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Digital Game and Simulation-Based Instruction for Energy Learning in Primary School: Evidence from a Two-Cohort Quasi-Experimental Study

[1] **Polymerou Dimitra,** [2] **Loukopoulos Athanasios,** [3] **Vavougios Dionisios**
[1, 2] Department of Computer Science and Biomedical Informatics, University of Thessaly, Greece
[3] Department of Physics, University of Thessaly, Greece

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Corresponding Author: **Polymerou Dimitra**

Abstract
Energy is a fundamental yet conceptually demanding topic in primary science education. This study examined a curriculum-aligned digital instructional model for teaching energy concepts to Grade 5 students in Greece. A quasi-experimental design was implemented across two consecutive school years with two independent cohorts comprising 78 students. The experimental groups participated in instruction integrating simulations, educational games, interactive assessment, collaborative activities, and student-generated video, whereas the control groups received conventional textbook-based instruction. The pre-test was used diagnostically. Quantitative analysis focused on final assessment worksheets administered after instruction. Post-test performance was compared separately within each cohort using independent-samples t-tests, with Welch's correction where appropriate, and complementary Mann–Whitney U tests because responses followed an ordinal four-category coding scheme and distributions deviated from normality. The experimental groups generally achieved stronger post-test performance. Parametric analyses identified significant differences in five of ten categories in the first cohort and eight of ten in the second. The non-parametric analyses confirmed three differences in the first cohort and all eight in the second. The most consistently supported findings across both cohorts concerned energy forms, multiple-choice reasoning, and energy transformations. Classroom observations additionally indicated enthusiasm, sustained participation, collaboration, friendly competition, and repeated attempts to improve performance during the digital activities. Overall, the findings suggest that the structured integration of digital technologies may complement conventional primary science instruction by supporting conceptual understanding, visualization, feedback, persistence, and collaboration.

Keywords: Digital Game-Based Learning, Educational Simulations, Primary Science Education, Energy Concepts, Student-Generated Video

1. Introduction

The increasing urgency of global environmental and energy-related challenges has intensified the need for effective energy education across all levels of schooling. Climate change, unsustainable patterns of energy consumption, and growing environmental pressures require citizens to develop not only scientific knowledge but also responsible attitudes and decision-making skills regarding energy use and sustainability. Within this context, primary education plays a particularly important role, as children begin to form foundational scientific understandings and environmental attitudes during their early school years. Consequently, contemporary STEM education increasingly emphasizes the development of energy literacy through learning experiences that connect scientific concepts with everyday life and sustainability-oriented thinking [1, 2].

Despite its central role in science education, energy remains one of the most conceptually demanding topics for primary school students. Research consistently demonstrates that children experience significant difficulties in understanding energy forms, transformations, conservation, and degradation, while often confusing scientific and everyday meanings of the term "energy" [3]. Young learners frequently perceive energy as something that is "used up" or "produced" rather than converted from one form to another, and they often struggle to reason about invisible or system-level energy processes. These misconceptions are reinforced when instruction relies primarily on textbook-based explanations and static visual representations that do not adequately support conceptual visualization and inquiry-based reasoning [4]. As a result, traditional teacher centered approaches may limit students' opportunities to actively explore and reconstruct their understanding of complex energy-related phenomena.

To address these challenges, educational technology has increasingly been incorporated into STEM instruction to support conceptual understanding through interactive and multimodal learning environments. Digital simulations enable students to visualize abstract scientific processes, manipulate variables, and observe cause and effect relationships in real time, thereby supporting inquiry based learning and conceptual change [5, 6]. Similarly, digital game-based learning environments have been associated with increased engagement, motivation, and conceptual reinforcement, especially when they are integrated into structured pedagogical sequences rather than used as isolated activities [7, 8]. Interactive assessment platforms additionally provide immediate feedback and opportunities for self-regulated learning, while student-generated multimedia activities encourage learners to organize, represent, and communicate scientific ideas through collaborative and multimodal forms of expression [9, 10]. As part of the integrated instructional model, students in both cohorts collaboratively produced short educational videos to synthesize and communicate their understanding of energy concepts through multimodal representation.

Building on these developments, the present study examines an integrated, curriculum-aligned digital instructional approach for teaching energy concepts to Grade 5 students in primary education. Implemented with two independent cohorts across consecutive school years, the study compares students' final assessment performance following digitally supported instruction with that of students receiving conventional textbook-based instruction. It also examines the consistency of the observed between-group differences across the two classroom implementations. Descriptive classroom observations provide complementary evidence concerning students' participation, persistence, collaboration, and responses to the digital activities, including student-generated video.

The study was guided by the following research questions:

- What differences in final assessment performance are observed between Grade 5 students receiving the integrated digital instructional approach and those receiving conventional textbook-based instruction within each cohort?
- Which energy concepts show the most consistent between-group differences across the two independent cohorts?
- What do descriptive classroom observations indicate about students' participation, persistence, collaboration, and engagement during the digital learning activities, including student-generated video production?

1.1 Digital Game-Based Learning in Primary STEM Education

Digital game-based learning has increasingly been recognized as an effective approach for supporting engagement, motivation, and conceptual understanding in STEM education. Educational games provide interactive environments in which learners actively explore concepts, solve problems, and receive immediate feedback, thereby promoting active participation and iterative learning processes [7, 11]. In primary education, game-based learning environments appear particularly effective when activities are aligned with explicit learning objectives and integrated within structured instructional sequences rather than used as isolated entertainment tools [8].

Research has shown that digital games can support conceptual understanding in science domains by reducing cognitive load and presenting abstract ideas through multimodal and interactive representations [12]. Features such as repetition, time-based challenges, categorization tasks, and immediate feedback have been associated with improved engagement and conceptual consolidation among younger learners [13]. Recent studies in STEM education further suggest that game-based learning environments can facilitate reasoning and decision-making processes when students are encouraged to apply scientific concepts in authentic or problem-oriented contexts [14].

1.2 Simulations and Energy Learning

Computer-based simulations have been extensively studied as tools for teaching abstract scientific concepts by enabling students to visualize invisible processes and explore dynamic systems. PhET simulations have received substantial empirical support in science education due to their grounding in cognitive and learning sciences [5]. These simulations allow learners to manipulate variables, observe real-time effects, and test hypotheses in a risk-free environment, thereby promoting inquiry-based learning and conceptual change [6].

