Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

TRANSFORMING ELEMENTARY SCIENCE EDUCATION THROUGH GENERATIVE AI-AUGMENTED STEM LEARNING ON RENEWABLE ENERGY

Arip Nurahman[1*], Irma Fitria[1], Surya Gumilar[1], Ali Ismail[2], Rizal Adimayuda[2], Dini Andriani[1]
[1]Department of Physics Education, Institut Pendidikan Indonesia, Garut, Indonesia
[2] Department of Elementary School, Universitas Pendidikan Indonesia, Sumedang, Indonesia
[*] Email: *aripnurahman@institutpendidikan.ac.id*

Abstract

The integration of renewable energy education into elementary science learning is essential for developing students' sustainability awareness and scientific literacy from an early age. This study explores the implementation of Generative Artificial Intelligence (GenAI) augmented STEM learning on solar cell technologies in elementary science education. The research aims to investigate how AI-supported STEM activities can improve students' understanding of renewable energy concepts, engagement in science learning, and environmental awareness. Using a design-based research approach, elementary students participated in project-based science activities involving simple solar cell experiments and renewable energy exploration. Generative AI tools were utilized to assist students in visualizing scientific concepts, generating ideas, supporting inquiry-based discussions, and enhancing problem-solving processes during classroom learning. The learning framework integrated STEM education principles with renewable energy content and sustainability-oriented science learning. The findings indicate that GenAI-augmented STEM learning positively supports students' conceptual understanding of solar energy, creativity, collaborative learning, and motivation in elementary science classrooms. The study also highlights the potential of Generative AI as an innovative educational tool for promoting future-oriented and sustainability-focused science education in primary schools.

Keywords: *Science Education; Generative AI; STEM Education; Elementary School; Renewable Energy*

INTRODUCTION

The rapid advancement of renewable energy technologies and artificial intelligence has transformed the landscape of science education, particularly in promoting sustainability-oriented learning in primary schools. Recent educational reforms increasingly emphasize the integration of Science, Technology, Engineering, and Mathematics (STEM) education with Education for Sustainable Development (ESD) to prepare students with future-oriented competencies, environmental awareness, and problem-solving skills relevant to the challenges of the twenty-first century. Renewable energy education, especially solar energy learning, has become an important context for introducing sustainability concepts and scientific literacy in elementary science classrooms.

Previous studies have demonstrated that STEM-based learning can significantly improve students' scientific literacy, creativity, critical thinking, and engagement in science learning. Research conducted by Elsevier and Springer Nature indexed journals has shown that project-based STEM learning on renewable energy topics positively influences students' conceptual understanding and environmental attitudes. Several studies also reported that solar cell experiments provide authentic and contextual learning experiences for students in science education. Furthermore, inquiry-based and project-based STEM approaches have been widely implemented to support sustainability education in elementary and secondary schools.

In recent years, the emergence of Generative Artificial Intelligence (GenAI) has attracted increasing attention in educational research. Studies have explored the use of GenAI tools to

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

support personalized learning, visualization of scientific concepts, interactive learning environments, and AI-assisted inquiry activities. Research on AI in education indicates that GenAI can enhance students' creativity, engagement, and conceptual understanding through adaptive and interactive learning experiences. Several studies have also highlighted the potential of AI-supported STEM education in fostering future-ready competencies and digital literacy among learners.

Despite the growing body of research on STEM education, renewable energy learning, and AI-assisted education, several important gaps remain. First, most previous studies focused on secondary or higher education contexts, while research involving elementary school students in renewable energy learning is still limited. Second, studies integrating GenAI into STEM learning environments have primarily emphasized general science or technology learning rather than renewable energy education. Third, the integration of Generative AI with STEM-based solar cell learning in elementary science education remains underexplored, particularly in the context of sustainability-oriented learning. Existing studies rarely examine how GenAI can support young learners in understanding renewable energy concepts through inquiry-based STEM activities in primary school science classrooms.

