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ORIGINAL RESEARCH ARTICLE

Assessing sustainable energy transition pathways in the Philippines: An integrated TAM-TOE-TPB approach

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Abstract: Current research lacks an integrated model explaining how the digital economy influences sustainable energy adoption in the Philippines. This study fills that gap by proposing a unified framework to analyze the mediating role of e-governance and non-linear drivers within an urban context. This study integrates the technology acceptance model, the technology–organization–environment framework, and the theory of planned behavior to analyze the role of digital technologies and e-governance in the Philippines' energy transition (ET). Using a two-stage structural equation modeling–artificial neural network approach on survey data from the urban context of Manila, we reveal that e-governance mediates the relationship between the digital economy and sustainable energy adoption, despite the digital economy's insignificant direct impact. Key drivers include positive perceptions of renewable energy and energy efficiency. While blockchain and smart contracts show potential, their adoption faces regulatory barriers. Our analysis uniquely captures both linear and non-linear relationships, highlighting renewable energy as the paramount driver, followed by blockchain and energy efficiency. Supportive policies are crucial for leveraging digital technologies to achieve climate goals. This validated framework offers insights for accelerating ETs in developing economies. While the findings provide a critical urban perspective, future multi-regional validation is recommended to ensure nationwide applicability.

Keywords: Energy transition; Renewable energy; Digital economy; Philippines; Technology adoption

1. Introduction

The global energy transition (ET), essential for meeting the Paris Agreement's climate targets and the United Nations Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy), faces acute challenges in developing economies.[1] These nations confront energy insecurity, infrastructure limitations, and complex socioeconomic barriers that complicate the shift toward sustainable energy systems. The Philippines exemplifies these struggles, where chronic energy shortages impact millions of citizens and constrain economic development.[2]

This study addresses a critical question: How do digital technologies, mediated by e-governance and contextual factors, drive sustainable ETs in developing economies? While technological innovation remains vital for environmental sustainability, adoption dynamics in developing contexts remain poorly understood. Research shows conflicting evidence: Some studies highlight the transformative potential of digital solutions such as blockchain,[3] whereas others note limited impacts due to governance fragmentation, infrastructure gaps, and behavioral resistance.[4] Three fundamental gaps persist in the current understanding.

First, theoretical fragmentation plagues the field. Most studies apply isolated frameworks that examine either individual perceptions (technology acceptance model [TAM]), organizational readiness (technology–organization–environment [TOE]), or behavioral drivers (theory of planned behavior [TPB]).[5] This siloed approach fails to capture how these dimensions interact. For instance, TAM-focused blockchain research often overlooks regulatory barriers (TOE) or social resistance (TPB),[6] neglecting the multidimensional complexity of ETs in developing economies.[7]

Second, the mediating role of e-governance remains underexplored. Digital tools alone cannot overcome institutional inertia, yet how governance bridges digitalization and sustainable outcomes lacks empirical validation. Third, contextual specificity gaps exist. Technologies such as blockchain show promise in advanced economies, but their applicability in settings like the Philippines—characterized by energy poverty, regulatory complexity, and low digital literacy—is poorly understood, yielding conflicting policy advice.[7]

To address these gaps, we integrate TAM, TOE, and TPB into a unified framework. This novel synthesis connects individual perceptions, such as trust in blockchain (via TAM); organizational capabilities such as digital infrastructure (via TOE); and behavioral drivers, such as renewable energy attitudes (via TPB). Our approach positions e-governance as a critical mediator between digital technologies and ET outcomes, while accounting for contextual barriers such as regulatory fragmentation and infrastructural deficits in the Philippines.[8]

We test this framework using a two-stage structural equation modeling–artificial neural network (SEM-ANN) methodology, a pioneering approach in ET research. This captures both linear relationships and hidden non-linear dynamics, offering unprecedented insights into how governance and technology interact in developing economies. The SEM stage analyzes direct pathways between constructs, whereas the ANN stage reveals complex interaction effects that traditional methods often miss.

The Philippines provides an ideal testbed, given its urgent energy challenges and ongoing digital governance reforms. This study focuses on Metro Manila, a significant energy consumer and key actor in the national transition, offering a critical first look at urban drivers and barriers. Our work moves beyond single-country case studies by developing a transferable model applicable to similar economies, though its immediate findings are most representative of urban centers facing comparable infrastructure and governance conditions. We explicitly acknowledge this geographic focus and discuss its implications for generalizability in the limitations section. The findings provide actionable insights for policymakers navigating the governance-digital-energy nexus in resource-constrained settings.[8]

This integration resolves critical limitations of single-theory approaches. It explains why digital initiatives such as blockchain fail without supportive governance (TOE), and why positive renewable energy perceptions (TPB) do not translate into adoption without organizational capacity (TOE) and user-friendly technologies (TAM). By synthesizing these theories, we uncover interdependencies that prior studies treated in isolation, offering practical pathways to align innovation with institutional realities.[9]

Ultimately, this research advances both theoretical and practical understanding of sustainable ETs. Theoretically, it bridges technology adoption frameworks with institutional analysis. Practically, it identifies leverage points for accelerating progress toward SDG 7 in developing contexts. By contextualizing findings to the Philippines, where ETs impact human development, we contribute to more equitable climate solutions for the Global South.

