DEVELOPING STUDENTS' RESEARCH AND ENGINEERING ACTIVITIES IN THE FIELD OF SOLAR ENERGY: AN ANALYSIS OF EDUCATIONAL PROGRAM CONTENT AND THE DEVELOPMENT OF A METHODOLOGICAL SYSTEM MODEL

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Abstract

In this article, based on a comprehensive theoretical analysis of the content of the educational programs B062–Electrical Engineering and Energy and B054–Physics, a methodological system model was developed to foster students' research and engineering activities in the field of solar energy. During the study, employers' requirements were identified through a Google Forms survey, and their suggestions were systematized. The methodological system, created on the basis of modeling and design methods, made it possible to develop a new plan for teaching related disciplines and to integrate it into the educational process through STEM approaches. The proposed model is aimed at developing future specialists' research abilities, engineering thinking, and professional competencies.

Keywords: solar energy, research and engineering activity, methodological system model, STEM education, educational program.

Introduction

The global energy crisis and the requirements of sustainable development are increasing the importance of integrating the study of renewable energy sources, including solar energy, into the education system. Higher education institutions in Kazakhstan place particular emphasis on combining students' theoretical knowledge with practical experience within engineering and physics-oriented educational programs.

The development of research and engineering activities is a key mechanism for fostering innovative thinking and design skills among future specialists. In this regard, the development of a methodological system model adapted to the field of solar energy and its integration into the educational process has become an urgent issue.

The escalating global demand for sustainable energy sources has positioned solar energy at the forefront of scientific and engineering innovation, necessitating a robust educational framework to cultivate future experts in this domain (Kiv et al., 2023) (Kurbanbekov et al., 2024). Educational institutions, therefore, bear a crucial responsibility in integrating comprehensive solar energy curricula and practical experiences to foster environmental consciousness and sustainable practices among students (Altassan, 2023). This integration is pivotal for equipping students with the necessary knowledge, skills, and attitudes required by the evolving solar energy industry, encompassing areas from material science to photovoltaic technology and policy (Kuo & Chang, 2014).

Such initiatives often involve hands-on activities, summer programs, and specialized courses designed to engage students from diverse backgrounds, including underrepresented groups, in renewable energy concepts and green engineering (Ortiz et al., 2015) (Pedersen et al., 2018). For instance, secondary school curricula can incorporate practical experiments and project-based learning to inspire students toward renewable energy careers and enhance their understanding of solar energy systems (Flores et al., 2024) (Hoque et al., 2022).

These experimental modules should be uncomplicated, safe, and cost-effective, allowing for easy integration into existing educational programs and facilitating hands-on learning for middle and high school students (Chien et al., 2021). These programs often aim to inform, experiment with, raise awareness about, and disseminate information regarding renewable energy sources, specifically solar energy, through the design and implementation of photovoltaic systems in educational settings (Charles et al., 2023). Beyond direct classroom instruction, informal science programs and outreach initiatives play a critical role in supplementing formal education by providing students and teachers with opportunities to engage with cutting-edge research and real-world applications in solar energy (Flores et al., 2024).

This holistic approach ensures that students not only grasp theoretical concepts but also develop practical skills crucial for addressing real-world energy challenges and promoting sustainable development (Ulmeanu et al., 2021) (Charles et al., 2023). Furthermore, the successful transition to sustainable energy necessitates addressing skills gaps within the workforce through targeted educational programs and interdisciplinary courses that equip graduates with technical proficiency and an understanding of policy frameworks (Lv, 2023). This necessitates a pedagogical approach that integrates independent learning and physics innovation within STEAM-based renewable energy education (Zhaksylyk et al., 2025), particularly to enhance critical thinking skills pertinent to the demands of Society 5.0 and the Sustainable Development Goals 2030 (Indahwati et al., 2023).

