PjBL-STEM for Environmental Citizenship: The Design of an Alternative Energy Module in Elementary School

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ABSTRACT
This research aims to develop and test the feasibility of a Project-Based Learning STEM (PjBL-STEM) Teaching Module integrated with citizenship skills for fifth-grade elementary students on the topic of Alternative Energy. The study addresses the need for learning environments that develop 21st-century skills, in line with Indonesia's Merdeka Curriculum. The research method employed is Educational Design Research (EDR), consisting of three stages: Analysis and Exploration, Design and Construction, and Evaluation and Reflection. The analysis revealed a need among teachers for a systematic guide to implementing PjBL-STEM integrated with character strengthening. Based on this, a prototype module was designed and validated by experts with a "Very Suitable" rating. The evaluation was conducted through two trial cycles. The first cycle identified challenges with compressed lesson time and the assessment of citizenship skills. After revisions—dividing the lesson into two days and adding performance assessment notes—the second cycle showed significant improvement. Teacher response scores increased from 77.08% ("Suitable") to 95.8% ("Very Suitable"), particularly in practicality and character-building effectiveness. These findings confirm that the developed PjBL-STEM module is feasible and effective for fostering meaningful, contextual learning that enhances students' citizenship skills.

Keywords: Teaching Module, PJBL-STEM, Citizenship Skills, Alternative Energy, Educational Design Research (EDR).

1. INTRODUCTION

The Imperative of Integrated STEM Education in the 21st Century

The current global educational paradigm shift demands a transformation from rote learning-centered instruction to the development of competencies relevant to the 21st century [1]. Amidst rapid technological advancements, there is an urgent need to prepare a young generation that not only masters academic knowledge but also possesses critical thinking, problem-solving, collaboration, and innovation skills [1]. In this context, Science, Technology, Engineering, and Mathematics (STEM) education plays a central role. Effective STEM education is not merely the teaching of separate disciplines, but rather an interdisciplinary approach that enables students to apply knowledge and skills from all four fields to solve complex, real-world problems [2,3]. This approach aims not only to meet the future demand for a STEM-literate workforce but also to equip all students to participate actively and informedly in a society increasingly influenced by science and technology.

Project-Based Learning (PjBL) as a Vehicle for Authentic STEM Engagement

The effective implementation of integrated STEM education requires a pedagogical approach that can facilitate active and contextual learning. Project-Based Learning (PjBL) has been widely recognized as one of the most powerful approaches to achieve this goal [4,5]. PjBL is a dynamic learning model that engages students in a continuous inquiry process centered on authentic and complex questions or problems [6,7]. Through project work, students not only acquire deep content knowledge but also develop essential 21st-century skills. Various studies have demonstrated the effectiveness of PjBL in increasing student engagement, learning motivation, critical thinking skills, and learning outcomes in science and STEM subjects [8-11]. According to Krajcik and Czerniak, there are five essential features of PjBL in science learning: (1) building relevance to students' lives through exploration and questioning; (2) engaging students in science and engineering practices; (3) encouraging collaboration with peers and the community; (4) utilizing technology as a learning tool; and (5) creating artifacts as a manifestation of understanding [7].

The Neglected 'C': Integrating Citizenship Skills into STEM Education

While the focus on cognitive and technical skills in STEM is crucial, there is a critical dimension that is often overlooked: the development of citizenship skills. Citizenship education aims to prepare students to become active, informed, and responsible members of society, capable of thinking critically about social issues and contributing positively to their communities [12,13]. The integration of these skills into STEM is becoming increasingly urgent, given that many global challenges—such as climate change, the energy crisis, and pandemics—are rooted in science and technology but have profound social, ethical, and political implications.

The Socio-Scientific Issues (SSI) framework offers a powerful pedagogical bridge to connect STEM content with citizenship education [14]. SSI are defined as complex and open-ended social dilemmas rooted in science, which involve moral, ethical, and social considerations in their decision-making processes [14]. The topic of "alternative energy," which is the focus of this research, is a classic example of an SSI. This topic not only demands an understanding of scientific concepts (e.g., energy conversion) and technology (e.g., solar panels) but also encourages students to consider collective responsibility for environmental sustainability and energy justice. Thus, using a PjBL-STEM approach to explore an SSI like alternative energy creates a natural and authentic context for students to develop citizenship competencies, such as understanding social roles and responsibilities, actively engaging in communal problem-solving, and interacting effectively in groups [12]. This approach shifts the learning goal from merely "learning about STEM" to "educating citizens through STEM."

