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DEVELOPING RENEWABLE ENERGY COMPETENCE IN ENGINEERING EDUCATION: A SUSTAINABLE DEVELOPMENT PERSPECTIVE

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Abstract. *Renewable energy competence has become an essential outcome of engineering education as universities are increasingly expected to prepare graduates capable of addressing global energy transition and sustainability challenges. Although Project-Based Learning (PBL) has been widely implemented to promote authentic learning and practical skill development, the instructional, technological, and psychological mechanisms through which students develop renewable energy competence remain insufficiently understood. This study proposes an integrated framework by examining the roles of PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, and Performance in explaining the development of renewable energy competence among engineering students. Using survey data collected from 110 undergraduate engineering students at the Faculty of Engineering, Universitas Negeri Medan, Indonesia, this study employs Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine both direct and indirect relationships among the proposed constructs. The findings reveal that PBL Strategy significantly enhances students' self-efficacy, learning motivation, and academic performance, while Digital Literacy positively influences self-efficacy. Self-efficacy significantly improves learning motivation, and learning motivation positively contributes to academic performance. Academic performance emerges as the only direct predictor of renewable energy competence, whereas the direct effects of self-efficacy and learning motivation on renewable energy competence are not statistically significant. Mediation analysis further indicates that self-efficacy mediates the relationship between digital literacy and learning motivation, while learning motivation and self-efficacy mediate the effects of PBL Strategy on renewable energy competence. These findings suggest that competency development in renewable energy is primarily achieved through interconnected instructional and psychological processes rather than through isolated direct effects. This study contributes to the literature on engineering education and competency-based learning by providing an integrated model that explains how project-based learning, digital literacy, and psychological factors collectively foster renewable energy competence in technology-enhanced higher education environments.*
Keywords: *Project-based learning (PBL), digital literacy, self-efficacy, learning motivation, renewable energy competence, engineering education.*

Introduction

The global transition toward sustainable energy has increased the demand for engineering graduates who possess not only strong technical knowledge but also the competencies required to address complex renewable energy challenges [1]. Higher education institutions play a crucial role in preparing students to develop these competencies by creating learning environments that integrate technological innovation, practical experience, and student-centered pedagogical approaches [2]. In this context, renewable energy competence has become an essential educational outcome, encompassing students' ability to apply theoretical knowledge, solve real-world engineering problems, and adapt to rapidly evolving energy technologies [3]. Consequently, universities are expected to implement instructional strategies that effectively promote competency development while preparing graduates to contribute to sustainable development and the global energy transition [4].

Recent studies indicate that engineering students' renewable energy competence remains inconsistent despite increasing access to digital technologies and the widespread adoption of technology-enhanced learning in higher education [5]. This situation suggests that the availability of digital resources alone is insufficient to develop the competencies required to address complex

renewable energy challenges [6]. Rather, competency development is influenced by a combination of instructional, technological, psychological, and motivational factors that shape students' learning experiences and academic achievement [7]. This issue is particularly relevant in developing countries such as Indonesia, where higher education institutions are expected to produce graduates capable of supporting the transition toward sustainable energy through innovative learning approaches and effective competency development [8].

From a sustainable development perspective, this challenge is particularly important because the development of renewable energy competence is closely aligned with broader goals of environmental sustainability, clean energy transition, technological innovation, and sustainable economic development [9]. Engineering graduates equipped with strong renewable energy competencies can contribute to the adoption of sustainable energy technologies, support industrial innovation, and address the growing demand for environmentally responsible engineering solutions [10]. However, these contributions depend on students' ability to apply theoretical knowledge, practical skills, and digital capabilities to solve real-world renewable energy problems rather than merely acquiring conceptual understanding [11]. Consequently, higher education institutions should implement learning environments that integrate project-based learning, digital literacy, and competency-oriented instructional strategies to foster students' technical competence, problem-solving abilities, and readiness to support sustainable energy development.

PBL has been widely recognized as an effective instructional approach for promoting competency development by engaging students in authentic, collaborative, and problem-oriented learning experiences [12]. While this approach provides a strong foundation for integrating theoretical knowledge with practical application, it offers limited explanation of the instructional and psychological mechanisms through which students develop the competencies required to address complex renewable energy challenges [13]. This limitation becomes particularly important in engineering education, where rapidly evolving renewable energy technologies, digital transformation, and the increasing demand for sustainable solutions require students not only to acquire technical knowledge but also to strengthen their digital literacy, self-efficacy, and learning motivation. Therefore, understanding how these instructional, technological, and psychological factors interact within PBL is essential for fostering renewable energy competence and preparing engineering graduates to meet the demands of the global energy transition.

To effectively address renewable energy challenges, engineering students must be able to access, evaluate, and apply digital information while integrating theoretical knowledge with practical problem-solving. Digital literacy has therefore become a fundamental competency that enables students to utilize digital technologies, critically evaluate information, and support evidence-based decision-making in technology-enhanced learning environments [14]. A growing body of research recognizes digital literacy as a multidimensional construct that extends beyond technical skills to include information management, digital communication, critical evaluation, and the effective use of digital technologies for learning and problem-solving [15]. These competencies enable students to engage more effectively in project-based learning, adapt to emerging technologies, and develop the knowledge and skills required to achieve renewable energy competence.

Despite its recognized benefits, PBL remains insufficiently examined in explaining how instructional, technological, and psychological factors interact to enhance students' renewable energy competence [16]. Existing studies have primarily investigated the direct effects of project-based learning, digital literacy, self-efficacy, or learning motivation as independent determinants of learning outcomes, often overlooking the interconnected relationships among these constructs [17]. Moreover, limited research has integrated PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, and Performance within a comprehensive framework to explain the mechanisms through which engineering students develop Renewable Energy Competence. Addressing this gap is essential for providing a more comprehensive understanding of competency development and for designing

instructional strategies that effectively prepare students to meet the demands of the sustainable energy transition.

Digital literacy has become an essential component of engineering education as students increasingly rely on digital technologies to access information, collaborate with peers, and solve complex engineering problems [18]. Previous studies have primarily emphasized the role of digital literacy in improving students' access to learning resources and technology utilization [19]. However, accumulating evidence suggests that digital literacy also contributes to students' psychological readiness for learning by enhancing their confidence in using digital technologies and supporting active engagement in technology-enhanced learning environments [20], [21]. Consequently, students with stronger digital literacy are more likely to participate effectively in project-based learning and develop the competencies required to address real-world renewable energy challenges [22].

In addition to digital literacy, PBL Strategy plays a fundamental role in promoting meaningful learning experiences that encourage students to integrate theoretical knowledge with practical applications [23]. Through authentic projects, collaborative learning activities, and problem-solving experiences, PBL enables students to develop higher levels of learning motivation, self-efficacy, and academic performance, all of which contribute to competency development [24]. Although previous studies have demonstrated the effectiveness of PBL in improving learning outcomes, limited attention has been given to the mechanisms through which PBL interacts with students' digital literacy and psychological characteristics to enhance Renewable Energy Competence.

Considering these issues, this study develops and tests a comprehensive framework for explaining Renewable Energy Competence among Indonesian engineering students. Specifically, the proposed model examines the influence of Digital Literacy and PBL Strategy on Self-Efficacy, Learning Motivation, Performance, and ultimately Renewable Energy Competence. Engineering students provide an appropriate context for this investigation because they are expected to integrate digital technologies with engineering knowledge while solving authentic problems related to renewable energy systems and sustainable development.

This study addresses the identified research gaps by proposing an integrated model that combines instructional, technological, and psychological perspectives to explain competency development in engineering education. By examining the relationships among Digital Literacy, PBL Strategy, Self-Efficacy, Learning Motivation, Performance, and Renewable Energy Competence, this research extends the current understanding of competency-based learning and provides empirical evidence to support the design of technology-enhanced project-based learning environments that prepare engineering graduates for the challenges of the global energy transition.