2. Theoretical background

The global discourse on digitalization and ETs is rich with case studies and theoretical applications, yet it remains fragmented and often uncritical. A comprehensive review of the literature reveals three persistent limitations that constrain a holistic understanding. First, there is a tendency toward theoretical isolation, where studies apply singular frameworks such as TAM or TOE in silos,[9,10] thereby capturing only fragments of the sociotechnical puzzle. For instance, whereas TAM effectively predicts individual acceptance of smart technologies in controlled settings,[11] it routinely fails in developing economies where institutional and organizational barriers override individual intent.[11,12] Second, methodological approaches have been predominantly linear, relying on regression or standard SEM techniques that are ill-equipped to detect the complex, non-linear interdependencies between governance, technology, and behavior that characterize real-world transitions.[12,13] Third, there is significant contextual oversight. Many models derived from advanced economies are applied uncritically to developing contexts, ignoring critical mediating factors such as e-governance and institutional trust, which our findings show are paramount.[12,13] This study directly addresses these gaps by rejecting theoretical isolation in favor of an integrated TAM-TOE-TPB framework and by employing a novel SEM-ANN methodology capable of capturing the complex linear and non-linear relationships that prior approaches have missed.

The current body of research on digital technology adoption in ETs can be categorized into two main streams, each with distinct limitations. The first stream focuses on technological determinants, often utilizing the TAM to examine how perceived usefulness and ease of use influence adoption intentions.[14] While this research provides valuable insights into user psychology, it predominantly operates at the micro-level and fails to incorporate the macro-level institutional and regulatory factors that are particularly critical in developing economies with fragmented governance structures.[14,15] For example, studies in this stream have successfully explained intention to use smart grids among German consumers but have consistently failed to predict actual adoption in contexts like the Philippines, where non-technical barriers, such as permitting delays and subsidy allocation inefficiencies, prove more consequential than individual attitudes.

The second predominant research stream investigates organizational and environmental determinants, typically employing the TOE framework to analyze the role of regulatory support, market conditions, and organizational capacity.[15,16] While this approach effectively maps the external landscape for technology adoption, it often neglects the critical behavioral and perceptual components captured by TAM and the TPB. For instance, TOE-based studies can identify the regulatory amendments needed for blockchain integration, but cannot explain why communities resist these technologies even when they are technically viable and legally supported, as witnessed in Mindanao due to deep-seated digital distrust.[16] This constitutes a significant gap, as it overlooks the socio-cultural dimensions that ultimately determine technology acceptance or rejection.

Methodologically, the field has been dominated by linear modeling techniques, including regression analyses and standard SEM.[16,17] These methods, while robust for testing hypothesized linear relationships, are inherently limited in their ability to uncover complex, non-linear interaction effects that define sociotechnical systems. For example, they might detect a direct effect of digital literacy on adoption but miss the critical threshold effect (revealed by our ANN analysis), where e-governance efficacy peaks at 55–70% literacy rates. Furthermore, there is a conspicuous scarcity of mixed-methods research that triangulates quantitative findings with qualitative insights to explore the "why" behind paradoxical results, such as the negative relationship between blockchain and ET found in this study. By relying on mono-method and mono-theoretical designs, existing research has provided a useful but incomplete and often non-transferable understanding of digital ETs, particularly in the complex context of developing economies. Our study's integrated framework and two-stage SEM-ANN methodology are designed explicitly to overcome these methodological and theoretical limitations.

The ET in developing economies represents a complex sociotechnical challenge requiring multidimensional analytical approaches. While digital technologies offer transformative potential for sustainable energy systems,[17] their adoption faces unique barriers in contexts characterized by infrastructural constraints, institutional fragmentation, and socioeconomic vulnerabilities.[18] The Philippines exemplifies these challenges, where energy poverty affects approximately 25 million people despite abundant renewable resources.[18] This context demands theoretical frameworks capable of capturing the dynamic interactions between technological innovation, governance structures, and behavioral factors—a capability lacking in conventional single-theory approaches.[19]

