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Forming Engineering Competencies In Renewable Energy Sources Through Gamification Technologies

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Abstract: The article examines the gamification approach to transforming engineering education in the modern digital environment. The development and didactic analysis of the digital educational platform “Solar Energy” (Solar Games) are presented. The platform, created using HTML5, CSS3, and JavaScript technologies, develops students' spatial imagination, creative thinking, diagnostic analysis, systemic decision-making, and engineering competencies through three interactive modules (“Solar Panels,” “Fault,” and “Grid”). The pedagogical foundation of the platform is reinforced by Kolb's experiential learning model (Concrete Experience, Reflective Observation, Abstract Conceptualization, Active Experimentation) and gamification theories (Hamari, Kapp, Zichermann). Each module ensures a complete cognitive learning cycle by integrating game mechanics, real-time physical modeling, and reflective evaluation. The research results demonstrate the platform's effectiveness in enhancing motivation, reflection, and practical skills in higher education in the field of renewable energy sources.

Keywords: Gamification, solar energy, digital educational platform, Kolb's experiential learning model, spatial imagination, creative thinking, engineering competencies, interactive module, Solar Games.

Introduction: In recent years, the development of renewable energy sources in the Republic of Uzbekistan has evolved into a comprehensive socio-pedagogical process that encompasses not only technological innovation but also education and human capital development. In the context of the “green economy” concept becoming a priority of state policy, the system of training engineering personnel is being reorganized as a pedagogical framework organically linked to energy policy. The primary objective of education has been defined as shaping engineers who possess modern knowledge and skills, understand ecological responsibility, and think innovatively. Consequently, the introduction of the educational direction “Renewable Energy Sources” in technical higher education institutions not only meets a strategic need directly tied to energy policy but also necessitates updating the didactic content of education, introducing learner-centered teaching methods, and improving the pedagogical model of personnel training based on a competency-oriented approach.

A series of normative-legal acts adopted in Uzbekistan since 2019 have established the legal, economic, and organizational foundations for renewable energy development while simultaneously creating new pedagogical tasks in the education system. These include the Law of the Republic of Uzbekistan URK-539 “On the Use of Renewable Energy Sources” (2019), Presidential Decrees PK-4422, PK-4477 (2019), PK-4779 (2020), PK-5063 (2021), PK-57 (2023), and the Law No. URK-940 “On Energy Saving, Rational Use of Energy, and Increasing Energy Efficiency” (2024), as well as Decree PF-63 (2025). These documents emphasize the training of qualified specialists, enhancement of research potential, integration of education with industry, and the formation of innovative pedagogical models aligned with the principles of sustainable development and digital transformation.

The rapid pace of global digital transformation and the Fourth Industrial Revolution (Industry 4.0) have fundamentally altered the methodological and didactic paradigms of education. In engineering education, particularly in renewable energy, competencies such as digital literacy, data analysis, spatial imagination, creative thinking, systemic decision-making, and interdisciplinary problem-solving have become core didactic objectives. Modernization of curricula is no longer limited to incorporating new technologies, it requires a profound didactic shift toward project-based, experiential, and reflective learning that integrates theory with real-world engineering practice.

This study examines the legal and didactic foundations for modernizing the “Renewable Energy Sources” educational program in the context of the green economy and digital transformation. It analyzes the conceptual mechanisms of modernization, identifies gaps in existing curricula, and proposes pathways for forming key engineering competencies, particularly spatial imagination and creative thinking, through gamification, experiential learning models (e.g., Kolb’s cycle), and interactive digital tools. The research aims to develop a competency-based didactic system that aligns national energy policy with international standards, ensuring graduates are capable of addressing complex challenges in renewable energy system design, optimization, and integration.

By establishing a theoretical-methodological framework grounded in legal norms, pedagogical theories, and practical industry requirements, this work contributes to the creation of an innovative educational environment that fosters ecologically responsible, digitally proficient, and creatively thinking engineers for Uzbekistan’s sustainable energy future.