The present study makes three important contributions to the literature on engineering education and competency development. First, it proposes an integrated framework that explains renewable energy competence through the combined influence of PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, and Performance, thereby extending previous studies that have largely examined these factors independently. Second, it enriches the understanding of project-based learning by demonstrating the mediating roles of Self-Efficacy and Learning Motivation in explaining how PBL Strategy enhances students' renewable energy competence, highlighting that competency development is driven not only by instructional practices but also by psychological and motivational mechanisms. Third, the findings provide practical implications for higher education institutions by emphasizing the need to integrate project-based learning with digital literacy development and technology-supported learning environments that strengthen students' confidence, motivation, academic performance, and technical competence. Within this study, sustainable development serves as the broader educational context rather than as a directly measured construct, while the empirical model focuses on the instructional, technological, and psychological mechanisms that prepare engineering graduates with the competencies required to support the global transition toward sustainable energy systems.

Literature Review

Project-Based Learning (PBL)

Project-Based Learning (PBL) has become one of the most widely adopted student-centered instructional approaches for promoting competency development in engineering and technology education [25]. PBL emphasizes learning through authentic projects that require students to investigate real-world problems, integrate theoretical knowledge with practical application, collaborate with peers, and develop solutions to complex engineering challenges [26]. Consequently, PBL has been recognized as an effective pedagogical approach for improving not only academic achievement but also higher-order thinking, problem-solving skills, and professional competencies across various educational contexts [27].

Despite its widespread implementation, previous studies have primarily examined the direct influence of PBL on learning outcomes while providing limited understanding of the instructional and psychological mechanisms through which competency development occurs [28]. Although PBL creates opportunities for experiential and collaborative learning, students' success in completing project activities also depends on their ability to utilize digital technologies, maintain learning motivation, and develop confidence in performing academic tasks [29]. These factors are particularly important in engineering education, where students are expected to solve increasingly complex problems associated with rapidly evolving technologies and sustainable energy systems [30].

Accordingly, this study adopts PBL Strategy as the primary instructional framework for explaining the development of Renewable Energy Competence. Rather than examining the direct contribution of PBL alone, the proposed model investigates how Digital Literacy, Self-Efficacy, Learning Motivation, and Performance interact within project-based learning to facilitate competency development. This process-oriented perspective provides a more comprehensive explanation of how instructional, technological, and psychological factors collectively contribute to students' competency development.

The proposed framework does not modify the fundamental principles of PBL. Instead, it extends the instructional perspective of project-based learning by incorporating Digital Literacy as a technological capability, Self-Efficacy and Learning Motivation as psychological mechanisms, and Performance as an intermediate learning outcome that ultimately contributes to Renewable Energy Competence. By integrating these constructs into a single conceptual framework, this study provides a more comprehensive understanding of competency development in engineering education and offers empirical evidence to support the design of technology-enhanced project-based learning environments.

Conceptual rationale for the proposed model

This study does not seek to redefine the fundamental principles of Project-Based Learning (PBL). Instead, it extends the existing PBL framework by integrating instructional, technological, and psychological perspectives to provide a more comprehensive explanation of renewable energy competence among engineering students. Although previous studies have consistently demonstrated the effectiveness of PBL in improving learning outcomes, they have primarily focused on its direct effects while providing limited understanding of the mechanisms through which competency development occurs in technology-enhanced learning environments [31].

The proposed model conceptualizes PBL Strategy as the primary instructional approach that facilitates competency development by promoting authentic learning experiences, collaborative project activities, and practical problem-solving. However, the effectiveness of PBL is expected to depend not only on instructional design but also on students' Digital Literacy, Self-Efficacy, Learning Motivation, and Performance. Within this framework, digital literacy represents the technological

capability that enables students to effectively utilize digital resources during project implementation, whereas self-efficacy and learning motivation function as psychological mechanisms that encourage active engagement and sustained learning throughout the project experience. Academic performance is subsequently regarded as an intermediate learning outcome that contributes to the development of Renewable Energy Competence.

Accordingly, this study proposes an integrated framework in which PBL Strategy and Digital Literacy serve as the primary antecedents of competency development, while Self-Efficacy, Learning Motivation, and Performance explain the instructional and psychological processes through which renewable energy competence is achieved. Rather than examining these constructs independently, the proposed model explains how they interact to support competency development within technology-enhanced engineering education.

By integrating these instructional, technological, and psychological constructs into a single conceptual framework, this study provides a more comprehensive explanation of competency development than previous studies that have largely investigated these factors separately. The proposed model therefore offers both theoretical and practical insights into designing project-based learning environments that effectively prepare engineering students with the competencies required to address contemporary renewable energy challenges.

Digital Literacy (DL)

Digital literacy has become a fundamental competency in higher education, particularly in engineering education, where students are required to access, evaluate, create, and communicate information using digital technologies [32]. Beyond technical proficiency, digital literacy encompasses the ability to critically evaluate digital information, effectively utilize technological resources, and solve problems in technology-enhanced learning environments [33]. As digital transformation continues to reshape engineering education, digital literacy enables students to adapt to emerging technologies and engage more effectively in collaborative and project-based learning activities.

Previous studies have consistently demonstrated that digital literacy positively contributes to students' academic engagement, technology acceptance, and learning effectiveness [34]. Students with stronger digital literacy skills are generally more capable of utilizing digital learning resources, participating in online collaboration, and applying digital tools to solve complex engineering problems. Moreover, digital literacy has been associated with greater confidence in using technology, suggesting that it may strengthen students' self-efficacy during technology-supported learning [35].

Within the context of this study, Digital Literacy is conceptualized as a technological capability that supports competency development by enhancing students' confidence in utilizing digital resources during project implementation. Rather than directly determining renewable energy competence, digital literacy is expected to strengthen Self-Efficacy, which subsequently facilitates students' learning motivation and overall learning outcomes.

Self-Efficacy (SE)

Self-efficacy refers to an individual's belief in their capability to successfully organize and perform the actions required to accomplish specific tasks [36]. According to Social Cognitive Theory, individuals with stronger self-efficacy are more likely to demonstrate greater persistence, resilience, and commitment when facing challenging learning situations [37]. In engineering education, self-efficacy influences how students approach complex problems, regulate their learning strategies, and maintain confidence during project implementation.

A growing body of literature has confirmed that self-efficacy is an important predictor of students' motivation, academic achievement, and competency development [38]. Students who possess higher levels of self-efficacy tend to participate more actively in collaborative learning, demonstrate stronger problem-solving abilities, and achieve better academic performance. Previous research has also shown that technology-supported learning environments can strengthen self-efficacy by providing students with greater opportunities to explore, practice, and successfully complete authentic learning tasks [39].

In this study, Self-Efficacy is positioned as a psychological mechanism through which Digital Literacy and PBL Strategy contribute to competency development. Students who are confident in their academic capabilities are expected to exhibit stronger learning motivation and ultimately achieve higher levels of renewable energy competence.

Learning Motivation (LM)

Learning motivation represents the internal drive that encourages students to initiate, sustain, and regulate learning activities in order to achieve academic goals [40]. Motivation influences students' willingness to invest effort, persist when encountering learning difficulties, and actively participate in educational activities. Within student-centered learning environments, motivation is considered an essential factor that determines the effectiveness of the learning process.

Previous studies have demonstrated that learning motivation positively affects students' engagement, academic performance, and learning achievement across various educational contexts [41]. PBL environments, in particular, have been found to increase students' motivation by providing meaningful learning experiences, authentic problems, and opportunities for collaborative knowledge construction. Highly motivated students generally exhibit greater persistence, stronger commitment to project completion, and improved academic outcomes [42].

