Journals Scientica Education Journal
E-ISSN : 3046-8523
https://nawalaeducation.com/index.php/SEJ/index
Vol.2.No.5 November 2025
DOI: https://doi.org/10.62872/k4qsmt87

Implementation of Project-Based Learning in Renewable Energy Materials: Analysis of Implementation and Its Impact on Students' 21st Century Skills

Ratna Puspitasari
UIN Siber Syekh Nurjati Cirebon

Email: ratnapuspitasari@syekhnurjati.ac.id

Inputed : October 21, 2025 *Revised : October 26, 2025*
Accepted : November 22, 2025 *Published: November 28, 2025*

ABSTRACT

The urgency of renewable energy education has become increasingly important in developing students' 21st-century skills and environmental awareness. Project-Based Learning (PjBL) emerges as an innovative pedagogical approach that can effectively integrate theoretical knowledge with practical implementation in renewable energy topics. This study aims to analyze the implementation of Project-Based Learning in renewable energy materials and examine its impact on students' 21st-century skills development, particularly critical thinking, creativity, collaboration, and environmental consciousness. This qualitative descriptive study employs a multiple case study approach, analyzing various implementations of PjBL in renewable energy education across different educational levels. Data were collected through document analysis, observation records, and implementation reports from 15 selected studies representing diverse contexts of PjBL application in renewable energy materials. The analysis reveals that PjBL implementation in renewable energy materials consistently enhances students' conceptual understanding, critical thinking skills, creativity, and collaboration abilities. Integration with STEM/STEAM approaches and ethnoscience further enriches the learning experience and increases local relevance. Key success factors include innovative learning media development, hands-on projects, and systematic teacher training. Project-Based Learning proves to be highly effective in renewable energy education, significantly improving both cognitive and affective learning outcomes. However, successful implementation requires systematic support including teacher training, appropriate learning resources, and institutional commitment.

Keywords: *Project-Based Learning, Renewable Energy, 21st Century Skills, STEM Education.*

INTRODUCTION

The global energy crisis and climate change impacts demand fundamental transformation in educational systems to prepare generations who understand and can implement sustainable energy solutions. Renewable energy materials have become essential components in modern science curricula, not only as theoretical knowledge transfer but also as vehicles for developing 21st-century skills including critical thinking, creativity, collaboration, and communication (Rizki & Suprapto, 2024).

Conventional learning that still dominates renewable energy education is often limited to delivering theoretical concepts without providing meaningful practical experiences. This results in low student engagement and limited applicative understanding of renewable energy technologies (Serevina et al., 2024). This condition requires pedagogical innovation that can bridge the gap between theory and practice while developing students' holistic competencies.

Project-Based Learning (PjBL) emerges as a promising pedagogical approach to address these challenges. PjBL is a learning model that organizes learning around complex and authentic projects, involving students in investigations centered on challenging questions or problems, requiring 21st-century skills, and producing products or presentations for real audiences (Bell, 2010). The main characteristics of PjBL include: (1) focus on questions or problems that encourage students to face main concepts and principles of a discipline, (2) involve students in constructive investigation, (3) student-centered, and (4) realistic (Krajcik & Blumenfeld, 2006).

In the context of renewable energy, PjBL enables students to be directly involved in designing, creating, and evaluating alternative energy systems, thereby enhancing conceptual understanding and practical skills simultaneously. Renewable energy education plays a crucial role in preparing students to face future sustainability challenges, not only covering understanding of various alternative energy sources such as solar, wind, hydro, and biomass, but also involving technical, economic, social, and environmental aspects of sustainable energy technology implementation (Ulazia & Ibarra-Berastegi, 2020).

The 21st-century skills framework developed by the Partnership for 21st Century Skills encompasses three main categories: (1) learning and innovation skills (critical thinking, creativity, communication, collaboration), (2) information, media, and technology skills, and (3) life and career skills. In the context of science education, PjBL has proven effective in improving learning motivation, conceptual understanding, and students' inquiry skills, enabling students to construct their own knowledge through direct experience and reflection, in line with constructivism principles (Trilling & Fadel, 2009).

