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Empowering Students' Research through STEM: Using Vernier Sensors to Explore Renewable Energy

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ABSTRACT

Purpose. In today's education system, the application of STEM (Science, Technology, Engineering, Mathematics) approaches has become a powerful tool to enhance students' research activities. The main purpose of this study is to identify the impact of applying STEM methods within the context of renewable energy on students' research engagement and to evaluate the effectiveness of hands-on lessons utilizing Vernier sensors. **Methodology**. The methodology involved investigation of the power output characteristics of solar panels, measurment of variables such as temperature and light intensity, and analysis of collected data. This pedagogical study employed mathematical and statistical analysis using the JASP software to examine the relationship between the use of STEM-based Vernier sensors and students' research activities. **Results** The results indicate that integrating STEM approaches with Vernier sensors significantly enhances students' research competencies. Students not only expanded their theoretical understanding, but also developed essential skills such as data collection, graphical representation, mathematical analysis, and drawing scientifically grounded conclusions. A comparison of post-experimental results between the control and experimental groups revealed a significant difference: $t = -25.156$, $p < 0.001$, indicating that the average performance of the experimental group was substantially higher than that of the control group. This demonstrates the strong positive impact of STEM methods on teaching effectiveness.**Implications for research and practice** The findings highlight the potential of STEM-based methods to enhance experiential learning and bridge the gap between theory and practice in energy education. This study offers a framework for designing engaging, hands-on lessons that improve both cognitive and practical skills.

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Introduction

The integration of STEM (Science, Technology, Engineering, and Mathematics) education has been proven to significantly enhance students' scientific research engagement, particularly in the context of renewable energy sources. This integration supports students in applying interdisciplinary knowledge to real-world challenges, fostering a holistic understanding of complex issues. The use of Vernier sensors (https://www.vernier.com) as essential tools for data collection and analysis, serves as a practical example of how STEM integration can be effectively implemented in educational settings focused on renewable energy.

Research has shown that integrated STEM education promotes the development of students' higher-order thinking skills and problem-solving abilities. For instance, Nugroho and colleagues highlight that participation in technology- and engineering-based educational practices fosters creativity and higher-order thinking, which are essential for addressing real-world problems in the field of renewable energy (Nugroho et al., 2019). Similarly, Sarican and Akgündüz demonstrate that integrated STEM education positively influences students' academic performance and reflective thinking skills, while also enhancing their conceptual understanding and memory retention (Sarican & Akgunduz, 2018). These findings are supported by Eshaq, who found a positive correlation between STEM teaching and mathematics achievement, indicating that students with strong mathematical skills are better prepared to solve engineering challenges in renewable energy contexts (Eshaq, 2023).

The importance of integrating various STEM disciplines is also emphasized by Pimthong and Williams, who argue that solving complex, real-life problems requires knowledge and skills drawn from multiple subjects (Pimthong & Williams, 2021). This is particularly relevant in the study of renewable energy, where students must work at the intersection of science, technology, and engineering to develop viable solutions. In such educational contexts, the use of Vernier sensors allows students to conduct data-driven investigations, thereby enhancing their research abilities and decision-making skills based on empirical evidence.

Vernier sensors play a crucial role in collecting accurate data related to various renewable energy sources such as solar, wind, and wave energy. Thus, this research addresses both scientific and practical gaps in the field by identifying the deficiencies like lack of methodological guidelines for using Vernier sensors in teaching renewable energy topics. Their application in educational processes enables students to engage in authentic scientific research and gain a deeper understanding of energy-related concepts. For example, Jafari and colleagues explore the use of linear permanent magnet Vernier generators in wave energy generation, illustrating how these technologies can be applied to demonstrate renewable energy production principles in educational settings (Jafari et al., 2022). Practical experiments using Vernier sensors help students visualize and analyze data, which is essential for developing research competencies.

The effectiveness of STEM education in improving learning outcomes has been widely studied. Awaludin and colleagues emphasize that the STEM teaching model significantly enhances students' academic achievement and highlights the importance of integrating technological and engineering concepts into the curriculum (Awaludin et al., 2024). This is particularly relevant when students use Vernier sensors to conduct experiments related to renewable energy, as it enables them to apply theoretical knowledge in practical situations.

Consequently, STEM education contributes to students' deeper understanding of scientific principles and their effective application in real-life contexts.