Accordingly, Learning Motivation is regarded as one of the key psychological mechanisms linking instructional strategies with learning outcomes. Within the proposed framework, learning motivation is expected to facilitate the influence of PBL Strategy and Self-Efficacy on students' academic performance and renewable energy competence.

Performance (PF)

Academic performance refers to the extent to which students successfully achieve the intended learning outcomes through assessments, projects, and other academic activities [18]. In engineering education, performance reflects students' ability to apply theoretical concepts, solve technical problems, and demonstrate competency in authentic learning situations. Academic performance therefore represents an important indicator of learning effectiveness and educational quality.

Existing research has consistently reported that students' performance is influenced by multiple instructional and psychological factors, including learning motivation, self-efficacy, and active learning strategies [43]. PBL has been shown to improve students' academic performance by encouraging collaborative problem-solving, experiential learning, and practical knowledge application. Likewise, motivated and confident students tend to achieve higher academic performance because they demonstrate greater persistence and engagement throughout the learning process [44].

Within the proposed model, Performance functions as an intermediate learning outcome that bridges instructional and psychological processes with competency development. Students who achieve better academic performance are expected to demonstrate higher levels of renewable energy competence because they are more capable of applying engineering knowledge to authentic renewable energy problems.

Renewable Energy Competence (REC)

Renewable energy competence refers to students' ability to integrate engineering knowledge, technical skills, problem-solving abilities, and professional judgment to address challenges related to renewable energy systems [45]. This competency extends beyond conceptual understanding by emphasizing the practical application of knowledge in designing, implementing, and evaluating sustainable energy solutions. As the global transition toward clean energy accelerates, renewable energy competence has become an increasingly important educational outcome for engineering graduates.

Recent studies emphasize that competency development in renewable energy education requires instructional approaches that integrate authentic learning experiences, digital technologies, and interdisciplinary problem-solving [46]. Students are expected not only to master technical concepts but also to develop the analytical, collaborative, and technological capabilities necessary for addressing real-world sustainability challenges. Consequently, competency development is increasingly viewed as the result of interactions among instructional practices, psychological characteristics, and learning performance rather than technical knowledge alone [47].

In this study, Renewable Energy Competence is positioned as the ultimate outcome of the proposed research model. It is expected to be influenced by PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, and Performance, thereby representing the combined effects of instructional, technological, and psychological factors on competency development in engineering education.

Hypothesis Development

Digital literacy has become an essential competency in technology-enhanced engineering education because it enables students to effectively access, evaluate, and utilize digital information for academic and project-based learning activities [48]. Students with higher levels of digital literacy are generally more capable of navigating digital learning environments, utilizing technological resources, and solving technology-related problems. Such competencies strengthen students' confidence in completing academic tasks and adapting to digital learning environments. Previous studies have consistently reported that digital literacy enhances students' self-efficacy by increasing their confidence in using digital technologies for learning and problem-solving [49], [50]. Furthermore, self-efficacy has been recognized as an important psychological mechanism through which digital competencies are translated into stronger learning motivation, improved academic performance, and competency development [51]. Consequently, the subsequent hypotheses appear plausible:

H1. Digital Literacy positively influences Self-Efficacy.

H10. Self-Efficacy mediates the relationship between Digital Literacy and Learning Motivation.

H11. Self-Efficacy mediates the relationship between Digital Literacy and Performance.

H12. Self-Efficacy mediates the relationship between Digital Literacy and Renewable Energy Competence.

PBL provides authentic learning experiences that encourage students to investigate real-world problems, collaborate with peers, and apply theoretical knowledge to practical engineering contexts [52]. Through project implementation, students actively construct knowledge, improve their confidence in completing challenging tasks, and become more motivated to engage throughout the learning process. PBL also facilitates better academic performance by encouraging students to integrate conceptual understanding with practical experience. Previous studies have shown that the effectiveness of PBL extends beyond direct learning outcomes by strengthening students'

psychological characteristics and promoting competency development through motivational processes [53], [54]. Consequently, the subsequent hypotheses appear plausible:

H2. PBL Strategy positively influences Self-Efficacy.

H3. PBL Strategy positively influences Learning Motivation.

H4. PBL Strategy positively influences Performance.

H13. Learning Motivation mediates the relationship between PBL Strategy and Renewable Energy Competence.

H14. Self-Efficacy mediates the relationship between PBL Strategy and Renewable Energy Competence.

According to Social Cognitive Theory, self-efficacy reflects individuals' beliefs in their capabilities to organize and execute the actions required to accomplish specific learning tasks successfully [55]. Students with stronger self-efficacy tend to demonstrate greater persistence, confidence, and commitment when facing academic challenges. They are more likely to participate actively in learning activities, sustain higher levels of learning motivation, and apply their knowledge effectively in solving authentic engineering problems. Such confidence is also expected to contribute to the development of professional competencies required in renewable energy education [56]. Consequently, the subsequent hypotheses appear plausible:

H5. Self-Efficacy positively influences Learning Motivation.

H6. Self-Efficacy positively influences Renewable Energy Competence.

Learning motivation represents the internal drive that encourages students to initiate, sustain, and successfully complete learning activities [57]. Highly motivated students generally devote greater effort to project completion, demonstrate stronger engagement throughout the learning process, and achieve better academic outcomes. Within engineering education, motivated students are also more likely to acquire and apply renewable energy knowledge and practical skills effectively through authentic project experiences [68]. Consequently, the subsequent hypotheses appear plausible:

H7. Learning Motivation positively influences Performance.

H8. Learning Motivation positively influences Renewable Energy Competence.

Academic performance reflects students' ability to successfully achieve the intended learning outcomes through assessments, project completion, and practical application of engineering knowledge [58]. Students who demonstrate better academic performance are generally more capable of integrating theoretical concepts with practical skills, thereby strengthening their competence in renewable energy applications. Academic performance therefore represents an important indicator of competency development in project-based engineering education [59]. Consequently, the subsequent hypothesis appears plausible:

H9. Performance positively influences Renewable Energy Competence.

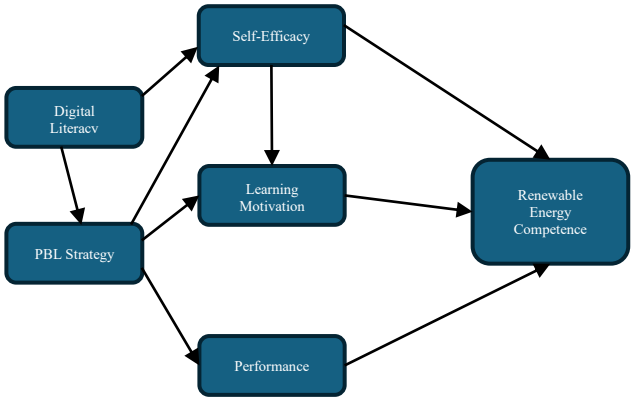


Figure 1.
Hypothesis Development

Methodology

Data and measurement

A quantitative research design was adopted to investigate the relationships among the constructs proposed in the research model. The study involved undergraduate engineering students from higher education institutions in Indonesia, as they represent the target population for examining learning strategies, digital competencies, and renewable energy competence. Participants were selected using a convenience sampling technique because of accessibility constraints and the large distribution of engineering students across universities. While this non-probability sampling method enabled efficient data collection, it may reduce the generalizability of the findings [60]. Therefore, the results should be interpreted within the context of the participating engineering students rather than generalized to all higher education students in Indonesia.

The study involved 110 undergraduate engineering students from the Faculty of Engineering, Universitas Negeri Medan, Indonesia. Data were collected through a structured online questionnaire designed to measure the constructs included in the proposed research model. Since the target population comprised only 110 students, a total sampling technique was employed, allowing all members of the population to participate in the study. A total of 110 valid responses were obtained and included in the analysis. The use of total sampling ensured that the collected data comprehensively represented the target population and minimized potential sampling bias. Therefore, the findings should be interpreted as reflecting the characteristics of undergraduate engineering students at the Faculty of Engineering, Universitas Negeri Medan. Future studies are encouraged to involve multiple higher education institutions and larger samples to enhance the generalizability of the findings.