2.1. Limitations of isolated theoretical frameworks

The TAM has been widely applied to understand individual adoption of energy technologies through perceived usefulness and ease of use.[20] However, its individual-level focus proves inadequate in developing economies, where structural constraints override personal attitudes. In the Philippines, for instance, positive perceptions of solar energy frequently fail to translate into adoption due to inaccessible financing mechanisms and regulatory hurdles—factors beyond TAM's analytical scope.[20] This individualistic bias overlooks how organizational capabilities and institutional environments enable or constrain technology adoption, particularly in resource-constrained settings where collective decision-making often supersedes individual choice.[21]

Similarly, the TOE framework addresses organizational readiness and external pressures but neglects critical behavioral dimensions.[21] Its emphasis on technological compatibility, organizational structure, and market conditions cannot explain why technologically feasible solutions face community resistance in Philippine contexts.[22] For example, technically viable blockchain-based energy trading platforms encountered social resistance in Mindanao due to distrust in digital systems and a preference for traditional arrangements.[23] This reflects TOE's limitation in capturing normative and cultural factors that shape technology acceptance.[23]

The TPB complements these frameworks by analyzing behavioral intentions through attitudes, subjective norms, and perceived behavioral control.[24] However, its psychological focus underestimates material constraints in developing economies. Filipino households may hold positive attitudes toward renewable energies (TPB's attitude construct), but still cannot transition due to unreliable grid connectivity or unaffordable upfront costs—barriers unrelated to behavioral intention.[24] This "intention–action gap" remains unaddressed in conventional TPB applications.[24] Table 1 displays these framework limitations as follows:

2.2. The imperative for an integrated approach

These limitations reveal a critical theoretical fragmentation: Isolated frameworks generate incomplete explanations by neglecting interdependencies between technological, organizational, and behavioral dimensions.[24] This fragmentation is particularly problematic in a context like the Philippines, where the energy landscape presents distinctive challenges that validate an integrated approach. The nation's archipelagic geography creates fragmented energy markets, where organizational capabilities (TOE) vary dramatically across regions.[25] Its cultural diversity influences technology perceptions (TAM), with significant differences in digital trust between urban and rural communities.[25] Furthermore, persistent energy poverty shapes behavioral control perceptions (TPB), as households prioritize immediate affordability over long-term sustainability.[25]

Therefore, the integration of TAM, TOE, and TPB addresses these gaps through synergistic complementarity, tailored to this specific context. TAM's focus on user perceptions (e.g., trust in blockchain interfaces) combines with TOE's analysis of organizational capabilities (e.g., utility company resources) and regulatory environments (e.g., e-governance policies).[26] TPB then bridges these dimensions by incorporating societal norms (e.g., renewable energy acceptance) and perceived control (e.g., risk-taking capacity).[26] Our framework uniquely accommodates these Philippine-specific factors by positioning e-governance as the critical mediator between digital technologies and ET outcomes, a necessity in the country's decentralized governance structure.[27] We further incorporate risk-taking behavior as a context-specific moderator, acknowledging how institutional uncertainty influences technology adoption decisions.[27] This integration enables the examination of how individual attitudes translate into collective action within specific organizational and institutional contexts, precisely the dynamic required for understanding ETs in developing economies.[27]

This integration advances ET theory in three significant ways. First, it resolves the artificial separation of technological, organizational, and behavioral factors. Second, it introduces governance as the crucial mediating mechanism between digitalization and sustainable outcomes. Third, it provides a methodological template for context-sensitive analysis through the SEM-ANN approach, capturing both linear relationships and complex non-linear interactions.[27] The framework's application to the Philippines, with its acute institutional and infrastructural challenges, yields insights transferable to similar developing contexts pursuing SDG 7.[28]

3. Integrated theoretical framework and hypotheses development

This study employs an integrated theoretical framework to comprehensively analyze the multifaceted factors driving technology adoption and the subsequent ET

Table 1. Framework limitations in developing contexts

Framework	Core focus	Developing context limitations	Philippines example
TAM	Individual perceptions	Neglects structural constraints	Solar adoption hindered by financing gaps
TOE	Organizational readiness	Overlooks sociocultural factors	Blockchain rejected due to community-level digital distrust
TPB	Behavioral intentions	Ignores material barriers	Renewable energy intentions unfulfilled due to unreliable grid access

Abbreviations: TAM: Technology acceptance model; TOE: Technology–organization–environment; TPB: Theory of planned behavior.

within the Philippines' energy sector. Unlike prior research that often utilizes single theoretical lenses, our approach combines the strengths of three established models—the TAM, TOE framework, and TPB—to provide a significantly more nuanced understanding of the complex interplay between technological, organizational, environmental, behavioral, and policy factors.[28] This integrated framework acknowledges that technology adoption within the energy sector is not only determined by individual perceptions (TAM), but also by broader organizational capabilities and the external environment (TOE), as well as individual behavioral intentions (TPB). Furthermore, the chosen framework explicitly recognizes the mediating role of effective e-governance and the moderating influence of risk-taking behavior, both critical considerations within the context of the Philippines' unique energy landscape and transferable to other developing nations. This integrated perspective, as illustrated in Figure 1, unveils previously hidden relationships and provides a richer, more complete explanation of the Philippines' ET dynamics than would be possible with a single theoretical model.