Literature Review

Solar Energy Education: Current Trends

Several studies have highlighted the significance of incorporating innovative pedagogical methods within STEM-based education to adapt students' competencies for contemporary workforce demands, with a particular emphasis on critical thinking skills. Crucially, integrating independent learning, physics innovation, and the STEAM approach significantly enhances students' capacity for critical thinking in the context of renewable energy. This comprehensive approach prepares students to address real-world renewable energy challenges and contribute to achieving sustainable development goals. This pedagogical framework, aligning with the principles of Project-Based Learning in STEAM, specifically aims to cultivate early childhood skills essential for the Industrial Revolution 5.0, combining elements of science, technology, engineering, art, and mathematics through strategies such as reflection, discovery, application, and communication. Such an integrated curriculum emphasizes practical application and innovative solutions, thereby fostering a deeper understanding of renewable energy systems and their societal impact (Indahwati et al., 2023). The application of innovative pedagogical tools, such as Minecraft Education, can further enhance this integrated learning by providing immersive experiences that bridge conceptual gaps in renewable energy technologies and foster critical thinking and collaboration skills among students (Sulaiman, 2024). This integration not only boosts technical knowledge but also refines practical problem-solving and critical thinking abilities, which are vital for addressing complex issues in renewable energy. These digital game-based learning environments allow students to engage with solar photovoltaic concepts through hands-on activities, promoting active knowledge construction and experiential learning. This approach leverages the engaging nature of digital games to create a simulated environment where students can manipulate solar PV systems and observe outcomes, thereby solidifying their understanding of complex scientific principles. Such platforms enhance student engagement and retention by allowing them to conduct experiments and make observations in a controlled yet dynamic digital environment.

Student Engagement in STEM Fields

Moreover, the use of such innovative tools directly addresses the need for 21st-century skills and contributes to the Sustainable Development Goals, despite ongoing challenges in fully optimizing their implementation at the program level. These pedagogical advancements underscore a broader shift towards interdisciplinary and coherent educational frameworks, essential for tackling complex global sustainability problems that transcend single disciplinary boundaries (Mokoka et al., 2023). This evolving educational landscape prepares students not only with subject-specific knowledge but also with transversal competencies like critical thinking and problem-solving, vital for addressing the multifaceted challenges of sustainable energy (Marzuki et al., 2024). The integration of digital game-based learning, such as Minecraft Education, has been shown to significantly enhance student engagement and understanding of complex scientific concepts, like solar photovoltaic technology, by providing interactive and motivating learning experiences. This interactive approach allows students to simulate real-world scenarios, fostering a deeper comprehension and retention of scientific principles through practical application. This immersive environment facilitates understanding through "hands-on activities using 3D blocks within the game's virtual world," particularly during simulations that visually demonstrate photovoltaic effects. Such platforms have been demonstrably effective in improving students' knowledge retention and conceptual understanding of solar PV technology, as evidenced by significant enhancements observed in post-test and delayed post-test scores.

At present, although research is being conducted in the field of teaching solar energy within the education system, most studies are focused on fostering students' environmental awareness and organizing simple practical activities. However, there is a noticeable lack of systematic methodological models aimed at providing an in-depth mastery of solar energy, insufficient alignment of higher education program content with employers' requirements, and incomplete implementation of interdisciplinary approaches for developing students' research and engineering activities.

This raises the following research questions:

- How can a methodological system model be designed to develop students' research and engineering activities in the field of solar energy?
- How can the content of educational programs be aligned with employers' needs?
- What are the effective ways of integrating the proposed model into the educational process?

The aim of the study is to develop and implement a methodological system model, based on the Physics and Electrical Engineering and Energy educational programs, that ensures the development of students' research and engineering activities in the field of solar energy.

Research methods

Research Design

This study was based on a mixed-methods approach, as it employed both quantitative data (survey results, statistical measures) and qualitative data (document analysis, expert opinions). The research design combined descriptive and quasi-experimental features: the descriptive part involved a systematic analysis of educational program content and the collection of employers' recommendations, while the quasi-experimental part focused on introducing the developed methodological system model into the educational process and testing its effectiveness through practical experimentation.