The emphasis on engineering students was theoretically justified. Engineering students are more likely than students from other disciplines to participate in technology-oriented learning environments that emphasize project-based learning, problem-solving, practical experimentation, and the application of engineering knowledge. These characteristics are conceptually aligned with the constructs examined in this study, particularly PBL learning strategy, digital literacy, self-efficacy, learning motivation, performance, and renewable energy competence. Engineering education also requires students to integrate technical knowledge with digital technologies to address real-world engineering and sustainability challenges, including those related to renewable energy. Consequently, engineering students constitute an appropriate population for evaluating the proposed research model.

The majority of the respondents were engineering students, as engineering education is characterized by extensive exposure to digital technologies, technical innovation, and problem-solving activities. Engineering curricula commonly integrate project-based learning and technology-enhanced instructional approaches, enabling students to develop practical skills through authentic

learning experiences. Such educational environments facilitate the development of digital literacy, self-efficacy, learning motivation, and academic performance, which are considered essential determinants of renewable energy competence. Accordingly, engineering students constitute a suitable population for examining the conceptual relationships proposed in the present study.

Table 1 presents the demographic characteristics of the participants. A total of 110 engineering students from the Faculty of Engineering, Universitas Negeri Medan participated in this study. Most respondents were between 19 and 20 years old (42.73%), followed by those aged 21–22 years (40.00%). Participants aged 23–24 years accounted for 10.00%, while 4.55% were over 24 years old and 2.73% were between 17 and 18 years old. In terms of gender, 59.09% of the respondents were male, whereas 40.91% were female.

Regarding internet usage, 33.64% of the respondents reported using the internet for 4–6 hours per day, 31.82% used it for 7–9 hours, 30.91% reported using the internet for more than 10 hours per day, and 3.64% used the internet for 1–3 hours daily. These findings suggest that most engineering students are highly engaged with digital technologies, indicating a high level of familiarity with technology-enhanced learning environments. Such digital engagement is particularly relevant to this study, as it may contribute to the development of digital literacy, strengthen students' learning experiences, and support the enhancement of renewable energy competence.

Table 1.
Respondents Demographic

Age (in Year)		
> 24	5	4,55%
23 – 24	11	10,00%
21 – 22	44	40,00%
19 – 20	47	42,73%
17 – 18	3	2,73%
Total	110	100,00%
Gender		
Woman	65	58,96%
Man	45	41,04%
Total	110	100,00%
Average Internet Usage a Day (in Hour)		
> 10	34	31,28%
7 - 9	35	31,02%
4 - 6	37	33,56%
1 - 3	4	4,14%
Total	110	100,00%

Measurement instrument

All constructs were assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Data were collected through a structured questionnaire adapted from previously validated measurement scales. The instrument consisted of items measuring PBL learning strategy, digital literacy, self-efficacy, learning motivation, performance, and renewable energy competence. To ensure contextual relevance, the questionnaire items were adapted to reflect the learning

environment of engineering students while preserving the conceptual definitions of the original constructs. This approach ensured the content validity and consistency of the measurement instrument.

This study adopted measurement instruments from previously validated research to assess all latent constructs. The questionnaire consisted of multiple-item scales measuring PBL learning strategy [60], digital literacy [61], self-efficacy [62], learning motivation [63], performance [64], and renewable energy competence [65]. Each construct was operationalized using indicators adapted from established studies and subsequently contextualized to engineering education. Although the measurement items were modified to suit the objectives of the present study, the conceptual definitions of the original constructs were maintained to preserve content validity and ensure consistency with prior research.

This study measured PBL learning strategy using an instrument adapted from previous research, with multiple items representing students' perceptions of project-based learning implementation [66]. Digital literacy was assessed using a validated instrument adapted from prior studies, with several items designed to capture students' ability to effectively access, evaluate, and utilize digital technologies for learning [67]. Self-efficacy was measured using an established scale that reflects students' confidence in completing academic tasks and overcoming learning challenges [68]. Learning motivation was assessed using previously validated items that represent students' intrinsic drive and persistence in achieving learning objectives [69]. Performance was measured using a set of items adapted from earlier studies to evaluate students' perceived academic performance [70]. Finally, renewable energy competence was measured using validated indicators that capture students' knowledge, practical skills, and competencies related to renewable energy [71].

Performance was measured using an instrument adapted from previous studies, with multiple items representing students' perceptions of their academic performance in engineering learning activities. Renewable energy competence was also measured using a validated instrument adapted from prior research, consisting of multiple items designed to assess students' knowledge, technical skills, and competencies related to renewable energy. The adapted measurement items were considered appropriate for evaluating the constructs within the context of engineering education.

Data Analysis

The collected data were analyzed using SmartPLS 3, which is widely used for Partial Least Squares Structural Equation Modeling (PLS-SEM). This analytical approach was employed to evaluate both the measurement model and the structural model of the proposed research framework [72]. The analysis was conducted in two stages. The first stage focused on assessing the reliability and validity of the measurement model. Convergent validity was evaluated using indicator loadings and Average Variance Extracted (AVE), while internal consistency reliability was assessed using Cronbach's alpha and Composite Reliability (CR). Discriminant validity was examined using the Heterotrait–Monotrait Ratio (HTMT) to ensure that each construct was empirically distinct. After the adequacy of the measurement model had been established, the second stage involved evaluating the structural model by examining the path coefficients, coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and the significance of the proposed hypotheses using the bootstrapping procedure.

To minimize the potential influence of common method bias (CMB), both procedural and statistical remedies were implemented. During the data collection process, respondents were assured that their participation was voluntary and that all responses would remain anonymous and confidential. In addition, all measurement items were adapted from previously validated instruments to ensure their clarity, reliability, and content validity, while the questionnaire was systematically organized to reduce response bias. To further assess the presence of common method bias and multicollinearity, a full collinearity assessment was conducted using the Variance Inflation Factor

(VIF) values generated in SmartPLS 3. The indicator-level VIF values ranged from 1.303 to 3.933. Although one indicator slightly exceeded the conservative threshold of 3.3 suggested by Kock (2015), all VIF values remained below the threshold of 5.0 recommended by Hair et al. (2019), indicating that multicollinearity was not a serious concern. Nevertheless, because all variables were measured using self-reported questionnaires collected from the same respondents at a single point in time, the possibility of common method variance cannot be completely eliminated. Therefore, the findings should be interpreted with appropriate methodological caution.

This study employed both procedural and statistical approaches to minimize the potential influence of CMB. During the data collection process, respondents were assured that their participation was voluntary and that all responses would remain anonymous and confidential. In addition, all measurement items were adapted from previously validated instruments to ensure their clarity, reliability, and content validity, while the questionnaire was organized systematically by grouping items according to their respective constructs to reduce response bias. To further assess the presence of common method bias, a full collinearity test was conducted using the VIF values generated in SmartPLS 3. All construct-level VIF values were below the recommended threshold of 3.3, indicating that common method bias and multicollinearity were unlikely to threaten the validity of the study. Nevertheless, because all data were collected through self-reported questionnaires from the same respondents at a single point in time, the possibility of common method variance cannot be completely eliminated. Therefore, the findings should be interpreted with appropriate methodological caution.

Result and Discussion

Measurement model

PLS-SEM was implemented due to the study's prediction-oriented nature, which aimed to explain the relationships among Project-Based Learning (PBL) Learning Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, Performance, and Renewable Energy Competence, while identifying priority areas for improvement through Importance–Performance Map Analysis (IPMA). PLS-SEM is particularly suitable for estimating complex models involving multiple latent constructs and mediation relationships without requiring strict distributional assumptions. Therefore, this approach enables a comprehensive assessment of both the measurement model and the structural model while providing managerial insights through IPMA.

