

Energy Systems Engineering and Education: A Serious Game for Literacy

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Abstract: Energy literacy requires understanding how electricity systems operate under conditions of variability, resource constraints, and environmental trade-offs. This paper presents *Primary Energy*, a data-driven serious game designed to support systems-based reasoning in energy education. The game uses authentic hourly renewable energy production data to create 24 sequential missions in which players must balance electricity demand while managing carbon emissions, land-use constraints, and energy storage limitations. Developed within a design-based research framework, the game was implemented in Unity and incorporates real-world renewable variability from the Portuguese electricity system. Unlike many educational energy games that rely on simplified representations, *Primary Energy* exposes learners to the operational challenges associated with renewable integration and electricity balancing through constrained decision-making and multi-objective trade-offs. A preliminary classroom deployment involving 31 students aged 12–18 years examined usability, engagement, and emergent decision-making behaviours. Observations and participant feedback suggest that learners were able to engage with system constraints, adapt strategies in response to changing renewable availability, and reflect on environmental impacts associated with different energy sources. While learning outcomes were not formally assessed, the results indicate that the platform is technically viable and pedagogically promising. The paper contributes the design and initial classroom evaluation of a serious game that supports systems-based reasoning and energy literacy through authentic energy-system dynamics.

Keywords: Energy systems modelling, Game-based learning, Serious games, Systems thinking, Energy literacy, Sustainability education, Simulation-based learning, Design-based research, STEM education

1. Introduction

Contemporary energy systems are undergoing profound transformation as countries seek to decarbonise electricity production while maintaining reliability and affordability. The increasing integration of renewable energy sources introduces new operational challenges associated with intermittency, storage limitations, fluctuating demand, and environmental trade-offs. As a result, energy literacy is increasingly understood not simply as knowledge of energy sources, but as the ability to reason about complex and dynamic systems characterised by interacting constraints and competing objectives (DeWaters & Powers, 2013; Lee et al., 2015).

Despite growing recognition of the importance of energy literacy, educational approaches often remain focused on declarative knowledge acquisition. Learners may be able to identify renewable and non-renewable energy sources yet struggle to understand how electricity systems operate under conditions of variability, uncertainty, and resource constraints. Research on systems thinking suggests that individuals frequently have difficulty reasoning about dynamic systems, particularly when outcomes emerge from multiple interacting variables and delayed consequences (Sterman, 2000). In energy contexts, this may lead to simplified assumptions regarding renewable reliability, storage capacity, or the environmental implications of different production strategies.

Digital serious games and simulation-based learning environments offer promising opportunities to address these challenges. By enabling learners to experiment with decisions, observe system responses, and explore trade-offs within realistic scenarios, such environments can support systems-oriented reasoning and active engagement with complex sustainability issues (Djaouti et al., 2011; Zyda, 2005). Within science, engineering, and sustainability education, simulation-based approaches have been shown to facilitate understanding of interdependencies and dynamic processes that are difficult to convey through conventional instructional methods (Sterman, 2014).

However, many existing digital games and educational simulations addressing sustainability and energy transition rely on simplified or aggregated representations of energy production. While these approaches can support awareness and engagement, they rarely expose learners to authentic temporal variability derived from real operational energy data. Consequently, opportunities to develop procedural understanding of renewable intermittency, constrained electricity balancing, and environmental trade-offs remain limited.

To address this gap, this paper presents *Primary Energy*, a data-driven digital serious game designed to support systems-based energy literacy through constrained electricity-balancing tasks. The game incorporates authentic hourly renewable energy production data from the Portuguese electricity system and structures gameplay around 24 sequential missions. Players must satisfy electricity demand while simultaneously managing carbon emissions, land-use constraints, and energy storage limitations. Rather than emphasising competition or factual recall, the game focuses on decision-making under realistic operational constraints and changing system conditions.

The study adopts a Design-Based Research (DBR) approach to guide both the development of the game and its preliminary classroom evaluation. DBR is particularly appropriate for educational innovation because it supports the iterative design, implementation, and refinement of learning interventions while simultaneously generating theoretical and practical insights regarding learning processes and instructional design (Reeves, 2006; Wang & Hannafin, 2005).

The paper addresses the following research questions:

RQ1: How can authentic temporal renewable variability be integrated into digital serious game design for energy education?

RQ2: To what extent does gameplay promote systems-oriented reasoning about constrained energy balancing?

