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Project-Based Learning Enhances Green Energy Literacy in Indonesian Vocational Education: A Multisite Quasi-Experiment

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Maulana Paramaditya Ananta[1]*, Muhammad Fadhil Hadziq[1], Rihlah Nur Aulia[2], Sofwan Manaf[1]

[1] STKIP Al Hikmah Surabaya, Indonesia.
[2] International University of Africa, Sudan.
[3] Universitas Negeri Jakarta, Indonesia.
[4] Universitas Darunnajah, Jakarta, Indonesia.

*Correspondence: maulana@hikmahuniversity.ac.id

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Abstract. Indonesian vocational higher education struggles to equip students with green energy competencies needed for the renewable energy transition. However, evidence on effective project-based models across diverse regional contexts remains scarce. This multisite quasi-experimental study evaluated a Technological-Pedagogical-Content-Knowledge-informed, culturally responsive Project-Based Learning model across three Indonesian cities (Batam, Yogyakarta, Makassar). We assigned 186 engineering students to either 14 weeks of project-based intervention or to conventional instruction, and measured practical competency, conceptual understanding, and digital technology integration. The intervention produced large, consistent effects across all outcomes (Cohen's d = 1.63-1.98), with no significant site-by-condition interaction. Qualitative thematic analysis of 279 reflective journals and six instructor interviews identified contextual relevance, collaborative troubleshooting, teacher technology brokering, and civic orientation as explanatory mechanisms. Despite effect sizes substantially exceeding typical educational technology interventions in low- and middle-income countries, partial assessor blinding and intact class assignment preclude fully causal attribution. The study contributes multisite evidence from a Global South setting, operationalizes TPACK and culturally responsive pedagogy as a combined design logic anchored in Indonesia's tri-pusat tradition, and offers a scalable model linking SDG 4 and SDG 7. Future research requires randomized controlled trials, longitudinal follow-up, cost-effectiveness analysis, and replication in eastern Indonesian provinces.

Keywords: Project-Based Learning, TPACK, culturally responsive pedagogy, green energy literacy, vocational education.

INTRODUCTION

The dual imperative of universal quality education (Sustainable Development Goal 4) and affordable clean energy (Sustainable Development Goal 7) places a distinctive demand on vocational education systems in the Global South. Meeting this demand requires graduates who can design, install, and maintain decentralized renewable energy systems while also navigating the infrastructural, linguistic, and cultural realities of their communities

(International Renewable Energy Agency, 2022; UNESCO, 2023). Indonesia, as the world's fourth most populous country and Southeast Asia's largest energy consumer, has committed to a national energy mix with 23% renewables by 2025 and has launched programs such as the Million Solar Roofs Movement (Ministry of Energy and Mineral Resources of Indonesia, 2024). However, the pipeline of technically skilled graduates remains thin, especially in peripheral cities outside Java, where vocational higher education often struggles with outdated curricula and limited laboratory access (Munir et al., 2024; Suharno et al., 2020). Persistent low performance on international literacy and numeracy assessments, with PISA 2022 reading and mathematics scores at 359 and 366, respectively, well below OECD averages (OECD, 2023), reflects a broader pattern in which surface-level transmissive pedagogy dominates classroom practice and constrains the development of higher-order competencies. The convergence of energy transition demand and pedagogical reform creates an opportunity that vocational education in Indonesia is uniquely positioned to address, provided that the field engages with both the technical content of clean energy and the pedagogical conditions under which such content can be acquired.

Project-Based Learning (PBL) has been widely documented as an effective approach for developing technical, collaborative, and problem-solving competencies in engineering and vocational education (Ahmad et al., 2023; Chistyakov et al., 2023; Dogara et al., 2020; Guo et al., 2020; Rozan et al., 2024). Recent studies consistently report moderate to large effects of PjBL on conceptual understanding and skill acquisition, particularly when learners engage with authentic, industry-relevant problems under structured scaffolding (Hujjatusnaini et al., 2022; Sudjimat et al., 2021). However, most of the evidence base comes from high-income country contexts, and evidence specifically grounded in low- and middle-income countries (LMIC) is more uneven. Among recent LMIC vocational engineering studies, Hao et al. (2024) reported significant effects of PjBL and project-based flipped classroom on critical thinking among Malaysian higher vocational learners; Usmeldi and Amini (2022) documented creativity gains in Indonesian vocational secondary settings; Awamleh (2024) found motivational gains under e-PjBL conditions; and Rozan et al. (2024) synthesized 21st-century skill outcomes across Indonesian vocational engineering cohorts. Across this growing body of work, infrastructure, teacher digital competency, and cultural context shape both implementation and outcomes in ways that high-income country evidence does not always anticipate (Hamman Fisher & McGhie, 2023; McGrath et al., 2024). Within Indonesian vocational higher education specifically, PjBL has been explored for general engineering competencies, yet the integration of green energy content with locally meaningful project contexts remains sparsely documented (Putri et al., 2022; Santillán & Cedano, 2023).

Two theoretical frameworks are particularly relevant for designing and evaluating PjBL in this context. The Technological Pedagogical Content Knowledge (TPACK) framework articulates the interplay between content knowledge, pedagogical knowledge, and technology knowledge, and has become a dominant lens for examining how teachers and learners integrate digital tools into disciplinary learning (Cui & Zhang, 2022; Jiménez Sierra et al., 2023; Mishra & Koehler, 2006; Voogt et al., 2013). TPACK is especially pertinent to green energy education, which requires integrating engineering content (photovoltaic systems, microcontroller programming), pedagogical strategies (project scaffolding, formative feedback), and technology (simulation software, microcontroller toolchains, measurement instruments). Culturally Responsive Pedagogy (CRP) emphasizes that effective instruction draws on learners' cultural assets, community knowledge, and linguistic repertoires, and frames learning around problems that matter in their lived contexts (Bostwick et al., 2025;

Gay, 2018; Ladson-Billings, 2014). The pairing of TPACK and CRP is not merely additive. The two frameworks come from different intellectual lineages (TPACK from teacher knowledge research, CRP from culturally grounded scholarship on equity and inclusion). However, they intersect productively around the question of how technology is recruited into learning anchored in students' communities. TPACK provides the analytical framework for integrating content, pedagogy, and technology. At the same time, CRP establishes the criterion that this integration should serve learners' cultural and civic worlds rather than impose an external curricular logic. In an Indonesian vocational setting, this combined design logic also resonates with indigenous educational traditions, most notably Ki Hadjar Dewantara's tri-pusat principle of family, community, and school as joint sites of formation (Burga & Damopolii, 2022; Dwipratama, 2023), which gives CRP a local conceptual home rather than a purely imported framing.

