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<https://doi.org/10.52269/SEPT2632058>**STEM EDUCATION IN PHYSICS AND ITS IMPACT ON STUDENTS' RESEARCH SKILLS**

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The aim of this study is to systematically evaluate, through a meta-analysis, the impact of STEM instruction based on solar energy on students' research abilities. In the study, 10 empirical works published over the past decade were selected, and their standardized effect sizes were synthesized. The analysis was conducted using a random-effects model. The results showed a pooled mean effect size of $d = 1.488$ (95% CI: 0.942–2.035, $p < 0.001$), indicating a strong positive effect of STEM interventions in the context of solar energy on research abilities. Heterogeneity among studies was at a moderate level ($I^2 = 58\%$), suggesting that the magnitude of the effect may vary depending on the educational context.

The results of publication bias assessment confirmed the stability of the overall effect. In addition, meta-regression analysis showed that the most pronounced effect of the STEM approach was observed in the domain of research skills ($p < 0.01$). To complement the meta-analytic findings, an additional cross-sectional correlational study was conducted with 49 students who participated in a solar energy-based STEM learning program. Students' engagement in STEM activities and their research competence were assessed using two composite indicators, STEM Level and Research Activity, each standardized on a 0–100 scale. Pearson's correlation analysis was used to examine the relationship between these indicators. The complementary empirical analysis revealed a strong positive correlation between STEM Level and Research Activity ($r = 0.807$, $p < 0.001$), providing convergent contextual evidence consistent with the direction of the meta-analytic findings.

Keywords: STEM education, solar energy, photovoltaic education, research skills, meta-analysis, project-based learning, renewable energy education, engineering thinking, inquiry-based learning.

**ФИЗИКАДАҒЫ STEM ОҚЫТУ ЖӘНЕ ОНЫҢ СТУДЕНТТЕРДІҢ
ЗЕРТТЕУШІЛІК ҚАБІЛЕТТЕРІНЕ ӘСЕРІ**

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Бұл зерттеудің мақсаты – күн энергетикасына негізделген STEM оқытудың білім алушылардың зерттеушілік қабілеттеріне әсерін мета-талдау арқылы жүйелі бағалау. Зерттеу барысында соңғы он жылда жарияланған 10 эмпирикалық еңбек іріктеліп, олардың стандартталған әсер мөлшерлері біріктірілді. Талдау кездейсоқ әсерлер моделі негізінде жүргізілді. Нәтижелер біріктірілген орташа әсер мөлшерінің $d = 1,488$ (95% сенімділік аралығы: 0,942–2,035, $p < 0,001$) болғанын көрсетті, бұл күн энергетикасы контекстіндегі STEM интервенцияларының зерттеушілік қабілеттерге күшті оң әсер ететінін білдіреді. Зерттеулер арасындағы гетерогенділік орташа деңгейде болды ($I^2 = 58\%$), бұл әсер мөлшерінің білім беру контекстіне байланысты өзгеруі мүмкін екенін көрсетеді. Жарияланымдық ауытқуды бағалау нәтижелері жалпы әсердің тұрақтылығын растады. Сонымен қатар мета-регрессиялық талдау STEM тәсілінің ең айқын әсері зерттеушілік дағдылар саласында байқалғанын көрсетті ($p < 0,01$). Мета-талдау нәтижелерін толықтыру мақсатында күн энергетикасына негізделген STEM оқыту бағдарламасына қатысқан 49 білім алушының қатысуымен қосымша көлденең корреляциялық зерттеу жүргізілді. Білім алушылардың STEM іс-әрекеттеріне қатысу деңгейі мен зерттеушілік құзыреттілігі 0–100 шкаласы бойынша стандартталған STEM Level және Research Activity атты екі жиынтық көрсеткіш арқылы бағаланды. Осы көрсеткіштер арасындағы байланысты анықтау үшін Пирсонның корреляциялық талдауы қолданылды.

Қосымша эмпирикалық талдау STEM Level пен Research Activity арасында күшті оң корреляция бар екенін көрсетті ($r = 0,807$, $p < 0,001$). Бұл нәтиже мета-талдау қорытындыларының бағытымен сәйкес келетін контекстік дәлелдерді ұсынады.

Түйінді сөздер: STEM білім беру, күн энергиясы, фотоэлектрлік білім беру, зерттеушілік дағдылар, мета-анализ, жобалық оқыту, жаңартылатын энергия көздері бойынша білім беру, инженерлік ойлау, зерттеуге негізделген оқыту.