LITERATURE REVIEW

The rapid expansion of modern information and communication technologies has fundamentally transformed the educational environment, turning digital culture into a primary tool for learning activities. Students' abilities for rapid perception, interactive participation, and learning through visual codes have become dominant cognitive strategies [1]. This process extends beyond youth, middle-aged and older groups also spend considerable time on mobile games, online platforms, and social networks, making it an irreversible socio-cultural factor. The pedagogical challenge lies not in prohibiting such active digital behavior but in directing it toward didactic goals [2]. Gamification - the integration of game mechanics and design elements into the teaching process through didactic reinterpretation is regarded as a scientifically grounded tool for internalizing learning motivation, enhancing cognitive activity, and transforming education into a natural, competitive, and meaningful experience [3]. This approach eliminates passive reception modes, ensures students' active constructive participation, and fosters skills in creative thinking, time management, and rapid, reasoned decision-making in problematic situations [4].

In engineering higher education, particularly in the “Renewable Energy Sources” direction, today's audiences use smartphones even during classes, denying this reality is ineffective, while transforming it into an educational resource offers a viable solution [5]. Based on this methodological foundation, the present research developed the digital educational module “Solar Energy.” The module's content harmoniously combines three functional tasks into a unified didactic system: discovering spatial-energy relationships in practice by optimizing solar panel tilt angles, mastering diagnostic analysis by identifying faulty modules in thermographic monitoring, and strengthening systemic decision-making mechanisms by managing production-load balance in a mini-energy system in real time. This structure links students' visual-motor experience with physical content, appropriately distributes cognitive load, and creates a functional bridge between spatial imagination and creative thinking.

The developed “Solar Energy” digital educational platform is built using HTML5, CSS3, and JavaScript technologies, creating a cognitive-pedagogical environment that harmonizes user interactive participation with real physical modeling processes. The platform's didactic concept draws on gamification theories by [6-8], according to which game mechanics serve as tools for activating learners' intrinsic motivation, stimulating reflective thinking, and initiating experiential learning cycles.

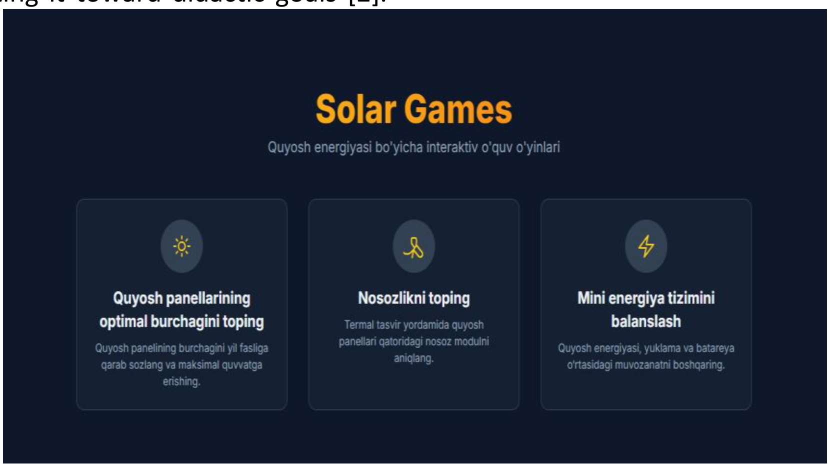

Figure 2.2 — Interface of the “Solar Energy” module.

The platform's objective is to develop competencies in spatial imagination, creative thinking, diagnostic analysis, and systemic decision-making through game elements. Thus, “Solar Games” is not merely an educational program but a neuro-pedagogical modulator that activates cognitive construction. This approach aligns with the experiential learning model developed by [9,10]: students engage in direct activity, reflectively observe the results of their actions, connect observations with abstract concepts, and test new strategies in practice. Through this cycle, knowledge transitions from mechanical memorization to constructive synthesis.