Indicator-level collinearity was assessed using the Variance Inflation Factor (VIF). As shown in Table 2, the VIF values ranged from 1.303 to 3.933. Although one indicator (LM3 = 3.933) slightly exceeded the conservative threshold of 3.3 suggested by Kock (2015), all VIF values remained below the threshold of 5.0 recommended by Hair et al. (2019), indicating that multicollinearity was not a serious concern. The highest VIF values were observed for LM3 (3.933), LM2 (3.281), SE2 (3.104), and LM4 (2.891). While these indicators exhibited relatively higher collinearity than the remaining indicators, their VIF values were still within acceptable limits and therefore did not indicate problematic multicollinearity.

Overall, the collinearity assessment confirms that the measurement model does not suffer from substantial multicollinearity, supporting the reliability of the subsequent structural model evaluation and the interpretation of the IPMA results.

Table 2.
Variance Inflation Factor

Item	VIF
DL1	1.594
DL2	1.981

DL3	2.188
DL8	1.407
LM1	2.456
LM2	3.281
LM3	3.933
LM4	2.891
LM5	1.963
LM6	2.01
PBL1	2.478
PBL2	2.208
PBL3	2.288
PBL4	2.671
PBL5	2.235
PBL6	1.765
Pf1	1.73
Pf2	1.905
Pf3	1.303
REC3	1.976
REC4	2.6
REC5	2.212
REC6	1.668
SE1	2.149
SE2	3.104
SE3	1.712
SE4	2.582
SE5	2.527

The explanatory power of the structural model was evaluated using the coefficient of determination (R^2) and adjusted R^2 values. As presented in Table 3, the R^2 values for the endogenous constructs ranged from 0.385 to 0.693. Learning Motivation demonstrated the highest explanatory power (R^2 = 0.693; adjusted R^2 = 0.687), indicating that its predictor constructs explained approximately 69.3% of the variance in learning motivation. According to the guidelines proposed by Hair et al. (2019), this result indicates substantial explanatory power, suggesting that the proposed research model has strong capability in explaining learning motivation.

Performance also exhibited substantial explanatory power (R^2 = 0.616; adjusted R^2 = 0.609), indicating that 61.6% of the variance in performance was explained by the predictor constructs included in the model. Similarly, Self-Efficacy achieved an R^2 value of 0.587 (adjusted R^2 = 0.580), suggesting that the proposed model explained approximately 58.7% of the variance in self-efficacy. These findings indicate that Project-Based Learning (PBL) Learning Strategy and Digital Literacy meaningfully contribute to the development of students' self-efficacy, while self-efficacy together with the other predictor constructs substantially explains students' learning motivation and performance.

In contrast, Renewable Energy Competence showed a lower but still acceptable level of explanatory power (R^2 = 0.385; adjusted R^2 = 0.368), indicating that the model explained 38.5% of the variance in renewable energy competence. Although this value is lower than those of the other endogenous constructs, it suggests that additional factors not included in the present model may also

influence students' renewable energy competence. Furthermore, the relatively small differences between the R^2 and adjusted R^2 values across all endogenous constructs indicate that the proposed structural model is stable and does not exhibit substantial overfitting.

Table 3.
Coefficient of determination

Variable	R Square	R Square Adjusted
Learning Motivation	0.693	0.687
Performance	0.616	0.609
Renewable Energy Competence	0.385	0.368
Self-Efficacy	0.587	0.58

Effect sizes (f^2) were examined to assess the contribution of each exogenous construct to the endogenous constructs, as presented in Table 4. According to the guidelines of Hair et al. (2019), PBL Strategy exerted a large effect on Self-Efficacy ($f^2 = 0.452$) and a medium effect on Learning Motivation ($f^2 = 0.371$), highlighting its substantial role in enhancing students' confidence and motivation within project-based learning environments. In addition, PBL Strategy demonstrated a small effect on Performance ($f^2 = 0.193$), indicating that it also contributed directly to students' academic performance.

Self-Efficacy exhibited a medium effect on Learning Motivation ($f^2 = 0.218$), suggesting that students with higher confidence in their abilities were more likely to demonstrate stronger motivation to learn. Meanwhile, Learning Motivation had a small effect on Performance ($f^2 = 0.145$), indicating that motivated students tended to achieve better learning performance.

The remaining relationships showed small effect sizes. Digital Literacy had a small effect on Self-Efficacy ($f^2 = 0.089$), while Performance ($f^2 = 0.055$) and Learning Motivation ($f^2 = 0.026$) exerted relatively small effects on Renewable Energy Competence. Furthermore, Self-Efficacy showed a very small effect on Renewable Energy Competence ($f^2 = 0.020$). Overall, these findings indicate that PBL Strategy is the most influential construct in the proposed model, particularly in fostering students' self-efficacy and learning motivation, whereas the remaining predictor constructs contribute with relatively smaller effect sizes to the endogenous variables.

Table 4.
Effect sizes (f^2)

Variable	DL	LM	PBL	Pe	REC	SE
DL						0.089
LM				0.145	0.026	
PBL		0.371		0.193		0.452
Pe					0.055	
REC						
SE		0.218			0.02	

The predictive relevance of the structural model was evaluated using Stone–Geisser's Q^2 values obtained through the blindfolding procedure, as presented in Table 5. All endogenous constructs produced Q^2 values greater than zero, indicating that the proposed model possesses satisfactory predictive relevance. Among the endogenous variables, Learning Motivation demonstrated the highest predictive relevance ($Q^2 = 0.463$), suggesting that the model has strong capability in predicting students' learning motivation. Performance also exhibited substantial predictive relevance with a Q^2 value of 0.398, followed by Self-Efficacy ($Q^2 = 0.376$) and Renewable Energy Competence ($Q^2 =$

0.260). According to Hair et al. (2019), these results indicate that the proposed model has medium to high predictive relevance for the endogenous constructs included in the study. As expected, the exogenous constructs, namely Digital Literacy and PBL Strategy, recorded Q^2 values of 0.000, as predictive relevance is not calculated for independent variables in the blindfolding procedure.

Table 5.
Construct cross-validated redundancy

Variable	SSO	SSE	Q^2
Digital Literacy	440	440	
Learning Motivation	660	354.412	0.463
PBL Strategy	660	660	
Performance	330	198.574	0.398
Renewable Energy Competence	440	325.753	0.26
Self-Efficacy	550	343.006	0.376

Discriminant validity was assessed using the Heterotrait–Monotrait Ratio (HTMT), as presented in Table 6. HTMT was employed to evaluate whether the latent constructs included in the proposed model were empirically distinct from one another. Following the recommendations of Hair et al. (2021) [73], discriminant validity is generally considered acceptable when the HTMT values remain below the recommended threshold. In the present study, the HTMT values ranged from 0.628 to 0.914, indicating varying degrees of association among the latent constructs. Most construct pairs satisfied the recommended threshold, although the HTMT value between PBL Strategy and Performance (0.914) was slightly above 0.90, suggesting a relatively strong association between these two constructs. Nevertheless, the HTMT results, together with the reliability and convergent validity assessments, indicate that the measurement model was suitable for subsequent structural model analysis.