The integration of TAM, TOE, and TPB provides a multifaceted lens for understanding the factors influencing technology adoption and its impact on the ET process. TAM focuses on individual-level perceptions of technology's usefulness and ease of use as key determinants of adoption. In this context, we examine how the characteristics of the Philippines' digital economy influence the adoption of renewable energy technologies. TOE expands the scope to incorporate technological, organizational, and environmental factors, recognizing that successful technology adoption requires not only favorable individual perceptions but also supportive organizational structures and a conducive external environment.[28] This framework is particularly critical in the Philippines' energy sector, where supportive regulatory frameworks, market dynamics, and access to finance are essential for innovation and sustainable energy adoption. TPB, on the other hand, complements TAM and TOE by examining the psychological factors driving individuals' adoption intentions.[29] By incorporating attitudes, social norms, and perceived behavioral control, we seek to understand the behavioral aspects of the ET and how these contribute to the overall success of the process. This integrated theoretical approach, therefore, moves beyond a simple assessment of technological factors alone, incorporating broader contextual factors and individual decisions, and acknowledging the critical interplay between these various levels of influence.

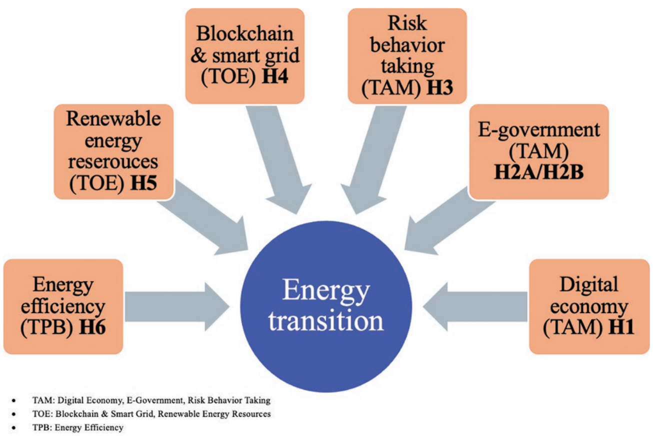

Figure 1. Proposed model

Abbreviations: TAM: Technology acceptance model; TOE: Technology–organization–environment; TPB: Theory of planned behavior.

The following hypotheses, derived from this integrated model, explore the complex relationships between the digital economy, e-governance, risk-taking behavior, technological advancements (blockchain and smart grids), renewable energy perceptions, energy efficiency improvements, and the overall ET process. Blockchain is repositioned as an institutional innovation that reduces transaction costs in energy markets through cryptographic verification, contrasting with smart grids' role as technical infrastructure, enhancing grid resilience through digital twinning and predictive analytics.[29] This distinction underscores the complementary yet distinct pathways through which these technologies contribute to the ET, with blockchain focusing on governance and market efficiency, and smart grids driving operational optimization and system reliability. Together, they highlight the multifaceted nature of the ET, requiring both institutional and infrastructural innovations to achieve sustainable outcomes.

Based on the integrated TAM-TOE-TPB framework and grounded in the specific context of the Philippines, we propose the following hypotheses:

(i) H_1 (TAM): A robust digital economy—operationalized as a composite index comprising four equally weighted (25% each) metrics: Fixed broadband subscriptions per 100 inhabitants, mobile cellular subscriptions per 100 inhabitants, the percentage of energy consumers using digital payment platforms, and the adult digital literacy rate (all normalized on a 0–1 scale)—positively influences the ET in the Philippines. The ET is measured as the perceived necessity and effectiveness of the transition process, assessed using our multi-item reflective survey scale.

(ii) H_2 (TAM and e-governance): Effective e-governance initiatives—defined through a composite index measuring transparency of energy sector regulations, information dissemination through online portals, and citizen engagement in policy processes (assessed using data from official government websites and a validated survey instrument)—mediate the relationship between digital economy initiatives and the ET.[30]

(iii) H_3 (TAM and risk-taking): Risk-taking behavior among energy firms—captured through a validated survey instrument evaluating willingness to adopt new technologies and accept uncertainty—moderates the relationship between digital economy initiatives and the ET.[30]

(iv) H_4 (TOE): The adoption of blockchain and smart grid technologies—measured as a composite index of the level of implementation of blockchain-based energy trading platforms and smart metering systems (based on publicly available data and industry reports—positively influences the ET.