This gap indicates the need for innovative learning models that combine Generative AI, STEM education, and renewable energy learning in elementary science education. The novelty of this study lies in the integration of GenAI-assisted STEM learning with solar cell technology topics to support sustainability literacy and science learning among elementary school students. Unlike previous studies that mainly focused on conventional STEM implementation or AI-assisted digital learning separately, this research proposes a sustainability-oriented learning framework that combines renewable energy education, STEM pedagogy, and Generative AI in primary science classrooms.

Therefore, this study aims to investigate the implementation of Generative AI-augmented STEM learning on solar cell technologies in elementary science education and to examine its potential in enhancing students' renewable energy understanding, science engagement, creativity, and sustainability awareness.

RESEARCH METHOD

This study employed a Design-Based Research (DBR) approach to develop and implement Generative Artificial Intelligence (GenAI)-augmented STEM learning on solar cell technologies in elementary science education. DBR was selected because it enables iterative development, implementation, evaluation, and refinement of innovative learning interventions in authentic classroom settings. The study focused on integrating STEM education, renewable energy learning, and Generative AI into elementary science learning activities.

Research Design

The research was conducted through four stages: (1) preliminary analysis and instructional design, (2) development of GenAI-augmented STEM learning activities, (3) classroom implementation, and (4) evaluation and reflection. In the preliminary stage, curriculum analysis and literature reviews related to STEM education, renewable energy learning, and AI-assisted learning were conducted to design the instructional framework. The learning activities were designed using project-based STEM learning integrated with inquiry-based science instruction.

Students participated in simple solar cell exploration activities, including observing solar energy conversion processes, constructing miniature solar-powered devices, and discussing

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

renewable energy applications in daily life. Generative AI tools were used to support students in visualizing scientific concepts, generating design ideas, answering inquiry questions, and facilitating collaborative discussions during classroom activities.

Participants and Research Setting

The study involved 32 sixth-grade students (Grade VI) from a public elementary school in Indonesia. Participants were selected using purposive sampling based on the school's readiness to implement STEM-based science learning and digital learning technologies. The research was conducted during elementary science (IPA) lessons on renewable energy and environmental sustainability over four weeks.

Data Collection Techniques

Data were collected using multiple instruments to ensure triangulation. Observation sheets were used to examine students' engagement, collaboration, and participation during STEM learning activities. Students' worksheets and project outputs were collected to analyze conceptual understanding and creativity in solar energy learning. Semi-structured interviews were conducted with selected students and the science teacher to explore perceptions toward GenAI-assisted STEM learning.

In addition, pre-test and post-test instruments were administered to measure students' understanding of renewable energy and solar cell concepts before and after the learning intervention. Documentation, including classroom photographs, learning recordings, and AI-generated student outputs, was also collected to support qualitative analysis.

Data Analysis

Quantitative data from pre-test and post-test scores were analyzed using descriptive statistics and paired sample t-tests to identify improvements in students' conceptual understanding after the implementation of the learning intervention. Qualitative data obtained from observations, interviews, and students' project documents were analyzed using thematic analysis. The analysis focused on identifying patterns related to students' engagement, creativity, collaborative learning, sustainability awareness, and responses toward the use of Generative AI in STEM learning activities.

To ensure the validity of the findings, data triangulation, member checking, and peer debriefing techniques were applied throughout the analysis process. The integration of qualitative and quantitative findings was conducted to comprehensively evaluate the effectiveness of GenAI-augmented STEM learning on solar cell technologies in sixth-grade elementary science education.

RESULTS AND DISCUSSION

Improvement of Students' Renewable Energy Understanding

The implementation of Generative AI (GenAI)-augmented STEM learning on solar cell technologies demonstrated positive impacts on sixth-grade students' understanding of renewable energy concepts in elementary science education. Based on the pre-test and post-test results, students showed noticeable improvement in understanding solar energy conversion, the function of solar cells, and the importance of renewable energy for environmental sustainability.