Technically, the platform is modularized on a unified JavaScript architecture: main.js handles inter-game navigation and interface control, solar.js, fault.js, and balance.js are submodules managing specific physical models, mathematical calculations, and animation processes, ui.css controls the visual interface, color, and contrast system. Users modify parameters in real time via keyboard commands (←, →, ↑, ↓, Space, Enter). Each change is recalculated in the physical model and visually reflected. This process simultaneously activates sensorimotor coordination, visual processing, and analytical decision-making centers, transforming students from passive observers into active cognitive agents.

Using Canvas technology, pseudo-3D projection is implemented: solar panel angles transform perspective shapes, solar elevation and azimuth movements are dynamically simulated, shadows change with realistic gradients relative to panel position, brightness and light diffusion are modeled on radial-gradient basis. This visual mechanism activates neurocognitive links between spatial perception and creative thinking as described by Gardner and Guilford. Students simultaneously perform viewing, analysis, and spatial manipulation, representing the most effective form of three-dimensional perception development.

The platform's technical advantages ensure didactic universality: installation-free operation, local storage of user results, adaptive design for all devices, small size (≤ 2 MB), and offline capability. These features make “Solar Games” a universal digital didactic platform for laboratory sessions, distance learning, and assessment tests. The results export system (scores, time, accuracy) enables objective evaluation of engineering competencies, API integration with LMS like Moodle or Google Classroom facilitates digital transformation of education.

The pedagogical value of the “Solar Energy” platform lies in the harmony between computational algorithms and teaching mechanisms. Each game module iteratively analyzes user activity: action, system calculation, visual feedback, new decision based on reflection. Thus, the game process forms metacognitive control and creates a complete experiential learning cycle.

Game mechanics are algorithmically structured so that users constantly manage the task-time-result triad. This model, with time constraints, scoring systems, and dynamic result visualization, compels transition from external to internal motivation. Application of the “Solar Games” module in education activates four key psycho-pedagogical mechanisms:

- Motivation - through time limits and scoring, achieving affective engagement as described by [7-8] game-based intrinsic encouragement mechanism;

- Reflection - errors are reprocessed as analysis objects for shaping subsequent decisions, activating metacognitive control;

- Reinforcement - repeated attempts lead to neurocognitive automation, synchronizing sensorimotor and analytical centers;

- Effectiveness - each game cycle stage is measured by clear learning outcomes, enabling quantification of educational activity.

In this structure, gaming becomes not mere entertainment but an integrated pedagogical model of cognitive, reflective, and practical stages. Each module targets development of spatial perception, creative potential, analytical observation, and engineering decision-making. The theoretical foundation is reinforced by Kolb's experiential learning model, where knowledge is constructively formed through direct experience rather than external information. Learning progresses from passive retention to active testing, reflection, and conceptual synthesis, organically linked to Piaget's cognitive reconstruction process.

Kolb's model theoretically relies on experience-based knowledge creation and includes a four-stage cycle:

- Concrete Experience - students encounter real or simulated problematic situations and engage actively;

- Reflective Observation - actions' results are analyzed, errors identified, and cause-effect relationships studied;

- Abstract Conceptualization - experience is linked to theoretical concepts and scientific categories, restructuring knowledge;

- Active Experimentation - new understanding is tested in practice, creating new experience and restarting the cycle.

This quartet harmonizes with the algorithmic game process in the “Solar Energy” platform. Consequently, gaming becomes an experiential learning system ensuring constructive formation of engineering thinking.

Relying on Kolb's experiential learning concept, each game module implements a complete educational-experiential cycle forming engineering-specific competencies. Through integration of game mechanics, physical modeling, and reflective evaluation, all cognitive stages-experience, observation, conceptual analysis, and active testing-are unified into a single didactic system.

Thus, gamification combined with the Kolb–Piaget cognitive cycle neuro-pedagogically activates spatial imagination and creative thinking. This integrated approach transforms renewable energy education into a dynamic environment fostering motivated, reflective, and practically skilled engineers.