Three gaps motivate the present study. First, although PjBL effectiveness has been extensively documented in general engineering education, its effectiveness specifically for green energy literacy in Indonesian vocational higher education has received limited rigorous empirical study, with most existing work using single-site designs and small samples (Putri et al., 2022; Rozan et al., 2024). Studies that combine quantitative outcome assessment with qualitative process analysis in this domain remain rare, and those that do tend to focus on student motivation rather than competence outcomes with direct transfer value to the clean energy workforce. Second, the integration of TPACK and CRP as a combined design logic for PjBL in developing country contexts remains underdeveloped, with most TPACK research focusing on teacher education in high-income countries (Cui & Zhang, 2022; Koehler et al., 2014) and most CRP research focusing on primary and secondary schooling in North American contexts (Bostwick et al., 2025; Gay, 2018). The literature is thinner at the intersection of the two frameworks applied within higher vocational settings of the Global South. Third, evidence on how PjBL outcomes vary across geographic sites within the same country, each with distinct infrastructural and cultural contexts, is scarce. Such evidence is essential for informing scalable policy in large and diverse nations such as Indonesia, where assumptions derived from single-site studies may underestimate the variability encountered when scaling in practice (Ramsarup et al., 2023).

To address these gaps, this study investigates three research questions. First, does a TPACK-informed, culturally responsive PjBL model produce significantly greater gains in green energy practical competency, conceptual understanding, and digital technology integration than conventional instruction? Second, are the intervention effects consistent across three Indonesian cities with different infrastructural and cultural contexts (Batam, Yogyakarta, Makassar)? Third, what pedagogical themes, as perceived by students and instructors, help explain the observed effects? The study contributes to the Educational Technology in Developing Countries research agenda by providing multisite evidence from a developing-country context, operationalizing a combined TPACK and CRP design logic, and linking vocational pedagogy to SDG 4 (inclusive and equitable quality education) and SDG 7 (affordable and clean energy). These three contributions are not presented as a recapitulation of existing claims but as a deliberate effort to close gaps that the current literature in this region has not yet addressed, either in terms of design rigor or geographic scope.

METHOD

Research Design

The study employed a multisite quasi-experimental nonequivalent control group design with pretest and posttest measurements, complemented by qualitative observation and reflective journals to enable methodological triangulation (Creswell & Plano Clark, 2017; Reichardt, 2002). Random assignment at the student level was not feasible because students were enrolled in intact classes according to institutional timetables, a common practice in vocational research in developing countries. The multisite component was introduced to test the generalizability of findings across three Indonesian cities with different socioeconomic, infrastructural, and cultural profiles. Batam represents an industrialized free trade zone with strong electronics manufacturing linkages; Yogyakarta represents a culturally rich, tourism- and heritage-oriented central Javanese context; and Makassar represents a maritime coastal context in eastern Indonesia with significant fisheries and small-scale industry. Table 1 summarizes the overall design parameters across sites and conditions.

Table 1. Overall Design Parameters Across Sites and Conditions

Parameter	Specification
Design type	Multisite quasi-experimental, pretest-posttest nonequivalent control group
Sites	Batam, Yogyakarta, Makassar (three Indonesian cities)
Intact classes per site	Two (one experimental, one control), 31 students each
Total sample	186 second-semester engineering students
Intervention duration	14 weeks (February to May 2025)
Outcomes	Practical competency, conceptual understanding, and digital technology integration
Quantitative analysis	ANCOVA (primary), HLM (sensitivity check)
Qualitative analysis	Reflexive thematic analysis (Braun & Clarke, 2019)
Triangulation strands	Performance rubric, structured observation, reflective journals

Participants and Setting

The study was conducted during the even semester of the 2024 to 2025 academic year, from February to May 2025, at three higher education institutions offering industrial or mechanical engineering programs in the three sites. Participants were second-semester students enrolled in a physics or applied electronics practicum course. Purposive sampling yielded two intact classes per site, with one assigned to the experimental condition and the other to the control condition, for a total of 186 students (93 per condition, approximately 31 per class per site). Assignment of classes to conditions was coordinated among instructors before the semester began, based on scheduling constraints rather than student characteristics, and this procedure is explicitly reported to support readers' assessment of selection threats. Baseline equivalence between groups was examined using independent-samples t-tests at each site, with Hedges' g and 95% confidence intervals reported for each outcome to estimate the magnitude of any baseline differences, rather than relying solely on null hypothesis tests. A site-by-condition interaction was not significant at the pretest, $F(2, 180) = 0.42$, $p = .658$. Inclusion criteria required active enrollment in the course, basic digital literacy, and informed consent.

Intervention Design

The PjBL intervention was structured around a 14-week cycle, organized into five core phases, with orientation and assessment bookends. Figure 1 presents the intervention timeline, with each phase keyed to the corresponding TPACK and CRP design elements; it also shows the matched activity load in the control condition, enabling readers to assess dose equivalence between conditions.