STEM-ОБУЧЕНИЕ В ФИЗИКЕ И ЕГО ВЛИЯНИЕ НА ИССЛЕДОВАТЕЛЬСКИЕ СПОСОБНОСТИ СТУДЕНТОВ

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Цель данного исследования заключается в систематической оценке посредством метаанализа влияния STEM-образования, основанного на использовании солнечной энергетики, на исследовательские способности обучающихся. В исследовании были отобраны 10 эмпирических работ, опубликованных за последнее десятилетие, и синтезированы их стандартизированные размеры эффекта. Анализ проводился с использованием модели случайных эффектов. Результаты показали, что объединённый средний размер эффекта составил $d = 1,488$ (95% доверительный интервал: $0,942-2,035$, $p < 0,001$), что свидетельствует о сильном положительном влиянии STEM-интервенций в контексте солнечной энергетики на исследовательские способности обучающихся. Гетерогенность между исследованиями находилась на умеренном уровне ($I^2 = 58\%$), указывая на то, что величина эффекта может варьироваться в зависимости от образовательного контекста. Результаты оценки публикационного смещения подтвердили устойчивость общего эффекта. Кроме того, метарегрессионный анализ показал, что наиболее выраженный эффект STEM-подхода наблюдался в области исследовательских навыков ($p < 0,01$). Для дополнения результатов метаанализа было проведено дополнительное поперечное корреляционное исследование с участием 49 обучающихся, прошедших программу STEM-образования, основанную на солнечной энергетике. Вовлечённость обучающихся в STEM-деятельность и их исследовательская компетентность оценивались с использованием двух интегральных показателей — STEM Level и Research Activity, каждый из которых был стандартизирован по шкале от 0 до 100. Для изучения взаимосвязи между данными показателями применялся корреляционный анализ Пирсона. Дополнительный эмпирический анализ выявил сильную положительную корреляцию между STEM Level и Research Activity ($r = 0,807$, $p < 0,001$), что обеспечивает согласованные контекстуальные доказательства, соответствующие направлению результатов метаанализа.

Ключевые слова: STEM-образование, солнечная энергия, фотоэлектрическое образование, исследовательские навыки, мета-анализ, проектное обучение, образование в области возобновляемой энергетики, инженерное мышление, исследовательское обучение.

Introduction. Contemporary global development trends require a fundamental transformation of energy systems. Climate change, the depletion of natural resources, rapid population growth, and increasing energy demand are driving the global community toward a low-carbon development model. The decarbonization process is no longer solely an environmental objective but has become a strategic prerequisite for economic sustainability and technological independence.

In this context, renewable energy sources, particularly solar energy, are regarded as one of the key pillars of the global energy transition. Solar energy is a clean and environmentally friendly energy source that significantly reduces greenhouse gas emissions while decreasing dependence on fossil fuels [1]. Over the past decades, the cost of photovoltaic technologies has declined substantially, enabling solar electricity to become economically competitive with conventional energy sources in many regions worldwide [2].

Another important advantage of solar energy is its virtually inexhaustible potential. The amount of solar radiation reaching the Earth's surface exceeds current global energy consumption by several orders of magnitude, making solar power a cornerstone of long-term sustainable development [3]. Furthermore, the adoption of solar technologies enhances national energy security, reduces reliance on imported fossil fuels, and mitigates geopolitical risks associated with energy supply [4].

From a social perspective, solar photovoltaic systems provide an effective solution for supplying electricity to remote and off-grid communities. Their modular design and installation flexibility enable widespread deployment at the local level [5]. This contributes to improving quality of life while supporting the

development of education, healthcare, and communication services. In addition, investments in the solar energy sector create new employment opportunities, stimulate local manufacturing, and promote technological innovation [6].

The global energy transition also places new demands on education systems. Future professionals should possess not only theoretical knowledge but also the ability to work with real technological systems, analyze data, and make engineering decisions. In line with the Sustainable Development Goals (SDGs), educational curricula should be updated to integrate green technologies and digital tools into the learning process [7].

Solar energy provides an effective interdisciplinary platform for education. By integrating physics, mathematics, engineering, information technology, and environmental science, it enables students to engage in authentic, practice-oriented learning experiences. Activities such as investigating the operating parameters of photovoltaic modules, analyzing the effects of solar irradiance and incident angle, and evaluating temperature dependence contribute to the development of students' practical and analytical skills [8].

The STEM (Science, Technology, Engineering, and Mathematics) approach represents an integrated model of contemporary education. This framework combines natural sciences, technology, engineering design, and mathematical analysis into a unified learning system. STEM-based instruction emphasizes problem-solving, project-based activities, and evidence-based reasoning [9].

Teaching solar energy within the STEM framework enables students to engage in authentic research activities through interaction with real engineering systems [10]. Since photovoltaic systems are based on measurable physical variables, they provide an ideal environment for conducting experiments, formulating hypotheses, collecting empirical data, and performing statistical analyses.

Research skills refer to an individual's ability to formulate scientific questions, design research procedures, collect and analyze data, interpret findings, and propose evidence-based conclusions [11]. In today's technology-driven society, these competencies are considered among the most essential professional skills required for future specialists.

Previous studies have demonstrated that STEM instructional models implemented in the context of solar energy—including Project-Based Learning STEM (PjBL-STEM), the 5E-based STEM model, SESTEM, prototype-based instruction, and industry-oriented learning modules—significantly enhance students' creativity, critical thinking, engineering design skills, and academic achievement. However, most of these studies have focused on individual interventions, specific instructional modules, or localized experimental groups, limiting the generalizability of their findings.