Beyond conventional computer simulations, recent research has highlighted the educational value of immersive virtual environments for energy education. Guerra-Mota *et al.* demonstrated that three-dimensional virtual learning environments can support students' exploration of sustainable energy concepts through interactive experiences that encourage inquiry, visualization, and active participation [15].

In the context of energy education, simulations have been shown to be particularly effective in supporting understanding of energy transformations, conservation, and system behavior. Lye *et al.* demonstrated that integrating energy simulations within the 5E instructional model significantly improved primary students' conceptual understanding [16]. Similarly, Banda and Nzabahimana reported that simulation-based instruction facilitated deeper reasoning about energy conversion and reduced common misconceptions [17]. More recent studies confirm that PhET simulations can help students overcome substance-based conceptions of energy by making system-level processes visible and manipulable [4, 18].

Teachers play a crucial role in scaffolding students' exploration, prompting explanations, and helping them connect simulation outcomes to scientific principles [19].

1.3 Student-Generated Video and Multimodal Learning

Researchers have increasingly recognized the pedagogical value of student-generated digital artefacts, particularly educational video, as tools for multimodal learning and assessment. According to multimedia learning theory, student-created videos help learners combine visual and verbal information, supporting deeper understanding and long-term retention of scientific concepts [9]. This aligns with constructivist perspectives that view learning as an active process of knowledge construction rather than passive reception.

At the primary level, student-generated video has been shown to promote collaboration, communication, and metacognitive awareness, as learners must negotiate meanings, translate scientific ideas into everyday language, and justify their representations [20, 21]. Previous studies have demonstrated that video-based learning can support conceptual consolidation by encouraging students to revisit and refine their understanding during the production process. Empirical studies indicate that video production can enhance content understanding, engagement, and self-efficacy in STEM subjects [10].

1.4 Synthesis and Research Gap

Overall, the reviewed literature indicates that digital games, simulations, and student-generated multimedia can support science learning by facilitating visualization, inquiry, participation, and conceptual understanding. However, important limitations remain. Previous research has often examined these technologies separately rather than as components of a coherent, curriculum-aligned instructional sequence [2, 3]. Furthermore, many studies have involved single cohorts or short-term implementations, limiting evidence concerning the consistency of outcomes across different classroom groups. Relatively little research has also examined the inclusion of student-generated educational video in primary energy education. These limitations provide the rationale for investigating integrated digital learning approaches across repeated classroom implementations.

The present study addresses these gaps by examining a curriculum-aligned digital instructional model for primary energy education across two independent cohorts in consecutive school years. Its principal contribution lies in evaluating the consistency of post-instructional differences between experimental and control groups across two authentic classroom implementations. The study additionally documents, through descriptive classroom observations, students' participation, persistence, collaboration, and responses to the digital activities, including student-generated video production. The video activity is therefore considered a component of the integrated instructional model rather than an independently evaluated intervention.

2. Materials and Methods

2.1 Research Design

This study adopted a quasi-experimental, non-equivalent group design to examine post-instructional differences in Grade 5 students' understanding of energy concepts following two different instructional approaches. Random assignment of individual students was not feasible because the study was conducted in authentic school settings in which students participated as members of intact classes [22]. Quasi-experimental designs are commonly used in educational technology research conducted in real classrooms, as they allow the investigation of instructional approaches under ecologically valid conditions while acknowledging limitations in group equivalence and causal inference [23, 25].

The study was implemented across two consecutive school years with two independent cohorts. This two-cohort design enabled examination of whether the pattern of post-test differences between the experimental and control groups was consistent across separate classroom implementations, addressing the limitation of relying on a single, short-term implementation [24]. In each cohort, the control group received conventional textbook-based instruction aligned with the national curriculum, whereas the experimental group participated in a structured, curriculum-aligned digital instructional model integrating simulations, educational games, formative assessment, collaborative activities, and student-generated multimedia. The same core instructional sequence and learning objectives were maintained across both cohorts to support comparability.

The pre-test was used diagnostically to explore students' initial familiarity with the targeted energy concepts and was not included in the inferential statistical analysis. The quantitative component therefore focused on comparisons of the final assessment performance of the independent experimental and control groups within each cohort. Descriptive classroom observations were additionally used to document students' participation, persistence, collaboration, and responses to digital activities.

Accordingly, the study focused on three dimensions:

- Post-instructional performance in the assessed energy concepts;
- The consistency of between-group differences across the two independent cohorts; and
- Descriptively observed participation, persistence, collaboration, and engagement during the digital learning activities, including student-generated video production [20].

2.2 Participants and Educational Context

The study involved 78 Grade 5 students (aged 10–11 years) from public primary schools in Greece. During the first school year, 42 students participated (21 experimental and 21 control), while during the second year, 36 students participated (18 experimental and 18 control). Experimental groups participated in the integrated digital instructional model, whereas control groups received traditional textbook-based instruction aligned with the national curriculum.

The participating schools were comparable in terms of socioeconomic background, digital infrastructure, and access to computer laboratories with internet connectivity. All instructional activities were aligned with the official Greek National Science Curriculum for Grade 5 and the corresponding Teacher's Guide for Physics [26], which emphasizes the integration of energy concepts across multiple scientific contexts.

Although random assignment of individual students was not feasible, the experimental and control groups were comparable in age and educational level, as all participants attended Grade 5 classes within similar public-school contexts. The diagnostic pre-test was used only to explore students' initial familiarity with the targeted concepts and was not used to establish statistical equivalence between the groups.

2.3 Instructional Model

The instructional model was designed as a technology-enhanced, project-based learning sequence integrating PhET simulations, Wordwall educational games, Quizizz-based assessment, and student-generated multimedia activities within a coherent instructional framework. The instructional implementation comprised twelve teaching hours, followed by two additional hours devoted to module evaluation, resulting in a total duration of fourteen hours. The activities

were implemented in the school computer laboratory, where students worked in groups of three to four per computer. The teacher acted primarily as a facilitator, supporting inquiry, discussion, and collaborative problem solving [25].
Students used selected PhET simulations to explore energy forms, transformations, and energy systems through interactive manipulation of variables and real-time visualization of scientific processes. The simulations were integrated into guided inquiry activities that encouraged prediction, discussion, and conceptual reflection. Examples of the PhET interactive simulations incorporated into the instructional sequence are presented in Fig 1.