Students initially experienced difficulties in explaining how sunlight can be transformed into electrical energy and how solar technologies contribute to sustainable living. After participating in project-based STEM activities supported by Generative AI, students were able to explain renewable energy concepts more accurately and confidently. The integration of hands-on experiments and AI-assisted visualization enabled students to connect abstract science concepts with real-world applications.

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

The findings indicate that combining STEM learning with renewable energy projects provides contextual and meaningful science learning experiences for elementary students. This result aligns with previous studies reporting that project-based STEM learning improves conceptual understanding and scientific literacy through active exploration and inquiry activities.

Students' Engagement and Collaborative Learning

Classroom observations showed that students demonstrated high levels of engagement and participation during learning activities. Students actively collaborated in small groups while designing miniature solar-powered projects, discussing solar energy applications, and interacting with AI-generated learning materials.

The use of Generative AI increased students' curiosity and motivation during classroom discussions. Students frequently used AI tools to ask questions, generate ideas, and visualize solar energy systems in simple and understandable forms. This interactive learning environment encouraged students to participate more confidently in collaborative inquiry activities.

Furthermore, collaborative STEM learning promoted communication and teamwork skills among students. Group discussions allowed students to exchange ideas, solve problems collectively, and reflect on the environmental benefits of renewable energy technologies. These findings support previous research emphasizing that STEM learning environments can foster collaboration, creativity, and problem-solving competencies in science education.

Creativity and Sustainability Awareness

Students' project outputs revealed increased creativity in designing simple renewable energy models and proposing environmentally friendly solutions for daily life problems. Several groups successfully created miniature solar-powered devices using simple materials and demonstrated innovative ideas related to energy-saving practices in schools and homes.

The integration of Generative AI also contributed to students' creative thinking processes. AI-generated visualizations and prompts helped students develop new ideas and explore alternative solutions during project activities. Students reported that AI tools made science learning more interesting, interactive, and enjoyable.

In addition, students demonstrated improved sustainability awareness after the learning intervention. During interviews and classroom reflections, students expressed greater concern about environmental issues and recognized the importance of renewable energy for the future. They also showed positive attitudes toward using environmentally friendly technologies in daily life.

These findings suggest that integrating renewable energy education into elementary STEM learning can effectively support sustainability-oriented science education. The combination of STEM pedagogy and GenAI-assisted learning creates opportunities for young learners to develop environmental responsibility and future-oriented thinking skills from an early age.

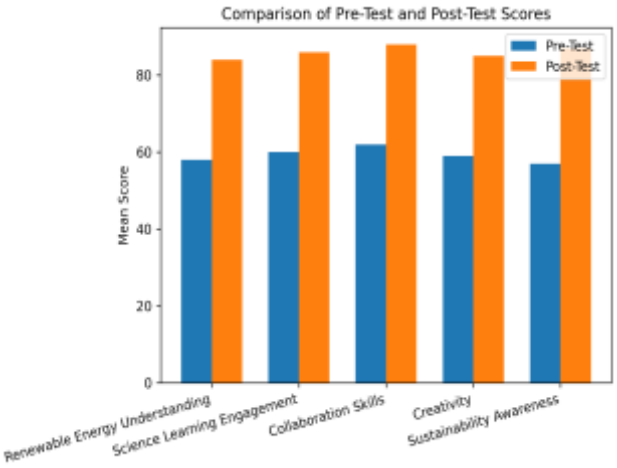

Figure 1. Comparison of Pre-Test and Post-Test Scores

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

The picture no 1 illustrates the comparison between the pre-test and post-test mean scores of sixth-grade students across five learning indicators following the implementation of Generative Artificial Intelligence (GenAI)-augmented STEM learning on solar cell technologies in elementary science education.

The results demonstrate a significant improvement in all indicators, including renewable energy understanding, science learning engagement, collaboration skills, creativity, and sustainability awareness. The pre-test means scores, which initially ranged from 57 to 62, increased substantially to 84–88 in the post-test after students participated in project-based STEM activities and solar energy exploration.