The aim of this study is to systematically evaluate the impact of solar energy-based STEM education in physics on students' research skills through a meta-analysis and to provide empirical support for the findings using data obtained from an additional pedagogical experiment.

The objectives of the study are as follows:

- To determine the standardized effect sizes of the selected studies and calculate the pooled overall effect size using a random-effects model.
- To statistically evaluate the impact of solar energy-based STEM interventions on students' research skills.
- To clarify the contribution of the STEM approach to the development of research skills through meta-regression analysis.
- To examine the relationship between students' level of engagement in solar energy-based STEM learning and their research activity through a complementary empirical study.
- To compare the direction and substantive interpretation of the empirical findings with the pooled results of the meta-analysis without statistically combining the two independent datasets.

Scientific Novelty of the Study. The scientific novelty of this study lies in the systematic evaluation of the impact of solar energy-based STEM education on students' research skills through a meta-analysis, providing robust statistical evidence of its pedagogical effectiveness. Standardized effect sizes from empirical studies published over the past decade were synthesized using a random-effects model, demonstrating that STEM interventions implemented in the context of solar energy have a strong positive effect on the development of students' research skills.

Furthermore, analyses of between-study heterogeneity, publication bias, and meta-regression provided scientific evidence that the effectiveness of the STEM approach may vary depending on the educational context. In addition, data obtained from a complementary pedagogical experiment revealed a strong positive relationship between the level of STEM implementation and students' research activity, thereby providing empirical support for the meta-analysis findings.

Overall, the study proposes solar energy-based STEM education as an effective pedagogical model for fostering students' scientific inquiry, strengthening research competencies, and preparing future professionals capable of meeting the demands of sustainable development.

Materials and Methods. Since the aim of this study was to comprehensively evaluate the impact of solar energy-based STEM interventions on students' research skills, it was necessary to synthesize evidence from individual empirical studies. Therefore, meta-analysis was selected as the most appropriate methodolo-

gical approach, as it enables the integration of findings from studies conducted in different educational contexts into a single quantitative model.

The study was organized as a two-component evidence synthesis design. The first component consisted of a systematic review and meta-analysis intended to estimate the pooled effect of solar energy-based STEM interventions across previously published studies. The second component consisted of a complementary empirical correlational study conducted in a local educational context. The purpose of the second component was not to include the local data as an additional effect size in the meta-analysis or to independently validate the pooled estimate. Rather, it was used to examine whether the relationship between participation in STEM-based learning and research competence demonstrated a direction consistent with the synthesized international evidence. The two components were interpreted through methodological triangulation at the discussion stage, while their samples, analytical procedures, and statistical results remained independent.

The literature search was conducted using internationally recognized peer-reviewed databases, including Web of Science, Scopus, ScienceDirect, ERIC, and SpringerLink. These databases were selected because they provide high-quality indexed publications in the fields of renewable energy, science education, and STEM education. The systematic review and study selection procedures were organized in accordance with the PRISMA 2020 recommendations. The literature search was conducted between 2020 and 2025. Search results from all databases were exported to [insert the reference management software, for example, Mendeley, Zotero, or EndNote], where duplicate records were identified and removed. The remaining records were screened in two stages: first by title and abstract and subsequently through full-text assessment. Study selection was performed independently by two reviewers. Any disagreement concerning eligibility was resolved through discussion and, when necessary, consultation with a third reviewer.

The search covered publications from the past ten years. This period was chosen to capture the rapid technological development of solar energy systems and the increasing implementation of STEM-based instructional approaches in education. Focusing on recent studies also ensured that the review reflected current research trends and contemporary educational practices.

The literature search employed the following keywords and their related terms: "solar energy," "solar power," "photovoltaic education," "STEM education," "project-based learning," "engineering education," "research skills," "inquiry skills," "research competence," and "renewable energy education." The core search strategy was formulated as follows: ("solar energy" OR "solar power" OR photovoltaic OR "renewable energy") AND ("STEM education" OR "STEM learning" OR "project-based learning" OR "engineering education") AND ("research skills" OR "inquiry skills" OR "research competence" OR "scientific reasoning"). The search syntax was adapted to the technical requirements of each database. Searches were conducted in titles, abstracts, and keywords where these search fields were available. In addition, the reference lists of the eligible publications were manually examined to identify potentially relevant studies not retrieved through the database search.

Studies included in the meta-analysis were selected according to predefined eligibility criteria. First, each study was required to investigate a STEM instructional intervention based on solar energy or photovoltaic systems. Second, students' research skills had to be assessed using quantitative measurement instruments. Third, the study was required to employ an experimental or quasi-experimental research design that enabled the evaluation of intervention effects. Finally, sufficient statistical information had to be reported to calculate effect sizes, and the study had to be published in a peer-reviewed scientific journal.

Several categories of studies were excluded during the screening process. Theoretical papers and literature reviews were excluded because they did not provide empirical data. Studies with insufficient quantitative information or inadequate statistical reporting for effect size calculation were also omitted. Furthermore, studies focusing exclusively on technological modeling without an educational component were excluded from the analysis.