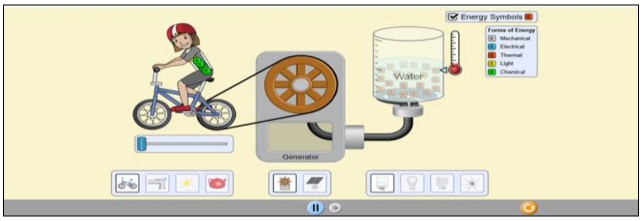

Fig 1: Examples of PhET interactive simulations used during the instructional sequence

To reinforce conceptual understanding, seven Wordwall educational games were developed focusing on energy forms, energy sources, transformations, renewable and non-renewable energy, and energy-saving behaviors. The games incorporated matching, classification, and quiz-based activities designed to support repetition, immediate feedback, and active engagement. Examples of the Wordwall educational games integrated into the instructional sequence are presented in Fig 2.

Fig 2: Examples of Wordwall educational games integrated into the instructional sequence

Quizizz was used throughout the instructional implementation to provide formative assessment and immediate feedback following key learning activities. At the end of the instructional sequence, students also completed an individual Quizizz activity consisting of 26 multiple-choice items covering the main instructional topics. This activity supported consolidation and provided descriptive information about students' responses but was not used as the principal outcome measure in the between-group statistical analyses. The quantitative comparisons between the experimental and control groups were based on the final assessment worksheets. Examples of the Quizizz activities are presented in Fig 3.

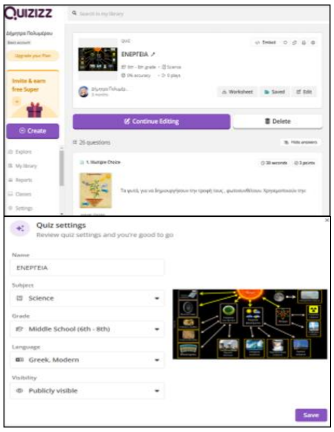

Fig 3: Examples of Quizizz-based assessment activities integrated into the instructional sequence

As a culminating activity, students collaboratively created short educational videos on energy concepts using drawings, narration, and simple digital editing tools. The video production activity encouraged students to organize and communicate scientific ideas, connect energy concepts with everyday contexts, and reflect on their learning through multimodal representation. An example of student-generated visual material developed as part of the multimodal learning activities is presented in Fig 4.

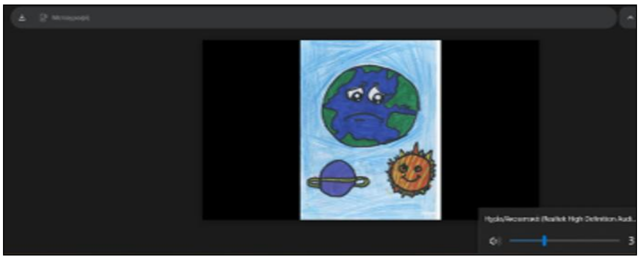

Fig 4: Example of student-generated visual material illustrating responsible energy use and environmental protection

The instructional sequence was designed to progress from exploration to consolidation. Students first explored energy concepts through PhET simulations, reinforced their understanding using Wordwall activities, received formative feedback through Quizizz, and finally synthesized their learning by producing collaborative educational videos.
Table 1 presents the organization of the instructional sequence, including the duration, thematic focus, learning objectives, and digital materials used in each stage of the implementation.

Table 1: Organization of the Energy Instructional Sequence

Duration (hours)	Topic	Learning objectives	Digital materials
2	Forms of energy	Students identify and describe different forms of energy.	PhET simulations; Wordwall games
1	Energy sources	Students identify and describe different energy sources used in everyday contexts.	PhET simulations; Wordwall games
1	Renewable and non-renewable energy sources	Students distinguish between renewable and non-renewable energy sources and discuss their environmental implications.	Worksheet; Wordwall games; collaborative activities
2	Energy transformations	Students explain how energy is transformed from one form to another and provide examples of energy transformations.	PhET simulations; Wordwall games; Quizizz
2	Food and energy	Students explain that the human body obtains energy from food and functions as an energy converter, relating energy intake to bodily energy demands.	PhET simulations; Quizizz
2	Energy use and conservation	Students explain the importance of energy conservation and identify practical energy-saving behaviors.	Wordwall games; Quizizz
2	Student-generated educational video	Students collaboratively create a dramatized educational video addressing renewable and non-renewable energy sources, energy transformations, and energy-saving practices.	Handmade animated sketches; role recording; CapCut; Runway
2	Module evaluation and consolidation	Students consolidate and evaluate their understanding of energy concepts and reflect on the usefulness of digital games and simulations for learning.	Quizizz; evaluation sheets

As shown in Table 1, the instructional sequence followed a structured progression from the recognition of energy forms and sources to more complex concepts involving energy transformations, renewable and non-renewable energy sources, energy use, and conservation. Digital simulations, educational games, worksheets, and interactive assessment activities were integrated throughout the sequence to provide multiple opportunities for exploration, practice, feedback, and conceptual consolidation. The student-generated educational video served as a culminating collaborative activity, enabling students to synthesize and communicate the energy concepts addressed during instruction. Overall, the instructional model comprised twelve teaching hours, followed by two additional hours devoted to module evaluation.

2.4 Learning Objectives and Instructional Task

The instructional model was aligned with the Greek National Science Curriculum for Grade 5 and the corresponding Teacher's Guide for Physics [26]. Nine learning objectives guided the instructional design, addressing students' understanding of energy forms, energy sources, renewable and non-renewable energy sources, energy transformations, energy use in technological and biological systems, energy degradation, and sustainability-oriented energy-saving behaviors.

The instructional sequence progressed from the recognition and classification of energy forms and sources to more complex reasoning about energy transformations, energy degradation, and energy use in natural, technological, and biological systems. Simulations, worksheets, digital games, formative assessment activities, and collaborative multimedia production were aligned with these objectives to provide multiple forms of representation, inquiry, practice, and conceptual consolidation [27, 28].