This study aims to analyze the implementation of Project-Based Learning in renewable energy materials across various educational levels, examine its impact on students' 21st-century skills development, and identify challenges and solutions in its implementation. This analysis is important to provide comprehensive understanding of PjBL effectiveness as an innovative approach in renewable energy education that can develop students' holistic competencies to face future challenges.

METHOD

This study employs a qualitative approach with descriptive analytical method. The chosen research design is a multiple case study that allows in-depth analysis of various PjBL implementations in renewable energy materials across different educational contexts.

Research data were obtained from document analysis and PjBL implementation reports in renewable energy materials. Case selection was based on criteria: (1) PjBL implementation in renewable energy materials, (2) involving students from various educational levels, (3) providing sufficient data for analysis, and (4) representative of various geographical and institutional contexts.

Data analysis was conducted through several stages:

1. Data Reduction: Identification and selection of relevant information from each case
2. Categorization: Data grouping based on main themes
3. Cross-Case Analysis: Comparison of implementation patterns and impacts across cases

4. Interpretation: Meaning-making of findings in theoretical and practical contexts

Validity of findings was strengthened through data source triangulation and theoretical triangulation, comparing findings with various theoretical perspectives on PjBL and science learning (Sugiyono, 2019).

RESULTS AND DISCUSSION

Analysis of 15 PjBL implementation cases shows significant variation in approaches and implementation contexts. Based on educational levels, implementation is distributed as follows:

Table 1. Distribution of PjBL Implementation by Educational Level

Educational Level	Number of Cases	Percentage	Main Focus
Elementary School	2	13.3%	Basic concepts of alternative energy
Junior High School	3	20.0%	Exploration of renewable energy sources
Senior High School/Vocational	8	53.3%	Design and implementation of energy systems
Higher Education	2	13.3%	Techno-economic analysis and innovation
Total	15	100%	

PjBL implementation in renewable energy materials shows unique characteristics based on educational levels. At elementary level, projects focus on understanding basic concepts through simple experiments like making mini windmills and simple solar panels. At junior high level, projects develop into exploration of various renewable energy sources with emphasis on understanding energy conversion principles. Solar photovoltaic projects demonstrate great potential in environmentally friendly physics learning (Jauhari et al., 2024). At senior high/vocational levels, implementation shows higher complexity with projects such as:

- Solar-based garden lamp construction (Mufidah & Saputra, 2023)
- Small-scale wind turbine design and construction (Azis et al., 2023)
- Off-grid photovoltaic systems (Haryudo et al., 2022)
- Biogas production from organic waste

Integration with STEM/STEAM Approaches

Most implementations (80%) integrate PjBL with STEM or STEAM approaches, creating holistic interdisciplinary learning.

Table 2. PjBL Integration Patterns with Other Approaches

Integration Approach	Number of Cases	Main Characteristics	Primary Impact
PjBL-STEM	8	Integration of science, technology, engineering, mathematics	Improved conceptual understanding and problem-solving skills
PjBL-STEAM	4	Addition of arts/creativity	Enhanced creativity and

Integration Approach	Number of Cases	Main Characteristics	Primary Impact
		elements	innovation
PjBL-Ethnoscience	2	Integration with local wisdom	Increased contextual relevance
Conventional PjBL	1	Focus on single discipline	Specific understanding improvement

STEM/STEAM integration allows students to understand renewable energy from multidisciplinary perspectives. For example, in wind turbine construction projects, students not only learn physics principles of kinetic energy conversion to electrical energy, but also engineering aspects in optimal blade design, mathematics in efficiency calculations, and technology in control and monitoring systems. STEM integration with engineering design process has proven effective in fostering students' system thinking skills (Abdurrahman et al., 2023). STEAM-based collaborative learning significantly enhances critical thinking and creativity (Ellianawati et al., 2025).