Data Extraction and Coding

Data were extracted using a standardized coding form developed prior to the analysis. For each eligible study, the following information was recorded: author and publication year, country, educational level, sample size, characteristics of the participants, type and duration of the STEM intervention, study design, characteristics of the comparison condition, outcome domain, measurement instrument, group means, standard deviations, and other statistics required for effect-size calculation. Data extraction was conducted independently by two researchers, and the extracted values were cross-checked against the original publications. Discrepancies were resolved through joint verification of the relevant tables and statistical results. When a study reported several research-related outcomes, the outcomes were coded according to the predefined domains of research skills, engineering thinking, and cognitive achievement.

A meta-analysis was conducted to estimate the overall effectiveness of solar energy-based STEM education. The extracted quantitative data were analyzed using Comprehensive Meta-Analysis (CMA) version 4.0 software.

- Standardized Mean Difference (Effect Size);
- Standard Error (SE).

The standardized mean difference was selected because the included studies assessed research-related outcomes using different measurement instruments and scales. For studies with intervention and comparison groups, the effect size was calculated from the post-intervention means, standard deviations, and sample sizes of the two groups. Where only change scores or other statistical indicators were available, the corresponding effect size was calculated using the conversion procedures available in CMA 4.0. To reduce small-sample bias, standardized mean differences were corrected using Hedges' *g*. Positive values indicated an advantage of solar energy-based STEM instruction over the comparison condition. A random-effects model was applied because variation was expected across participants, intervention formats, educational levels, and measurement instruments.

Results and Discussion. The results of the content analysis of empirical studies investigating the application of STEM approaches to teaching solar energy and renewable energy topics are summarized in Table 1. The studies included in the analysis examined the implementation of STEM and Project-Based Learning (PjBL) models in teaching solar energy, renewable energy, physics, and other science-related disciplines. Overall, the findings indicate that the STEM–PjBL approach serves as an effective pedagogical framework for increasing students' learning engagement, strengthening their interest in science, and fostering scientific thinking.

In particular, the integration of web-based STEM platforms, digital simulation tools, and interdisciplinary project-based activities was found to significantly enhance students' research skills. These learning environments provide opportunities for learners to formulate research questions, conduct experiments, analyze data, and develop evidence-based solutions to real-world engineering and environmental problems.

The reviewed studies further demonstrate that the STEM approach functions not only as a means of integrating disciplinary knowledge but also as an effective strategy for pedagogical innovation. By combining scientific inquiry with authentic engineering design and technology-enhanced learning, STEM-based instruction promotes higher-order thinking, problem-solving abilities, and research competence. These findings highlight the role of STEM education as both a content integration framework and a methodological approach for modernizing science education (Figure 1).

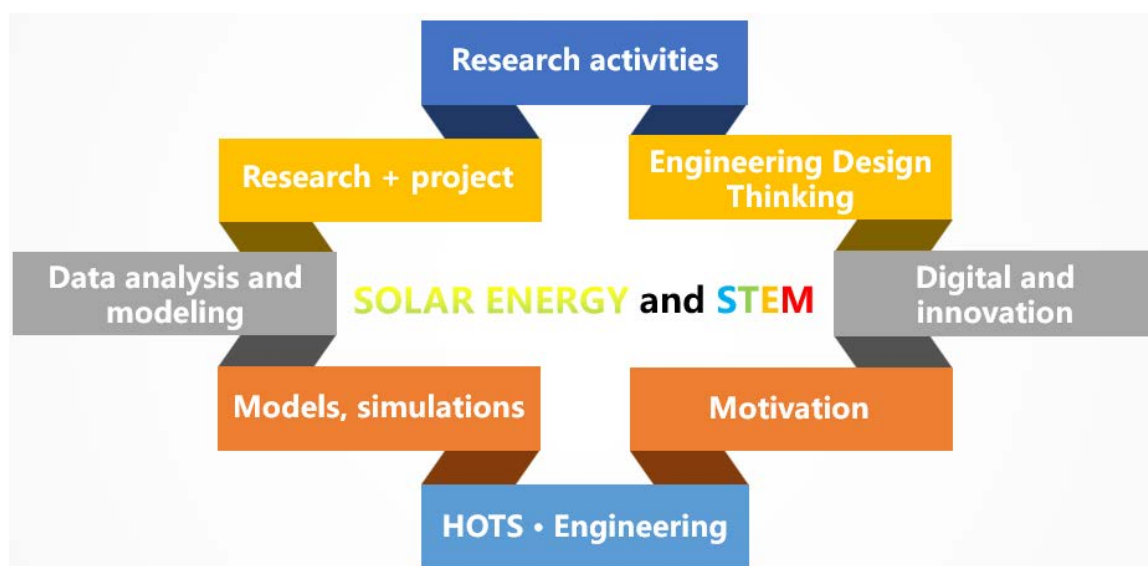


Figure 1 – Relationships among the Key Components of Solar Energy Education within the STEM Learning Process

Most of the reviewed studies demonstrated that organizing solar energy instruction through STEM and Project-Based Learning (PjBL) significantly enhances students' abilities in measurement, calculation, experimentation, and engineering decision-making. Activities such as analyzing the efficiency of photovoltaic panels, modeling energy generation processes, and monitoring changes in system parameters enabled students to connect theoretical knowledge with practical application. These hands-on learning experiences also promoted the development of essential research competencies, including formulating scientific questions, developing hypotheses, interpreting results, and drawing evidence-based conclusions.