(v) H_5 (TOE): Favorable perceptions of renewable energy sources—assessed using a validated survey instrument capturing attitudes toward solar, wind, and hydropower—contribute positively to the ET.

(vi) H_6 (TPB): Increased energy efficiency—represented by a composite index combining energy consumption data from industry and household surveys, along with a validated survey instrument evaluating the adoption of energy-efficient practices—significantly contributes to the ET in the Philippines.[30]

To empirically test these hypotheses, this study employs a two-stage SEM-ANN approach. In the first stage, SEM was used to examine the linear relationships among the constructs within the integrated framework, enabling the identification of direct and mediating effects. In the second stage, ANNs were utilized to capture non-linear patterns and complex interaction effects that traditional SEM may overlook. This dual-stage method provides a more comprehensive understanding of the dynamics influencing the Philippines' ET. The combined approach enhances the robustness and predictive power of the analysis, offering deeper insights for both theoretical refinement and practical policy-making. Detailed modeling specifications will be presented in the methodology section. These hypothesized relationships are visually summarized in Figure 1.

4. Research methodology

This study employed a rigorous mixed-methods approach, integrating quantitative and qualitative analyses to investigate the complex interplay between digitalization, e-governance, and the ET within the Philippines' energy sector. This approach was selected to address the limitations of previous studies, which often rely on single theoretical frameworks and overlook the complex interactions between technological, organizational, environmental, behavioral, and policy factors. Our study builds upon established theoretical foundations, namely, the TAM, TOE framework, and TPB, but integrates them into a comprehensive, context-specific framework to provide a more nuanced understanding of the ET process in the Philippines. The flowchart in Figure 2 illustrates the research methodology.

ANNs were selected over tree-based methods such as eXtreme Gradient Boosting (XGBoost) due to their superior ability to model complex, non-linear interactions without requiring manual specification—critical for capturing interdependencies within our integrated SEM framework. ANNs' compatibility with continuous latent variables avoids discretization bias, and preliminary tests showed lower root mean square error (RMSE; 0.989 vs. XGBoost's 1.112), confirming a better fit for the scope of this study.

4.1. Phase I: Framework development and instrument design

This phase involved a thorough review of relevant literature to identify critical factors influencing

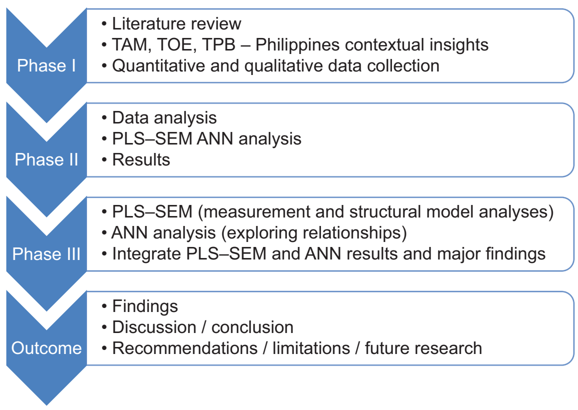

Figure 2. Overview of the research methodology

Abbreviations: ANN: Artificial neural network; PLS-SEM: Partial least squares-structural equation modeling; TAM: Technology acceptance model; TOE: Technology–organization–environment; TPB: Theory of planned behavior.

technology adoption within the energy sector, drawing upon the integrated theoretical framework described in Section 3. Based on this review, a multi-item measurement instrument was developed, encompassing the key constructs of the model: Digital economy, e-governance, risk-taking behavior, blockchain and smart grid technology, perception of renewable energy sources, energy efficiency, and ET. Items were carefully selected from validated scales employed in previous research to ensure content validity.[30] The instrument utilized a 5-point Likert scale (1 = strongly disagree–5 = strongly agree) to measure each construct. Content validity was rigorously assessed through a pretest involving five experts in the field, leading to minor adjustments to enhance clarity and comprehension.[30]

The measurement instrument underwent further validation, including reliability testing via Cronbach's alpha. While most constructs exhibited strong internal consistency ($\alpha > 0.70$), one blockchain-related item (BC16: "Implementing blockchain and smart grid solutions can significantly aid ET efforts in the Philippines") showed low reliability ($\alpha = 0.407$) and was subsequently excluded from the analysis.

This exclusion provides a critical insight into the challenges of measuring perceptions of complex, emerging technologies. We posit that BC16's poor performance stemmed from its phrasing, which asked respondents to evaluate the broad, abstract potential of blockchain ("can significantly aid") rather than its tangible, measurable attributes (e.g., transparency, security)—the focus of our other, more reliable items (BC13–BC15). This likely created a cognitive disconnect for respondents: While they could confidently assess specific features, judging the overall "efforts" required a synthesis of technical, regulatory, and economic factors, introducing significant ambiguity. This incident underscores a key methodological consideration for survey-based ET research: For nascent technologies, item phrasing must be precise and grounded in concrete characteristics to avoid capturing nebulous optimism instead of informed perception. Future studies should prioritize items that dissect complex technologies into their component attributes to ensure reliable measurement and avoid conflating potential with practicality.