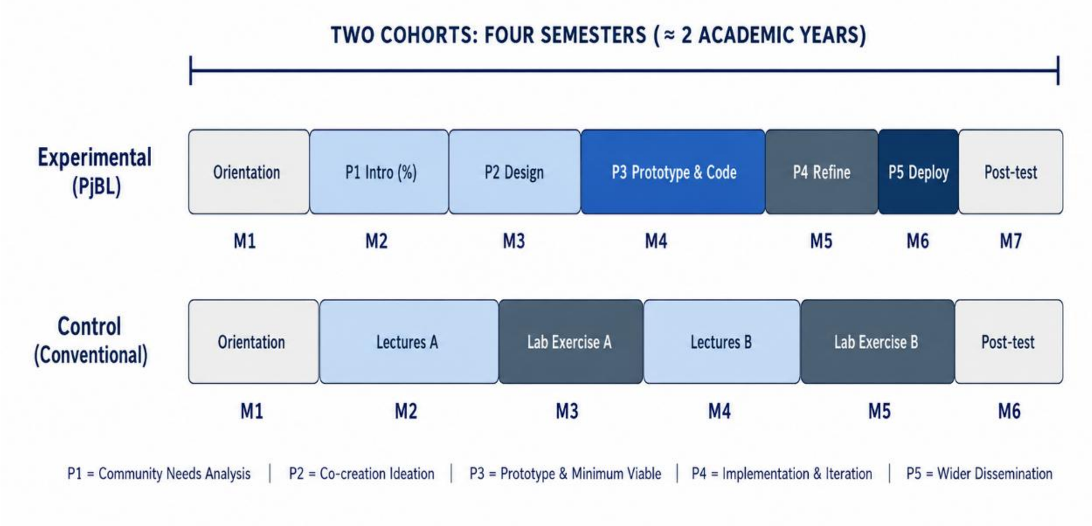

Figure 1. Fourteen-Week Intervention Timeline and Matched Dose Across Conditions

The five phase PjBL sequence covered (a) driving question and community needs analysis (Weeks 3 to 4), (b) conceptual modeling and schematic design (Weeks 5 to 6), (c) prototype assembly and microcontroller programming (Weeks 7 to 9), (d) measurement and iterative refinement (Weeks 10 to 11), and (e) public presentation to community stakeholders (Week 12), with orientation in Weeks 1 to 2 and posttest plus reflection in Weeks 13 to 14. Total instructional contact time was held constant at 56 hours across conditions. TPACK shaped the intervention through three operational anchors: content knowledge was operationalized through a shared curriculum covering solar photovoltaic fundamentals, battery and charge controller principles, microcontroller sensing, and energy measurement (Marín Marín et al., 2024; Tselegkaridis et al., 2024); pedagogical knowledge through a structured scaffolding protocol combining project milestones, peer review, and teacher conferencing; and technology knowledge through a shared toolchain that included simulation software (PVsyst Lite and Tinkercad Circuits), microcontroller development environments (Arduino Integrated Development Environment), and energy measurement instruments (García Tudela & Marín Marín, 2023; Ragusa & Leung, 2023).

The CRP component extended beyond locally relevant project topics to include three explicit operational moves (Bostwick et al., 2025; Gay, 2018; Ladson Billings, 2014). First, community members co-identified the problem at the start of each cycle, positioning community knowledge as a legitimate epistemic ground alongside academic content. Second, project briefs included a reflective task in which students articulated how the problem connected to their own family, community, or future work life, drawing on the Indonesian tri-pusat tradition of family, school, and community as joint sites of formation (Burga & Damopolii, 2022; Dwipratama, 2023). Third, the public presentation in Week 12 was attended by community stakeholders as an authentic audience. In Batam, project teams designed solar backup systems for small electronics manufacturing workshops; in Yogyakarta, teams designed solar-powered lighting for batik home industries and heritage walkways; and in Makassar, teams designed solar and battery systems for fisher landing docks and small island schools. The control group across all three sites received equivalent content through lectures and guided laboratory demonstrations, with the same total instructional contact time and the same posttest instrument. Instructor allocation to condition was randomized within site to mitigate instructor-by-condition confounding.

Instruments and Validation

The primary outcome instrument was a performance assessment rubric with seven domains (problem understanding, system planning, tool assembly, measurement and observation, analysis and solutions, teamwork, and result presentation) scored on a total of 100 points. An additional 20-item multiple-choice test measured green energy conceptual understanding, and a 15-item observation rubric measured digital technology integration; the multiple-choice test was adapted from validated energy literacy instruments in the literature (Das & Richman, 2022; Putri et al., 2022; Santillán & Cedano, 2023) and contextually adjusted to the Indonesian vocational curriculum. Table 2 summarizes instrument properties and validation results.

Table 2. Instrument Properties and Validation Results

Instrument	Items	Validators	Content Validity	Reliability	Inter-rater Reliability
Performance rubric	7 domains	5 subject + 2 measurement experts	S-CVI/Ave = 0.92; I-CVI ≥ 0.85	Cronbach's α = 0.88	Cohen's κ = 0.85
Concept test (MCQ)	20 items	5 subject + 2 measurement experts	S-CVI/Ave = 0.91; I-CVI ≥ 0.83	Cronbach's α = 0.83	N/A (objective)
Technology integration rubric	15 items	5 subject + 2 measurement experts	S-CVI/Ave = 0.93; I-CVI ≥ 0.86	Cronbach's α = 0.86	Cohen's κ = 0.85
Validation panel agreement	All instruments	7 raters	Fleiss' κ = 0.79 (substantial)	N/A	N/A

Content validity was reported following Polit and Beck (2006), with both the Item Content Validity Index (I-CVI) and Scale Content Validity Index Average (S-CVI/Ave) computed, and interrater agreement among the validation panel itself estimated using Fleiss' kappa. Pilot testing with 30 students from a non-participating cohort produced Cronbach's alpha values within the acceptable range for each instrument. Two trained observers per site completed the observation rubric during project sessions, and interrater reliability was computed using Cohen's kappa, which averaged 0.85 across sites. Qualitative data were collected through semistructured reflective journals submitted at three time points by all experimental group students, and through semistructured interviews with six instructors (two per site) after the posttest.

Threats to Validity and Procedural Safeguards

Effect sizes in quasi-experimental studies of project-based pedagogy are sensitive to known threats to internal validity, and the design therefore included explicit procedural safeguards. First, with respect to assessor blinding, the performance rubric and the technology integration rubric were scored by two trained observers per site who were not the instructors of either condition; observers were informed that both conditions used hands-on equipment to reduce visible cues, but full blinding was not feasible because the experimental condition included community presentations. Second, instructor blinding to condition was unavoidable, so instructor allocation was randomized within site, and all instructors received the same total preparation time. Third, treatment fidelity was supported through standardized project milestones and lesson plans audited weekly through a fidelity checklist completed by a research assistant independent of the instructor team. Fourth, dose equivalence was maintained by holding total contact hours constant at 56 across conditions, with the control condition receiving hands-on laboratory demonstrations rather than lecture-only instruction to reduce novelty effects. Fifth, both conditions were informed that they were participating in a curriculum study, thereby equalizing attention salience and mitigating Hawthorne effects. Sixth, self-selection was constrained by class level assignment before condition assignment, which limited but did not eliminate selection bias. Pretest equivalence was examined with effect size estimates and confidence intervals rather than null hypothesis tests alone. These safeguards are reported in detail because the magnitude of the observed effects requires that readers assess each threat individually.