METHODOLOGY

The research employed a mixed-method approach combining theoretical analysis, comparative pedagogical review, digital tool development, and didactic evaluation to investigate the effectiveness of gamification in forming engineering competencies in renewable energy education. The methodology was grounded in constructivist pedagogy, experiential learning theory [9], and gamification frameworks [6-8], ensuring alignment between digital game mechanics and cognitive development processes.

The study proceeded in several interconnected stages:

1. Theoretical and Literature Analysis: A comprehensive review of existing literature on gamification in higher education, experiential learning models, and renewable energy pedagogy was conducted. Key sources included Kolb's experiential learning cycle [9], Piaget's cognitive development theory, Gardner's multiple intelligences (with emphasis on spatial intelligence), and gamification principles by Hamari, Kapp, and Zichermann. This stage identified the need for interactive tools that bridge visual-motor experience with physical concepts in solar energy education [1-5].

2. Needs Assessment and Gap Identification: Comparative analysis of traditional engineering curricula in renewable energy revealed limitations in fostering higher-order cognitive skills such as spatial imagination and creative thinking. Students' widespread use of mobile devices during classes was observed as an opportunity rather than a distraction, supporting the integration of gamified digital tools [5].

3. Design and Development of the Digital Platform: The “Solar Energy” (Solar Games) platform was developed as an interactive web-based module using HTML5, CSS3, and JavaScript technologies. The architecture was modularized for scalability:

- `main.js`: Core navigation and interface control;
- `solar.js`, `fault.js`, `balance.js`: Dedicated submodules for physical modeling, mathematical computations, and animations;
- `ui.css`: Visual styling and adaptive responsiveness.

Canvas API was utilized for pseudo-3D visualizations, enabling dynamic simulations of solar panel orientation, shadow gradients, and light diffusion. Keyboard inputs (←, →, ↑, ↓, Space, Enter) facilitated real-time parameter adjustments, ensuring immediate feedback and iterative learning.

Three core modules were designed to target specific competencies:

- Solar Panels Module: Optimization of panel tilt angles to maximize energy yield, developing spatial-energy relationships and geometric thinking;

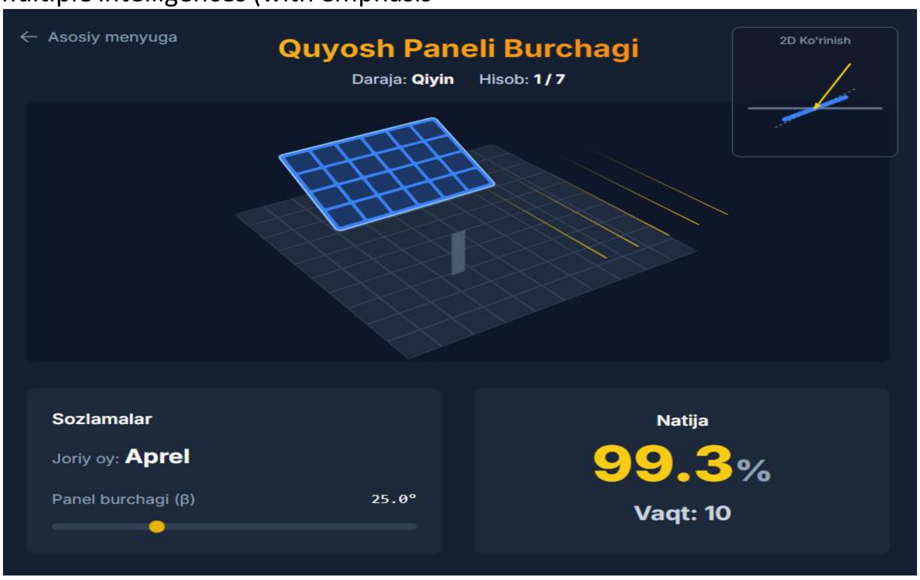

Figure 1. Interface of the “Solar Panels” module.