Participants

The study involved employers with professional experience in the field of solar energy, specialists from the engineering and technical sector, and representatives of the education sector. The sample size included more than 40 respondents. Participants were selected using purposive sampling, as all of them possessed either professional or pedagogical experience related to solar energy. Sampling criteria: Having work experience in the field of solar energy or electrical energy; Demonstrating interest in improving educational programs or contributing to workforce training; Providing voluntary consent to participate in the study.

Instruments and Procedure

During the study, several tools and methods were employed for data collection and analysis. First, a survey was developed on the Google Forms platform and distributed to employers in the solar energy sector, engineering and technical specialists, as well as representatives of the education sector. The survey questions were designed to identify the professional competencies required for developing students' research and engineering activities, gaps in subject content, and recommendations for improving curricula.

The research procedure consisted of several stages. In the first stage, the content of educational programs ("Physics," "Electrical Engineering and Energy") was analyzed, and the sections related to solar energy were systematized. In the second stage, the survey was conducted, employers' suggestions were collected, and a systematic analysis of the responses was carried out. In the third stage, based on the collected data, a methodological system model was constructed, incorporating laboratory tasks and project-based assignments adapted to the solar energy field.

The integrated use of these tools and procedures made it possible to identify discrepancies between employers' requirements and the content of education, as well as to develop, on an experimental basis, a methodological system model aimed at fostering students' research and engineering activities.

Data Collection and Analysis

The research data were collected using several methods. First, a survey was conducted via the Google Forms platform, involving employers working in the solar energy sector, engineering and technical specialists, and representatives of the education field. The survey included questions on professional competencies, subject content necessary for developing students' research and engineering skills, and directions for improving practical training. In addition, the document analysis method was applied to examine the curricula and subject content of the "Physics" and "Electrical Engineering and Energy" educational programs.

Results and Discussion

Results of the analysis of the content of educational programs

The curricula of the educational programs "B054 – Physics" and "B062 – Electrical Engineering and Energy" were examined. The analysis revealed that subjects directly related to solar energy were insufficiently represented. Although courses such as General Physics, Electrical Engineering, and Energy Sources were included, their content lacked adequately integrated modules specifically focused on solar energy. It was also found that the laboratory equipment and software used in research subjects and practical classes were insufficient.

Within the framework of the *"B054 – Physics"* group, it was found that a number of specialized courses are offered under the *"6B07106 – Electric Power Engineering"* program and related educational programs. In particular, students study the following subjects:

- *Renewable and Alternative Energy Sources*
- *Methods of Using Solar and Wind Energy* (in German)
- *Alternative Energy Sources*
- *Alternative and Renewable Energy Sources*
- *Technology, Calculations, and Modeling of Renewable Energy Sources*
- *Electrical Converters of Solar Energy*
- *Fundamentals of Non-Traditional and Renewable Energy*
- *Power and Drive Technology of Renewable Energy Sources*
- *Design of Solar and Wind Power Plants*
- *Alternative Energy Sources*
- *Adjustment, Operation, and Installation of Renewable Energy Sources*, and others.

In the *"B054 – Physics"* group, the *"6B05348 – Physics"* program and its related educational programs include such courses as *"Renewable Energy Sources," "Modern Energy Sources," "Alternative Energy Sources," "Advanced Energy Technologies,"* and *"Mechanical Devices."*

These subjects aim to provide students with fundamental knowledge in the field of renewable energy, enable them to master the theoretical foundations of solar and wind power, and develop practical application skills. However, the analysis showed that the course content does not sufficiently incorporate systematic project-based, practical, and modeling assignments aimed at developing students' research and engineering activities. Furthermore, there is a clear need to integrate modern digital tools and laboratory experiments that simulate real industrial conditions into the educational process.

Results Based on Employers' Recommendations

The survey consisted of a total of four sections and a comprehensive analysis was carried out based on the answers to the questions in each section.