The nine learning objectives were defined as follows:

O1: Recognize different forms of energy.

O2: Identify different energy sources.

O3: Distinguish between renewable and non-renewable energy sources.

O4: Understand that energy can be transformed from one form to another.

O5: Explain energy transformation chains in technological systems, such as a hydroelectric power plant.

O6: Recognize that humans intentionally transform energy to meet their needs.

O7: Explain that part of the energy in transformations is converted into heat.

O8: Identify the human body as an energy converter and relate food energy intake to bodily energy demands.

O9: Develop awareness of renewable energy use, environmental sustainability, and energy-saving behaviors.

To ensure systematic alignment between the learning objectives and the instructional activities, each major task was mapped onto the corresponding objective or objectives. Table 2 presents this alignment and summarizes the pedagogical rationale underlying each instructional task.

Table 2: Alignment of Instructional Tasks with Learning Objectives

Task Code	***Description of Task***	***Associated Objective(s)***	***Justification of Alignment***
T1	Identify and categorize different forms of energy (kinetic, potential, thermal, electrical, etc.).	**O1**	Supports the recognition and classification of different forms of energy through interactive simulations and digital activities.
T2	Identify energy sources and associate them with familiar everyday contexts and devices.	**O2**	Develops students' ability to recognize and identify different energy sources through simulations, digital games, and everyday examples.
T3	Distinguish between renewable and non-renewable energy sources and discuss their environmental implications.	**O2, O3, O9**	Supports the classification of energy sources and promotes sustainability-oriented reasoning through worksheets, Wordwall activities, and collaborative discussion.
T4	Explore energy transformations using interactive simulations in natural and technological systems.	**O4, O6**	Develops understanding energy of transformations and illustrates how humans intentionally transform energy for different purposes.
T5	Trace the complete energy transformation chain into a hydroelectric power plant.	**O4, O5**	Strengthens understanding of sequential energy transformations within a complex technological system through PhET simulations, teacher guidance, and Quizizz activities.
T6	Explain why part of the energy is converted into heat during energy transformations.	**O7**	Introduces energy degradation and supports students in recognizing that part of the energy involved in transformations is converted into heat.
T7	Relate food energy intake to bodily functions and recognize the human body as an energy converter.	**O8**	Integrates biological and physical perspectives on energy by connecting food energy with bodily functions and energy demands.
T8	Identify practical energy-saving behaviors and explain how renewable energy use contributes to environmental sustainability.	**O9**	Develops awareness of energy conservation, responsible energy use, and environmental sustainability through digital games and collaborative activities.
T9	Create a collaborative educational video presenting energy forms, renewable and non-renewable energy sources, energy transformations, and everyday energy-saving practices.	**O1, O3, O4, O9**	Enables students to synthesize and communicate their understanding through multimodal representation, integrating scientific concepts with sustainability and real-life applications.

As shown in Table 2, the instructional tasks were systematically aligned with the learning objectives, ensuring coherence between curriculum goals, instructional activities, and the digital tools employed. The sequence progressed from the recognition of basic energy concepts to more complex reasoning about energy transformations, energy degradation, and sustainability. The final student-generated video provided an opportunity for students to integrate and communicate multiple energy concepts through a collaborative and multimodal learning activity.

2.5 Data Collection Instruments

The study employed a quasi-experimental quantitative design supplemented by descriptive classroom observations and student artefacts. Data were collected through a diagnostic pre-test, final assessment worksheets, Quizizz performance data, classroom observations, and student-generated materials. The final assessment worksheets provided the principal quantitative outcome data, whereas the remaining sources were used diagnostically, formatively, or descriptively.

2.5.1 Diagnostic Pre-test and Final Assessment Worksheets

Students' familiarity with energy concepts was explored before instruction using a structured diagnostic pre-test. The pre-test included multiple-choice and open-ended questions addressing students' initial understanding of selected energy concepts. It was used exclusively for diagnostic purposes and was not subjected to inferential statistical analysis.

Following completion of the instructional implementation, the experimental and control groups completed final assessment worksheets covering ten conceptual categories. The assessment included multiple-choice items, matching tasks, table-completion activities, open-ended questions, and tasks requiring explanation of energy transformations in everyday and technological contexts. The items were aligned with the instructional objectives and reviewed by two experienced primary science educators to support content validity. Responses to the final assessment worksheets constituted the principal data used in the statistical comparisons.

2.5.2 Quizizz Performance Data

Quizizz platform data provided formative and descriptive information about students' responses and accuracy across conceptual areas such as energy forms, energy transformations, hydroelectric energy, and renewable and non-renewable energy sources. These data were used to support feedback and monitor students' progress during the instructional sequence but were not included in the inferential comparisons between the experimental and control groups.

2.5.3 Classroom Observations and Student Artefacts

Classroom observations were conducted throughout the instructional implementation to document students' participation, persistence, collaboration, and responses to digital activities. Attention was given to students' use of repeated attempts, responses to immediate feedback, collaborative problem solving, and friendly intergroup competition. Student-generated materials, including educational videos, were retained as examples of the collaborative and multimodal activities completed during the instructional sequence.

The observations were not scored using a standardized instrument or subjected to formal qualitative coding. They were therefore used only as complementary descriptive evidence and were not included in the statistical analysis.

Similarly, the student-generated videos were considered components of the integrated instructional model rather than independently evaluated outcome measures.

2.6 Data Analysis

Quantitative analyses were conducted using jamovi (version 2.7.38). The statistical analysis focused exclusively on students' responses to the final assessment worksheets administered after completion of the instructional implementation. The diagnostic pre-test, Quizizz performance data, classroom observations, and student-generated materials were not included in the inferential statistical analysis.

Students' responses to the final assessment worksheets were coded using four categories: 1 = correct, 2 = partially correct, 3 = incorrect, and 4 = no response. Consequently, lower scores represented better performance. Means and standard deviations were calculated separately for the experimental and control groups within each cohort.