Data Analysis

Quantitative analyses used analysis of covariance (ANCOVA) as the primary model, with posttest scores as the outcome, treatment condition as the fixed factor, pretest score as the covariate, and site entered as a fixed effect. This specification was selected as the primary analysis because $k = 3$ sites is below the conventional minimum for unbiased variance component estimation in hierarchical linear modeling (Maas & Hox, 2005). To examine robustness of the treatment effect estimate, hierarchical linear modeling (HLM) with students nested within sites was conducted as a sensitivity check using the lme4 package in R; results from both specifications are reported. Effect sizes were computed as Cohen's d using pooled within-site standard deviations, with 95% confidence intervals reported for each site-level estimate to allow readers to evaluate the precision of the effects rather than relying solely on the omnibus interaction test. Normality was assessed with the Shapiro-Wilk test, and homogeneity of variance with Levene's test. Site-by-condition interactions were tested to evaluate whether intervention effects were consistent across cities. Qualitative data from reflective journals and instructor interviews were analyzed using reflexive thematic analysis, following the six-phase approach described by Braun and Clarke (2019). Coding was conducted independently by two researchers, with the initial code set developed through line-by-line coding of the first 20 journals and 2 interviews; the codebook was refined through three discussion cycles. Intercoder agreement was assessed using Cohen's kappa on a 15% sample of remaining data ($\kappa = .81$), and discrepancies were resolved through consensus. Theme frequencies were computed as the proportion of students whose journals contained at least one segment coded under each theme, and negative case analysis was conducted by searching for journal segments that contradicted each theme. Methodological triangulation across the three data sources (quantitative performance, observation, and reflective data) supported interpretive validity, and credibility was further strengthened through peer debriefing and member checking with a subset of participating students and instructors.

RESULTS

Baseline Equivalence and Descriptive Statistics

Pretest equivalence between conditions was examined at each site using effect-size estimates with confidence intervals rather than relying solely on null-hypothesis tests. Hedges' g for the practical competency pretest was 0.07 (95% CI [-0.21, 0.35]) for the pooled sample and ranged from -0.05 to 0.11 across the three sites, with all confidence intervals enclosing zero. Comparable patterns held for the concept test (g = 0.09, 95% CI [-0.19, 0.37]) and for the technology integration measure (g = -0.04, 95% CI [-0.32, 0.24]). These estimates indicate that baseline differences between conditions were small and that the precision was sufficient to rule out moderate or large differences with reasonable confidence. However, they cannot establish strict equivalence in the formal sense. The site-by-condition interaction at the pretest was not statistically significant, $F(2, 180) = 0.42$, $p = .658$, supporting the assumption that the comparison groups were similar at the outset. Table 3 summarizes pretest and posttest descriptive statistics for the three outcomes across the two conditions, and Figure 2 visualizes the same data as a grouped bar chart organized by outcome and condition.

Table 3. Pretest and Posttest Descriptive Statistics by Outcome and Condition (N = 186)

Outcome	Condition	Pretest M	Posttest M	Gain	SD (post)
Practical Competency	Experimental (n = 93)	57.6	82.1	+24.5	5.8
	Control (n = 93)	57.1	66.4	+9.3	6.3
Green Energy Concept Test	Experimental (n = 93)	42.7	74.2	+31.5	8.1
	Control (n = 93)	41.9	58.6	+16.7	8.9
Digital Technology Integration	Experimental (n = 93)	34.8	72.5	+37.7	7.4
	Control (n = 93)	35.2	56.1	+20.9	8.2