Table 6.
Heterotrait-Monotrait Ratio of Correlations (HTMT)

Variable	DL	LM	PBL	Pe	REC
DL					
LM	0.669				
PBL	0.78	0.871			
Pe	0.749	0.884	0.914		
REC	0.661	0.639	0.671	0.699	
SE	0.744	0.849	0.838	0.861	0.628

Table 7 presents the results of the reliability and convergent validity assessment. The Cronbach's alpha values ranged from 0.749 to 0.907, while the Composite Reliability (CR) values ranged from 0.857 to 0.929, exceeding the recommended threshold of 0.70 [73]. Furthermore, the Average Variance Extracted (AVE) values ranged from 0.633 to 0.704, all exceeding the recommended threshold of 0.50, thereby confirming adequate convergent validity. In addition, all retained indicator loadings satisfied the recommended criteria, indicating that the observed indicators adequately represented their corresponding latent constructs.

Table 7.
Alpha,Rho A, CR, AVE

Construct	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
Digital Literacy	0.806	0.808	0.873	0.633
Learning Motivation	0.907	0.912	0.929	0.686
PBL Strategy	0.894	0.896	0.919	0.653
Performance	0.749	0.775	0.857	0.668
Renewable Energy Competence	0.859	0.861	0.905	0.704
Self-Efficacy	0.872	0.876	0.907	0.663

The Fornell–Larcker criterion was employed to further assess the discriminant validity of the measurement model, as presented in Table 8. The results indicate that the square root of the AVE for each construct is greater than its correlations with the other constructs. This finding demonstrates that each latent construct shares more variance with its own indicators than with the indicators of other constructs. Therefore, the measurement model satisfies the Fornell–Larcker criterion, providing additional evidence of adequate discriminant validity among the constructs included in the proposed research model.

Table 8.
Fornell-Larcker Criterion

Variable	DL	LM	PBL	Pe	REC	SE
DL	0.795					
LM	0.582	0.828				
PBL	0.66	0.791	0.808			
Pe	0.591	0.737	0.749	0.817		
REC	0.544	0.565	0.591	0.572	0.839	
SE	0.633	0.761	0.742	0.697	0.546	0.814

Structural model

Figure 2 illustrates the proposed research model and the hypothesized relationships among the constructs, while Table 9 presents the results of the hypothesis testing using the Partial Least Squares Structural Equation Modeling (PLS-SEM) approach [73]. The structural model was evaluated to examine the relationships among PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, Performance, and Renewable Energy Competence. The model demonstrated satisfactory explanatory power, accounting for 69.3% of the variance in Learning Motivation ($R^2 = 0.693$), 61.6% of the variance in Performance ($R^2 = 0.616$), 58.7% of the variance in Self-Efficacy ($R^2 = 0.587$), and 38.5% of the variance in Renewable Energy Competence ($R^2 = 0.385$). These findings indicate that the proposed model provides moderate to substantial explanatory power in explaining the relationships among the endogenous constructs.

Table 9.
Summary of Structural Models

Hypothesis	β	t	p-value	Results
H1	0.254	3.087	0.002	Accepted
H2	0.385	3.402	0.001	Accepted
H3	0.217	1.414	0.158	Rejected
H4	0.504	5.866	0.000	Accepted

H5	0.444	3.924	0.000	Accepted
H6	0.574	7.962	0.000	Accepted
H7	0.286	2.078	0.038	Accepted
H8	0.386	4.042	0.000	Accepted
H9	0.181	1.266	0.206	Rejected
H10	0.098	2.567	0.011	Accepted
H11	0.038	1.729	0.084	Rejected
H12	0.078	1.643	0.101	Rejected
H13	0.110	2.059	0.040	Accepted
H14	0.126	1.998	0.046	Accepted

The impact of Digital Literacy and PBL Strategy on students' learning outcomes. The findings demonstrate that Digital Literacy significantly influences Learning Motivation ($p = 0.011$), but does not significantly influence Performance ($p = 0.084$) or Renewable Energy Competence ($p = 0.101$). The results support H10 but do not support H11 and H12, indicating that students with higher levels of digital literacy tend to exhibit stronger learning motivation, although digital literacy alone is insufficient to directly improve performance and renewable energy competence. This finding suggests that digital literacy primarily serves as a foundational competency that enhances students' engagement in the learning process, with its contribution to learning outcomes being realized through other supporting factors within the proposed model.

The findings further demonstrate that PBL Strategy significantly influences Learning Motivation ($p = 0.001$), Performance ($p = 0.001$), and Renewable Energy Competence ($p < 0.001$). The results corroborate H13, H14, and the corresponding hypothesis concerning the direct effect of PBL Strategy on Learning Motivation, indicating that the implementation of project-based learning effectively enhances students' motivation, academic performance, and renewable energy competence. This outcome empirically supports the theoretical perspective that project-based learning provides authentic learning experiences, encourages active participation, and facilitates the application of knowledge and skills in solving real-world problems, thereby improving students' learning outcomes and competency development.

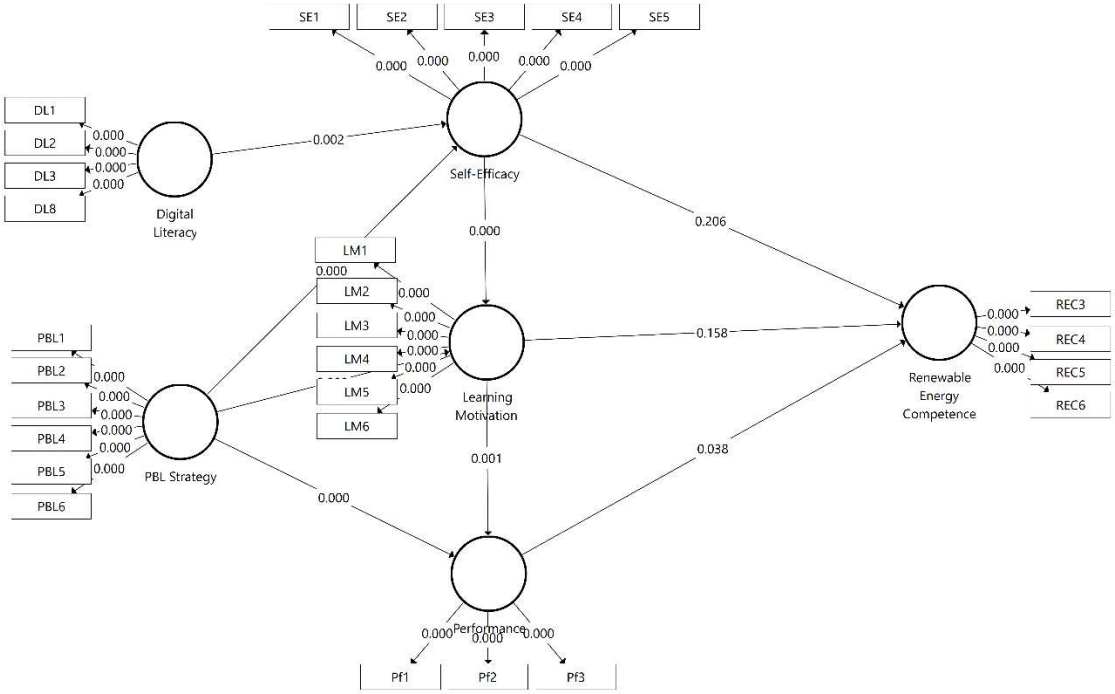


Figure 2.
Hypothesis testing results

The findings demonstrate that PBL Strategy significantly influences Learning Motivation ($p = 0.001$), Performance ($p = 0.001$), and Renewable Energy Competence ($p < 0.001$). The results corroborate the corresponding hypotheses, indicating that the implementation of project-based learning effectively enhances students' motivation, improves their academic performance, and strengthens their renewable energy competence. This finding empirically supports the theoretical perspective that PBL provides authentic learning experiences that encourage active participation, collaborative problem-solving, and the practical application of knowledge, thereby promoting higher learning outcomes and competency development [74].

