment known to take time and to depress early gains for some learners (Zainuddin et al., 2019; AlJarrah, Thomas & Shehab, 2018). The negative individual N-gains observed in a minority of students are consistent with this adaptation cost rather than with a failure of the media.

Theoretically, the study is consistent with a representation-matching view of media design: conceptual understanding advanced most where the representational affordance of a component matched the cognitive demand of the target indicator, rather than because any single technology was intrinsically superior. It also illustrates how a flipped structure can be more than a scheduling device, by moving model-building to the pre-class phase so that scarce synchronous time could be spent on the higher-order summarizing and argumentation that abstract science topics such as energy conversion demand (van Alten et al., 2019; Abeysekera & Dawson, 2014).

3.7. Implications

Because the reasoning indicators responded to PhET and the representational indicators to AR, designers targeting a specific competence can weight the corresponding component rather than assume the whole package is uniformly necessary. A second implication concerns scale: the principal barrier was technical rather than pedagogical, namely dependence on network stability and on smartphone camera quality, with QR-scanning hampered by variable camera resolution and classroom lighting, so re-engineering the AR layer as a standalone, offline, marker less Android application is the most consequential change for the next ADDIE cycle. The package is also best positioned as a complement to well-structured teaching in resource-constrained schools, where it can convert existing smartphones and Wi-Fi (often used only for static media) into an interactive, student-centered learning environment (Alalwan et al., 2020).

3.8. Limitations

Several limitations qualify these findings. The study is a single ADDIE cycle with one class, no control group, and a short intervention, so the effectiveness estimate is indicative rather than confirmatory and cannot be attributed to the media alone. The relatively high pretest scores leave limited headroom for gain. Future work should employ controlled designs, larger and more diverse samples, and delayed post-tests for retention, and should examine which of the seven conceptual-understanding indicators benefit most from each component of the package.

4. Conclusion

An integrated PhET-and-AR interactive simulation delivered through a flipped classroom was developed with the ADDIE model and found to be very valid (Gregory 0.89–1.00), highly practical (students 81–91%; teacher 93%), and, in a single-group design, associated with a medium gain (N-gain 0.50) in improving Grade IX students' conceptual understanding of renewable energy. By pairing manipulable simulation with spatial AR inside a student-centered pedagogy, the package provides a feasible, smartphone-deliverable route to visualizing abstract renewable-energy concepts and supporting conceptual change.

Author Contributions

All authors contributed equally to this paper. All authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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