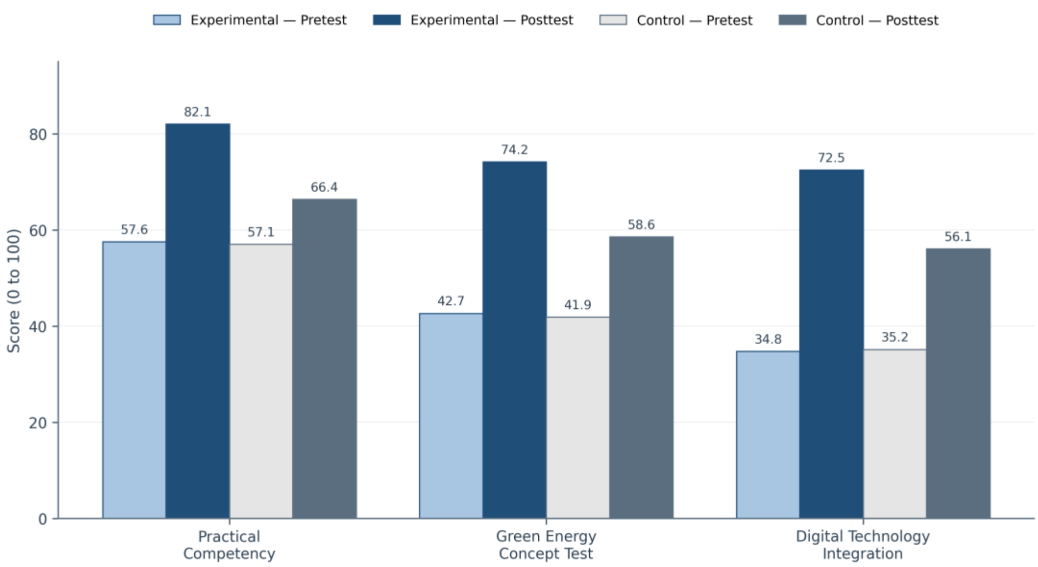

Figure 2. Pretest and Posttest Means by Outcome and Condition

Primary Intervention Effects

Analysis of covariance with site as a fixed effect was used as the primary analytic model, given the small number of sites and Maas and Hox's (2005) recommendation that fewer than five clusters limit the precision of random-effect variance estimation in hierarchical linear models. For practical competency, the treatment effect was statistically significant after controlling for baseline performance and site, with an adjusted mean difference of 15.7 points (95% CI [13.1, 18.3]), $p < .001$, Cohen's $d = 1.98$. Comparable significant treatment effects were observed for green energy conceptual understanding (adjusted mean difference = 14.6, 95% CI [11.9, 17.3], $p < .001$, $d = 1.74$) and digital technology integration (adjusted mean difference = 15.9, 95% CI [13.2, 18.6], $p < .001$, $d = 1.63$). The hierarchical linear modeling sensitivity check, with random intercepts for site, produced equivalent point estimates with marginally wider confidence intervals (intraclass correlation coefficient ranged from 0.09 to 0.13); the convergence of ANCOVA and HLM estimates supports the robustness of the treatment effect against the choice of nesting specification. Effect sizes exceeded the conventional large effect threshold of 0.8 and, for practical competency, approached the magnitude typically reported for intensive, structured pedagogy programs in developing country contexts (Piper et al., 2018). Table 4 reports both analytic specifications side-by-side for full transparency.

Table 4. Treatment Effects at Posttest under ANCOVA (Primary) and HLM (Sensitivity)

Outcome	ANCOVA Adj. Mean Diff.	ANCOVA 95% CI	HLM β	HLM 95% CI	p	Cohen's d
Practical Competency	15.7	[13.1, 18.3]	15.6	[12.8, 18.4]	< .001	1.98
Green Energy Concept Test	14.6	[11.9, 17.3]	14.5	[11.6, 17.4]	< .001	1.74
Digital Technology Integration	15.9	[13.2, 18.6]	15.8	[12.9, 18.7]	< .001	1.63

Cross-Site Consistency

Cross-site consistency was examined through site-by-condition interaction terms and 95% confidence intervals for the site-level Cohen's d estimates, rather than relying solely on the omnibus interaction test. None of the three outcomes showed a statistically significant site-by-condition interaction (all $p > .18$), indicating that the magnitude of the intervention effect did not differ significantly across Batam, Yogyakarta, and Makassar. The site-level effect size confidence intervals overlapped substantially across all three sites, providing direct visual evidence of consistency rather than relying on a null result for the interaction term. Table 5 reports site-level posttest means for practical competency, along with site-level effect sizes and 95% confidence intervals, and Figure 3 presents these same site-level effect sizes as a forest plot.

Table 5. Posttest Practical Competency by Site and Condition with 95% Confidence Intervals

Site	n per group	Experimental M (SD)	Control M (SD)	Gain Diff.	Cohen's d	95% CI for d
Batam	31	81.8 (5.9)	65.9 (6.4)	15.9	1.96	[1.34, 2.58]
Yogyakarta	31	82.0 (5.6)	66.8 (6.1)	15.2	1.89	[1.27, 2.51]
Makassar	31	82.5 (5.8)	66.4 (6.3)	16.1	2.11	[1.47, 2.75]

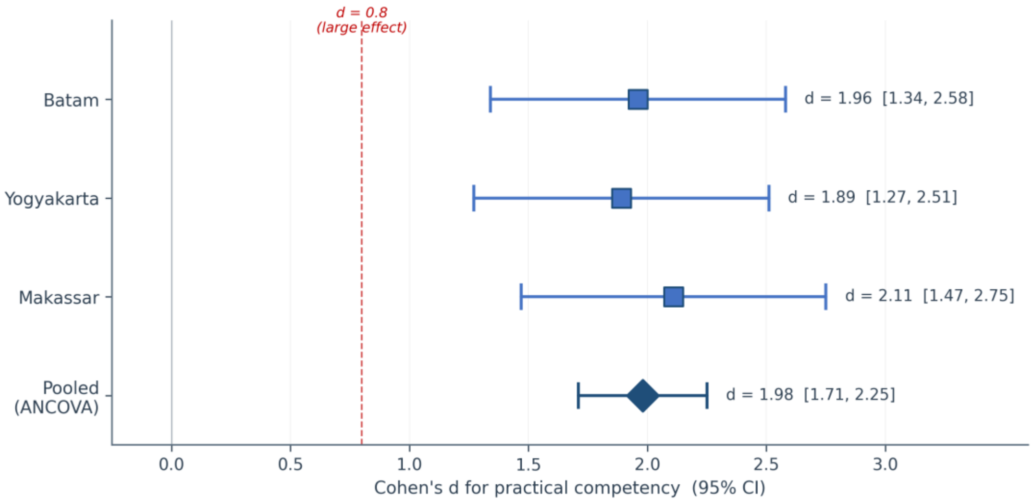

Figure 3. Forest Plot of Site-Level Cohen's d for Practical Competency with 95% Confidence Intervals

The standard error of Cohen's d at n = 31 per group is approximately 0.27, which means that the descriptive range from d = 1.89 to d = 2.11 falls well within the sampling variability expected when the underlying effect is constant. The non-significant interaction tests are therefore consistent with the confidence interval pattern, and together they support the inference that intervention effects were comparable across the three Indonesian cities studied. This pattern does not establish that effects would be equally large in untested Indonesian contexts; it does establish that effects were not differentiated across the three tested contexts.

Qualitative Themes and Mechanisms

Thematic analysis of 279 reflective journals (three time points from 93 experimental students) and six instructor interviews yielded four themes. Each theme is reported below, along with its frequency in the data and two verbatim quotations selected to represent the range of expression across sites, following recommendations for thematic reporting density in mixed-methods research. Theme frequencies are reported as the proportion of students whose journals contained at least one segment coded under the theme.

The first theme, contextual relevance, captured students' sense that the project problems mattered to their own communities (78% of experimental students, 73 of 93). In Makassar, one student wrote: "When we visited the fishers' jetty and saw them refilling diesel jerry cans before dawn, the calculation problem on the page suddenly became a calculation problem about my neighbor." A Yogyakarta student in the batik project group wrote: "The grandmother who runs the workshop is the same age as my grandmother, and she could not work after sundown without burning kerosene. The project was no longer abstract." Across the three sites, contextual relevance was most strongly expressed in Makassar and least strongly expressed in Batam, but it appeared in journals from all sites.