Research Problem: The Gap Between Policy and Practice

Despite global pushes and national curriculum goals, such as the Kurikulum Merdeka (Independent Curriculum) in Indonesia, which have emphasized the importance of integrated learning, a significant gap exists between policy aspirations and actual implementation in elementary school classrooms. The initial needs analysis conducted in this study reveals that although elementary school teachers understand the value of project-based learning, they often lack the specific knowledge, structured resources, and clear pedagogical models to implement PjBL-STEM effectively, especially with an integrated focus on citizenship skills. Existing teaching modules tend to be general, lack explicit detail in learning steps, and fail to integrate learning models systematically. This gap serves as the practical justification and urgency for this research.

Research Aims and Contributions

Based on the identified problems, this research aims to: (1) Analyze the needs and challenges in the implementation of a PjBL-STEM module integrated with citizenship skills in Indonesian elementary schools; (2) Design and develop a theoretically and practically grounded PjBL-STEM teaching module on the topic of alternative energy; and (3) Evaluate the validity, practicality, and effectiveness of the module through an iterative process of implementation and reflection.

The contributions of this research are twofold. Practically, it produces a validated, ready-to-use teaching module that teachers can utilize to implement meaningful STEM learning. Theoretically, this study offers transferable design principles for integrating citizenship education into the elementary STEM curriculum in similar contexts, providing guidance for future curriculum developers and researchers.

2. METHOD

Research Design: Educational Design Research (EDR)

This study employs the Educational Design Research (EDR) methodology, as conceptualized by McKenney and Reeves [15,16]. The choice of this methodology is based on the dual focus of EDR: (1) to solve complex practical problems in the world of education, and (2) to generate theoretical insights that can enrich the scientific knowledge base [17,18]. EDR is highly suitable for this research due to its iterative nature, which allows for the continuous development and refinement of an educational intervention (in this case, a teaching module) based on empirical data collected from a natural learning context [15]. As described by Plomp, EDR has five main characteristics adopted in this study: Interventionist (aiming to design a real-world intervention), Iterative (involving repeated cycles of analysis, design, evaluation, and revision), Process Oriented (focusing on understanding and improving processes), Utility Oriented (assessing success based on practicality for users), and Theory Oriented (contributing to theory building) [18].

Research Procedure

This research was conducted through the three main phases of the EDR model:

Phase 1: Analysis and Exploration. This phase aimed to comprehensively define the problem through a needs analysis. The activities included: (a) an in-depth literature review on PJBL-STEM, citizenship education, and the development of teaching modules; (b) the distribution of a Likert scale questionnaire to more than 50 elementary school teachers in the Tasikmalaya region to measure their perceptions and level of STEM literacy; (c) semi-structured interviews with two fifth-grade teachers to explore their understanding, practices, and challenges in implementing project-based learning; and (d) a documentary study of existing teaching modules to identify didactic, constructional, and technical shortcomings.

Phase 2: Design and Construction. In this phase, the findings from Phase 1 were synthesized to develop a prototype of the intervention, namely the PJBL-STEM Citizenship Skills Teaching Module. The module's design was based on the five-stage PJBL-STEM syntax (Reflection, Research, Discovery, Application, Communication) proposed by Laboy-Rush [5]. Furthermore, the module explicitly integrates three main indicators of citizenship skills adapted from Anggraeni et al., : (a) understanding roles and responsibilities, (b) actively engaging in problem-solving, and (c) interacting effectively [12]. The completed prototype module was then validated by two experts: one material expert (science education) and one pedagogical expert (elementary school learning) to ensure its content feasibility and pedagogical appropriateness before implementation.