General Information

The survey involved specialists working in the solar energy sector at various levels, including directors, chief specialists, lecturers, researchers, and representatives of the engineering and technical field. The main activities of their organizations covered the construction and operation of solar power plants, panel installation, design and engineering services, as well as education and professional training. It was found that the majority of participants had more than five years of work experience, indicating their substantial professional expertise.

Workforce Demand

According to employers, there is a high demand for experienced engineers, technicians, and designers in the solar energy sector, while in some areas there is also a shortage of qualified instructors. When evaluating the preparedness of recent graduates, employers noted that their theoretical knowledge was satisfactory, but their practical skills were insufficient. The most commonly missing competencies included practical skills, project-based thinking, the ability to use new technologies, teamwork, and decision-making abilities. Employers also emphasized that practical skills were one of the primary requirements in the hiring process.

University–Labor Market Connection

Most employers stated that current educational programs do not fully meet the requirements of the labor market. They recommended the introduction of additional courses such as specialized modules in solar energy, STEM-based education, artificial intelligence and automation, as well as academic writing. Some organizations reported active participation in joint projects with universities, while others expressed interest in such collaboration. Additional skills considered necessary for graduates included project management, automation of engineering calculations, and professional communication.

Conclusion

The majority of respondents predicted that the shortage of specialists in the solar energy sector will increase in the future. The main barriers identified in preparing young professionals were insufficient industrial internships, limited access to modern laboratories, and the predominance of theoretical over practical training. All participants highly valued the importance of STEM-based education. Employers also unanimously supported the view that student internships should start as early as the second year of study.

The survey results revealed the key gaps and strengths in the process of training specialists in the field of solar energy. The collected data made it possible to identify the specific requirements of employers, the weaknesses in the professional preparedness of recent graduates, and recommendations for improving the content of educational programs. These findings serve as an important reference point for developing a methodological system model aimed at fostering students' research and engineering activities. Furthermore, the survey highlighted the need to strengthen the connection between universities and the labor market, to increase the number of practice-oriented learning tasks, and to introduce new courses tailored to solar energy.

Results of the development of a methodological system model

As a result of the study, a methodological system model was developed to foster students' research and engineering activities in the field of solar energy. The goal-oriented component focuses on forming students' research and engineering competencies. The content component defines the structure of these activities and their indicators. The activity-based component is grounded in didactic conditions such as interdisciplinary integration, practice orientation, project-based and research approaches, and the application of STEM and digital technologies (Fig.1.).

Implementation of STEM Projects in the Field of Solar Energy

Goal-oriented component: the development of students' research and engineering activities in the field of solar energy

Content component

Components of research and engineering activities

Motivational	Content-related	Activity-based

Indicators of research and engineering activities

Interest in renewable energy, engineering calculations, and practical research. A strong motivation to achieve success in research activities within the field of solar energy, with a clear focus on results.	Possession of theoretical knowledge in physics, mathematics, computer science, and engineering subjects within the field of solar energy; mastery of research methods (observation, experimentation, modeling, comparative analysis); and an understanding of specific scientific and industrial areas such as solar en-	Application of technologies such as engineering design, 3D modeling, Arduino, and digital tools; recording and measuring experimental results, processing data using tables, graphs, and diagrams; analyzing the collected data, drawing conclusions, and making practical recommendations; fulfilling one's role in teamwork and project activities

Activity-based component

Key aspects of developing research and engineering activities

Didactic conditions: interdisciplinary integration; practice orientation; project-based and research method; application of STEM and digital technologies. **Principles of implementing STEM projects:** principle of creativity and innovation; principle of research and practical orientation; principle of accessibility and applicability; principle of practical relevance; principle of reflection and evaluation. **General pedagogical conditions:** ensuring students' independence and active participation in the learning process; linking the educational process with the digital learning environment (online platforms, virtual laborato-

Methods	Tools	Forms
STEM: solving practical tasks through the problem-based learning method; constructing solar panels through the project-based method; simulating solar energy processes using the modeling method (both numerical	STEM products, training stands, virtual laboratory platforms and digital measuring devices, solar power plants, and educational-methodological resources.	Laboratory and practical work, project-based learning, problem-based learning, group and collaborative work, seminar discussions, trainings and workshops, industrial practice and dual education, distance and online

Stages of developing research and engineering activities

Preparatory stage	Implementation stage	Final stage
Developing motivation, identifying the problem, defining goals and objectives, collecting and analyzing information.	Project design, conducting experiments, modeling, and testing engineering solutions.	Analyzing results, making interpretations, presenting the final product, reflection, and providing recommendations.