Although numerous studies have examined the integration of STEM education in the context of renewable energy, there remains a lack of empirical research that focuses specifically on the role of Vernier sensors in enhancing students' research skills and engagement in authentic inquiry. Previous works have often addressed STEM integration in general terms or within isolated disciplinary contexts, leaving a gap in understanding how technology-supported, hands-on data collection impacts students' capacity for research-based learning. This study was initiated to address this gap, particularly in light of recent educational policy shifts in Kazakhstan, Turkestan that emphasize renewable energy education as part of the national STEM agenda.

Overall, the literature demonstrates that integrating renewable energy topics into STEM education with the support of Vernier sensors fosters research competencies, interdisciplinary understanding, and the ability to critically evaluate sustainability issues. However, the specific ways in which Vernier sensors influence students' research processes and motivation in renewable energy contexts remain underexplored. Therefore, this study identified specific objectives: (1) to investigate the impact of Vernier sensor–assisted STEM activities in renewable energy contexts on students' research skills and engagement. (2) to evaluate the effectiveness of such integration in promoting authentic, inquiry-based learning experiences. (3) to provide a framework for incorporating similar technological tools into STEM curricula in secondary education. To achieve these objectives, the study was guided by the following research questions: (1) How does incorporating Vernier sensors into renewable energy projects affect students' research skills? (2) Does such integration increase students' motivation and interest in STEM subjects? (3) What role do Vernier-sensor-based STEM activities play in fostering interdisciplinary connections among STEM disciplines?

The rationale for conducting this research lies in the need to provide concrete, evidence-based insights into how Vernier sensor–supported activities can serve as a bridge between theoretical STEM instruction and practical, real-world problem-solving. Unlike previous studies, which predominantly focus on either technology integration or renewable energy concepts separately, this work adopts a combined approach. Furthermore, by systematically analyzing student engagement and research outcomes, this study contributes novel data to an area where most existing studies remain descriptive rather than empirical.

Literature Review

STEM (Science, Technology, Engineering, and Mathematics) education plays a crucial role in developing students' critical thinking, research skills, and ability to address real-world challenges. Studies indicate that STEM integration not only enhances academic performance but also strengthens students' self-efficacy, interest, and motivation (Aguilera et al., 2021; English, 2016). These outcomes are particularly evident when renewable energy topics are incorporated into the learning process, as they are directly aligned with global sustainable development goals. Smith et al. (2015) found that teachers' professional development is a decisive factor in the successful implementation of STEM projects. Well-trained educators are better prepared to manage complex, technology-rich projects, such as those involving Vernier sensors.

Empirical studies have demonstrated the effectiveness of Project-Based Learning (PjBL) and Inquiry-Based Learning within STEM contexts. The use of PjBL within the integrated STEM framework has been shown to improve students' interest in and understanding of renewable energy topics. This approach not only deepens students' conceptual understanding but also motivates them to develop research skills through data collection and analysis, fostering a sense of responsibility for their learning. Azis and colleagues, for instance, describe the effectiveness of a STEM-integrated PjBL model involving Vernier sensors, enabling students to investigate wind energy through hands-on modeling (Azis et al., 2023). They showed that a STEM-integrated PjBL model focused on renewable energy—specifically wind turbine modeling—enhanced students' higher-order thinking skills. Similarly, Gyam et al. (2023) and Okonkwo et al. (2024) reported that renewable energy projects not only build practical competencies but also shape positive attitudes toward sustainability.

The use of Vernier sensors has proven to be especially valuable in STEM education. Dou et al. (2019) found that hands-on activities and real-time data collection significantly increase student engagement and research competence. Bennett and Ruchti (2014) emphasized that experiments using sensors promote a deeper understanding of scientific principles, as well as mathematical and engineering concepts. Koculu and Topcu (2022) further demonstrated that engaging students in the engineering design process helps them test technical solutions and refine them based on empirical evidence.

Beyond technical skills, it is important to integrate economic and social perspectives into STEM projects. Galván et al. (2016) and Liu and Solangi (2023) showed that transitioning to renewable energy reduces greenhouse gas emissions and strengthens energy security. Ifat et al. (2020) highlighted that public awareness and willingness to pay are key determinants of technology adoption, while Kibar et al. (2023) provided evidence of biofuels and hydrogen effectively lowering carbon emissions. Including such dimensions in the curriculum enables students to assess technical solutions within broader social and economic contexts.

Methodology

Research design

This study employed a quasi-experimental research design with pre-test and post-test measures for both experimental and control groups. The aim was to evaluate the impact of STEM-based instructional methods, incorporating Vernier Science Education technologies, on students' research activities in the context of renewable energy education.