Phase 3: Evaluation and Reflection. This phase involved the iterative testing and refinement of the module in an actual classroom context. The implementation was carried out in two cycles. The first cycle was conducted at one school, where data on the module's practicality and effectiveness were collected. Based on the data analysis from the first cycle, the module was revised to address identified deficiencies. The revised module was then implemented in a second cycle at a different school to evaluate the impact of the improvements made.

Participants and Setting

The participants in this study consisted of several groups: (1) Students: Fifth-grade students (approximately 10-11 years old) from two public elementary schools in the city of Tasikmalaya, Indonesia. A total of 30 students participated in each implementation cycle. (2) Teachers: The fifth-grade teachers at each school acted as the implementers of the teaching module in their daily learning activities. The researcher served as a facilitator and observer during the implementation process. (3) Experts: Two university lecturers, one with expertise in science education (Material Expert) and another in elementary school pedagogy (Pedagogical Expert), acted as validators for the prototype teaching module. (4) The selection of schools was based on specific criteria, including the school administration's willingness to cooperate, the availability of adequate facilities for project activities, and the teachers' experience in implementing project-based learning.

Data Collection Instruments

Various instruments were used to collect comprehensive data in each phase of the research: (1) Teacher Questionnaire: A Likert scale questionnaire developed based on STEM literacy indicators from the NAE & NRC to assess teachers' awareness, familiarity, and application of STEM [3]. (2) Interview Guide: Semi-structured questions designed to explore teachers' understanding of the curriculum, PJBL-STEM, and the need for teaching module development. (3) Document Study Sheet: A checklist used to analyze existing teaching modules based on didactic, constructional, and technical requirements. (4) Expert Validation Sheet: A Likert scale assessment instrument for experts to evaluate the module's feasibility in terms of material suitability, PJBL-STEM syntax, clarity of scenarios, language, and the integration of citizenship skills. (5) Student and Teacher Response Questionnaire: A post-implementation questionnaire using a combination of a Likert scale and open-ended questions to gather data on the practicality, engagement level, material comprehension, and effectiveness of the module from the users' perspectives.

Data Analysis

A mixed-methods (qualitative and quantitative) data analysis technique was employed: (1) Qualitative Data: Data from interviews, open-ended questionnaire responses, and observation notes were analyzed using a thematic analysis approach, which included three stages: data reduction, data display, and conclusion drawing. (2) Quantitative Data: Data from the Likert scale questionnaires (expert validation, teacher perceptions, student and teacher responses) were analyzed using descriptive statistics. Raw scores from each item were converted into percentages to determine the level of feasibility or practicality. These percentages were then categorized based on predefined criteria (e.g., 85-100% = Very Feasible/Very Practical) to provide a qualitative interpretation of the quantitative data [19,20].

3. RESULTS AND DISCUSSION

3.1. Results

Phase 1: Needs Analysis Findings

The analysis and exploration phase revealed a clear need for the development of a structured PJBL-STEM teaching module. The results of the teacher perception questionnaire indicated that although teachers in the Tasikmalaya City and Regency areas have a high level of awareness regarding the important role of STEM in modern society (mean scores of 3.88 and 4.03 out of 5), their familiarity with basic STEM concepts remains at a neutral level (mean scores of 3.31 and 3.36). This indicates a gap between awareness and conceptual understanding.

These findings were reinforced by the interview results. The teachers stated that they had implemented project-based learning, such as creating respiratory models or simple traffic lights. However, these activities were not systematically structured according to the PJBL-STEM syntax and did not explicitly integrate the development of citizenship skills. The documentary study of existing Lesson Plans and teaching modules showed that while the main components were present, the learning steps were not detailed, and the syntax of the learning model used was not clearly stated. Collectively, these findings confirm an urgent need for a teaching module that is not only innovative but also provides clear and systematic guidance for teachers.

Phase 2: Module Design and Validation

Based on the findings of the needs analysis, a prototype of the PJBL-STEM Citizenship Skills Teaching Module on the topic of "Alternative Energy" was successfully designed. This module includes a teacher's guide, student worksheets, and a performance assessment rubric specifically designed to assess citizenship skills within the project context. The prototype was then validated by a material expert and a pedagogical expert. The validation results showed a very high level of feasibility, as presented in Table 1.