Result-oriented component

A specialist capable of research and engineering activities in the field of solar energy

Figure 1 – Methodological system model for developing students' research and engineering activities in the field of solar energy

The implementation of STEM projects is guided by principles of creativity and innovation, practice orientation, accessibility, practical relevance, and reflection. The general pedagogical conditions emphasize ensuring students' autonomy and engagement, as well as linking the learning process with a digital educational environment. The methods employed include project-based, laboratory, and modeling approaches; the tools comprise solar panels, Arduino, MATLAB/Simulink, and virtual laboratories; while the forms include lectures, laboratory classes, and project-based lessons. The development process unfolds across three stages—initial, formative, and outcome levels. The result-oriented component ensures the preparation of specialists capable of engaging in research and engineering activities within the solar energy sector.

The application of the developed methodological system proves to be effective in teaching courses such as "Alternative Energy Sources," "Renewable and Alternative Energy Sources," "Methods of Using Solar and Wind Energy," "Electrical Converters of Solar Energy," and *"Design of Solar and Wind Power Plants." This system integrates students' theoretical knowledge with practical application by organizing laboratory and project-based work on the basis of STEM and digital technologies. When implemented in the educational process, the course content is enriched through interdisciplinary integration, practice orientation is enhanced, and conditions are created to foster students' independence and active participation. As a result, graduates' research and engineering competencies are strengthened, ensuring the preparation of highly qualified specialists who meet the requirements of the labor market.

The model employs a design-based research approach to enhance the understanding of energy transfer in electrical systems, an important aspect that is often overlooked in traditional curricula (Høiby & Christensen, 2023). In addition, it integrates empirical evidence demonstrating the effectiveness of interactive, project-based learning experiences—such as virtual experiments with photovoltaic panels—in increasing student engagement and deepening their comprehension of complex scientific concepts (Sulaiman, 2024). Furthermore, the framework addresses the need for interdisciplinary approaches in STEM education by analyzing and measuring curriculum synergy, ensuring that solar energy concepts are not taught in isolation but are integrated across various scientific and engineering disciplines (Gim et al., 2025). Such comprehensive integration facilitates a deeper understanding of sociotechnical systems, enabling students to recognize how new practices, such as photovoltaic energy consumption, reshape existing methods and societal behaviors (Carvalhais & Pinto, 2022).

The influence of the model also extends to graduate programs and practitioners, offering valuable guidance for educational designers seeking to integrate STEM effectively (Gertz, 2024). This approach contributes to the development of students' critical thinking and collaboration skills while supporting a broader understanding of renewable energy technologies (Sulaiman, 2024;). Moreover, the framework aligns with global sustainability goals by providing a foundation for the development of curricula aimed at enhancing critical thinking skills essential for the Society 5.0 era, particularly in the field of renewable energy.

Conclusion

The research findings substantiated the relevance and effectiveness of developing a methodological system model aimed at fostering students' research and engineering activities in the field of solar energy. The analysis of educational program content revealed that, although courses related to solar energy exist, they are not fully covered from a practical and project-based research perspective. Employers' recommendations highlighted the need to strengthen practical skills as well as competencies in applying STEM and digital technologies.

Based on these insights, the proposed methodological system model was structured around goal-oriented, content, activity-based, and result-oriented components. It is designed to integrate students' theoretical knowledge with practice, enhance their project-based research capabilities, and develop professional competencies aligned with labor market demands. In conclusion, the integration of this model into the educational process will increase students' independence and engagement, while enabling the preparation of competitive specialists in the field of renewable energy.

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