Sampling and Participants

A total of 46 Physics majors from Khoja Akhmet Yassawi International Kazakh-Turkish University participated in the pedagogical experiment. Participants were selected through purposive sampling, as they were enrolled in relevant courses where renewable energy topics were taught. Of these, 20 students were assigned to the experimental group and 26 students to the control group. The control group received traditional instruction, while the experimental group was taught using a STEM-based approach integrated with Vernier technologies. Both groups included first-year master's students and fourth-year bachelor's students enrolled in the courses *Alternative Energy Technologies* and *Solar Radiation and Its Applied Aspects*. The Instructional Intervention involved the experimental group engaged in hands-on, project-based learning activities that emphasized solar, wind, and hydro energy systems. Vernier Science Education tools were integrated to enable real-time data collection and analysis. The control group followed the same curriculum content but without the STEM integration or use of Vernier technologies.

Research Instruments and Data Collection

To investigate renewable energy systems, the following instruments were used: (1) Solar energy experiments: Educational-Scientific Stand for Studying the Physical Characteristics of Solar Energy Converters to explore variables such as light incidence angle, light intensity, panel cleanliness, and temperature. (2) Vernier Science Education technologies: Energy sensors, voltage and current sensors, variable load modules, and Vernier Graphical Analysis software for experimental data collection and analysis.

Data were collected using pre- and post-intervention surveys — specially designed questionnaires to measure students' research skills, understanding of renewable energy concepts, and ability to apply theoretical knowledge to practical problems. Observation checklists were also prepared to track students' engagement and collaboration during project activities. Finally, experimental results revealed real-time data from Vernier sensors during laboratory and field tasks.

Research Hypotheses

H_0: *STEM-based instruction with Vernier technologies does not significantly affect students' research activity levels.*
H1: *STEM-based instruction with Vernier technologies significantly improves students' research activity levels.*

Data Analysis

Data analysis was conducted using JASP statistical software. Paired-sample *t*-tests were applied to compare pre-test and post-test results within each group, while independent-sample *t*-tests were used to compare outcomes between the experimental and control groups. Effect sizes were calculated to determine the magnitude of differences. Statistical significance was set at $p < 0.05$.

Results

In accordance with the content of the "Alternative energy technologies" and "Solar radiation" its applied aspects and courses, real-time Vernier sensors were used to study the types and principles of renewable energy. The results obtained from the sensors were processed and analyzed using the Vernier Graphical Analysis software. These sensors enabled students to observe, analyze, and perform calculations related to the efficiency of solar, wind, and hydro energy under various conditions, and to verify the relevant physical laws. This facilitated the integration of the key elements of the STEM approach—Science, Technology, Engineering, and Mathematics—into the learning process.

The pedagogical experiment consisted of the following four stages: In the first stage, theoretical materials on renewable energy sources (solar, wind, and water) and their underlying physical principles were presented within the "Alternative energy technologies" and "Solar radiation and its applied aspects" courses. This enabled students to learn the structure and operational principles of Vernier sensors, as well as how to use the Vernier Graphical Analysis software. The research objectives and methods were explained and students acquired skills in collecting, processing, and analyzing experimental data (Figure 1).

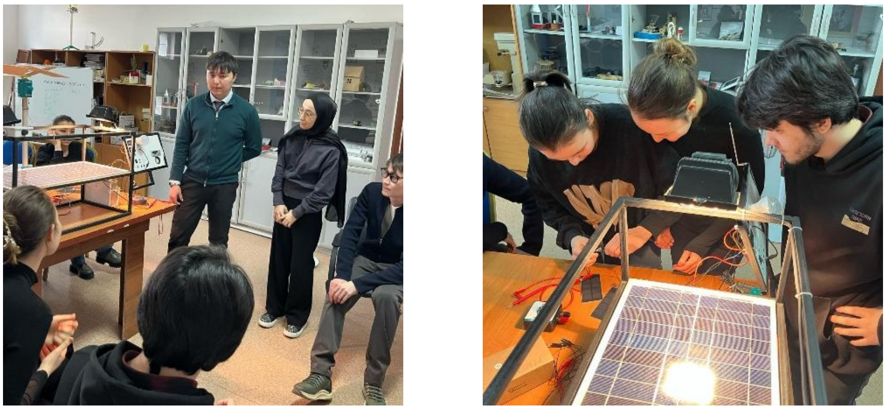

Figure 1: The course of students' research activities on alternative energy sources

In the second stage, students studied the efficiency of renewable energy sources in real time using Vernier sensors (solar panel efficiency, wind turbine performance, the effect of water flow, etc.). Various experimental conditions were created, and the dependencies of energy production parameters (light intensity, wind speed, water flow rate, etc.) were investigated. The data obtained through the sensors were processed in the Vernier Graphical Analysis software (https://www.vernier.com/downloads) and graphs and calculations are performed (Figure 2).