The highest improvements were observed in collaboration skills and sustainability awareness, indicating that project-based and AI-supported learning activities effectively promoted teamwork and environmental responsibility among students. Overall, the graph suggests that the integration of GenAI into STEM learning on renewable energy topics positively influenced students' learning outcomes, classroom engagement, and the development of twenty-first-century competencies in elementary science education.

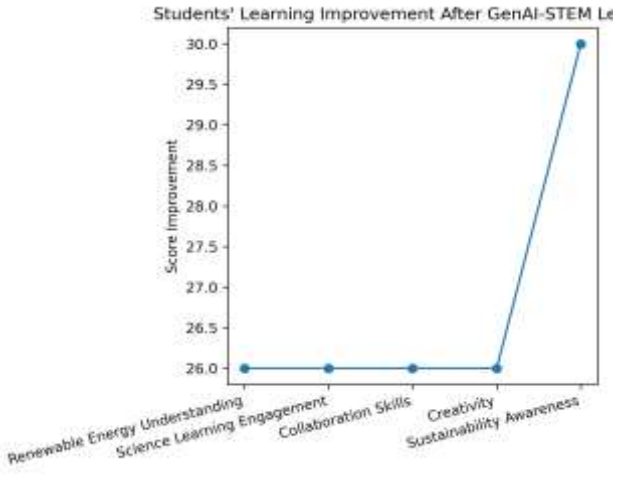

Figure 2. Improvement in Students' Learning Outcomes

The second figure illustrates the magnitude of students' learning improvement after participating in Generative Artificial Intelligence (GenAI)-augmented STEM learning on solar cell technologies in elementary science education. The graph shows that four indicators—renewable energy understanding, science learning engagement, collaboration skills, and creativity experienced consistent improvement scores of 26 points, indicating stable positive development across cognitive and collaborative learning dimensions.

Meanwhile, sustainability awareness demonstrated the highest improvement score of 30 points, suggesting that the integration of renewable energy topics with STEM and GenAI-based learning activities strongly influenced students' environmental consciousness and attitudes toward sustainable living. The findings indicate that project-based STEM learning supported by Generative AI not only enhanced students' scientific understanding but also promoted meaningful awareness of environmental sustainability. Overall, the graph confirms that GenAI-assisted STEM learning can effectively foster both academic achievement and sustainability-oriented competencies among sixth-grade students in elementary science classrooms.

Tabel 1. Students' Learning Outcomes

Indicator	Pre-Test Mean	Post-Test Mean
Renewable Energy Understanding	58	84
Science Learning Engagement	60	86
Collaboration Skills	62	88
Creativity	59	85
Sustainability Awareness	57	87

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

Table 1 presents the comparison of sixth-grade students' pre-test and post-test mean scores after the implementation of Generative Artificial Intelligence (GenAI)-augmented STEM learning on solar cell technologies in elementary science education. The results demonstrate substantial improvement across all measured indicators, including renewable energy understanding, science learning engagement, collaboration skills, creativity, and sustainability awareness. Students' mean scores increased from 58 to 84 in renewable energy understanding, from 60 to 86 in science learning engagement, from 62 to 88 in collaboration skills, from 59 to 85 in creativity, and from 57 to 87 in sustainability awareness. The highest post-test score was observed in collaboration skills, while the greatest improvement occurred in sustainability awareness. These findings indicate that the integration of GenAI-supported STEM learning effectively enhanced students' scientific understanding, active participation, collaborative competencies, creative thinking, and environmental consciousness. Overall, the table suggests that combining renewable energy education with AI-assisted STEM learning provides meaningful and impactful learning experiences for elementary science students.

The Role of Generative AI in Elementary Science Learning

The findings of this study highlight the significant role of Generative AI as a supportive educational technology in elementary science classrooms. GenAI facilitated students' understanding by providing visual explanations, interactive responses, and idea generation during inquiry-based learning activities.

Unlike conventional science instruction, GenAI-supported learning enabled students to access immediate feedback and alternative explanations adapted to their level of understanding. This condition helped reduce students' misconceptions and increased their confidence in participating in classroom discussions and STEM projects.