Several studies identified the STEM–PjBL approach as an effective mechanism for interdisciplinary integration. The content of physics, mathematics, engineering, and technology was integrated through unified project-based tasks, while solar energy topics were linked to authentic real-world challenges. Such an approach strengthened students' systems thinking, analytical reasoning, and practical problem-solving abilities.

Furthermore, studies employing digital simulations, virtual laboratories, and online learning platforms demonstrated that solar energy education can be delivered in a flexible and safe learning environment.

These technologies facilitate the visualization of complex physical and engineering processes, allow learners to compare outcomes by modifying system parameters, and support prediction through computational modeling.

Meta-analysis of the Selected Scientific Literature

The results of the meta-analysis evaluating the impact of solar energy-based STEM education on students' research skills are presented visually using a forest plot (Figure 2). This diagram displays the standardized effect size of each study included in the meta-analysis together with its 95% confidence interval within a single graphical framework.

The forest plot enables a comparative assessment of the magnitude, statistical significance, and direction of the effect reported by each individual study. In addition, the pooled effect size is represented by a diamond, providing a quantitative summary of the overall pedagogical effectiveness of solar energy-based STEM interventions. This approach also allows for the examination of between-study variability, the assessment of heterogeneity, and the evaluation of the robustness of the synthesized findings. Consequently, the forest plot serves as the principal analytical tool of the meta-analysis, offering comprehensive and evidence-based support for the positive impact of solar energy-based STEM education on students' research skills.

Meta analysis

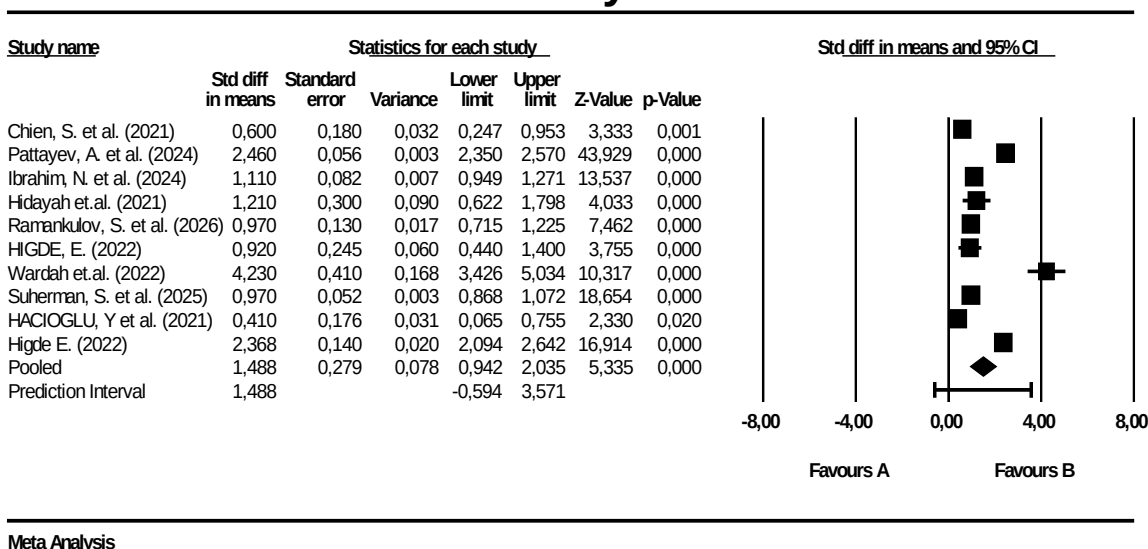


Figure 2 – Graphical Representation of the Meta-Analysis Results

The forest plot presents the results of ten studies evaluating the impact of solar energy-based STEM education on students' research skills, together with the pooled effect size obtained from the meta-analysis. All individual studies reported positive standardized mean differences, indicating that the STEM approach has a positive effect on students' research-related competencies.

The pooled effect size was $d = 1.488$ (95% CI: 0.942–2.035), with $Z = 5.335$ and $p < 0.001$. Since the confidence interval does not include zero, the overall effect is statistically significant. Moreover, because the effect size exceeds 1.0, it can be interpreted as a large educational effect, demonstrating substantial pedagogical effectiveness.

Overall, the meta-analysis provides strong evidence that solar energy-based STEM education has both statistically significant and educationally meaningful effects on the development of students' research skills.

Example of the Pedagogical Experiment: Comprehensive Investigation of the Output Parameters of Solar Panels

As part of this study, students conducted a laboratory experiment using a training platform designed for the comprehensive investigation of the output parameters of photovoltaic solar panels. The experimental setup consisted of two identical photovoltaic modules, a switching board allowing both series and parallel connections, an adjustable artificial light source, a dimmer for controlling light intensity, a mounting frame equipped with a mechanism for varying the angle of light incidence from 0° to 180° in 15° increments, a lux meter, a surface temperature sensor, and a protective enclosure integrating all experimental components.