RQ3: What usability and pedagogical insights emerge from preliminary classroom deployment?

By integrating authentic renewable energy data into mission-based gameplay and examining its initial classroom implementation, this study contributes the design and preliminary evaluation of a digital serious game intended to support systems-based reasoning and energy literacy in sustainability education.

2. Background and Related Work

Energy literacy has increasingly been recognised as a multidimensional competence extending beyond factual awareness of energy sources towards the ability to understand dynamic systems, evaluate environmental trade-offs, and make informed operational decisions (DeWaters & Powers, 2013; Lee et al., 2015). Within sustainability education, this perspective aligns with approaches that emphasise systems reasoning and decision-making under uncertainty rather than declarative knowledge acquisition alone. In contemporary energy systems, learners must understand not only the characteristics of renewable and non-renewable sources but also the interactions between electricity demand, renewable intermittency, emissions, and storage constraints.

Systems thinking provides an appropriate framework for approaching such complexity. Meadows (2008) described systems as interconnected structures characterised by feedback processes, accumulations, and non-linear interactions, while Sterman (2000) demonstrated that individuals frequently struggle to reason about dynamic systems due to simplified mental models and linear assumptions. Educational research similarly indicates that learners experience difficulties interpreting temporal variability and delayed environmental consequences (Assaraf & Orion, 2005). In energy education, these limitations may contribute to misconceptions regarding renewable reliability and the operational balancing requirements associated with electricity production.

Serious games and simulation-based learning environments have emerged as promising approaches for addressing these challenges because they allow learners to interact actively with complex systems through experimentation and iterative decision-making (Djaouti et al., 2011; Zyda, 2005). Within sustainability and engineering education, simulation-based environments can support understanding of interdependencies and trade-offs characteristic of energy systems (Sterman, 2014). Several educational platforms addressing sustainability and energy transition have been developed over recent years, including *Energities*, *ElectroCity*, and *Energy Transition Model Light*. Although these tools contribute to sustainability awareness, most operate at aggregated temporal scales and rarely incorporate authentic renewable variability derived from real operational datasets.

Existing literature also reveals important methodological limitations. Many educational games rely on static representations of energy production and focus primarily on engagement or usability metrics rather than examining systems reasoning and constrained decision-making processes. Furthermore, simplified simulations frequently overlook the operational variability associated with renewable integration and storage management.

Positioned within this context, *Primary Energy* was designed as a data-driven serious game intended to support systems-based energy literacy through constrained electricity balancing tasks. Unlike sustainability simulations

centred primarily on long-term planning, the game structures learning around sequential hourly missions derived from authentic renewable production data. Players must balance electricity demand while simultaneously managing emissions, storage depletion, and land-use constraints. By integrating real temporal variability into gameplay mechanics, the platform seeks to promote procedural energy literacy grounded in systems thinking and environmental trade-off evaluation.

3. Methodology: Design-based Research

This study adopted a Design-Based Research (DBR) methodology to guide the design, development, implementation, and preliminary evaluation of *Primary Energy*, a serious game intended to support systems-based energy literacy through authentic renewable energy data and constrained decision-making. DBR is particularly suitable for educational innovation because it combines the iterative development of learning interventions with the generation of practical and theoretical knowledge concerning learning processes and instructional design (Reeves, 2006; Wang & Hannafin, 2005).

Unlike traditional evaluation approaches that treat educational technologies as finished products, DBR views the intervention as both a learning environment and a vehicle for investigating how learners engage with specific pedagogical mechanisms. In the present study, *Primary Energy* served simultaneously as an instructional intervention designed to foster systems thinking and procedural energy literacy and as a research instrument through which learner interactions, decision-making strategies, and responses to operational constraints could be observed.

The first DBR cycle focused on three complementary objectives: (i) assessing the technical feasibility of integrating authentic renewable energy datasets into a serious game environment; (ii) evaluating the pedagogical viability of promoting systems-oriented reasoning through constrained electricity-balancing tasks; and (iii) identifying usability issues and interaction patterns to support subsequent design iterations.

3.1 Pedagogical Foundations and Design Principles

The design of *Primary Energy* was informed by three complementary principles derived from the literature on systems thinking, energy literacy, and simulation-based learning.

First, systems thinking principles guided the representation of electricity production as a dynamic and interconnected system characterised by renewable variability, storage limitations, environmental impacts, and demand fluctuations (Meadows, 2008; Sterman, 2000). Rather than presenting energy sources independently, the game requires learners to understand how decisions affecting one component influence the behaviour of the entire system.