However, several challenges were also identified during the implementation process. Some students required teacher guidance when interacting with AI tools to ensure appropriate use and accurate interpretation of AI-generated information. Technical limitations, including internet connectivity and device availability, also influenced the smoothness of classroom implementation. Therefore, teacher facilitation remains essential in managing AI-supported STEM learning environments in elementary education.

Overall, this study demonstrates that GenAI-augmented STEM learning on solar cell technologies has strong potential to transform elementary science education into a more interactive, contextual, and sustainability-oriented learning experience. The integration of renewable energy education, STEM pedagogy, and Generative AI can support the development of scientific literacy, creativity, collaboration, and sustainability awareness among primary school students.

CONLUSION

This study concludes that the implementation of Generative Artificial Intelligence (GenAI)-augmented STEM learning on solar cell technologies positively enhances elementary science education. The integration of renewable energy topics, project-based STEM activities, and AI-assisted learning significantly improved sixth-grade students' understanding of renewable energy, learning engagement, collaboration, creativity, and sustainability awareness. GenAI proved effective in supporting scientific visualization, inquiry-based learning, idea generation, and interactive classroom experiences, while also helping students connect scientific concepts with real-world environmental issues. Moreover, the combination of GenAI, STEM, and

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

sustainability-oriented education contributed to the development of twenty-first-century competencies, environmental responsibility, and future-oriented thinking among young learners. Although challenges related to technological access and teacher facilitation were identified, the findings indicate that GenAI-augmented STEM learning is a promising and innovative approach for creating more interactive, engaging, and sustainability-focused elementary science learning environments. Future studies are recommended to involve larger samples, longer implementation periods, and broader educational settings to further investigate the long-term impact of AI-assisted STEM learning in primary education.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the school principal, science teachers, and sixth-grade students who participated in this study for their valuable support, cooperation, and active involvement throughout the research process. The authors also appreciate the contributions of colleagues and academic reviewers whose feedback and suggestions helped improve the quality of this research.

Special appreciation is extended to Institut Pendidikan Indonesia for providing academic support and encouragement in conducting this study. The authors are also grateful for the advancement of Generative Artificial Intelligence technologies that supported the development of innovative STEM learning activities in elementary science education.

REFERENCES

Azizah, N., Suciptaningsih, O. A., Rufiana, I. S., Anggraini, A. E., & Mardhatillah. (2025). Exploring the emergence of scientific ethics in inquiry-based renewable energy learning: A case study in elementary school. *Jurnal Bidang Pendidikan Dasar*, *10*(1), 1–12. https://doi.org/10.21067/jbpd.v10i1.12431

Becker, K., & Park, K. (2011). Integrative approaches among science, technology, engineering, and mathematics (STEM) subjects on students' learning: A meta-analysis. *Journal of STEM Education: Innovations and Research*, *12*(5), 23–37.

Cao, C., Ding, Z., Lee, G. G., Jiao, J., Lin, J., & Zhai, X. (2023). Elucidating STEM concepts through generative AI: A multi-modal exploration of analogical reasoning. *arXiv preprint arXiv:2308.10454*. https://arxiv.org/abs/2308.10454

Chen, L., Chen, P., & Lin, Z. (2020). Artificial intelligence in education: A review. *IEEE Access*, 8, 75264–75278. https://doi.org/10.1109/ACCESS.2020.2988510

Cheng, C. C., Wang, J. S., Zhai, X., & Yang, Y. T. C. (2025). AI literacy and gender equity in elementary education: A quasi-experimental study of a STEAM–PBL–AIoT course with questionnaire validation. *International Journal of STEM Education*, *12*(1), 50. https://doi.org/10.1186/s40594-025-00574-y

El Fathi, T., Saad, A., Larhzil, H., Lamri, D., & Al Ibrahmi, E. M. (2025). Integrating generative AI into STEM education: Enhancing conceptual understanding, addressing misconceptions, and assessing student acceptance. *Disciplinary and Interdisciplinary Science Education Research*, *7*(1), 6. https://doi.org/10.1186/s43031-025-00125-z