The two cohorts were analyzed separately because they comprised different and independent samples. In the first cohort, the experimental and control groups each included 21 students; in the second cohort, each group included 18 students. Independent samples t-tests were used to compare post-test performance between the experimental and control groups across the ten conceptual categories. Levene's test was used to assess the assumption of homogeneity of variance. When this assumption was violated, Welch-adjusted t-statistics and degrees of freedom were reported.

Shapiro–Wilk tests indicated significant deviations from normality across the assessed categories. Given these results, the ordinal response-coding structure, and the relatively small sample sizes, *Mann–Whitney U tests* were additionally conducted as complementary non-parametric analyses. *Cohen's d* and rank-biserial correlations were calculated as effect-size measures for the parametric and non-parametric analyses, respectively. All statistical tests were two-tailed, and statistical significance was set at $p < .05$.

Finally, the pattern of statistically significant and non-significant findings was compared descriptively across the two independent cohorts. This cross-cohort examination was used to identify conceptual categories showing consistent between-group differences across the two classroom implementations and was not treated as a longitudinal comparison of the same students.

2.7 Ethical Considerations

The study followed ethical guidelines for educational research. Participation was voluntary, written parental consent was obtained for all participating students, and anonymity and confidentiality were ensured throughout data collection and analysis. All findings are reported in aggregate form without identifying individual participants.

3. Results and Discussion

The quantitative results presented in this section are based primarily on the final assessment worksheets completed by the experimental and control groups after the instructional implementation. Quizizz performance is reported separately as descriptive formative evidence. The classroom observations are also presented separately and were not included in the statistical analyses.

3.1 Descriptive Quizizz Performance

Quizizz was used during the instructional sequence to provide immediate feedback and opportunities for practice and consolidation. Table 3 summarizes the experimental-group students' descriptive performance across the main conceptual categories included in the Quizizz activities. These results were not used in the inferential comparisons between the experimental and control groups.

Table 3: Descriptive performance across the Quizizz conceptual categories

Conceptual category	*Related items (Q.No.)*	*Mean correct (%)*	*Range (%)*	*Key observation*
Energy forms and identification	2, 3, 4, 12, 17–20	89	76–100	Very high performance in identifying kinetic, potential, thermal, nuclear, and electrical energy
Energy transformations and conversions	5–11	82	67–100	Strong understanding in familiar, everyday contexts; lower performance in less familiar transformations
Photosynthesis and biological energy	1, 5	91	81–100	Good understanding of energy use in biological processes and the human body as an energy converter
Hydroelectric energy	13–16	62	24–100	Conceptual difficulty in tracing complete energy conversion chains
Renewable vs non-renewable sources	22, 23	64	29–100	Higher success with renewable sources; difficulty when visual cues were absent
Environmental benefits of renewable energy	24	86	—	Most students recognized environmental advantages of renewables
Energy-saving behaviours	25	100	—	Excellent understanding of practical energy-saving actions

As shown in Table 3, students demonstrated high performance in identifying different forms of energy, recognizing energy transformations in familiar contexts, and understanding energy use in biological systems. The highest percentages were recorded for energy-saving behaviors (100%), photosynthesis and biological energy (91%), energy forms and identification (89%), and environmental benefits of renewable energy (86%).

Lower performance was observed for hydroelectric energy (62%) and the distinction between renewable and non-renewable energy sources (64%). These descriptive results suggest that students experienced greater difficulty when required to trace complete energy-transformation chains or distinguish systematically between different types of energy sources. Because these data were obtained from formative Quizizz activities completed during the instructional sequence, they are interpreted descriptively and not as independent evidence of intervention effectiveness.

3.2 Post-Test Comparison Between Experimental and Control Groups: First Cohort

In the first cohort, the experimental and control groups each consisted of 21 students. Post-test performance was compared across ten conceptual categories using independent-samples *t-tests. Welch's* correction was applied where Levene's test indicated unequal variances. Because the response scale was ordinal and the distributions deviated significantly from normality, *Mann–Whitney U* tests were additionally conducted as complementary non-parametric analyses. Table 4 presents the results.

Table 4: Post-test comparison between the experimental and control groups in the first cohort

Conceptual category	*Control group M (SD)*	*Experimental group M (SD)*	*Test*	*t*	*df*	*p*	*Mann–Whitney U*	*p (U)*
Energy forms	2.57 (0.93)	1.00 (0.00)	Welch	7.78	20.00	< .001	52.50	< .001
Fill-in-the-blank tasks	2.67 (1.15)	1.86 (1.39)	Student	2.05	40	.047	156.00	.080
Multiple-choice reasoning	2.10 (1.09)	1.19 (0.60)	Welch	3.33	31.13	.002	125.00	.003
Table completion	1.90 (1.09)	1.38 (0.81)	Welch	1.77	36.79	.085	166.00	.091
Energy degradation	3.57 (0.51)	3.57 (1.08)	Student	0.00	40	1.000	171.00	.119
Matching activities	2.33 (1.24)	1.76 (1.26)	Student	1.48	40	.146	169.50	.154
Hydroelectric power plant operation	3.62 (0.74)	2.67 (1.49)	Welch	2.62	29.25	.014	156.50	.065
Renewable versus non-renewable energy sources	2.57 (1.17)	2.19 (1.29)	Student	1.00	40	.321	180.50	.301
Energy transformations	3.10 (0.83)	2.29 (0.90)	Student	3.02	40	.004	115.50	.005
Energy consumption decisions	2.24 (1.26)	1.71 (1.31)	Student	1.32	40	.194	175.00	.191

The parametric analyses identified statistically significant differences in five of the ten conceptual categories. The experimental group achieved significantly lower mean scores, indicating better performance, in energy forms *(p < .001),* fill-in-the-blank tasks *(p = .047),* multiple-choice reasoning *(p = .002),* hydroelectric power plant operation *(p = .014),* and energy transformations *(p = .004).*

The complementary *Mann–Whitney U* analyses confirmed statistically significant differences in energy forms *(p < .001),* multiple-choice reasoning (p = .003), and energy transformations *(p = .005).* However, the differences in fill-in-the-blank tasks *(p = .080)* and hydroelectric power plant operation *(p = .065)* were not statistically significant under the non-parametric analysis. These two findings should therefore be interpreted cautiously.