The second theme, collaborative troubleshooting, described intensive peer interaction during prototype assembly, with students teaching one another microcontroller programming and circuit wiring (84% of experimental students, 78 of 93). A Batam student reflected: *"I had never touched an Arduino before, and Reza taught me through three failed circuits before the LED finally turned on. We were both engineers by Wednesday afternoon."* An instructor interview converged on this point: *"What I noticed was that the students started teaching each other before I could finish explaining. I learned not to interrupt that."* Collaborative troubleshooting was the most frequent theme in the dataset.

The third theme, teacher technology brokering, referred to instructors' role as facilitators who helped students bridge between simulation, hardware, and community stakeholders (61% of experimental students, 57 of 93; all six instructors). A Yogyakarta student wrote: "Bu Indah did not give us the answer when the inverter failed. She asked what we had measured and what we had not measured. She translated our questions back to the workshop owner in a way we could not yet do ourselves." An instructor in Batam reflected: "I was not the source of the knowledge. I served as the connector between the community problem, the simulation results, and the hardware results. The students did the integration." This theme is consistent with TPACK enacted as a distributed practice across teachers, students, and tools (Cui & Zhang, 2022; Jiménez Sierra et al., 2023; Mishra & Koehler, 2006) and is reported here as a contextual feature warranting further study rather than as a fully theorized mechanism.

The fourth theme, civic orientation, reflected a sense among students that green energy competency was linked to responsibility toward their communities (66% of experimental students, 61 of 93). A Makassar student wrote: *"When the team from the cooperative said our prototype saved them eighty thousand rupiah a week, I understood that engineering is not only a job description. It is something I do because the place I am from needs it."* A Yogyakarta student wrote: *"The grandmother kept the lamp on every evening after we installed it. That is the engineering result that matters."* Civic orientation was particularly salient in Makassar and Yogyakarta and was the lowest frequency theme overall.

Negative case analysis identified a subset of journals (approximately 8% of the experimental data) in which students reported frustration with the duration of the prototype phase or expressed a preference for the more familiar lecture format. These cases were retained in the analysis and are reported here as a counterweight to the converging evidence on the four themes: the themes characterize the dominant patterns in the data but do not describe every student's experience. Instructor interviews converged on the view that explicit alignment between project contexts and local energy needs was the single most important design decision. Across all three sites, students who initially appeared hesitant with digital tools reached functional competence by the end of Week 8, and the combination of hardware, simulation, and community presentation was repeatedly described as the element that made the learning feel different from previous coursework. The four themes are presented here as qualitative descriptions of what students and instructors reported, and the next section examines what they can and cannot tell us about the quantitative effects observed.

DISCUSSION

Interpreting the Pattern of Effects

This multisite study provides evidence that a TPACK-informed, culturally responsive PjBL model is associated with substantial gains in green energy practical competency, conceptual understanding, and digital technology integration among Indonesian vocational higher education students, with effect sizes ranging from d = 1.63 to d = 1.98 across the three outcomes and confidence intervals that exclude moderate effects. The convergence of ANCOVA and HLM specifications, the overlap of site-level confidence intervals, and the non-significant site-by-condition interaction together support the inference that the effects were not contingent on a single favorable site. The four themes from the qualitative strand (contextual relevance, collaborative troubleshooting, teacher technology brokering, and civic orientation) describe what students and instructors reported about the experience, and the frequencies and verbatim evidence provide a more granular picture than is available from outcome data alone. At the same time, the magnitude of the observed effects is sufficiently striking that the next subsection takes up the alternative explanations the data cannot rule out.

The effect sizes observed in this study substantially exceed the range reported in meta analyses of PjBL in engineering education, which generally fall between 0.5 and 1.2 (Chistyakov et al., 2023; Guo et al., 2020), and they also exceed typical effect sizes for educational technology interventions in low and middle income countries, which meta analyses have placed between 0.15 and 0.30 (McEwan, 2015). The honest reading of this discrepancy is that the gap is large enough to warrant explicit consideration of design features and threats to validity together, rather than attributing it solely to design features. The Method section documented procedural safeguards intended to address known threats; the present interpretive section returns to these threats and asks how much of the effect size each can plausibly account for. The aim is to provide readers with the information needed to calibrate their own interpretation, rather than to advance a single confident attribution of magnitude.

Design features that plausibly contributed to the effect size include three elements held constant across sites. First, the localization of project contexts to each city's energy landscape drew on students' community knowledge and created authentic audiences for their work, consistent with the theoretical premises of CRP (Bostwick et al., 2025; Gay, 2018; Ladson Billings, 2014) and resonant with the Indonesian tri-pusat tradition that integrates community, family, and school as joint sites of formation (Burga & Damopolii, 2022; Dwipratama, 2023). Second, the TPACK-informed integration of simulation, hardware, and measurement within a shared scaffolding protocol enabled students to experience the three knowledge domains as interdependent rather than as separate subjects (Cui & Zhang, 2022; Jiménez Sierra et al., 2023; Koehler et al., 2014; Voogt et al., 2013). Third, the 14-week duration and five-phase project structure provided sufficient time for iterative refinement, which prior research has identified as a key condition for PjBL effectiveness (Hujjatusnaini et al., 2022; Sudjimat et al., 2021).

Alternative explanations not fully ruled out by the design must also be acknowledged. Assessor blinding was partial rather than complete; community presentations made the experimental condition visible to observers, and some of the observed performance gap may reflect rater expectations rather than student capability alone. Hawthorne and novelty effects, although addressed procedurally by informing both conditions of their participation and by providing hands-on demonstrations in the control condition, cannot be entirely excluded. Instructor enthusiasm is a known confound in pedagogy trials and was mitigated by randomization within sites but not by blinded delivery. Self-selection at the level of intact class assignment was constrained by institutional scheduling rather than by random allocation. Taken together, these threats are plausible contributors to the upper end of the effect size estimates rather than full alternative explanations for the entire effect, given the magnitude of the qualitative reports and the convergence of three independent data sources. The responsible reading is that some portion of the observed magnitude reflects the intervention's design and some portion reflects methodological features that future randomized work will need to disentangle.