Jang, J., Jeon, J., & Jung, S. K. (2022). Development of STEM-based AI education program for sustainable improvement of elementary learners. *Sustainability*, *14*(22), 15178. https://doi.org/10.3390/su142215178

Jung, Y. S., & Lee, S. H. (2025). The effects of environmental education utilizing generative AI on elementary school students' environmentally friendly

Vol. 07 No. 01, Mei 2026
p-ISSN: 2774-8596 e-ISSN: 2774-8979
Terakreditasi Sinta 4

attitudes and environmental literacy. *Journal of the Korean Society of Earth Science Education, 18*(4), 421–431. https://doi.org/10.15523/JKSESE.2025.18.4.421

Jurenka, I., Kunesch, M., McKee, K. R., Gillick, D., Zhu, S., Wiltberger, S., ... & Ibrahim, L. (2024). Towards responsible development of generative AI for education: An evaluation-driven approach. *arXiv preprint arXiv:2407.12687*. https://arxiv.org/abs/2407.12687

Lestari, H. D., Rahmawati, Y., & Usman, H. (2024). STEM-PjBL learning model to enhance critical thinking skills of students on magnets, electricity, and technology. Jurnal Penelitian Pendidikan IPA, 10 (8), 6027–6037. https://doi.org/10.29303/jppipa.v10i8.8153

Memari, M., & Ruggles, K. (2025). Artificial Intelligence in Elementary STEM Education: A Systematic Review of Current Applications and Future Challenges. *arXiv preprint arXiv:2511.00105*. https://arxiv.org/abs/2511.00105

Nasution, A. A., Simanjuntak, M. D. H., Ghazali, A., Siahaan, N., & Gaol, M. L. (2025). Implementation of digital technology-based STEM approach in elementary schools: A systematic literature review. *Humanities & Language: International Journal of Linguistics, Humanities, and Education, 5*(1), 45–58. https://doi.org/10.32734/1z2c4333

Nurahman, A. (2024). Physics education student's interpretation of drawings depicting dye-sensitized solar cell as STEM-ESD activities created by Generative AI. In Book of Abstract of *EASE-ICMScE Joint Conference 2024 (pp. 44–45)*. Universitas Pendidikan Indonesia.

Nurahman, A., & Pribadi, P. (2022). Pemanfaatan kecerdasan buatan pada media pembelajaran berbantuan Google Assistant. *Jurnal Genesis Indonesia, 1*(1), 24–32. https://doi.org/10.56741/jgi.v1i01.17

Nurahman, A., Gumilar, S., & Ismail, A. (2024). *Modul Praktikum STEM-ESD Sel Surya.* Garut: Institut Pendidikan Indonesia Garut.

Nurahman, A., Hamdani, N. A., & Maulani, G. A. F. (2024). *Alat Peraga Sel Surya DSSC Berbasis STEM-ESD*. Garut: Institut Pendidikan Indonesia Garut.

Relmasira, S. C., Lai, Y. C., & Donaldson, J. P. (2023). Fostering AI literacy in elementary science, technology, engineering, art, and mathematics (STEAM) education in the age of generative AI. *Sustainability, 15*(18), 13595. https://doi.org/10.3390/su151813595

Setiawan, B., Ardianto, D., & Windiyani, T. (2025). AI-based website for integrating STEM and ESD: Enhancing students' creative thinking, creative products, and self-reflection. *Buana Pendidikan: Jurnal Fakultas Keguruan dan Ilmu Pendidikan Unipa Surabaya, 21*(2), 1–15. https://doi.org/10.36456/bp.vol21.no2.a10749

Sukmawati, W., Adlawan, H. A., & Andarawan, N. D. (2025). Analysis of science literacy and environmental awareness of elementary school students through the use of STEM-based solar sprinkle and ecoburn media in science learning. *Jurnal Penelitian Pendidikan IPA, 11 (5), 274–281.* https://doi.org/10.29303/jppipa.v11i5.11470