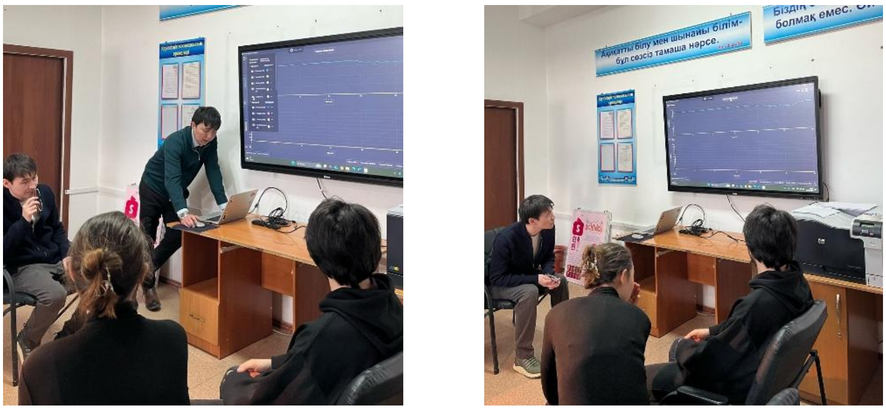

Figure 2: Data processing and results research in Vernier Graphical Analysis software

In the third stage, students analyzed the obtained results and integrated them according to the key elements of the STEM approach: *Science (S): identifying the principles of energy generation, Technology (T): data collection and processing, Engineering (E): optimizing the performance of energy sources, Mathematics (M):* conducting statistical analysis of the collected data (Figure 3).

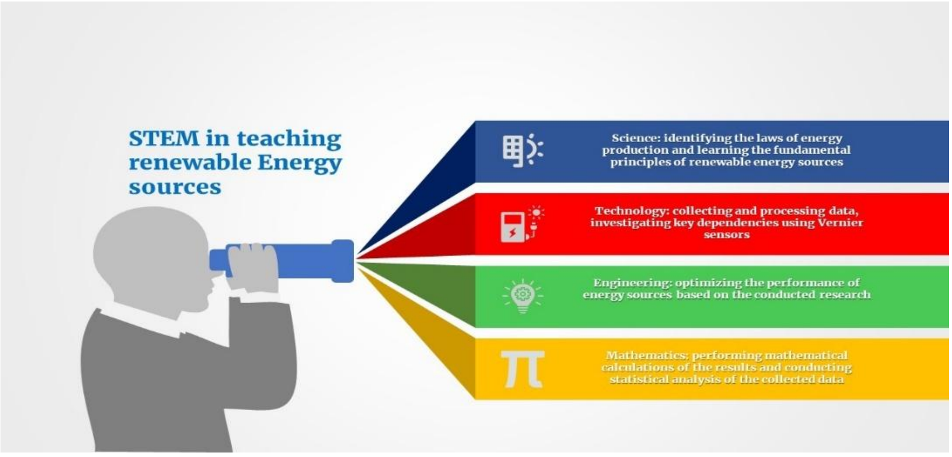

Figure 3: STEM stages of educational and research work on the topic of renewable energy sources

Finally, based on the experimental results, students prepared a scientific report, formulated patterns, and made recommendations. The level of students' scientific research skills was assessed in this stage, and the effectiveness of the pedagogical experiment was evaluated (Figure 4).

Figure 4: Educational and research process of students by STEM stages

The amount of electric energy that a solar panel can generate depends on factors such as light intensity, angle of incidence, temperature, and others. In this experiment, students investigate how the current and voltage produced by the solar panel depend on the brightness and intensity of the light source. They also calculate the efficiency of converting light energy into electrical energy using a photovoltaic cell. By connecting the solar panel (KidWind 2V solar panel and educational stand) to Vernier sensors (voltage, current, or energy) and linking it with the Vernier Graphical Analysis software, students gain a deeper understanding of the phenomenon. A light source (lamp) is positioned at varying brightness levels to measure the current (I) and voltage (V) generated by the solar panel. The brightness of the lamp and natural light sources is measured using the Go Direct Light and Color sensor.