Neither analysis identified statistically significant differences in table completion, energy degradation, matching activities, renewable versus non-renewable energy sources, or energy consumption decisions. Energy degradation was particularly notable because both groups obtained the same mean score *(M = 3.57),* although their score distributions differed.

Overall, the first-cohort results indicate stronger experimental-group performance in several conceptual categories. The most robust findings concerned energy forms, multiple-choice reasoning, and energy transformations, as these differences were supported by both the parametric and non-parametric analyses.

3.3 Post-Test Comparison Between Experimental and Control Groups: Second Cohort

The second cohort consisted of 18 students in the experimental group and 18 students in the control group. The same analytical procedure was applied: independent-samples t-tests were conducted, *Welch's* correction was used where appropriate, and *Mann–Whitney U* tests provided complementary non-parametric evidence. Table 5 presents the results.

Table 5: Post-test comparison between experimental and control groups in the second cohort

Conceptual category	*Control group M (SD)*	*Experimental group M (SD)*	*Test*	*t*	*df*	*p*	*Mann–Whitney U*	*p (U)*
Energy forms	3.06 (1.21)	1.00 (0.00)	Welch	7.20	17.00	< .001	36.00	< .001
Fill-in-the-blank tasks	2.17 (1.25)	1.50 (1.15)	Student	1.67	34	.105	117.00	.091
Multiple-choice reasoning	2.39 (1.33)	1.22 (0.65)	Welch	3.34	24.60	.003	85.00	.004
Table completion	2.67 (1.41)	1.33 (0.77)	Welch	3.52	26.20	.002	78.00	.002
Energy degradation	3.50 (1.15)	2.50 (1.54)	Welch	2.20	31.40	.035	108.00	.038
Matching activities	2.89 (1.13)	1.72 (1.23)	Student	2.96	34	.006	87.00	.011
Hydroelectric power plant operation	2.89 (1.28)	1.67 (1.28)	Student	2.86	34	.007	91.00	.013
Renewable versus non-renewable energy sources	2.17 (1.25)	1.50 (1.15)	Student	1.67	34	.105	117.00	.091
Energy transformations	2.06 (1.06)	1.00 (0.00)	Welch	4.24	17.00	< .001	63.00	< .001
Energy consumption decisions	2.56 (1.46)	1.00 (0.00)	Welch	4.51	17.00	< .001	72.00	< .001

The parametric analyses identified statistically significant differences in eight of the ten conceptual categories: energy forms *($p < .001$)*, multiple-choice reasoning *($p = .003$)*, table completion *($p = .002$)*, energy degradation *($p = .035$)*, matching activities ($p = .006$), hydroelectric power plant operation *($p = .007$)*, energy transformations *($p < .001$)*, and energy consumption decisions *($p < .001$)*. In every significant category, the experimental group obtained a lower mean score than the control group.

The Mann–Whitney U analyses confirmed the same eight differences: energy forms *($p < .001$)*, multiple-choice reasoning *($p = .004$)*, table completion *($p = .002$)*, energy degradation *($p = .038$)*, matching activities *($p = .011$)*, hydroelectric power plant operation *($p = .013$)*, energy transformations *($p < .001$)*, and energy consumption decisions *($p < .001$)*. This agreement between the parametric and non-parametric analyses provides a consistent pattern of results within the second cohort.

No statistically significant differences were identified for fill-in-the-blank tasks or renewable versus non-renewable energy sources. Although the experimental group obtained numerically lower mean scores in both categories, the differences did not reach statistical significance under either analytical approach.

Overall, the second-cohort results indicate a broad pattern of stronger post-test performance in the experimental group. Unlike the first cohort, all statistically significant parametric findings were confirmed by the corresponding non-parametric analyses.

3.4 Cross-Cohort Comparison

The cross-cohort comparison examined the consistency of the pattern of between-group differences across the two independent classroom implementations. Because different students participated in the two cohorts, this comparison was descriptive rather than longitudinal.

Based on parametric analyses, energy forms, multiple-choice reasoning, hydroelectric power plant operation, and energy transformations showed statistically significant differences in both cohorts. However, the complementary *Mann–Whitney U* analyses produced a more conservative cross-cohort pattern. Energy forms, multiple-choice reasoning, and energy transformations were the only categories showing statistically significant differences under both analytical approaches in both cohorts.

Hydroelectric power plant operation was significant in both cohorts according to the parametric analyses, but its first-cohort *Mann–Whitney* result did not reach statistical significance *($p = .065$)*. Fill-in-the-blank tasks reached parametric significance only in the first cohort and were not confirmed by the corresponding non-parametric analysis. Table completion, energy degradation, matching activities, and energy consumption decisions showed significant differences only in the second cohort. Renewable versus non-renewable energy sources did not show a statistically significant between-group difference in either cohort.

Taken together, the findings indicate a core pattern of consistently stronger experimental-group performance in energy forms, multiple-choice reasoning, and energy transformations. The remaining categories demonstrated cohort-specific variation or differences between the parametric and non-parametric results. Accordingly, the evidence supports an association between participation in the integrated digital instructional model and stronger post-test performance in selected conceptual areas, while not establishing an exclusive causal effect of the instructional approach.

3.5 Descriptive Findings from Classroom Observations

Descriptive classroom observations indicated high levels of enthusiasm and sustained participation during the simulations, digital games, Quizizz activities, and student-generated video production. Students remained focused on completing the activities, discussed possible solutions within their groups, and responded actively to the immediate feedback provided by the digital environments.

The opportunity to repeat the activities was used extensively. Students frequently attempted the games more than once until they achieved the correct result or improved their performance. Friendly competition was also evident, particularly when groups compared scores and attempted to achieve the highest ranking. Collaborative discussion and peer support were observed during the simulations, games, and video-production activities.

These observations were not derived from the final assessment worksheets, were not scored using a standardized observation instrument, and were not included in the statistical analysis. They are therefore interpreted only as complementary descriptive evidence of participation, persistence, collaboration, and engagement during the instructional implementation.