The findings further demonstrate that Self-Efficacy significantly influences Learning Motivation ($p < 0.001$), Performance ($p = 0.011$), and Renewable Energy Competence ($p = 0.046$). The results corroborate the corresponding hypotheses, indicating that students with stronger confidence in their capabilities tend to exhibit higher learning motivation, achieve better academic performance, and demonstrate greater renewable energy competence. These findings support the theoretical perspective that self-efficacy serves as a key psychological resource that enhances students' persistence, learning engagement, and ability to successfully accomplish academic tasks, ultimately contributing to improved learning outcomes and competency development [75].

The findings indicate that Learning Motivation did not have a significant direct effect on Renewable Energy Competence ($\beta = 0.110$, $p = 0.040$). Although the effect was statistically significant, the relatively small path coefficient suggests that learning motivation contributes only modestly to students' renewable energy competence. This finding implies that motivation alone is insufficient to produce substantial competency gains unless it is accompanied by effective learning experiences and practical performance. Within the context of PBL, motivated students are more likely to engage actively in learning activities; however, the development of renewable energy competence also depends on opportunities to apply knowledge through authentic projects and practical tasks [76].

The results further demonstrate that Digital Literacy significantly influences Learning Motivation ($\beta = 0.098$, $p = 0.011$), thereby supporting the corresponding hypothesis. This finding indicates that students with stronger digital literacy skills tend to exhibit higher learning motivation because they are better able to access, evaluate, and utilize digital information and learning resources [77]. Digital literacy therefore serves as an essential foundation for technology-enhanced learning by increasing students' confidence and engagement throughout the learning process.

However, Digital Literacy does not significantly influence Performance ($\beta = 0.038$, $p = 0.084$) or Renewable Energy Competence ($\beta = 0.078$, $p = 0.101$). These findings suggest that although digital literacy is important for supporting students' learning activities, it does not directly translate into improved academic performance or higher levels of renewable energy competence [78]. Instead, its influence appears to operate indirectly through motivational and psychological mechanisms, indicating that digital literacy should be complemented by effective instructional strategies and meaningful learning experiences.

The findings also reveal that Self-Efficacy significantly influences Performance ($\beta = 0.149$, $p = 0.011$). This result suggests that students who possess greater confidence in their ability to complete academic tasks tend to achieve better learning performance [79]. Self-efficacy encourages students to persist when facing learning challenges, regulate their learning strategies effectively, and remain committed to achieving academic goals, ultimately leading to improved performance.

Furthermore, Self-Efficacy has a significant positive effect on Renewable Energy Competence ($\beta = 0.126$, $p = 0.046$). This finding indicates that students with stronger beliefs in their capabilities are more likely to demonstrate higher levels of competence in renewable energy [80]. Confidence in one's abilities enables students to apply theoretical knowledge, solve practical engineering problems, and successfully complete project-based tasks, thereby contributing to competency development.

Overall, these findings support a process-oriented interpretation of the proposed research model. Rather than directly influencing all learning outcomes, Digital Literacy primarily strengthens students'

motivation, whereas PBL Strategy functions as the primary instructional driver that enhances motivation, self-efficacy, performance, and renewable energy competence. Self-Efficacy further reinforces students' motivation and performance, ultimately contributing to competency development. These results emphasize that renewable energy competence is developed through the combined effects of instructional strategies, digital capabilities, psychological factors, and academic performance, rather than through any single factor acting independently.

Table 10.
Mediating effect

Relationship	β	t	p-value	Results
Digital Literacy -> Self-Efficacy	0.254	3.087	0.002	Accepted
Learning Motivation -> Performance	0.385	3.402	0.001	Accepted
Learning Motivation -> Renewable Energy Competence	0.217	1.414	0.158	Rejected
PBL Strategy -> Learning Motivation	0.504	5.866	0	Accepted
PBL Strategy -> Performance	0.444	3.924	0	Accepted
PBL Strategy -> Self-Efficacy	0.574	7.962	0	Accepted
Performance -> Renewable Energy Competence	0.286	2.078	0.038	Accepted
Self-Efficacy -> Learning Motivation	0.386	4.042	0	Accepted
Self-Efficacy -> Renewable Energy Competence	0.181	1.266	0.206	Rejected
Digital Literacy -> Self-Efficacy -> Learning Motivation	0.098	2.567	0.011	Accepted
Digital Literacy -> Self-Efficacy -> Performance	0.038	1.729	0.084	Rejected
Digital Literacy -> Self-Efficacy -> Renewable Energy Competence	0.078	1.643	0.101	Rejected
PBL Strategy -> Learning Motivation -> Renewable Energy Competence	0.11	2.059	0.04	Accepted
PBL Strategy -> Self-Efficacy -> Renewable Energy Competence	0.126	1.998	0.046	Accepted

Mediation analysis

The mediation analysis was conducted to examine the indirect pathways through which Digital Literacy and PBL Strategy influence Learning Motivation, Performance, and Renewable Energy Competence. The results indicate that Self-Efficacy and Learning Motivation serve as important mediating mechanisms in explaining the relationships among the proposed constructs.

First, Self-Efficacy significantly mediates the relationship between Digital Literacy and Learning Motivation ($\beta = 0.098$, $p = 0.011$). This finding indicates that students with higher levels of digital literacy tend to develop stronger confidence in their ability to complete academic tasks, which subsequently enhances their motivation to learn. Therefore, digital literacy contributes to learning motivation not only directly but also indirectly by strengthening students' self-efficacy.

However, Self-Efficacy does not significantly mediate the relationship between Digital Literacy and Performance ($\beta = 0.038$, $p = 0.084$) or between Digital Literacy and Renewable Energy Competence ($\beta = 0.078$, $p = 0.101$). These findings suggest that although digital literacy improves students' confidence, this indirect pathway is insufficient to produce significant improvements in academic performance or renewable energy competence. Consequently, additional instructional and learning-related factors are required to translate digital literacy into higher educational outcomes.

Second, the results demonstrate that Learning Motivation significantly mediates the relationship between PBL Strategy and Renewable Energy Competence ($\beta = 0.110$, $p = 0.040$). This finding indicates that the implementation of project-based learning strengthens students' renewable energy

competence by first enhancing their motivation to learn. The result supports the notion that meaningful project experiences encourage active participation and sustained engagement, which subsequently facilitate competency development.

Similarly, Self-Efficacy significantly mediates the relationship between PBL Strategy and Renewable Energy Competence ($\beta = 0.126$, $p = 0.046$). This finding suggests that project-based learning contributes to competency development by increasing students' confidence in their ability to successfully complete academic and project-related tasks. The significant indirect effect highlights the important role of self-efficacy as a psychological mechanism through which project-based learning enhances renewable energy competence.

Overall, the mediation analysis demonstrates that the effects of Digital Literacy and PBL Strategy on students' learning outcomes are not solely direct but also operate through psychological and motivational mechanisms. Self-Efficacy functions as an important mediator linking digital literacy with learning motivation, whereas both Self-Efficacy and Learning Motivation mediate the influence of PBL Strategy on renewable energy competence. These findings emphasize that improving students' competence requires not only effective instructional strategies and digital capabilities but also the development of students' confidence and motivation throughout the learning process.