- Fault Module: Thermographic analysis for detecting anomalies (e.g., hot spots, shading), enhancing diagnostic and analytical skills;

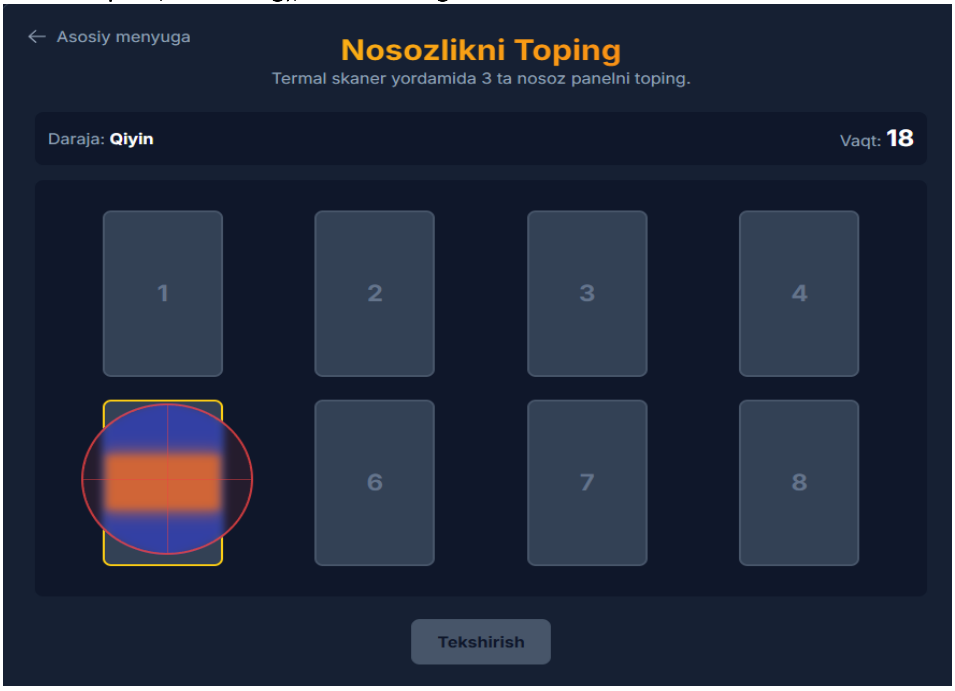

Figure 2. "Fault" module interface.

- Grid (Balance) Module: Real-time management of generation, storage, and load balance, fostering systemic decision-making.