In addition, PASCO current, voltage, and light sensors were employed, while experimental data were digitally recorded and analyzed using the SPARKvue software. This experimental platform enabled students to investigate the physical principles governing photovoltaic systems through hands-on experimentation, compare measurement accuracy, and comprehensively evaluate the capabilities of conventional measuring instruments and digital sensing technologies.

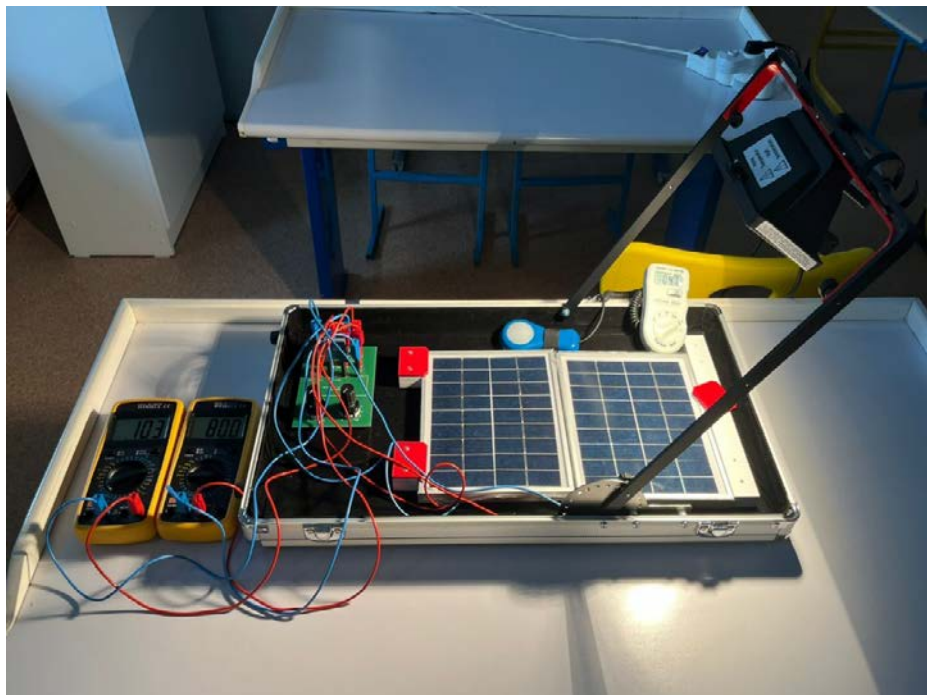


Figure 3 – General Structure of the Experimental Stand

During the experiment, students investigated the dependence of the output current and voltage of photovoltaic solar panels on light intensity. The photovoltaic modules were first connected in both parallel and series configurations, and measurements were performed for each connection type. Light intensity was gradually adjusted using a dimmer, while electrical current (I), voltage (U), illuminance (E), and surface temperature were recorded at each measurement point. In addition, the angle of light incidence was systematically varied to evaluate the influence of the angle of insolation on the electrical output parameters of the photovoltaic modules.

Analysis of SPARKvue Results

The SPARKvue software recorded the temporal variation of the measured parameters, where Y1 represents electrical current (A), Y2 denotes light intensity (W/m^2), and Y3 corresponds to voltage (V). As illustrated in the recorded graphs, light intensity was gradually increased throughout the experiment, resulting in corresponding changes in the electrical output characteristics of the photovoltaic system.

As light intensity increased from approximately 0 to 70 W/m^2 , the output current increased proportionally. During the initial stage of the experiment, corresponding to low irradiance conditions, the measured current was close to zero. As solar irradiance increased, the current exhibited an approximately linear increase, reaching about 0.10 A. These results are consistent with the photovoltaic effect, demonstrating experimentally that an increase in photon flux generates a greater number of charge carriers, thereby increasing the electrical current.

The voltage exhibited a more gradual response than the current. Initially, the output voltage remained at very low levels and then increased progressively with increasing irradiance, reaching approximately 0.017 V. These observations are consistent with the current–voltage (I – V) characteristics of photovoltaic cells, where voltage depends on incident light intensity but generally varies over a smaller range than current.

The smooth and continuous trends observed in the graphs enabled students to identify an approximately linear relationship between light intensity and output current, while also recognizing the gradual saturation behavior of the output voltage. Furthermore, continuous digital data acquisition facilitated the monitoring of dynamic parameter changes, improved measurement accuracy, and provided a reliable dataset for subsequent mathematical analyses, including regression analysis and correlation coefficient estimation.

Overall, the digitally recorded experimental results confirmed that the dependence of photovoltaic output parameters on light intensity is consistent with established theoretical principles. In addition, the experiment enhanced students' abilities to interpret experimental data, analyze graphical results, and draw engineering-based conclusions, thereby strengthening their research competencies within a STEM learning environment.