Impact on 21st Century Skills

Analysis of PjBL impact on 21st-century skills development shows significant improvement across various dimensions:

Table 3. PjBL Impact on 21st Century Skills

Skills	Improvement Level	Main Indicators	Evaluation Methods
Critical Thinking	High (87% cases)	Energy problem analysis, alternative solution evaluation	Pre-test/post-test, assessment rubrics
Creativity	High (80% cases)	Design innovation, creative solutions	Project portfolios, peer assessment
Collaboration	Very High (93% cases)	Effective teamwork, task distribution	Observation, self-assessment
Communication	Moderate (67% cases)	Result presentations, project reports	Presentation rubrics, document analysis
Digital Literacy	High (73% cases)	Simulation software use, information search	Technology usage analysis

Critical Thinking

Critical thinking skills development is consistently observed across different implementations. Students demonstrate ability to:

- Analyze efficiency of various renewable energy systems
- Evaluate factors affecting system performance
- Compare alternative energy solutions based on technical and economic criteria
- Identify limitations and challenges in renewable energy technology implementation

Rizki & Suprapto (2024) reported significant improvement in high school students' critical thinking abilities after SR-STEM based PjBL implementation, with large effect size (d = 1.23).

Creativity and Innovation

Renewable energy projects provide extensive space for students' creative expression. Some examples of resulting innovations include:

- Hybrid system designs combining solar and wind energy
- Mobile applications for renewable energy system monitoring
- Aesthetic integration in solar panel design for buildings
- Use of recycled materials in energy system construction

Innovative Learning Media and Resources

PjBL implementation in renewable energy is enriched with development of various innovative learning media and resources:

Table 4. Types of Learning Media Developed

Media Type	Usage Frequency	Effectiveness	Implementation Challenges
Renewable Energy Kits	60%	Very High	Procurement costs
Project-Based Worksheets	87%	High	Content development
Interactive E-Modules	40%	High	Teachers' digital skills
Simulation Software	53%	Moderate	Technology access
Models/Prototypes	73%	Very High	Construction time

Renewable energy kits prove to be the most effective learning media, enabling students to conduct hands-on experiments with various alternative energy technologies. Haryudo et al. (2022) developed off-grid photovoltaic system training kits that significantly improved vocational students' learning outcomes. The development of problem-based e-modules also demonstrates high effectiveness in distance learning contexts (Ashnam et al., 2022). Renewable energy kits prove effective in developing students' both lower and higher-order thinking skills (Yennita et al., 2024). Project-based learning approach has been successfully implemented in electric vehicle development projects (Ariza & Olatunde-Aiyedun, 2023). Development of differentiated PjBL-integrated worksheets proves effective in training science process skills (Ellianawati et al., 2024).

Implementation Challenges and Solutions

Despite showing consistent positive impacts, PjBL implementation in renewable energy materials faces various challenges:

Table 5. Implementation Challenges and Solutions

Challenges	Frequency of Occurrence	Impact	Applied Solutions
Time Constraints	73%	High	Curriculum integration, blended learning
Lack of Teacher Training	67%	Very High	Continuous training programs, mentoring
Resource Limitations	60%	High	Industry partnerships, grant funding
Resistance to Change	40%	Moderate	Socialization, gradual implementation
Assessment Complexity	53%	Moderate	Rubric development, authentic assessment

Comparative Analysis Based on Context

PjBL implementation shows variation based on geographical and socio-economic contexts:

Table 6. Implementation Comparison by Context

Context	Implementation Characteristics	Advantages	Limitations
Urban	Technology-rich, industrial partnership	Resource access, networking	High cost, competition
Rural	Community-based, local wisdom integration	Contextual relevance, sustainability	Limited resources, connectivity
Developing	Cost-effective solutions, creative adaptations	Innovation, resilience	Infrastructure constraints
Developed	Sophisticated equipment, research integration	Quality, advancement	Complexity, over-engineering

Rural contexts show uniqueness in integrating local wisdom and community resources. Putri et al. (2025) reported successful integration of seaweed ethnoscience with STEM-PjBL that not only improved students' creativity but also developed entrepreneurial skills based on local potential.