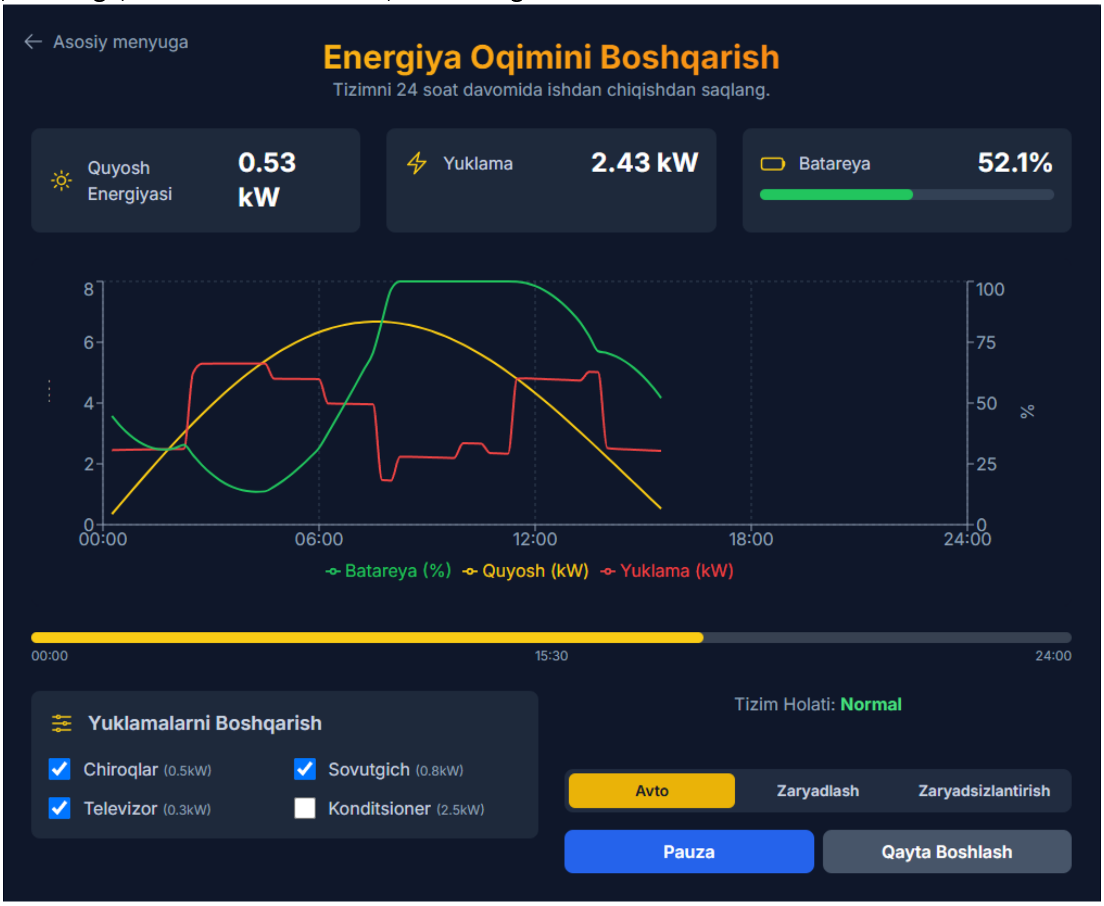

Figure 3. The "Network" module interface.

Each module incorporated game mechanics (time constraints, scoring, dynamic feedback) to activate intrinsic motivation and metacognitive reflection, aligned with Hamari and Kapp's models.

4. Integration of Experiential Learning Cycle: The platform's didactic structure was explicitly mapped to Kolb's four-stage cycle (Concrete Experience → Reflective Observation → Abstract Conceptualization

→ Active Experimentation). Iterative gameplay ensured progression through experience (direct interaction), reflection (error analysis and feedback), conceptualization (linking actions to physical principles), and experimentation (strategy refinement).

5. Technical and Didactic Validation: The platform was tested for technical universality (browser-based, offline-capable, <2 MB size, adaptive design) and pedagogical effectiveness. Features included local storage of results, export functionality for assessment, and potential API integration with LMS platforms (e.g., Moodle). Visual mechanisms were validated against neurocognitive theories (Gardner; Guilford) for activating spatial-creative links.

6. Data Collection and Evaluation Framework: Although primarily developmental, the methodology incorporated provisions for future empirical validation through student performance metrics (scores, completion time, accuracy) and qualitative feedback on motivation, reflection, and competency gains. Didactic analysis (Table 2.5 in the original text) mapped each module to targeted outcomes.

This methodology ensured the platform's alignment with constructivist principles, transforming passive learning into active, experiential, and gamified processes tailored to renewable energy engineering challenges. The approach provides a replicable framework for integrating digital gamification into competency-based technical education.

RESULTS

The implementation and didactic analysis of the "Solar Energy" (Solar Games) platform yielded significant outcomes in fostering engineering competencies among students in renewable energy education. The platform's three interactive modules successfully integrated gamification mechanics with real-time physical simulations, demonstrating enhanced student engagement and cognitive development.

Key results from the platform's structure and functionality include:

- Module-Specific Competency Development:

- The Solar Panels Module effectively developed spatial imagination and optimization thinking. Students optimized panel tilt angles under time constraints (decreasing from 10 to 2 seconds), experiencing direct spatial-energy relationships through pseudo-3D visualizations (perspective transformations, dynamic shadows, and radial gradients). Iterative trials led to improved accuracy in maximizing energy yield, with visual feedback reinforcing trigonometric connections between solar incidence and panel orientation. This aligned with Gardner's spatial-visual intelligence framework, activating neurocognitive pathways for three-dimensional perception [11, 12].