3.6 Discussion

The present study examined an integrated, curriculum-aligned digital instructional model for teaching energy concepts in Grade 5 across two independent school-year cohorts. Overall, the experimental groups generally obtained lower post-test scores, indicating stronger performance under the coding scheme employed. However, the degree of statistical support varied between cohorts and analytical approaches. In the first cohort, the parametric analyses identified significant differences in five of ten categories, whereas the complementary Mann–Whitney U tests confirmed three. In the second cohort, both analytical approaches identified the same eight significant differences. This general pattern is consistent with previous research indicating that simulations and digital game-based learning can support conceptual understanding and active participation when integrated into structured pedagogical sequences [5, 8, 12, 14].

The most robust cross-cohort findings concerned energy forms, multiple-choice reasoning, and energy transformations. These categories showed statistically significant differences under both the parametric and non-parametric analyses in both cohorts. Hydroelectric power plant operation was significant in both cohorts according to the parametric analyses, but the first-cohort Mann–Whitney result did not reach statistical significance. Consequently, the hydroelectric finding should be interpreted more cautiously.

3.7 Learning Outcomes in Relation to the Instructional Objectives

Energy forms and energy transformations produced the most consistently supported between-group differences. These concepts were addressed through simulations, digital games, visual materials, collaborative activities, and interactive assessment. This combination may have offered repeated opportunities to identify energy forms, observe transformations dynamically, practice conceptual classifications, and receive immediate feedback.

This interpretation is consistent with studies showing that simulations can facilitate the visualization of abstract or otherwise invisible scientific processes and support inquiry-oriented conceptual development [5, 6, 16, 18]. Energy concepts are often difficult because students tend to develop fragmented rather than integrated representations of forms, transfers, and transformations [3, 4]. The recurrence of differences in energy forms and transformations across both cohorts suggests that these concepts were particularly compatible with the visual, interactive, and practice-oriented features of the instructional model [27, 28].

Energy transformations constitute a particularly relevant finding because understanding transformation processes requires students to move beyond naming isolated forms of energy and consider how energy changes within a system. Dynamic representations may have supported this transition by making transformation sequences visible and allowing students to explore relationships among system components. Previous research has similarly identified the value of interactive simulations for supporting the understanding of dynamic systems and energy transformations [6, 16, 18].

Hydroelectric power plant operation also involved a multi-stage transformation sequence connecting water, motion, turbines, generators, and electrical energy. Although the parametric analyses indicated significant differences in both cohorts, the first-cohort non-parametric result was marginal and non-significant. The results therefore provide some evidence that visualization and guided exploration supported understanding of this complex system, but the cross-cohort evidence is less robust than for energy forms and energy transformations. Research on interactive and virtual environments nevertheless supports the value of visualization and active exploration for learning about complex energy systems [15, 16].

3.8 Differences Across Conceptual Categories and Cohorts

The results were not uniform across all conceptual categories. In the second cohort, both analytical approaches identified differences in table completion, energy degradation, matching activities, and energy consumption decisions. These categories did not show significant differences in the first cohort. Conversely, fill-in-the-blank tasks reached significance only in the first-cohort parametric analysis and were not confirmed by the corresponding Mann–Whitney test.

This variation demonstrates that the instructional model was not associated with an identical pattern of results in every classroom implementation. Such variation is plausible in authentic educational settings involving independent groups of students. It also illustrates the importance of reporting both analytical approaches, particularly when outcomes are based on an ordinal coding system and relatively small samples.

Renewable versus non-renewable energy sources did not show a significant between-group difference in either cohort under either analytical approach. The descriptive Quizizz results also indicated moderate performance in this area. Although students could recognize familiar examples, systematic classification may require more explicit conceptual organization and opportunities to apply the distinction across varied contexts. This issue is important within approaches to energy literacy that connect scientific understanding with informed decision-making about energy use and sustainability [1, 2].

Energy degradation also produced different patterns across cohorts. No significant difference was found in the first cohort, whereas both analyses identified a significant difference in the second. Research has consistently shown that energy degradation, conservation, and system-level energy reasoning are demanding for students [3, 4]. Understanding degradation requires more than recognizing a transformation; students must also consider how energy becomes dispersed, often as heat, and become less useful for performing processes. This concept may therefore require additional instructional time, carefully sequenced representations, explicit teacher guidance, and tasks designed specifically to support system-level reasoning [3, 4].

3.9 Digital Games, Simulations, Feedback, and Engagement

The findings support the pedagogical value of integrating different digital resources into a coherent instructional sequence. Research on digital game-based learning indicates that games can encourage participation, practice, feedback, and conceptual reinforcement when they are aligned with explicit learning objectives [7, 8, 12, 14]. In the present study, the games were used within a broader sequence rather than as isolated recreational activities.

Simulations performed a complementary function by enabling students to interact with dynamic representations, manipulate variables, observe relationships, and explore processes that are difficult to represent through static textbook materials [5, 6]. Research in energy education has also highlighted the potential of simulations and virtual environments for exploring transformations and sustainable energy systems [15, 18].

Descriptive classroom observations indicated enthusiasm and sustained participation during the simulations, games, Quizizz activities, and video production. Students frequently repeated activities until they obtained a correct result or improved their performance. Friendly competition between groups and collaborative discussion were also observed. These behaviors suggest that immediate feedback and repeated attempts may have supported persistence and active participation. Nevertheless, these observations were not collected through a standardized engagement scale and should therefore be interpreted descriptively rather than as measured changes in motivation.

The persistence of difficulties in energy degradation and renewable versus non-renewable sources demonstrates that technology alone does not guarantee conceptual understanding. Digital tools are most educationally meaningful when embedded in purposeful instructional designs incorporating teacher guidance, discussion, feedback, and targeted scaffolding [6, 8, 12, 13].

3.10 Consistency Across Two Independent Implementations

The implementation of the same core instructional model with two independent cohorts provided an opportunity to examine the consistency of the observed pattern. Under both analytical approaches, energy forms, multiple-choice reasoning, and energy transformations showed significant differences in both cohorts. The second cohort exhibited a broader pattern, with eight categories reaching significance under both the parametric and non-parametric analyses.

These findings indicate a consistent core accompanied by cohort-specific variation. They do not demonstrate longitudinal improvement because different students participated in each implementation. Nor do they establish full reproducibility or an exclusive causal effect of the instructional model. Instead, they show that stronger experimental-group performance in selected conceptual areas appeared across two separate classroom applications.