Students use the following formula to calculate the efficiency (coefficient of performance) of the solar panel,

$$\eta = \frac{power\ out\ per\ square\ meter\ of\ the\ solar\ panel}{power\ available\ from\ the\ sunlight} \times 100\% \quad (1)$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Here, P_{out} - refers to the power output per square meter of the solar panel, while P_{in} – represents the solar irradiance (incoming solar power) per square meter. To determine the power output per square meter, students use the Vernier Graphical Analysis software and calculate the surface area of the solar panel modules. They record the maximum power value from the graph or the data table. The surface area is calculated by multiplying the number of modules by the area of a single module.

Procedure:

Required equipment includes: Go Direct Energy, Go Direct Light and Color sensors, a variable load (Rheostat 6 Ohm–255 Ohm), and a solar panel (Figure 5). These components are assembled as shown in Figure 6, and the sensors are connected to the computer via USB or Bluetooth.

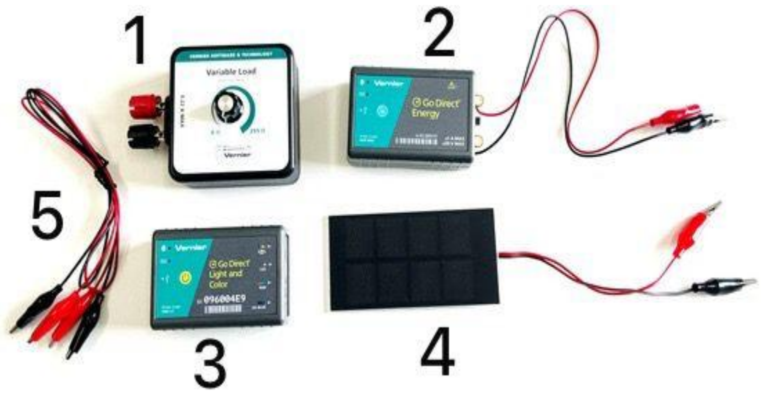

Figure 5: Vernier Science Education technologies used in the research

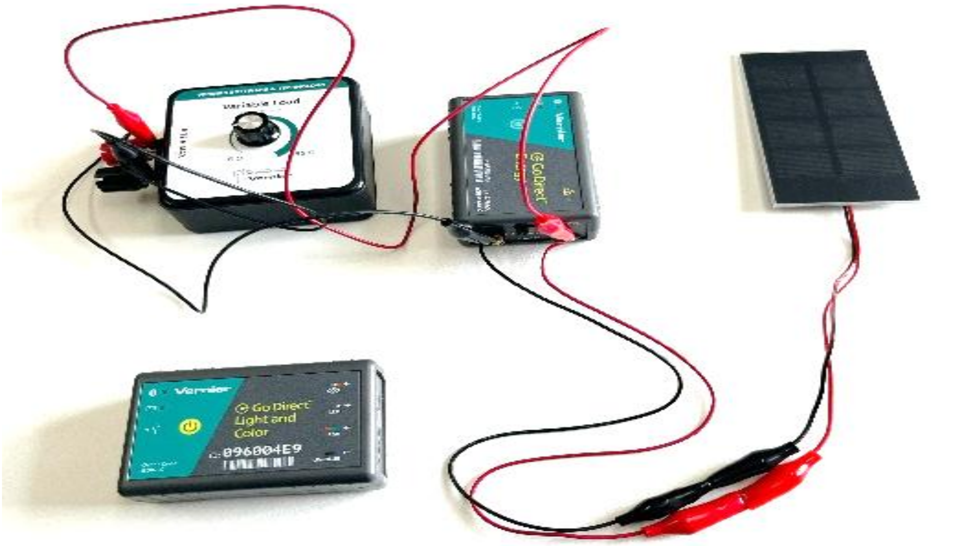

Figure 6: Experimental setup of the research study

After both sensors were connected, students used the Vernier Graphical Analysis software to select illuminance, voltage, and current from the data table and obtained the following relationship graph (Figure 7).