Table 1. Expert Validation Results for the PJBL-STEM Teaching Module

Validated Aspect	Content Expert's Assessment	Pedagogical Expert's Assessment	Average Score	Qualification
Content Feasibility and Accuracy	100%	100%	100%	Highly Suitable
Pedagogical Appropriateness (PJBL-STEM Syntax)	100%	100%	100%	Highly Suitable
Language and Presentation	100%	100%	100%	Highly Suitable
Integration of Citizenship Skills	100%	100%	100%	Highly Suitable
Overall Validity	**100%**	**100%**	**100%**	**Highly Suitable**

Both experts gave the maximum score on all aspects, indicating that the teaching module is theoretically valid, accurate in content, pedagogically appropriate, and successfully integrates STEM concepts with citizenship skills. With these results, the module was declared suitable for trial in a classroom setting.

Phase 3: Implementation, Evaluation, and Reflection (Cycles 1 & 2)

This phase constitutes the core of EDR, where comparative data from the two implementation cycles demonstrate the effectiveness of the iterative design process.

Table 2. Comparison of Student Response Data from Cycle 1 and Cycle 2

Indicator	**Cycle 1 (% Positive Response)**	**Cycle 2 (% Positive Response)**	Change
Engaging Teaching Methods	93,3%	93,3%	0
Had no difficulty working on the project	56,7%	83,3%	+26,6%
Understanding the learning material	70,0%	75,6%	+5,6%
Collaborates effectively with others	81,7%	86,7%	+5,0%
Willing to learn with this model again	70,0%	90,0%	+20,0%
Overall Average Positive Response	75,3%	81,3%	+6,0%

Table 3. Comparison of Teacher Responses from Cycle 1 and Cycle 2

Aspect	**Cycle 1 (Average Score %)**	**Cycle 1 Results**	**Cycle 2 (Average Score %)**	**Cycle 2 Results**
Meaningfulness of Material and Context	75,0%	Sesuai	87,5%	strongly supports
Student Activity and Participation	75,0%	consistent with	100,0%	strongly supports
Ease of Implementation (Practicality)	75,0%	consistent with	100,0%	strongly supports
Effectiveness for Citizenship Skills	62,5%	Largely consistent with	87,5%	strongly supports
Overall Practicality & Effectiveness	77,1%	consistent with	95,8%	strongly supports

Qualitative Findings from the Iterative Process

The significant differences between the results of Cycle 1 and Cycle 2 were driven by the qualitative findings that informed the revision process.

Findings from Cycle 1: The implementation of the module in a single day (equivalent to 4 lesson hours) was found to cause cognitive and physical fatigue in students. Observations showed that students appeared rushed in completing their projects, and questionnaire data confirmed that 56.7% of students experienced difficulties with the project work. Furthermore, the teacher's response indicated the lowest score was in the effectiveness aspect for citizenship skills (62.5%), suggesting that although the activities were present, their assessment remained implicit and lacked direction.

Revisions for Cycle 2: Based on these findings, two major revisions were made. First, the learning time allocation was changed from one day to two days. The first day focused on the Reflection, Research, and Discovery stages to build conceptual understanding. The second day was dedicated to the Application (project work) and Communication (presentation) stages, providing students with more ample time. Second, the teaching module and performance assessment sheets were revised by adding explicit markers that linked specific project activities (e.g., task delegation, solution discussions) with the assessed citizenship skills indicators. This aimed to make the assessment process more transparent and focused for the teacher.

3.2. Discussion

Efficacy of the PJBL-STEM Module in a Real-World Context

The positive results from Cycle 2, marked by high response scores from students (81.3%) and the teacher (95.8%), provide strong evidence for the efficacy of the developed teaching module. This success can be attributed to the application of core PJBL principles that create a student-centered, authentic problem-based, and hands-on learning experience [4,6,21]. The significant improvement from Cycle 1 to Cycle 2, particularly in the ease with which students completed the project (+26.6%) and the teacher's perception of the module's practicality (from 75% to 100%), directly demonstrates the positive impact of the revisions informed by the EDR process. This confirms that good instructional design depends not only on solid content but also on structure, flow, and time allocation that consider real classroom conditions.