Correlation Analysis Procedure

A correlation analysis was conducted to examine the relationship between students' level of participation in STEM-based learning and their research activity. Correlation analysis is a statistical technique used to determine the direction and strength of the linear relationship between two quantitative variables. The Pearson correlation coefficient (r) ranges from -1 to $+1$, where positive values indicate that both variables increase together, negative values indicate an inverse relationship, and values close to zero suggest little or no linear association.

The analysis was performed exclusively for students in the experimental group ($n = 24$), as this group participated in a solar energy-based STEM instructional program. Two primary quantitative variables were included in the analysis: STEM Level and Research Activity.

Both variables were assessed using predefined evaluation criteria and converted into standardized scores.

STEM Level (0–100 scale) was calculated as a composite indicator representing students' level of engagement in STEM-based learning activities. The score was derived from several assessment components, including participation in STEM learning tasks, involvement in laboratory activities, the quality of project presentations, and the effective use of digital technologies such as SPARKvue and PASCO sensors. Each component was evaluated using a standardized assessment rubric, and the total score was normalized to a 100-point scale.

Research Activity (0–100 scale) was defined as an integrated measure of students' research competence. The assessment was based on the fundamental stages of the scientific inquiry process, including the quality of hypothesis formulation, experimental design and control of variables, accuracy of data collection, ability to perform graphical and quantitative data analysis, and the strength of evidence-based conclusions. Each component was evaluated separately, and the overall score was converted to a 100-point scale.

The collected data were entered into the JASP statistical software. Only participants from the experimental group were selected using the filtering function. Pearson's correlation analysis was conducted through Analyses → Regression → Correlation, and the software generated the correlation coefficient together with its 95% confidence interval and a corresponding scatter plot for graphical visualization of the relationship between the variables.

Table 1 – Results of the Correlation Analysis Obtained Using JASP Software

Pearson's Correlations						
	Pearson's r	p	Lower 95% CI	Upper 95% CI	Effect size (Fisher's z)	SE Effect size
Research Activity – STEM level	0.807	< .001	0.598	0.913	1.117	0.218
* $p < .05$, ** $p < .01$, *** $p < .001$						

According to the analysis, the Pearson correlation coefficient was $r = 0.807$ ($p < .001$). The 95% confidence interval ranged from 0.598 to 0.913. Since the confidence interval does not include zero, the observed relationship is considered both statistically significant and reliable. The correlation coefficient of $r = 0.807$ indicates a strong positive relationship between students' STEM level and their research activity. In other words, as students' engagement in STEM-based learning increases, their research skills also improve substantially (Figure 4).

The coefficient of determination was $r^2 \approx 0.65$, indicating that approximately 65% of the variance in students' research activity can be explained by their STEM level. Within the context of educational research, this represents a relatively large effect, highlighting the substantial contribution of the STEM approach to the development of students' research competencies.

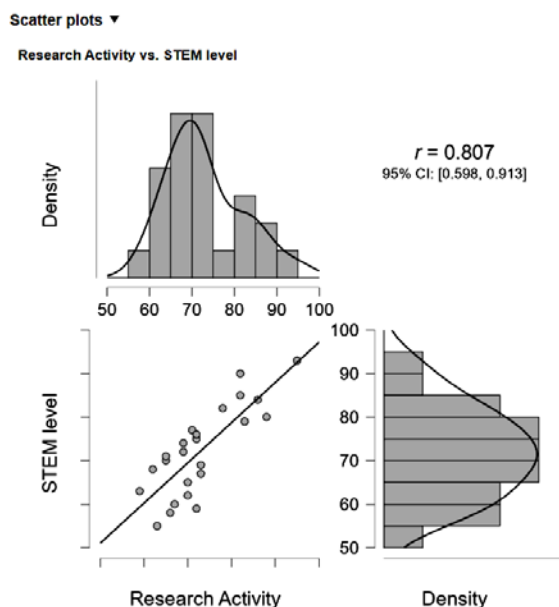


Figure 4 – Graphical Representation of the Meta-Analysis Results

Visual inspection of the scatter plot revealed that the data points were distributed along an upward-sloping trend line, indicating a clear positive trend and a strong linear relationship between the variables. The accompanying histograms showed that both variables were approximately normally distributed, confirming the statistical appropriateness of applying Pearson's correlation analysis.

Overall, a strong and statistically significant positive relationship was identified between the level of STEM-based learning and students' research activity within the experimental group. These findings provide empirical evidence that teaching solar energy through a STEM approach effectively develops students' scientific inquiry skills, including hypothesis formulation, experimental design, data collection, data analysis, and evidence-based conclusion drawing. Consequently, the analysis provides correlational evidence that stronger engagement in the implemented STEM learning activities is associated with higher levels of research competence. Because the complementary study did not include a control group or a pre-test–post-test comparison, the result should not be interpreted as definitive evidence of a causal intervention effect.