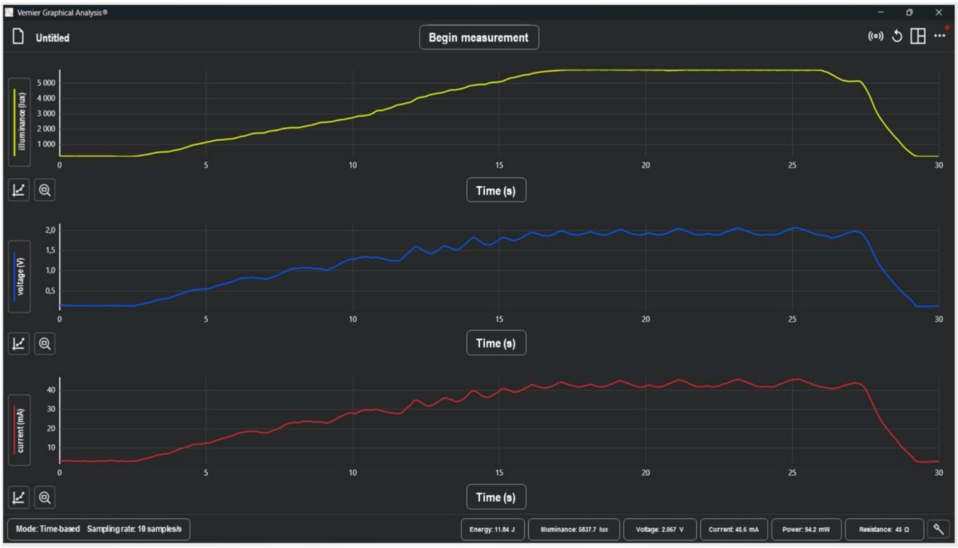

Figure 7: Graph showing the relationship between illuminance, voltage, and current

From Figure 7, students could clearly observe the relationship between illuminance and the performance of the solar panel. The level of illumination (lux) is shown by the yellow line, which gradually increases over time and reaches a maximum at around the 15th second, then remains stable. During the lab activity, the educational stand's light source was used, as the dimmer allowed for easy control of light intensity. At approximately the 26th second, the light source was turned off, which is also visible in the graph. Correspondingly, the voltage (blue line) and current (red line) show a gradual increase between 0–15 seconds. The maximum voltage value from the graph is approximately 2.067 V, and the current is 45.7 mA, which can be determined by clicking on the peak points in the graph. Using the identified maximum values of voltage and current, students calculate the power output of the solar panel:

$$P_{max} = I \times V = 2.067 \times 45.7 \times 10^{-3} = 94.5 \times 10^{-3} = 94.5mW \quad (2)$$

Additionally, by changing the parameter of the energy sensor, a power graph can be displayed on a single axis. The power output can be determined by marking the peak point on the graph (Figure 8).

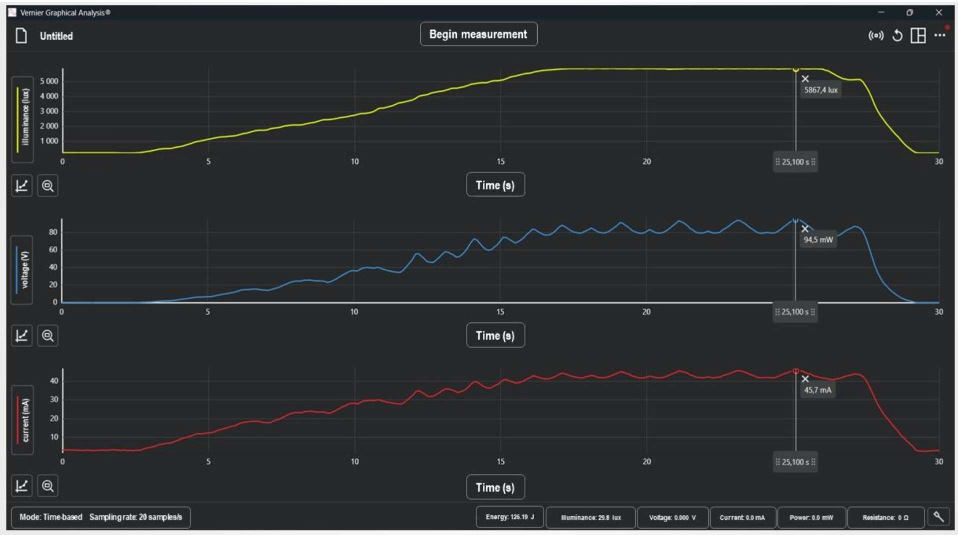

Figure 8: Graph showing the relationship between illuminance, power, and current

As seen in Figure 8 and calculated using the formula, the power value was 94.5 mW. To further determine the efficiency of the solar panel, the identified maximum power (P_{max}) is divided by the surface area of the solar panel modules (S_{sc}). That is,

$$P_{out} = \frac{P_{max}}{S_{sc}} \quad (3)$$

Here, S_{sc} represents the surface area of the solar panel modules, which is equal to the number of cells on the panel multiplied by the area of each individual cell. In our case, the number of cells is 8, and the width and length of each cell are 2 cm and 2.5 cm, respectively. Thus,

$$S_{sc} = number\ of\ cells\ on\ panel \times area\ of\ one\ cell \quad (4)$$
$$S_{sc} = 8 \times 0.02 \times 0.025 = 4 \times 10^{-3} m^2$$