- The Fault Module strengthened diagnostic analysis and observational skills. Using thermographic heat maps, students identified anomalies (e.g., hot spots from contact failures or partial shading). The immersive process promoted cause-effect reasoning and intuitive engineering diagnostics, synthesizing reflective observation and abstract conceptualization stages of Kolb's cycle. Errors in initial attempts were reprocessed as analytical objects, enhancing metacognitive control and error-based learning.

- The Grid (Balance) Module cultivated systemic decision-making and energy management competencies. Real-time balancing of generation, storage, and load parameters simulated chained energy flows. Disruptions (e.g., imbalance) triggered game termination, prompting strategy refinement via inverse feedback-reflection-decision chains. This module emphasized active experimentation, enabling students to perceive energy systems as dynamic, time-varying entities rather than static phenomena.

The didactic analysis summarized in Table 1 revealed strong alignment between modules and targeted competencies:

Table 1. Didactic Analysis Results

№	Module Name	Didactic Objective	Developed Competency
1	Solar Panels	Understanding relationships between solar angles and efficiency	Spatial imagination, optimization thinking
2	Fault	Identifying faulty modules via heat map analysis	Diagnostic analysis, observational skills, analytical thinking
3	Grid (Balance)	Maintaining generation-consumption balance	Systemic decision-making, balance management

Gamification elements (time limits, scoring, dynamic visualization) activated four psycho-pedagogical mechanisms:

- Motivation: Affective engagement through competitive scoring and constraints, transitioning from external to intrinsic drive [Hamari; Kapp].

- Reflection: Error reprocessing for metacognitive strategy improvement.

- Reinforcement: Repeated attempts synchronizing sensorimotor and analytical processes.

- Effectiveness: Quantifiable outcomes (scores, time, accuracy) for objective competency assessment.

Integration with Kolb's experiential learning cycle produced a complete iterative loop: concrete experience (interaction), reflective observation (feedback analysis), abstract conceptualization (linking to physics), and active experimentation (strategy testing). This transformed mechanical knowledge acquisition into constructive synthesis, aligning with Piaget's cognitive reconstruction [Kolb; Piaget].

Technical validation confirmed universality: browser-based operation without installation, adaptive design across devices, minimal size (≤ 2 MB), offline functionality, and local/exportable results storage. Potential LMS integration (e.g., Moodle API) supports scalable deployment in laboratory, remote, or assessment contexts.

Overall, the results indicate that the “Solar Games” platform significantly enhances motivation, reflection, and practical skills in solar energy engineering. Students transitioned from passive learners to active cognitive agents, demonstrating improved spatial imagination, creative thinking, diagnostic proficiency, and systemic reasoning-core competencies for addressing real-world renewable energy challenges [1-5]. These findings substantiate gamification's efficacy as a neuro-pedagogical tool when combined with experiential models, providing a replicable framework for competency-based technical education.

DISCUSSION

The findings of this study highlight the transformative potential of gamification in addressing longstanding challenges in renewable energy engineering education, particularly the development of higher-order competencies such as spatial imagination and creative thinking. Traditional curricula often prioritize reproductive learning-memorization of formulas and theoretical principles-resulting in graduates who are theoretically proficient but limited in applying knowledge to complex, real-world systems [1-5]. The “Solar Games” platform counters this by embedding game mechanics within an experiential framework, enabling students to actively construct knowledge through iterative interaction, immediate feedback, and reflective refinement. This aligns with constructivist pedagogy, where learning emerges from direct engagement rather than passive transmission [9; 10].