Second, the game was designed around constrained decision-making. Real electricity systems operate under multiple technical and environmental constraints and therefore cannot be optimised according to a single objective. Consequently, players must simultaneously satisfy electricity demand, manage carbon emissions, respect land-use limitations, and maintain sufficient storage reserves. This structure was intended to expose learners to the trade-offs inherent in real-world energy management.

Third, the design emphasised procedural energy literacy rather than factual recall. Following contemporary energy literacy frameworks (DeWaters & Powers, 2013; Lee et al., 2015), learning was expected to emerge through repeated interaction with operational challenges requiring analysis, adaptation, and strategic decision-making under changing conditions.

3.2 Design and Development of the Serious Game

Development followed an iterative DBR process comprising problem analysis, instructional design, software development, classroom implementation, formative evaluation, and refinement.

The game was developed using the Unity engine and designed for desktop environments. Renewable electricity production data for solar and wind generation were obtained from the Portuguese REN Data Hub and incorporated directly into gameplay. These datasets provide authentic hourly renewable generation profiles, allowing the simulation to reproduce real temporal variability observed in the Portuguese electricity system.

The instructional design adopts a challenge-based learning structure. Players assume the role of energy managers responsible for maintaining system operation throughout a complete 24-hour cycle. The cycle is divided into 24 sequential hourly missions, each representing one hour of system operation and requiring players to adapt their decisions according to changing renewable energy availability and operational conditions.

Unlike many educational energy simulations that employ static or aggregated scenarios, *Primary Energy* incorporates authentic renewable intermittency, creating uncertainty and requiring continuous adaptation. This approach was intended to promote deeper understanding of the operational challenges associated with renewable integration and electricity balancing.

3.3 System Architecture and Implementation

The architecture of the proposed solution is illustrated in Figure 1.

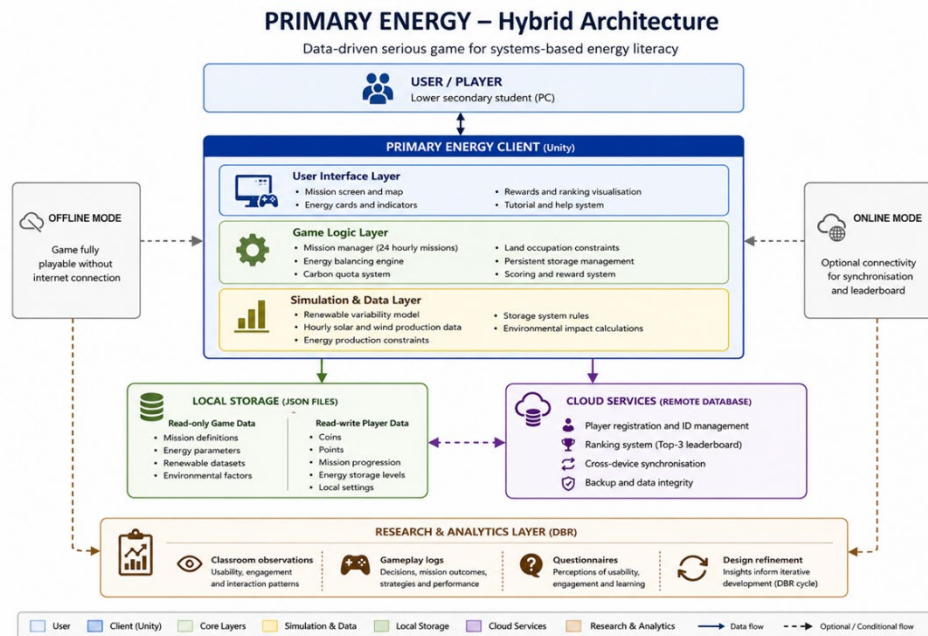


Figure 1: Diagram of the architecture of the proposed solution

The platform follows a hybrid local–cloud architecture composed of four functional layers.

The first layer corresponds to the game engine, implemented in Unity, which manages gameplay logic, mission progression, user interaction, and visualisation. This layer provides the interface through which players interact with the simulation.

The second layer consists of the energy simulation module, which models electricity demand, renewable and conventional energy production, storage behaviour, carbon emissions, and land occupation. This module operationalises the educational objectives of the game by transforming player decisions into system-level consequences.