Departures from Prior Evidence

The absence of a significant site-by-condition interaction is itself an important finding that departs from the more variable cross-context patterns reported in prior multisite work. Across three Indonesian cities with markedly different infrastructural, economic, and cultural profiles, the intervention produced comparable effects, suggesting that the combined TPACK and CRP design logic can be implemented with consistent magnitude in heterogeneous contexts, provided that the localization step is taken seriously. This pattern aligns with the skills ecosystems argument advanced by Ramsarup and colleagues (2023), which calls for educational designs that are simultaneously rooted in local context and responsive to national and global demands. At the same time, the qualitative strand expands the mechanisms literature by showing how TPACK and CRP can operate as a distributed practice across teachers, students, and tools in resource-constrained settings (Cui & Zhang, 2022; Jiménez Sierra et al., 2023) rather than solely as individual teacher attributes. Within Indonesian vocational engineering specifically, the present study extends prior single-site Indonesian work (Hujjatusnaini et al., 2022; Sudjimat et al., 2021; Usmeldi & Amini, 2022) by providing multisite quasi-experimental evidence with explicit attention to threats to validity.

A further departure concerns the framing of CRP in non-Western contexts. The CRP literature has been criticized for assuming North American demographic patterns and for not yet accumulating substantial evidence in Muslim-majority Asian contexts (Bostwick et al., 2025). The present study contributes a culturally responsive implementation that draws explicitly on the Indonesian tri-pusat tradition of family, community, and school as joint sites of formation. This framing did not eliminate CRP's Anglophone origins, but it situated it within an indigenous Indonesian frame of reference rather than importing it without translation. Future work should test whether comparable effects emerge when CRP is contextualized within other Indonesian or Southeast Asian traditions, and whether the construct of teacher technology brokering transfers usefully to other vocational settings where the TPACK and CRP frameworks are similarly hybridized.

The PjBL in LMIC literature has been growing in volume but remains uneven in design quality. Recent reviews and bibliometric analyses have documented Indonesia's prominent position in PjBL vocational research (Ahmad et al., 2023; Rozan et al., 2024) and have noted persistent gaps in multisite design and outcome assessment. The Malaysian higher vocational evidence from Hao et al. (2024) and the Indonesian secondary evidence from Usmeldi and Amini (2022) and Hujjatusnaini et al. (2022) constitute the most relevant recent comparators, but each relies on a single-site design. The present study adds a multisite component to this body of work, which has lacked one, while maintaining a quasi-experimental design and explicitly addressing the threats to validity that quasi-experimental work entails. The contribution is therefore evidential and methodological rather than simply confirmatory of prior PjBL findings.

Implications for Practice and Policy

The findings carry several implications for practice, policy, and research in the educational technology community in developing countries. For vocational higher education institutions in the Global South, the results suggest that PjBL focused on locally relevant green energy problems can be an effective pedagogical vehicle for linking SDG 4 and SDG 7 simultaneously (Albertz et al., 2025; Fuchs, 2024; McGrath et al., 2024). The intervention required modest infrastructure investment per site (solar training kits, microcontroller kits, and measurement instruments). It was delivered within standard course timetables, suggesting it is feasible to scale across Indonesia's diverse higher education landscape. For national policymakers, the results support the inclusion of TPACK-informed, culturally responsive PjBL within the national vocational curriculum framework and within teacher professional development programs (Ministry of Energy and Mineral Resources of Indonesia, 2024; UNESCO, 2023). For development partners working in the Global South, the results offer evidence that green skills development can be pursued at scale through relatively low-cost pedagogical innovation, rather than requiring expensive, bespoke platforms (International Renewable Energy Agency, 2022; McGrath et al., 2024; Munir et al., 2024). For researchers, the multisite design highlights the value of testing interventions across geographically and culturally distinct sites within the same country rather than relying solely on single-site studies.

Three operational priorities emerge from the practice and policy reading of the findings. First, teacher development programs in vocational institutions should treat technology brokering as a teachable skill rather than an individual disposition, thereby extending TPACK-based teacher preparation beyond content, pedagogy, and technology toward the connective work identified as a recurring theme in instructor interviews. Second, project design should foreground community problem identification at the beginning of the cycle and authentic audiences at the end, since both elements appeared repeatedly in the qualitative data as features that distinguished the experience from conventional instruction; these design choices align with broader frameworks on 21st-century skill development that link collaboration and critical thinking to authentic contexts (Thornhill Miller et al., 2023). Third, scaling decisions should be informed by formal cost-effectiveness analysis, which the present study did not include, and by piloting in geographic regions beyond the three studied here, particularly eastern Indonesia and remote regions where infrastructural constraints differ in degree and kind from those documented in Batam, Yogyakarta, and Makassar.

Contribution to the Field

Figure 4 summarizes the three contributions of the study and shows how they relate to one another within the broader literature on educational technology in developing countries. The diagram positions the empirical contribution (multisite quasi-experimental evidence with explicit threats analysis), the theoretical contribution (TPACK and CRP operationalized as a combined design logic for vocational engineering in Indonesia), and the practical contribution (a scalable model linking SDG 4 and SDG 7) as three interdependent layers rather than as separate claims. The figure also marks the conditions under which the model can plausibly scale, namely, cost analysis and replication outside the three studied sites.