Integration of the Meta-Analytic and Empirical Findings

The meta-analysis and the complementary empirical study addressed the same general construct—the development of students' research competence through solar energy-based STEM learning—but did so at different levels of evidence. The meta-analysis estimated the average effect of structured STEM interventions by synthesizing findings from independent experimental and quasi-experimental studies. In contrast, the complementary study examined the relationship between students' STEM engagement and research activity within one local educational context. Therefore, the correlation coefficient obtained from the local sample was not directly compared with or incorporated into the pooled standardized mean difference.

The findings were integrated through a convergence approach. The large positive pooled effect identified in the meta-analysis indicated that solar energy-based STEM interventions were generally associated with improved research-related outcomes. Similarly, the local empirical study demonstrated that higher STEM Level scores were associated with higher Research Activity scores. The consistency in the direction of these findings provides contextual support for the general interpretation that active engagement in STEM tasks, laboratory investigations, digital data collection, and project activities is related to the development of research competence. However, differences in study design, sample size, educational context, and statistical indicators limit direct quantitative comparability.

Accordingly, the empirical study should be regarded as supplementary evidence illustrating how the relationship identified in the broader literature may manifest in a specific educational setting, rather than as an independent statistical confirmation of the pooled meta-analytic effect.

Conclusion. This study comprehensively evaluated the impact of solar energy-based STEM education on students' research skills using advanced statistical analyses and demonstrated its high pedagogical effectiveness. The meta-analysis yielded a pooled effect size of $d = 1.488$ (95% CI: 0.942–2.035, $p < 0.001$). According to established educational research benchmarks, this represents a large effect, indicating that STEM interventions are substantially more effective than conventional instructional approaches in developing students' research competencies.

The meta-regression analysis further revealed that the strongest and statistically significant effect of STEM interventions was observed in the research skills domain ($\beta = 1.82$, $p < 0.01$). Although positive effects were also found for engineering thinking and cognitive achievement, these effects were not statistically significant. These findings suggest that STEM-based instruction is particularly effective in developing scientific inquiry competencies, including hypothesis generation, control of experimental variables, experimental planning, data analysis, and evidence-based reasoning.

The results of the pedagogical experiment provided additional empirical support for the findings of the meta-analysis. A strong positive correlation was identified between students' STEM level and research activity ($r = 0.807$, $p < 0.001$), with a coefficient of determination of $r^2 \approx 0.65$. This indicates that approximately 65% of the variance in students' research activity can be explained by their level of engagement in STEM-based learning.

The findings also demonstrate that STEM instructional models implemented in the context of solar energy effectively integrate theoretical knowledge with practical application, enabling students to develop competencies in measurement, modeling, data interpretation, and engineering decision-making. In particular, hands-on experience with real photovoltaic systems, together with the use of digital sensors and visualization tools, plays a crucial role in fostering students' scientific reasoning and research culture.

Recommendations:

Based on the findings of this study, the systematic integration of solar energy-based STEM education into higher education curricula is recommended, as this instructional approach has demonstrated high effectiveness in developing students' research competencies, scientific reasoning, and engineering decision-making skills. Educational programs should incorporate authentic learning experiences involving photovoltaic systems, digital sensors, simulation and visualization technologies, as well as practical activities focused on experimental design, data analysis, and evidence-based interpretation of results.

Furthermore, STEM interventions should be adapted to different educational levels, disciplinary contexts, and institutional settings to maximize their educational effectiveness. Future research should investigate the long-term impact of solar energy-based STEM education, further examine its influence on engineering thinking and cognitive development, and identify moderator variables that may affect learning outcomes.

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DIDACTIC INTEGRATION OF DIGITAL TECHNOLOGIES IN PHYSICS TEACHER EDUCATION

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Amid the rapid digitalization of education, the use of information and communication technologies (ICT) in physics education is no longer limited to proficiency in individual digital tools and requires a didactic understanding of their application. However, the mere availability of digital technologies in the educational process does not, in itself, guarantee their pedagogical appropriateness or methodological integration into lesson structure. The aim of this study is to analyze undergraduate educational programs for pre-service physics teacher education in terms of the extent to which they include courses focused on the pedagogically grounded use of ICT in instructional design. The empirical basis includes 20 educational programs in the B010 «Physics Teacher Training» group. The analysis is based on a formalized content analysis of discipline titles and the calculation of integral indices reflecting digital, experimental, and research orientation. The results indicate that, despite the consistent presence of experimental and research-oriented courses, the didactically grounded integration of digital technologies is fragmented and, in most cases, remains primarily instrumental in nature. The overwhelming majority of educational programs do not include courses explicitly focused on the methodologically informed use of ICT in physics education. These findings substantiate the need to develop an interdisciplinary core in pre-service physics teacher education that ensures coherence among the subject-specific, methodological, and digital components of professional preparation. The findings may also be used to inform the improvement of teacher education programs.

Keywords: training of future physics teachers, ICTs in education, digital technologies, educational programs, design.

ФИЗИКА МҒАЛІМДЕРІН ДАЯРЛАУДАҒЫ ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАРДЫҢ ДИДАКТИКАЛЫҚ ИНТЕГРАЦИЯСЫ

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