The third layer is the data management component. Mission configurations, renewable production datasets, gameplay parameters, and player progress are stored locally using JSON files. This approach enables offline gameplay while preserving access to authentic operational data.

The fourth layer comprises cloud-based services that support player authentication, score synchronisation, leaderboard management, and data backup whenever internet connectivity is available.

The architecture was designed to support both educational and research functions. From an educational perspective, the simulation module provides learners with a simplified but structurally authentic representation of electricity-system operation. From a research perspective, gameplay interactions generate observable behavioural data concerning decision-making strategies, adaptation to renewable variability, and responses to environmental constraints.

3.4 Ethical Considerations

Ethical procedures were established before classroom implementation and data collection.

Participation was voluntary and conducted within an educational setting. Students and teachers were informed about the objectives of the activity and the nature of the data being collected. Data collection focused exclusively

on gameplay interactions, usability observations, and participant feedback. No sensitive personal information was collected, stored, or analysed.

As this study reports the first DBR cycle, the primary objective was not to establish causal evidence of learning effectiveness but rather to examine feasibility, usability, and pedagogical potential.

3.5 Participants and Educational Context

The preliminary implementation involved 31 participants aged between 12 and 18 years. The sample included 23 lower-secondary school students and eight additional participants recruited through school educational activities.

The intervention was conducted in an authentic educational context. Prior to gameplay, participants received a brief introduction covering energy-system concepts, game objectives, mission rules, and interaction mechanisms. Following this introduction, participants interacted with the game individually or in small groups while researchers and teachers observed gameplay behaviour.

3.6 Data Collection

Consistent with DBR methodology, multiple sources of evidence were collected to support formative evaluation and iterative refinement.

Classroom observations were conducted throughout gameplay sessions to identify usability barriers, interaction difficulties, and emerging decision-making behaviours. Particular attention was given to how participants responded to renewable variability, storage depletion, and environmental constraints.

Following gameplay, participants completed an exploratory questionnaire addressing perceived usability, engagement, challenge level, and educational value. Open-ended questions additionally examined participants' perceptions regarding renewable energy integration, environmental impacts, and electricity-system operation.

Participating teachers provided complementary qualitative feedback concerning classroom applicability, curriculum alignment, gameplay complexity, and pedagogical relevance.

3.7 Data Analysis

The analysis adopted an exploratory and formative orientation consistent with the objectives of the first DBR cycle. Given the preliminary nature of the implementation, the focus was placed on identifying patterns of interaction, usability issues, and indicators of systems-oriented reasoning rather than measuring learning gains.

Quantitative questionnaire responses were analysed using descriptive statistics, including frequencies, percentages, means, and standard deviations where appropriate.

Qualitative data obtained from classroom observations, open-ended questionnaire responses, and teacher feedback were analysed thematically. Particular attention was given to evidence of adaptation to renewable variability, recognition of environmental trade-offs, and management of operational constraints during gameplay.

The purpose of the analysis was to evaluate the alignment between the pedagogical mechanisms embedded in the game design and the behaviours observed during implementation. Findings from this process informed the identification of design improvements and priorities for subsequent DBR iterations.

3.8 Case Study: Primary Energy

Primary Energy is a data-driven serious game designed to support systems-based energy literacy through simulation of electricity-system operation under realistic environmental and operational constraints.

Gameplay represents a complete 24-hour operational cycle divided into 24 sequential hourly missions. Each mission corresponds to one hour of system operation and incorporates authentic renewable production values obtained from Portuguese national energy datasets. This structure ensures consistency between the underlying renewable energy data and the progression of gameplay.

Players must satisfy electricity demand while simultaneously managing carbon emissions, land-use impacts, and storage availability. Six energy sources are available: coal, petroleum, natural gas, hydroelectric, solar, and wind power.

Renewable generation varies dynamically according to authentic hourly production profiles, whereas fossil-based sources provide greater operational stability at the cost of increased emissions. Consequently, players must continuously evaluate trade-offs between reliability and sustainability while adapting their strategies to changing system conditions.

To balance simulation fidelity and pedagogical usability, several engineering simplifications were intentionally introduced. Electricity markets, reserve mechanisms, transmission constraints, frequency regulation, and economic dispatch models were excluded from the simulation. However, the core dynamics of renewable intermittency, electricity balancing, storage management, emissions control, and resource constraints were preserved.

This balance allowed the game to maintain educational accessibility for secondary-school learners while retaining the essential characteristics of real-world electricity-system operation.