This interpretation is consistent with research emphasizing that technology-enhanced learning depends not simply on access to digital tools but on their integration into coherent, curriculum-aligned pedagogical designs [7, 8, 11, 12]. The results provide evidence that the structured combination of simulations, games, interactive assessment, and collaborative activities can be implemented across different cohorts while maintaining a generally favorable, although not identical, pattern of outcomes.

3.11 Student-Generated Video as a Multimodal Synthesis Activity

Student-generated video was included as a culminating collaborative activity through which students organized and communicated energy concepts using narration, drawings, role recording, and simple digital editing. This activity is compatible with multimedia learning theory, which emphasizes the active selection, organization, and integration of verbal and visual information [9]. Previous research also suggests that student-created videos can promote participation, collaboration, and ownership by positioning students as producers rather than passive recipients of content [10, 20].

In the present study, however, video production was not investigated as an independent instructional variable, and the resulting videos were not subjected to formal qualitative coding. No separate conclusion can therefore be drawn about the specific effect of video production on conceptual understanding. The activity should instead be understood as one component of the integrated instructional model. Descriptive observations indicated that students collaborated actively during video production and remained focused on completing the shared multimedia product.

3.12 Curriculum Alignment and Sustainability-Oriented Energy Literacy

A strength of the instructional model was its alignment with the Greek National Science Curriculum for Grade 5 and the corresponding Teacher's Guide [26]. The systematic mapping of learning objectives onto instructional tasks supported coherence among curriculum goals, classroom activities, and digital resources. Such alignment is important for the practical implementation of educational technologies in primary education, where instructional time and mandated learning outcomes must be considered.

The inclusion of renewable energy, energy-saving behavior, and sustainability-oriented contexts also reflects approaches to energy literacy that combine conceptual knowledge with informed decision-making [1, 2]. The strong descriptive Quizizz performance in energy-saving behaviors suggests that familiar, everyday contexts were accessible to students. However, the absence of significant between-group differences in distinguishing renewable from non-renewable sources demonstrates that general sustainability awareness should not be equated with systematic conceptual classification.

3.13 Implications for Instructional Design

The findings suggest several implications for the design of primary energy instruction. First, simulations, digital games, and interactive assessment can be combined to provide complementary opportunities for visualization, exploration, practice, repetition, and immediate feedback. The consistent findings for energy forms and transformations indicate that this combination may be particularly appropriate for concepts that benefit from dynamic and visual representation.

Second, abstract concepts such as energy degradation require more explicit scaffolding. Instruction could include additional simulation scenarios emphasizing energy dispersion, structured teacher prompts addressing everyday expressions such as "energy is used up," and activities that require students to trace energy through complete systems [2, 3, 4].

Third, digital games should allow repeated attempts accompanied by explanatory feedback rather than merely displaying scores. The classroom observations suggested that students made active use of repetition and were motivated to improve their performance. Friendly competition can support participation, but it should be balanced with collaboration and conceptual discussion.

Finally, student-generated video can be retained as a collaborative synthesis activity, particularly when students are asked to explain concepts, connect them with everyday contexts, and communicate them through multiple representations [9, 10, 20]. Future studies should evaluate video production independently through systematic analysis of the resulting artefacts or through designs capable of distinguishing its contribution from that of the other components.

Overall, the study provides evidence of an association between participation in a curriculum-aligned digital instructional model and stronger post-test performance in selected energy concepts. The most consistently supported findings concerned energy forms, multiple-choice reasoning, and energy transformations. At the same time, differences between cohorts and persistent difficulty in selected areas underline the importance of cautious interpretation, targeted scaffolding, and further research with larger samples and additional educational contexts.

4. Conclusion

This study examined an integrated, curriculum-aligned digital instructional model for teaching energy concepts in Grade 5 primary education across two independent cohorts. Overall, the experimental groups generally achieved stronger post-test performance than the control groups, although the pattern and strength of the statistical evidence varied between cohorts and analytical approaches.

In the first cohort, the parametric analyses identified significant between-group differences in five of the ten conceptual categories, whereas the complementary Mann–Whitney U tests confirmed three. In the second cohort, both analytical approaches identified the same eight significant differences. The most consistently supported findings across both cohorts concerned energy forms, multiple-choice reasoning, and energy transformations. Hydroelectric power plant operation reached significance in both cohorts under the parametric analyses, but the corresponding first-cohort Mann–Whitney result was not significant and should therefore be interpreted cautiously.

The findings suggest that digital technologies may be educationally valuable when purposefully integrated into a coherent instructional sequence. Within the present model, simulations supported visualization and exploration, digital games offered opportunities for practice and repeated attempts, and interactive assessment provided immediate feedback. Student-generated video served as a collaborative multimodal synthesis activity rather than as an independently evaluated instructional component. Descriptive classroom observations additionally indicated enthusiasm, persistence, collaboration, friendly competition, and sustained participation during digital activities.

The results were not uniform across all conceptual areas. Renewable versus non-renewable energy sources did not show significant between-group differences in either cohort. Energy degradation showed a significant difference only in the second cohort, indicating that abstract and system-level energy concepts may require more explicit scaffolding, additional instructional time, and carefully sequenced representations.

The findings should be interpreted considering several limitations. The study used a quasi-experimental design with intact groups, relatively small samples, ordinal response coding, and no delayed post-test. The two cohorts consisted of different students and therefore cannot provide evidence of longitudinal improvement. Classroom observations were descriptive and were not recorded using a standardized observation instrument. Furthermore, because the digital activities were implemented as an integrated model, the study cannot determine the independent contribution of simulations, games, interactive assessment, collaboration, or student-generated video.

Future research should examine the instructional model with larger and more diverse samples, across multiple educational contexts, and include delayed assessments of knowledge retention. Further studies could also use designs capable of examining the individual and combined contributions of the model's components and standardized measures of engagement, collaboration, and motivation. Finaly, future studies could incorporate a delayed assessment within the same school year, before students complete primary education, to examine the retention of conceptual understanding.

Overall, the findings support the structured integration of digital technologies as a complement to conventional primary science instruction. When aligned with clear learning objectives and appropriate teacher guidance, such approaches may provide meaningful opportunities for visualization, exploration, feedback, persistence, collaboration, and the development of energy understanding.

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