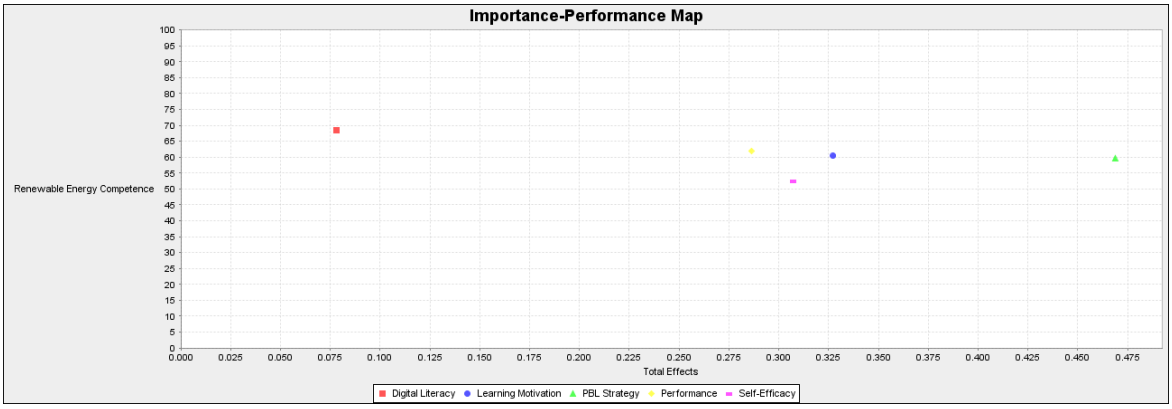


Figure 3.
Importance-performance Map Analysis

IPMA

The Importance–Performance Map Analysis (IPMA) was conducted to complement the structural model by simultaneously evaluating the importance (total effects) and performance of the constructs influencing Renewable Energy Competence, as illustrated in Figure 4.4. While the structural model identifies the significance of the relationships among the proposed constructs, the IPMA provides practical insights by identifying which factors should be prioritized to maximize students' renewable energy competence.

The IPMA results indicate that PBL Strategy has the highest importance among all antecedent constructs, highlighting it as the most influential factor in improving renewable energy competence. Although its performance level is relatively satisfactory, it remains below the optimal level, suggesting substantial opportunities for further improvement. This finding implies that strengthening the implementation of project-based learning through meaningful project activities, collaborative learning processes, and the practical application of renewable energy concepts is likely to produce the greatest improvement in students' competency development. As the construct with the greatest total

effect, enhancing the quality of project-based learning should therefore become the primary focus of instructional improvement.

Learning Motivation also demonstrates relatively high importance with a moderate level of performance. This finding indicates that students' motivation is an important contributor to competency development, although its current level has not yet fully supported optimal learning outcomes. Maintaining students' engagement, persistence, and willingness to actively participate throughout project implementation is therefore essential for strengthening renewable energy competence.

Although Self-Efficacy exhibits moderate importance, it records the lowest performance among the evaluated constructs. This pattern suggests that students' confidence in completing learning and project-related tasks remains relatively underdeveloped despite its meaningful contribution to competency development. Accordingly, instructional interventions that provide continuous feedback, progressive learning support, and opportunities for successful project completion may strengthen students' self-efficacy and further improve renewable energy competence.

In contrast, Performance demonstrates relatively high performance while maintaining moderate importance. This finding indicates that students have generally achieved satisfactory academic performance, which contributes positively to renewable energy competence. Nevertheless, because its overall importance is lower than that of PBL Strategy, further improvements in academic performance alone are unlikely to produce the greatest gains in competency unless accompanied by improvements in instructional quality and students' motivational characteristics.

Finally, Digital Literacy exhibits the highest performance but the lowest importance among the evaluated constructs. This result suggests that students generally possess adequate digital literacy skills, and additional improvements in this area are unlikely to substantially increase renewable energy competence. Rather than functioning as a direct driver of competency development, digital literacy appears to provide a foundational capability that supports learning indirectly by enhancing students' confidence and facilitating engagement with technology-supported learning environments.

Overall, the IPMA findings demonstrate that PBL Strategy represents the highest priority for educational intervention because it combines the greatest influence on renewable energy competence with performance that still has considerable room for improvement. In addition, Self-Efficacy should receive particular attention due to its comparatively low performance despite its meaningful contribution to competency development. These findings provide important practical implications for higher education institutions, suggesting that efforts to improve renewable energy competence should prioritize strengthening project-based instructional practices while simultaneously fostering students' confidence and motivation to engage effectively in technology-enhanced learning environments.

Conclusion

This study investigated the factors influencing Renewable Energy Competence among engineering students by integrating PBL Strategy, Digital Literacy, Self-Efficacy, Learning Motivation, and Performance within a structural equation modeling framework. The proposed model provides a comprehensive understanding of how instructional, technological, and psychological factors interact to enhance students' competency development in renewable energy education.

The findings demonstrate that PBL Strategy is the most influential factor affecting students' learning outcomes. It significantly enhances Learning Motivation, Performance, and Self-Efficacy, while also exerting indirect effects on Renewable Energy Competence through both Learning Motivation and Self-Efficacy. In addition, Digital Literacy positively influences Self-Efficacy, which subsequently increases Learning Motivation, highlighting the important role of digital competence in supporting students' psychological readiness for learning. Furthermore, Performance was found to

have a significant direct effect on Renewable Energy Competence, confirming that students' academic achievement remains a key determinant of competency development.

The findings also reveal that not all hypothesized relationships are significant. Although Learning Motivation and Self-Efficacy contribute indirectly to competency development, their direct effects on Renewable Energy Competence are not statistically significant. Similarly, the indirect effects of Digital Literacy on Performance and Renewable Energy Competence through Self-Efficacy were not supported. These results suggest that competency development is achieved through a combination of instructional practices, psychological factors, and academic performance rather than through any single factor operating independently.

The IPMA results further demonstrate that PBL Strategy represents the highest priority for educational improvement because it combines the greatest importance with performance that remains below its optimal level. Self-Efficacy also deserves particular attention due to its relatively low performance despite its meaningful contribution to competency development. These findings provide practical implications for higher education institutions by emphasizing the importance of strengthening project-based instructional practices while simultaneously fostering students' confidence, motivation, and engagement in technology-supported learning environments.

This study has several limitations. First, the research employed a cross-sectional design, which limits the ability to establish causal relationships among the proposed constructs. Second, the sample was restricted to engineering students from a single higher education institution in Indonesia, which may limit the generalizability of the findings to other educational contexts. Third, the study focused primarily on instructional, technological, and psychological variables, while other factors that may influence renewable energy competence, such as collaborative learning, critical thinking, learning engagement, institutional support, or technology acceptance, were not included in the proposed model.

Future research is encouraged to validate the proposed model using larger and more diverse samples from different universities and educational settings. Longitudinal or experimental research designs are also recommended to examine the long-term effectiveness of project-based learning in developing renewable energy competence. Additionally, future studies may incorporate other relevant constructs, such as critical thinking, collaborative learning, technology acceptance, learning engagement, or artificial intelligence-assisted learning, to provide a more comprehensive understanding of competency development in engineering education.

In conclusion, Renewable Energy Competence is not developed solely through students' digital capabilities or learning motivation. Instead, competency development results from the interaction between effective project-based learning, students' digital literacy, psychological readiness, and academic performance. These findings underscore the importance of implementing student-centered, technology-supported project-based learning environments that simultaneously strengthen students' competence, confidence, and motivation, thereby better preparing engineering graduates to address the challenges of sustainable energy development.

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Declarations

Ethics approval

This study was approved by the Ethics Committee of Universitas Negeri Padang, Indonesia (Approval No. 04.01/KEP-UNP/V/2026). All procedures involving human participants were performed in accordance with the ethical standards of the institutional and national research committee and with the principles of the Declaration of Helsinki and its later amendments or comparable ethical standards.

Consent to Participate
Participation in this study was entirely voluntary. Prior to data collection, all participants were informed about the purpose of the study, the nature of their involvement, and the intended use of the collected data. Informed consent was obtained from all participants before participation. Participants were also informed that they could withdraw from the study at any time without any penalty or adverse consequences.

Consent to Publish
Not applicable. No identifiable personal data, images, or individual participant information are included in this manuscript.

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Not applicable.

Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request. The authors are willing to provide the research data, where appropriate and in accordance with ethical and institutional requirements, through the contact email provided in this manuscript.

Competing interests
The authors declare no competing interests.

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