4. Preliminary Classroom Evaluation and Discussion

A preliminary classroom evaluation was conducted to examine the technical feasibility, usability, and pedagogical potential of *Primary Energy* within an authentic educational setting. The evaluation involved 31 participants aged between 12 and 18 years, including 23 lower-secondary school students and eight additional participants recruited through complementary school educational activities.

Participants initially received a brief introduction to the educational objectives of the game, the underlying energy-system concepts, and the operational rules associated with mission completion, illustrated in Figure 2.

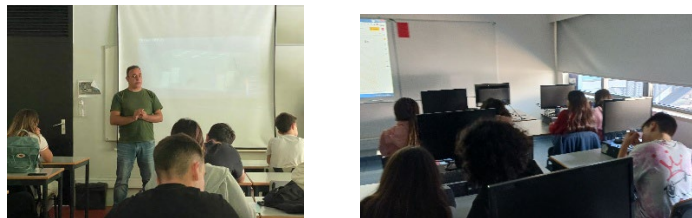


Figure 2: Preparation before game interaction

Following the introduction, participants interacted individually or in small groups with the platform while researchers observed gameplay behaviours, interaction patterns, and usability issues. Throughout the activity, teachers and researchers provided support when required and encouraged discussion concerning renewable energy, electricity production, and sustainability challenges.

Figure 3. shows students interacting with the *Primary Energy* platform during classroom implementation.

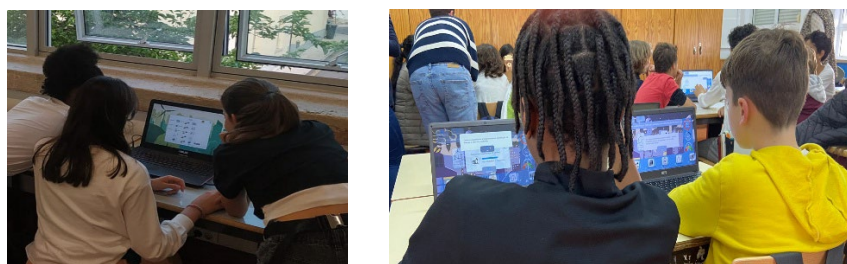


Figure 3: Game interaction from students

The evaluation adopted an exploratory and formative orientation consistent with the first cycle of the Design-Based Research methodology. Rather than measuring definitive learning outcomes, the primary objective was to assess usability, participant engagement, and indications of systems-oriented reasoning emerging during gameplay.

4.1 Evaluation Results

Classroom observations indicated that most participants were able to understand the mission structure and engage successfully with the constrained balancing mechanics after a short familiarisation period. Participants progressively demonstrated greater awareness of the environmental implications associated with different energy-production choices and increasingly considered the relationships between electricity demand, renewable availability, storage capacity, and carbon emissions when making decisions.

Several participants adapted their strategies throughout the simulation in response to changes in renewable generation and storage depletion. Instead of maintaining fixed decision patterns, players modified resource-allocation choices according to the evolving state of the simulated electricity system. This behaviour suggests engagement with the dynamic characteristics of renewable-energy integration and electricity balancing.

The evaluation also revealed several usability issues requiring refinement. The most frequently observed difficulties were associated with repeated drag-and-drop interactions and the selection of energy quantities across consecutive missions. Participants suggested more efficient interaction mechanisms and clearer visual indicators to support decision-making. These observations informed subsequent interface modifications and gameplay improvements.

Following gameplay, participants completed an exploratory feedback questionnaire focusing on engagement, usability, and perceived educational value. Approximately 80% of participants reported that the game was enjoyable and considered the challenge structure motivating. Several students additionally indicated that the game increased their awareness of environmental impacts associated with electricity production and improved their understanding of the challenges involved in balancing energy demand while reducing environmental impacts.

Teacher feedback was similarly positive. Educators highlighted the platform's potential to support classroom discussion concerning renewable intermittency, sustainability, carbon emissions, and electricity-system management. They also considered the game suitable for integration into science, technology, and environmental education activities.

To complement the classroom observations, quantitative evidence from the broader PAFSE educational intervention was examined. Within the "Energy Sources and Public Health Impact" scenario, students participating in the intervention demonstrated positive changes in Mathematics and Science interest scores following implementation. Mathematics increased from 3.364 to 3.515, while Science increased from 3.542 to 3.574. In contrast, the control group exhibited decreases across all STEM-related dimensions. Although these data do not directly measure learning outcomes associated with *Primary Energy*, they provide contextual evidence that educational activities centred on energy-system challenges can contribute positively to student engagement with STEM-related subjects.