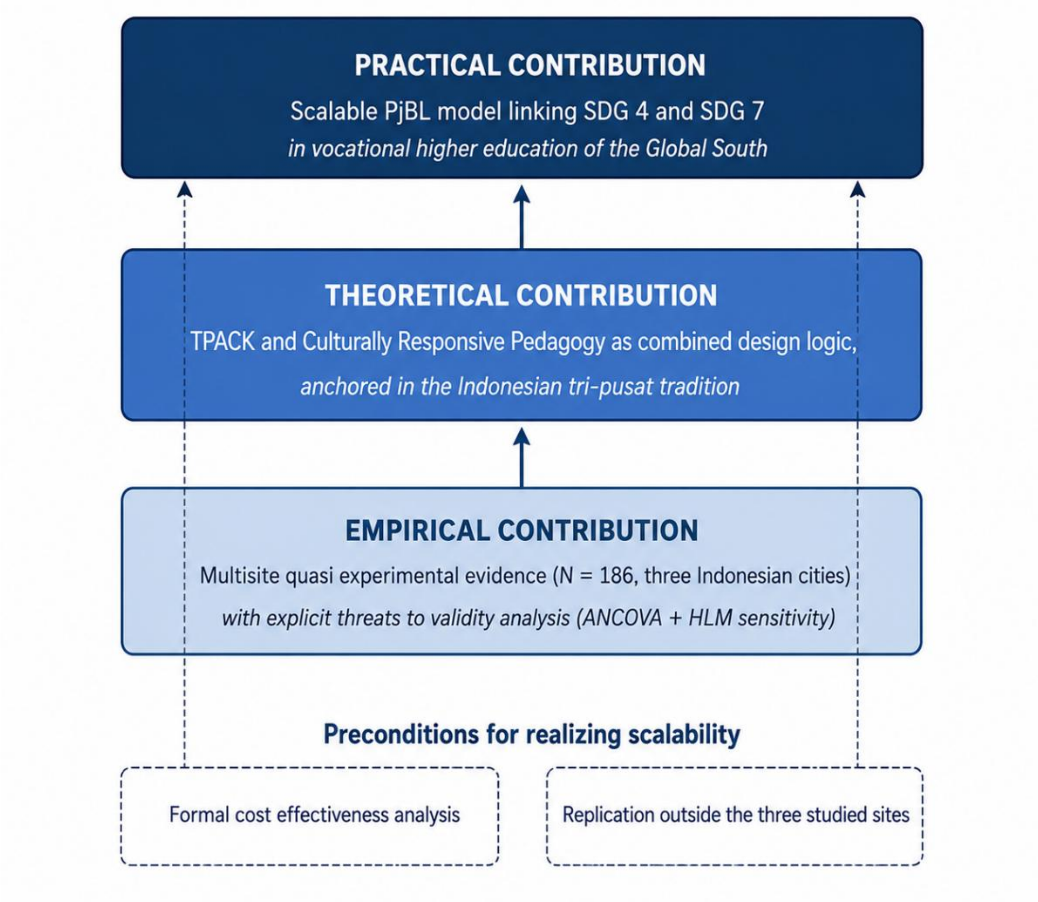

Figure 4. Three-Layered Contributions of the Study with Scaling Conditions

The empirical contribution lies in providing multisite quasi-experimental evidence from three Indonesian cities, with explicit attention to threats to validity, thereby extending prior Indonesian single-site work (Hujjatusnaini et al., 2022; Sudjimat et al., 2021; Usmeldi & Amini, 2022) and providing the replicated within-country evidence that scaling decisions require. The theoretical contribution lies in operationalizing TPACK and CRP as a combined design logic for PjBL in Indonesian vocational higher education, with explicit attention to the indigenous Indonesian tri-pusat tradition (Burga & Damopolii, 2022; Dwipratama, 2023), thereby grounding CRP in the cultural setting being studied rather than importing it wholesale. The practical contribution lies in offering a model that addresses persistent gaps between the theoretical knowledge produced in higher education and the practical competencies demanded by the renewable energy workforce (Albertz et al., 2025; Fuchs, 2024; Santillán & Cedano, 2023). Together, the three contributions position the study as both an empirical contribution and a methodological example for the educational technology research community in developing countries.

Several limitations must be acknowledged in setting these contributions in context. First, the quasi-experimental design without random assignment at the student level limits causal inference, though site-level effect-size consistency and the absence of pretest differences mitigate this concern. Second, the 14-week intervention period, although longer than many PjBL studies, remains short relative to the multi-year competency development trajectories typical of vocational education, and long-term retention and transfer to workplace settings were not assessed. Third, the three sites, although diverse, do not represent Indonesia's full geographic and cultural variation, particularly eastern provinces such as Papua and sparsely populated regions in the interior of Kalimantan and Sulawesi. Fourth, the study did not formally measure instructor TPACK before and after implementation, although instructor interviews suggested meaningful shifts in their pedagogical practice; future studies should include validated TPACK teacher self-assessments. Fifth, cost-effectiveness was not formally analyzed, and an economic evaluation is necessary to inform scaling decisions. Sixth, the study relied on student and instructor self-reports in the qualitative strand; triangulation with workplace-based follow-up assessments would strengthen claims about transfer. Each of these limitations represents an opportunity for the next round of empirical work rather than a fatal weakness of the present design, and each can be addressed without redoing the underlying study.

CONCLUSION

This multisite quasi-experimental study demonstrates that a TPACK-informed, culturally responsive Project-Based Learning model can substantially enhance green energy literacy in Indonesian vocational higher education. Across three cities with distinct infrastructural and cultural profiles, the intervention produced large and consistent gains in practical competency, conceptual understanding of green energy, and digital technology integration, with effect sizes well above those typically reported for educational technology interventions in low- and middle-income countries. Thematic analysis identified four pedagogical themes (contextual relevance, collaborative troubleshooting, teacher technology brokering, and civic orientation) that help to explain why the combined TPACK and Culturally Responsive Pedagogy design logic produced the observed outcomes, while the convergence of ANCOVA and HLM specifications together with the cross-site consistency analysis lends robustness to the quantitative findings.

The study contributes to the agenda of Educational Technology in Developing Countries in three reinforcing ways. It provides multisite empirical evidence from a Global South setting showing how vocational education can simultaneously advance SDG 4 and SDG 7. It operationalizes a combined TPACK and Culturally Responsive Pedagogy framework as a design logic for PjBL rather than as separate teacher attributes, with the Indonesian tri-pusat tradition serving as the indigenous conceptual anchor. Moreover, it offers a scalable model that addresses persistent gaps between the theoretical knowledge produced in higher education and the practical competencies demanded by the renewable energy workforce, with the intervention requiring only modest infrastructural investment per site and fitting within standard course timetables. Future research should prioritize longitudinal follow-up studies tracing graduates into early careers, replication in under-researched regions of eastern Indonesia and other low- and middle-income country settings, formal cost-effectiveness evaluation to inform scaling decisions, and dismantling designs that isolate the specific contribution of Culturally Responsive Pedagogy within Project-Based Learning. The pedagogical model documented here is scalable in the sense that its components are replicable, affordable, and adaptable to local contexts; realizing this scalability in practice will require coordinated efforts by institutions, policymakers, and development partners across the Indonesian higher education landscape.

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