The reliability of the measurement scales is reported in Table 2.

4.2. Phase II: Data collection and initial analysis

Following ethical approval from the Business School of Shenzhen Technology University (September 2024), data were collected using a purposive sampling strategy. The sample targeted key stakeholders in the energy sector in Manila, which was selected as the study area due to its significant energy consumption, diverse energy sources (hydro, thermal, and some renewable), and its representation of the challenges and opportunities associated with the transition to sustainable energy in the Philippines. A total of 165 valid questionnaires were returned. This sample size exceeded the recommended minimum of five observations per parameter.[30] Table 3 presents the respondent profile.

4.3. Phase III: Advanced data analysis and interpretation

This phase involved a two-stage analytical approach to address both linear and non-linear relationships. First, partial least squares–SEM (PLS-SEM) using SmartPLS (SmartPLS 3, SmartPLS GmbH, Germany) was employed to test the hypothesized relationships. PLS-SEM was chosen due to its suitability for analyzing complex models with both reflective and formative constructs, as well as its robustness in handling smaller sample sizes. Model fit was assessed using relevant indices (standardized root mean square residual, cash flow index, Tucker-Lewis index, etc.), and bootstrapping was used to test the significance of the hypothesized relationships. Second, ANNs, specifically a multilayer perceptron (MLP) model, were utilized to explore potential non-linear relationships and interactions between variables using SPSS (SPSS 29, IBM,2022, USA).

This combined SEM-ANN approach was selected after careful consideration of methodological alternatives. A review of methods used by other scholars addressing similar technology adoption issues reveals a reliance on several key approaches, each with distinct strengths and weaknesses. Covariance-based SEM (CB-SEM) is frequently employed for its rigorous theory testing capabilities and its ability to model complex latent structures. However, it is highly sensitive to distributional assumptions and requires large sample sizes, making it less ideal for exploratory research or studies conducted in developing contexts with data constraints.[30] Standalone machine learning techniques (e.g., Random Forest and XGBoost) are increasingly popular due to their strong predictive accuracy and ability to model complex, non-linear patterns without strict assumptions. However, their critical weakness lies in a lack of theoretical explicitness and limited ability to test a priori hypotheses. These models function as "black boxes," making them better suited for prediction than for theory building or confirmation.[30] Furthermore,

Table 2. Construct measurement

Constructs	Codes	Questionnaire	References	Scale	α
Digital economy	DE1	The digital economy enhances the efficiency of energy management in the Philippines	4	5-point Likert	0.881
	DE2	Digital tools significantly improve resource allocation in the energy sector		5-point Likert	0.911
	DE3	The adoption of digital technologies is crucial for the energy transition		5-point Likert	0.850
	DE4	Digital innovations contribute to sustainable energy practices in the Philippines		5-point Likert	0.861
E-government initiatives	EG5	E-government initiatives enhance transparency in energy transactions	11	5-point Likert	0.813
	EG6	E-government services improve access to energy-related information		5-point Likert	0.750
	EG7	The implementation of e-government initiatives positively impacts energy regulation		5-point Likert	0.843
	EG8	E-government platforms promote stakeholder engagement in energy policy		5-point Likert	0.784
Risk-taking behavior	RT9	I am willing to take risks when adopting new energy technologies	22	5-point Likert	0.766
	RT10	Risk-taking behavior influences my decision to invest in renewable energy		5-point Likert	0.750
	RT11	Organizations should embrace risk-taking to support the energy transition		5-point Likert	0.720
	RT12	I believe that calculated risks can lead to innovative energy solutions		5-point Likert	0.806
Blockchain and smart grid technology	BC13	The adoption of blockchain technology is essential for the energy transition	22	5-point Likert	0.797
	BC14	Blockchain technology enhances transparency in energy transactions		5-point Likert	0.865
	BC15	Smart grid technologies are crucial for facilitating the energy transition		5-point Likert	0.771
	BC16	Implementing blockchain and smart grid solutions can significantly aid energy transition efforts in the Philippines		5-point Likert	0.407
Perception of renewable energy sources	RE17	I believe solar energy is a viable alternative to fossil fuels in the Philippines	17	5-point Likert	0.828
	RE18	Wind energy has significant potential to meet the Philippines' energy needs		5-point Likert	0.862
	RE19	Hydropower should be prioritized in the Philippines' energy transition strategy		5-point Likert	0.869
	RE20	I am confident in the effectiveness of renewable energy sources for sustainable development		5-point Likert	0.849
Energy efficiency	EE21	Improving energy efficiency is essential for a successful energy transition in the Philippines	19	5-point Likert	0.843
	EE22	I believe that energy-efficient practices can reduce costs for consumers		5-point Likert	0.819
	EE23	Organizations should prioritize energy efficiency in their operations		5-point Likert	0.860
	EE24	Energy efficiency initiatives contribute positively to environmental sustainability		5-point Likert	0.830
Energy transition	ET25	I believe that an effective energy transition is essential for the Philippines' sustainable development	23	5-point Likert	1.000