PjBL Effectiveness in Renewable Energy Context

Research findings confirm PjBL effectiveness in renewable energy learning context, consistent with various international studies showing positive PjBL impact on student outcomes (Thomas, 2000; Krajcik & Blumenfeld, 2006). PjBL advantages in renewable energy context lie in its ability to:

1. Contextual Learning: Renewable energy as contemporary issue provides high relevance for students
2. Interdisciplinary Integration: Complex nature of renewable energy technology requires integration of various disciplines
3. Real-world Application: Project products have practical applications in daily life
4. Sustainability Awareness: Develops environmental awareness and social responsibility

21st Century Skills Development Mechanisms

Analysis shows that PjBL develops 21st-century skills through various mechanisms:

Collaborative Problem Solving: Complexity of renewable energy projects requires intensive collaboration, developing students' abilities in teamwork, communication, and conflict resolution.

Authentic Assessment: Performance and product-based assessment provides meaningful feedback and encourages continuous improvement.

Metacognitive Development: Systematic reflection on project processes and results develops students' metacognitive abilities.

Technology Integration: Use of various digital tools and simulation software enhances students' digital literacy. Digital skills development is also significantly enhanced through technology-based projects (Gunarathna et al., 2023). Digital skills development is also significantly enhanced through technology-based projects (Gunarathna et al., 2023).

Critical Success Factors

Based on cross-case analysis, several critical success factors for PjBL implementation have been identified:

1. Teacher Readiness: Teacher competence in content knowledge, pedagogical knowledge, and technological knowledge

2. Institutional Support: Systemic support from educational institutions in terms of policy, resources, and infrastructure
3. Student Characteristics: Student readiness to engage in active and collaborative learning
4. Community Partnership: External stakeholder involvement in supporting project implementation
5. Resource Availability: Adequate availability of materials, equipment, and funding

Active collaborative learning in renewable energy projects shows promising results (Roney, 2024).

Implications for Educational Practice

Research findings have several important implications for educational practice:
Curriculum Design: Need for curriculum redesign accommodating PjBL implementation with adequate time allocation and clear learning outcomes.
Teacher Professional Development: Development of comprehensive teacher training programs covering renewable energy content knowledge, PjBL pedagogy, and technology integration.

Assessment Reform: Development of assessment systems appropriate to PjBL characteristics, emphasizing authentic assessment and formative evaluation.
Infrastructure Development: Investment in supporting infrastructure such as laboratories, workshops, and technology access.

CONCLUSION

Based on comprehensive analysis of Project-Based Learning implementation in renewable energy materials, this study yields several main conclusions:

1. Implementation Effectiveness: PjBL proves highly effective in improving renewable energy conceptual understanding, with consistent positive impacts across different educational levels and contexts. Integration with STEM/STEAM approaches and ethnoscience further strengthens implementation effectiveness.

2. 21st Century Skills Development: PjBL implementation significantly develops students' 21st-century skills, particularly in collaboration (93% cases), critical thinking (87% cases), and creativity (80% cases). This indicates that PjBL not only improves cognitive outcomes but also social-emotional skills essential for the future.

3. Learning Innovation: PjBL encourages innovation in learning media development, creating hands-on learning experiences through renewable energy kits, project-based worksheets, and interactive e-modules that prove to enhance student engagement and learning outcomes.

4. Systemic Challenges: Despite effectiveness, PjBL implementation faces systemic challenges requiring holistic solutions, including teacher training (67% cases), resource limitations (60% cases), and time constraints (73% cases).

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