The values from expressions (4) and (2) are substituted into formula (3) to determine the solar panel's output power per unit area.

$$P_{out} = \frac{P_{max}}{S_{sc}} = \frac{94.5 \times 10^{-3}}{4 \times 10^{-3}} = 23.625 \frac{W}{m^2} \quad (5)$$

Next, the power of sunlight per square meter is determined based on the illuminance level. The available solar power per square meter is calculated by dividing the average illuminance (E_{av}) by 93. This factor is an approximate constant that converts illuminance into power per unit area and is based on the temperature of the sun.

$$P_{in} = \frac{E_{av}}{93} = \frac{5867.4}{93} \approx 63.1 \frac{W}{m^2} \quad (6)$$

The values from expressions (5) and (7) are substituted into formula (1).

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{23.625}{63.1} \times 100\% \approx 37.4\% \quad (7)$$

This study describes the method of using the Vernier Graphical Analysis software to determine the efficiency of a solar panel. The experimental results showed that the performance of the solar panel is directly dependent on the level of illumination. An increase in brightness led to higher voltage and current values, while turning off the light source resulted in a decrease in these values.

According to the calculations:

- The maximum power output of the solar panel was 94.5 mW.
- The total surface area of the panel was 4×10^{-3} m².
- The power output per square meter of the solar panel was calculated (23.625 W/m²).
- The power received from sunlight was determined (63.1 W/m²).
- Based on these values, the efficiency of the solar panel was calculated ($\eta \approx 37.4\%$).

To evaluate the outcomes of the pedagogical experiment, a survey was conducted with both the control and experimental groups. The survey aimed to compare the differences between the participants' prior knowledge and their post-intervention knowledge. The survey results were entered into the JASP software, and an Independent Samples t-test was performed. This Independent Samples t-test compared the Pre-test and Post-test results of the experimental and control groups (Table 1; Table 2).

Table 1

Pre-test and Post-test results of experimental and control groups

	t	df	p	Mean Difference	SE Difference	95% CI for mean difference		Cohen's d	SE Cohen's d
						Lower	Upper		
pre-test	-2.534	44	0.015[a]	-1.704	0.672	-3.059	-0.349	-0.754	0.315
post-test	-25.156	44	< .001[a]	-21.288	0.846	-22.994	-19.583	-7.482	1.079

Note. Student's t-test.

[a]Brown-Forsythe test is significant ($p < .05$), suggesting a violation of the equal variance assumption.

Table 2

Indicator of the coefficient of variation in control and experimental groups

	Group	N	Mean	SD	SE	Coefficient of variation
pre-test	Control	26	60.346	1.548	0.304	0.026
	Experimental	20	62.050	2.946	0.659	0.047
post-test	Control	26	63.462	2.044	0.401	0.032
	Experimental	20	84.750	3.640	0.814	0.043

The Pre-test results used to assess prior knowledge were as follows: t = -2.534, p = 0.015. Since p = 0.015 < 0.05, there is a statistically significant difference between the Pre-test results of the two groups. This indicates that the control and experimental groups already had a slight difference before the start of the experiment. This difference is assumed to be due to the participants' academic level – some were master's students while others were undergraduates. Mean Difference = -1.704: the experimental group's initial mean score was 1.704 points lower than that of the control group. Cohen's d = -0.754: this indicates a medium (effect size), suggesting a moderate difference between the two groups.

Post-test results used to evaluate learning outcomes after the experiment: t = -25.156, p < 0.001. Since p < 0.001, there is a highly significant difference between the Post-test results of the two groups. Mean Difference = -21.288: the experimental group's mean score was 21.288 points higher than that of the control group. Cohen's d = -7.482: this indicates a very large (effect size), showing that the impact of the STEM-based method was extremely strong.

Confidence Intervals (95% CI): For the Pre-test: [-3.059, -0.349] → This range includes zero, meaning the difference between the groups might not be substantial. For the Post-test: [-22.994, -19.583] → This range does not include zero, indicating that the STEM approach was significantly effective.