Fostering Citizenship through Socio-Scientific Inquiry

The most innovative aspect of this study is the deliberate effort to foster citizenship skills through STEM learning. The dramatic increase in the teacher's assessment of the module's effectiveness in fostering citizenship skills (from 62.5% to 87.5%) is a key finding. This improvement was not coincidental but was a direct result of revisions that made the assessment of citizenship skills more explicit and integrated into the learning flow.

This success is rooted in framing the topic of alternative energy as a Socio-Scientific Issue (SSI). This approach inherently encourages students to go beyond merely building a technical product. They were required to discuss the responsibility of energy use, collaborate to find efficient solutions, and consider the impact of their choices on their "miniature village"—a metaphor for the wider community. Thus, the project became a training ground for citizenship, where students practiced skills in negotiation, collective problem-solving, and understanding their roles as citizens concerned with communal issues [14,22]. This finding provides strong empirical support for using the SSI framework as a pedagogical approach to bridge the gap between STEM education and citizenship education.

The Power of Iterative Design: Lessons from Educational Design Research

The difference in outcomes between Cycle 1 and Cycle 2 serves as a powerful case study on the value of the EDR methodology. Had this research used a traditional, non-iterative design approach, the conclusion might have only stated that the module was "moderately effective." However, the reflective and cyclical nature of EDR allowed the researcher to identify crucial design weaknesses—such as inadequate time allocation and unclear assessments—and systematically rectify them [15,18].

This process enabled the formulation of a transferable design principle, which is one of the key theoretical outcomes of high-quality EDR. The initial design in Cycle 1 failed for two main reasons: excessive cognitive load due to a tight schedule and a weak, implicit integration of citizenship assessment. The revisions directly addressed these failures by extending the timeline and making the citizenship assessment explicit. The success of the revised design in Cycle 2, validated by both quantitative and qualitative data, leads to the following principle: To effectively integrate citizenship skills into PJBL-STEM in elementary schools, the instructional design must (a) allocate sufficient time over multiple sessions to allow for deep engagement in all project phases, and (b) explicitly link collaborative project activities with performance-based assessments of specific citizenship competencies. This principle is a key theoretical contribution of this study, as it provides actionable guidance for other teachers and researchers beyond the specific context of this research [23].

Research Limitations

To maintain academic integrity, it is important to acknowledge several limitations in this study. First, the relatively small sample size, limited to two schools in one city, restricts the generalizability of the findings to broader contexts. Second, the active role of the researcher in the classroom during implementation may have introduced a Hawthorne effect, where participants alter their behavior due to the awareness of being observed. These limitations, however, open opportunities for future research that could address these issues with more extensive designs.

4. CLOSURE

Based on the results of the research conducted through the three phases of Educational Design Research, it can be concluded that the developed PJBL-STEM Teaching Module is a valid, practical, and effective learning tool for teaching the concept of alternative energy while simultaneously fostering citizenship skills in elementary school students. The success of this module hinges on two key design principles identified through the iterative process: (1) the need for flexible time allocation, spread across multiple sessions, to avoid cognitive overload and allow for in-depth exploration, and (2) the importance of integrating explicit performance assessments to make the development of citizenship skills a directed and measurable learning objective.

This research affirms that the PJBL-STEM approach, when carefully designed, can be a powerful vehicle for interdisciplinary learning that is not only academically relevant but also socially meaningful. The findings of this study recommend adopting and adapting this PJBL-STEM model for other relevant Socio-Scientific Issues (SSI)-based topics, such as waste management, water conservation, or biodiversity. Furthermore, there is a need for continuous professional development programs that not only equip teachers with STEM content but also with pedagogical frameworks like PJBL and an understanding of design methodologies to create contextualized learning experiences (Gardner, Glassmeyer, & Worthy, 2019; Koehler & Mishra, 2009).

REFERENCES

[1] Trilling, B., & Fadel, C. (2009). 21st Century Skills: Learning for Life in Our Times. John Wiley & Sons.