Figure 4. presents the pre- and post-scenario-interest scores for intervention (PAFSE) and comparison groups (Control) in the "Energy Sources" serious game.

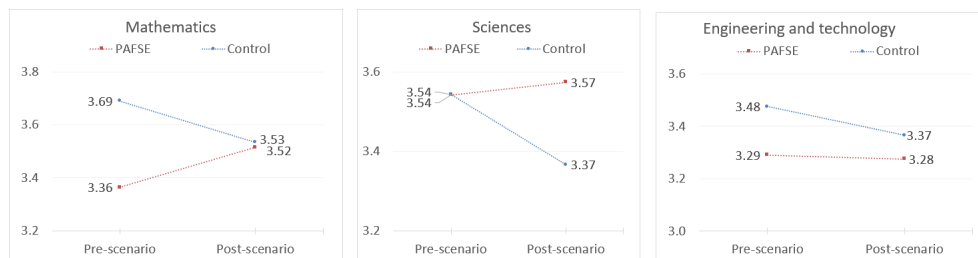


Figure 4: Questionnaire answers from students related to STEM areas

Students in the intervention group demonstrated positive changes, whereas the comparison group exhibited decreases across all STEM-related dimensions. The non-intervention group showed declining scores across all measured dimensions. Within the "Energy Sources" serious game, students participating in the intervention demonstrated positive changes in Mathematics and Science interest scores. In contrast, the comparison group exhibited decreases across all STEM-related dimensions.

4.2 Discussion

The results of the first Design-Based Research cycle provide preliminary evidence regarding the feasibility of integrating authentic renewable-energy data into a serious-game environment while maintaining educational accessibility and learner engagement.

One of the main objectives of the study was to investigate whether authentic renewable-energy variability could be effectively incorporated into serious-game design. The classroom evaluation demonstrated that participants actively responded to fluctuations in solar and wind generation and adapted their decisions according to

changing operating conditions. Rather than relying on static strategies, players modified energy-allocation decisions as renewable availability changed throughout the simulation.

These findings suggest that authentic temporal renewable-energy data can be integrated successfully into educational gameplay without compromising usability. The incorporation of real hourly production profiles also contributes to a more realistic representation of electricity-system operation than is typically found in simplified educational simulations.

A second objective was to explore whether the game could encourage systems-oriented reasoning through constrained decision-making. The observed gameplay behaviours provide encouraging evidence in this regard. Participants were required to consider multiple interconnected variables simultaneously, including electricity demand, renewable generation, storage capacity, and carbon emissions.

As gameplay progressed, learners increasingly recognised that decisions favouring one objective often generated consequences elsewhere within the system. The emergence of trade-off reasoning between environmental performance and operational reliability indicates that participants were engaging with the interconnected nature of electricity-system management rather than focusing exclusively on individual energy sources.

Although the present evaluation does not provide direct measurement of systems-thinking competencies, the observed behaviours are consistent with the pedagogical principles underpinning the game design and suggest that the simulation successfully promotes reflection on system-level interactions.

The evaluation demonstrated that the platform is technically functional and pedagogically accessible for secondary-level learners. Most participants were able to understand the gameplay mechanics after a short introduction and engage meaningfully with the mission structure. The positive feedback obtained from students and teachers further supports the educational potential of the platform.

The findings also validate the design decision to balance simulation fidelity with pedagogical usability. Several engineering complexities associated with real electricity systems, including electricity markets, reserve mechanisms, transmission constraints, and economic dispatch processes, were intentionally excluded from the simulation. However, the preservation of renewable intermittency, storage management, emissions control, and electricity balancing proved sufficient to create meaningful learning experiences while maintaining an appropriate level of complexity for the target audience.

The broader PAFSE results provide additional support for the educational relevance of energy-related learning activities. Although these data cannot be directly attributed to *Primary Energy*, the positive trends observed in Mathematics and Science interest suggest that energy-system challenges can serve as effective contexts for engaging students with STEM-related topics.

The findings of the first Design-Based Research cycle provide valuable guidance for the continued development of *Primary Energy*. The classroom implementation confirmed the feasibility of integrating authentic renewable-energy data into a serious-game environment while maintaining accessibility for secondary-level learners.