Therefore, the Post-test results (p < 0.001) provide strong evidence that the group taught using the STEM method outperformed the control group. The null hypothesis (H_0) is rejected, confirming that the STEM approach based on Vernier Science Education technologies significantly enhances students' research activities. This contributes to the development of learners' research engagement in the field of renewable energy and leads to a deeper understanding of alternative energy concepts.

Overall, the findings clearly demonstrate that the implementation of STEM-based instruction using Vernier Science Education technologies significantly improved students' research competencies in renewable energy topics. Quantitatively, the experimental group showed a substantial post-test performance gain compared to the control group (Mean Difference = 21.288, p < 0.001, Cohen's d = -7.482), confirming the strong positive effect of the intervention. The efficiency experiment with solar panels yielded a calculated efficiency of approximately 37.4%, which aligns with realistic photovoltaic performance under controlled laboratory conditions and validates the accuracy of the applied measurement and analysis methods.

Discussion

The findings of this study confirm that Vernier Science Education technologies based on STEM education have a positive impact on students' research engagement and motivation in the context of solar energy instruction. The Post-test results following the experiment support this conclusion ($t = -25.156$, $p < 0.001$). The practical project work bridges the gap between theoretical knowledge and its real-world application. The integration of engineering design processes into STEM curricula has been shown to positively influence student learning outcomes. For instance, Hiğde (2022) demonstrated in a study involving activities related to alternative energy sources that students who participated in projects such as designing wind-powered airplanes showed a significantly improved attitude toward learning STEM subjects. Such projects not only enhance creativity but also provide opportunities to apply theoretical knowledge in practice, contributing to a deeper understanding of alternative energy solutions.

In addition, the validation of instructional tools designed to facilitate the explanation of alternative energy concepts is equally important. For example, Satriawan and Rosmiati developed an instructional tool for a simple ocean wave energy converter and evaluated its effectiveness as a learning resource with the help of expert reviews (Satriawan & Rosmiati, 2022). Such teaching tools support experiential learning and allow for the visualization of complex concepts, thereby increasing students' interest in renewable energy technologies and improving their mastery of the subject.

Vernier Science Education tools can be especially effective in teaching alternative energy sources by supporting hands-on learning and facilitating data collection. For example, experiments using solar panels or wind turbines can be used to demonstrate principles of energy conversion and efficiency (Hermanto & Dzulfiqor, 2023). These practical applications not only enhance student engagement but also help them grasp complex scientific concepts related to energy production and consumption. Furthermore, the use of digital twins and simulation software enables students to better understand the operational dynamics of distributed renewable energy systems, allowing them to explore energy management and optimization scenarios (Gökkuş, 2021).

These outcomes are consistent with earlier findings in the literature showing that hands-on, STEM-integrated approaches enhance students' conceptual understanding and practical skills in renewable energy education. By reinforcing theoretical knowledge with real-time data collection, analysis, and problem-solving tasks, the approach adopted in this study addresses similar gaps identified in previous research, thereby contributing further empirical evidence to the growing body of work supporting STEM-based experimental learning in alternative energy instruction.

Conclusion

This study confirmed that integrating STEM approaches with Vernier sensor–based activities in teaching renewable energy sources has a significant positive effect on students' research engagement, data processing abilities, and scientific decision-making skills. Statistical analyses ($t = -25.156$, $p < 0.001$) demonstrated that the experimental group, which engaged in hands-on experiments and real-time data analysis, outperformed the control group. Students not only reinforced theoretical knowledge but also developed practical competencies in conducting experiments, analyzing data, and interpreting results, thereby fostering complex thinking skills and preparing them for future careers in science and engineering. The study was conducted with a relatively small sample size and within a specific academic context, which may limit the generalizability of the findings.

Additionally, the experiment focused primarily on solar energy applications; other renewable energy technologies were not examined in equal depth.

Further studies could explore the use of STEM-based Vernier technology in teaching other renewable energy systems such as biomass, geothermal, and ocean wave energy. Expanding the sample size and including participants from diverse educational backgrounds could provide more generalizable results. Longitudinal research could also assess the lasting impact of STEM integration on students' career choices and professional competencies.

The findings highlight the potential of STEM-based methods to enhance experiential learning and bridge the gap between theory and practice in energy education. For educators, this approach offers a framework for designing engaging, hands-on lessons that improve both cognitive and practical skills. For policymakers and curriculum developers, it underscores the value of incorporating advanced educational technologies to better prepare students for the demands of a sustainable energy future.

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