[2] Bybee, R. W. (2013). The case for STEM education: Challenges and opportunities. NSTA press.

[3] National Academy of Engineering & National Research Council. (2014). STEM integration in K-12 education: Status, prospects, and an agenda for research. National Academies Press.

[4] Bell, S. (2010). Project-Based Learning for the 21st Century: Skills for the Future. The Clearing House, 83(2), 39-43.

[5] Laboy-Rush, D. (2011). Integrated STEM education through project-based learning. Learning.com.

[6] Dewey, J. (1938). Experience and Education. Kappa Delta Pi.

[7] Krajcik, J., & Czerniak, C. M. (2018). Teaching science in elementary and middle school: A project-based approach. Routledge.

[8] Herak, R. (2021). Peningkatan Hasil Belajar IPA Peserta Didik Kelas VIII Materi Sistem Ekskresi melalui Pengaruh Model STEM. Jurnal Studi Guru Dan Pembelajaran, 4(1), 127-134.

[9] Kurt, G., & Akoglu, K. (2023). Project-based learning in science education: A comprehensive literature review. Interdisciplinary Journal of Environmental and Science Education, 19(3), e2311. https://doi.org/10.29333/ijese/13677

[10] Laili, I., & Dadang, S. (2022). Penerapan Model STEM Berbasis PJBL untuk Meningkatkan Keterampilan Pemecahan Masalah pada Peserta didik Sekolah Dasar. Jurnal Pendidikan Dasar Indonesia, 15(2), 110–120.

[11] Rahmania, I. (2021). Project based learning (PjBL) learning model with STEM approach in natural science learning for the 21st century. Budapest International Research and Critics Institute (BIRCI-Journal): Humanities and Social Sciences, 4(1), 1161-1167.

[12] Anggraeni, T., dkk. (2023). Keterampilan Abad 21: Mengintegrasikan Citizenship dalam Pembelajaran STEM. Penerbit Edupress.

[13] Kerr, D. (2000). Citizenship education: An international comparison. Education for citizenship, 200-227.

[14] Romero-Ariza, M., et al. (2024). Socioscientific issues in STEAM education: A scoping review. Sustainability, 16(14), 5827. https://doi.org/10.3390/su16145827

[15] McKenney, S., & Reeves, T. C. (2019). Conducting educational design research (2nd ed.). Routledge.

[16] Van den Akker, J., Gravemeijer, K., McKenney, S., & Nieveen, N. (Eds.). (2006). Educational design research. Routledge.

[17] Creswell, J. W. (2014). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (4th ed.). SAGE Publications.

[18] Plomp, T., & Nieveen, N. (Eds.). (2013). Educational design research: An introduction. SLO.

[19] Arikunto, S. (2010). Prosedur Penelitian Suatu Pendekatan Praktik. Rineka Cipta.

[20] Widoyoko, E. P. (2012). Teknik Penyusunan Instrumen Penelitian. Pustaka Pelajar

[21] Srirahmawati, A., Deviana, T., & Wardani, S. K. (2023). Peningkatan Keterampilan Abad 21 (6C) Peserta didik Kelas IV Sekolah Dasar Melalui Model Project Based Learning Pada Kurikulum Merdeka. Pendas: Jurnal Ilmiah Pendidikan Dasar, 8(1), 5283-5294.

[22] Lickona, T. (1991). Educating for Character: How Our Schools Can Teach Respect and Responsibility. Bantam Books.

[23] Miller, E. C., Severance, S., & Krajcik, J. (2021). Motivating teaching, sustaining change in practice: Design principles for teacher learning in project-based learning contexts. Journal of Science Teacher Education, 32(7), 757-779. https://doi.org/10.1080/1046560X.2021.1872207

[24] Gardner, K., Glassmeyer, D., & Worthy, R. (2019). Impacts of STEM professional development on teachers' knowledge, self-efficacy, and practice. Frontiers in Education, 4, 26. https://doi.org/10.33225/jbse/17.16.395

[25] Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge (TPACK)?. Contemporary Issues in Technology and Teacher Education, 9(1), 60-70.