The evaluation also identified opportunities for further enhancement. In particular, participants would benefit from improved visualisation of system states, more explicit feedback regarding the consequences of their decisions, and additional support mechanisms during the initial gameplay stages. These improvements are expected to strengthen the connection between player actions and system-level outcomes and further reinforce the systems-thinking objectives embedded in the instructional design.

The positive reception from both students and teachers suggests that the game has potential as a complementary educational resource for sustainability, renewable-energy, and science education contexts. Future development efforts will therefore focus on expanding gameplay scenarios, refining user interaction mechanisms, and enhancing the representation of energy-system trade-offs.

The final stage of the project included an open dissemination event involving participating schools, during which students shared experiences and reflected on the challenges associated with renewable-energy integration and sustainable electricity production, as shown in Figure 5.

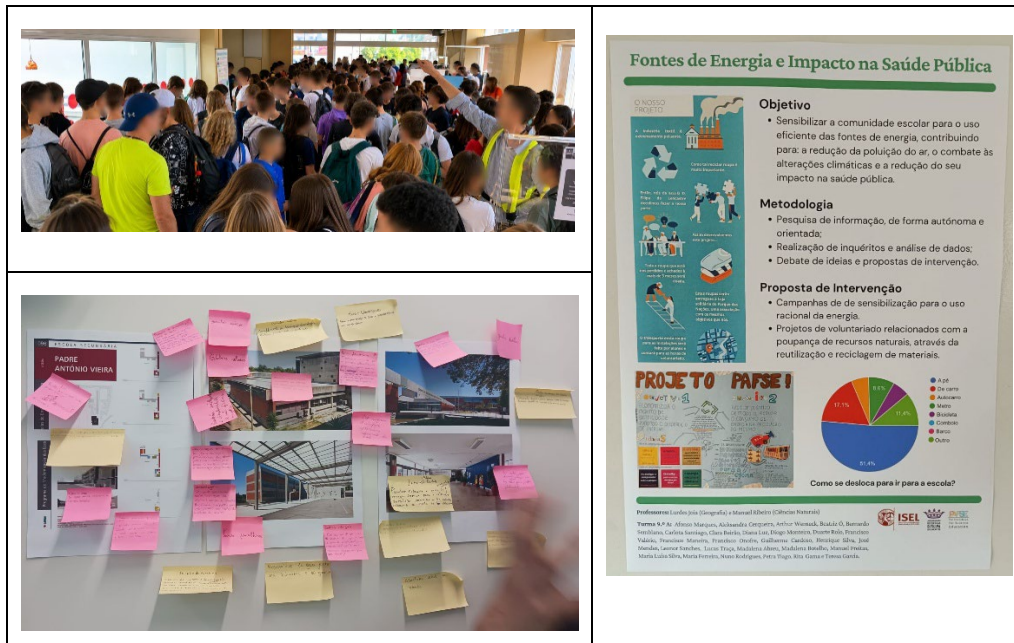


Figure 5: Dissemination and open day

The implementation cycle proves that integrating real temporal variability into mission-based gameplay is both technically viable and pedagogically promising, even for a small group. However, evidence concerning systems reasoning development and procedural energy literacy remains exploratory at this stage. Future research will therefore incorporate more systematic empirical evaluation, including pre–post assessments, gameplay log analysis, and structured examination of learner decision strategies over time.

Prior to the implementation of the educational scenario, students in the intervention group exhibited lower levels of interest in STEM-related studies than those in the comparison group. Following the intervention, interest in Mathematics and Science increased among students who participated in the serious game, while interest in Engineering and Technology remained relatively stable, showing only a marginal decrease. In contrast, students in the comparison group demonstrated declines across all STEM-related domains. The most notable positive change observed in the intervention group was in Mathematics, which showed the largest increase between the pre- and post-intervention assessments.

5. Conclusions

Applications that address these themes of public health, science and technology for teaching, require many difficulties to reach a final product, as it involves different profiles of several students, as well as involving them in real scenarios and conceptualize for recurrent themes. The development of this game tried to focus more on being fun, educational and, in the end, by meeting all the challenges, being able to understand the impacts of each energy and what it takes to produce an amount of energy per hour, making us reflect together and see what could be improved. The evaluation done until now gave us positive information to improve the game. Nevertheless, for future work, more consistent evaluation needs to be done, in particularly, the evaluation of the educational component.

Ethics Declaration: N/A

AI Declaration: No AI tools were used the creation of this paper.

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