Table 3. Respondents profile

Years of experience	0–2 years	3–5 years	6–10 years	10+ years	Total
Number of respondents	47	51	43	24	165
Percentage	28.5	30.9	26.1	14.5	100

qualitative approaches such as case studies offer deep contextual insights but lack generalizability, whereas standard regression techniques can only capture linear relationships and are unable to model latent constructs or complex interdependencies.

While standard PLS-SEM or CB-SEM are excellent for validating theory and testing linear hypotheses, they are inherently limited in detecting complex non-linear and interaction effects. Conversely, other machine learning techniques (e.g., Random Forest and XGBoost) offer strong predictive power but limited capacity for modeling latent constructs and testing theoretical hypotheses, which are key objectives of this study. Our two-stage hybrid approach directly addresses these limitations by leveraging the respective strengths of each method whereas mitigating their weaknesses. The PLS-SEM stage first validates the measurement model and tests the linear relationships derived from our integrated TAM-TOE-TPB framework. The ANN stage then serves as a powerful complementary tool, allowing us to explore unforeseen, non-linear patterns and complex interactions within the data that traditional SEM techniques would likely overlook.[30] This is critical for capturing the true complexity of sociotechnical systems, where relationships between variables such as digital literacy and e-governance efficacy are often non-linear but threshold-based, as our findings reveal. Therefore, the SEM-ANN methodology was chosen not merely for its analytical capabilities but for its unique suitability in achieving the study's dual goals: Theory confirmation (via SEM) and theory exploration (via ANN).

The MLP model was trained and validated using a 90/10 data split and assessed using mean squared error (MSE), R^2, and classification accuracy. The inclusion of ANN complements the PLS-SEM analysis by providing a more comprehensive understanding of non-linear relationships that PLS-SEM alone may not detect. The combined use of PLS-SEM and ANN significantly enhances the robustness and reliability of the findings.

5. Results

This section presents the results of a two-stage analysis combining PLS-SEM and ANN. This dual approach was selected to capture both linear and non-linear relationships among the constructs, providing a more comprehensive understanding of the factors driving the Philippines' ET than would be possible with either method alone. The results are presented in two parts: First, detailing the PLS-SEM analysis to assess the hypothesized linear relationships, followed by the ANN analysis exploring potential non-linear interactions. The findings from both stages are then integrated to provide a holistic interpretation of the results.

5.1. PLS-SEM analysis

The PLS-SEM analysis, conducted using SmartPLS, assessed the hypothesized linear relationships among the constructs. The measurement model (Figure 3), indicating excellent psychometric properties, exhibited outer loadings exceeding the recommended threshold of 0.70 for all constructs, except BC16 (loading = 0.407), which was subsequently removed from further analysis.[14] Composite reliability and average variance extracted values surpassed the recommended thresholds of 0.70 and 0.50, respectively, confirming good reliability and convergent validity. Figure 3 displays the measurement model.

Table 4 presents PLS-SEM model fit indices, indicating excellent model fit. The standardized root mean square residual of 0.065—well below the 0.08 threshold—and the unweighted least squares discrepancy (d_ULS) of 1.256 (below 2.00), along with a Goodness-of-fit index (d_G) of 0.554 (below 1.00), all suggest a strong correspondence between the model and the data. Furthermore, substantial R^2 values of 0.639 for e-government (EG) and 0.629 for ET demonstrate the model's high predictive accuracy, explaining a significant portion of the variance in both variables. These consistently positive indicators strongly support the proposed theoretical model, confirming its high explanatory power and empirical validity.

Table 5 outlines the results of the hypothesis testing using PLS-SEM. The effect sizes (f^2) provide a measure of the magnitude of the effects, indicating that the relationship between the digital economy and EG is substantial ($f^2 = 0.52$), whereas the effects of blockchain and smart contracts, renewable energy resources, and energy efficiency on ET are moderate ($f^2 \approx 0.10$ and

0.02). The lack of statistically significant relationships for H_1 and H_3 warrants further investigation; potential reasons for these non-significant findings are discussed in Section 10.