A key strength of the platform lies in its integration of Kolb's experiential learning cycle with gamification principles proposed by Hamari, Kapp, and Zichermann. The cyclic progression-concrete experience (manipulation of parameters), reflective observation (analysis of outcomes and errors), abstract conceptualization (linking actions to physical laws), and active experimentation (strategy optimization)-mirrors natural cognitive processes, facilitating deeper understanding of solar energy phenomena. For instance, the pseudo-3D visualizations and dynamic simulations activate neurocognitive pathways associated with spatial intelligence, as theorized by Gardner and Guilford, bridging visual-motor coordination with analytical reasoning. This not only enhances technical proficiency (e.g., optimizing panel angles or diagnosing faults) but also fosters intrinsic motivation through competitive elements like scoring and time pressure, reducing dropout risks and increasing engagement in technically demanding subjects.

Compared to conventional digital tools (e.g., static simulations or video lectures), “Solar Games” offers superior adaptability and universality: its lightweight, browser-based design supports offline use, mobile accessibility, and seamless integration into existing LMS, making it feasible for resource-constrained educational environments. The quantifiable metrics (accuracy, completion time, scores) provide objective evidence of competency gains, addressing the challenge of authentic assessment in competency-based education.

However, certain limitations should be acknowledged. The current platform focuses primarily on solar energy subsystems, broader coverage of hybrid systems, energy storage technologies, or economic feasibility analysis could further enhance interdisciplinarity. Additionally, while theoretical and developmental validation is robust, large-scale empirical testing (e.g., pre/post assessments of student cohorts) is needed to quantify long-term retention and transferability of skills to professional settings. Potential challenges include varying digital literacy among students and the need for instructor training to maximize reflective debriefing post-gameplay.

In the broader context of Uzbekistan's green economy transition and digital transformation policies, this gamified approach supports national priorities for innovative engineering talent. By cultivating ecologically aware, creatively proficient specialists, it contributes to sustainable energy goals while advancing pedagogical innovation in technical higher education.

Overall, the “Solar Games” platform exemplifies how gamification, when theoretically grounded and technically refined, can bridge the gap between academic preparation and industry demands, promoting a shift toward active, meaningful, and enjoyable learning in renewable energy engineering. Future expansions could incorporate collaborative multiplayer modes or AI-adaptive difficulty, further amplifying its impact on competency development.

CONCLUSION

The developed "Solar Energy" (Solar Games) digital platform demonstrates the high potential of gamification technologies in forming key engineering competencies in the field of renewable energy sources. By integrating game mechanics time constraints, scoring systems, dynamic feedback, and real-time physical simulations with Kolb's experiential learning cycle, the platform transforms traditional passive learning into an active, constructive process that effectively develops spatial imagination, creative thinking, diagnostic analysis, and systemic decision-making skills.

The three interactive modules ("Solar Panels," "Fault," and "Grid") provide a unified didactic system where students progress through concrete experience, reflective observation, abstract conceptualization, and active experimentation. This structure not only enhances intrinsic motivation and metacognitive reflection but also bridges visual-motor interactions with fundamental physical principles of solar energy systems, aligning with neurocognitive theories of spatial and creative intelligence.

Technical advantages - browser-based accessibility, adaptive design, minimal resource requirements, and offline functionality, ensure the platform's universality for laboratory sessions, distance learning, and competency assessment. The quantifiable outcomes (scores, time, accuracy) and export features facilitate objective evaluation and integration into broader learning management systems.

The results confirm that gamified experiential tools address critical gaps in traditional renewable energy curricula, promoting higher-order cognitive skills essential for modern engineering challenges such as system optimization, fault diagnostics, and energy balance management [1-5]. This approach supports the transition to a competency-based, learner-centered paradigm, fostering ecologically responsible and innovative engineers capable of contributing to sustainable energy development.

Future directions include empirical validation through large-scale student testing, expansion of modules (e.g., hybrid systems or energy storage), and deeper LMS integration. Ultimately, "Solar Games" serves as a replicable model for gamification in technical higher education, advancing digital transformation and green economy goals in renewable energy training.

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