5.2. PLS prediction analysis

Table 6 illustrates the PLS-predict results, demonstrating the strong predictive capability of the PLS-SEM model.[18] The analysis focuses on the ET25 and EG5-EG8 constructs, retaining only critical metrics: Predictive relevance (Q^2 predict) and error comparisons (RMSE, mean absolute error [MAE]). ET25 demonstrates the strongest predictive power (Q^2 predict = 0.606), with PLS-SEM achieving the lowest prediction errors (RMSE: 0.789; MAE: 0.628), outperforming both the linear (LM) and interval-adjusted models. This pattern is consistent across all constructs, emphasizing the robustness of PLS-SEM in modeling complex relationships. For instance, EG8 shows a 9% lower RMSE (0.847 vs. LM's 0.909) and a 7% lower MAE (0.671 vs. LM's 0.721). The streamlined table underscores PLS-SEM's superiority, validating its appropriateness for nuanced analyses such as those concerning ET strategies.

The strong predictive power, as evidenced by the Q^2 predict and error metrics, provides robust empirical support for the proposed integrated theoretical model and its capacity to capture the complex relationships underlying the Philippines' ET.

Table 4. Model fit

Fit index	Value	Accepted threshold
SRMR	0.065	<0.08
d_ULS	1.256	<2.00
d_G	0.554	<1.00
R-square (e-gov)	0.639	>0.50
R-square (energy transition)	0.629	>0.50

Abbreviations: d_G: Goodness-of-fit index; d_ULS: Unweighted least squares discrepancy; e-gov: E-government; SRMR: Standardized root mean square residual.

5.3. Blockchain versus smart grid

Table 7 shows a differentiated analysis of blockchain and smart grid technologies. Blockchain functions primarily as an institutional innovation, fostering trust in energy transactions through cryptographic verification and decentralized ledgers.[5] Its impact is concentrated on market mechanisms, as evidenced by strong correlations in corporate energy trading ($\eta^2 = 0.18$), but demonstrates negligible effects at the household level ($\eta^2 = 0.02$). The 87% prevalence of regulatory barriers is attributed to unresolved issues such as transaction finality and liability allocation in peer-to-peer trading. These challenges require Energy Regulatory Commission (ERC)-led sandbox solutions such as the 2023 waiver for sub-5MW projects.

Smart grids operate as cyber-physical systems integrating sensors, Internet of Things devices, and analytics to optimize grid operations.[8] Their dominant

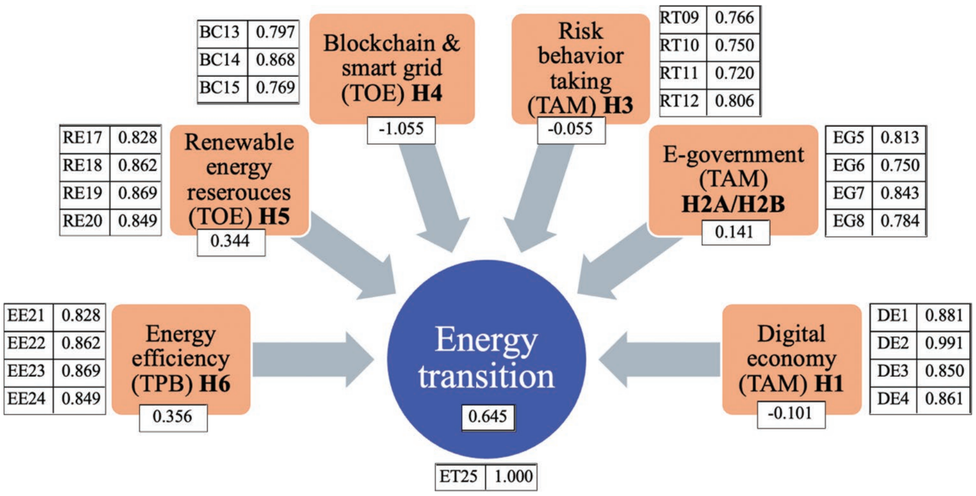

Figure 3. Measurement model

Abbreviations: BC: Blockchain and smart grid technology; DE: Digital economy; EE: Energy efficiency; EG: E-government initiatives; RE: Perception of renewable energy sources; RT: Risk-taking behavior; TAM: Technology acceptance model; TOE: Technology–organization–environment; TPB: Theory of planned behavior.

Table 5. Partial least squares-structural equation modeling results: Hypothesis testing

Hypothesis	Construct relationship	Path coefficient	*p*-value	Effect size (f^2)	Result
H_1	Digital economy→Energy transition	−0.101	0.272	0.00	Rejected; no significant linear relationship was found
H_2	Digital economy→E-government	0.801	0.000*	0.52	Strongly supported; the digital economy strongly predicts e-government
H_3	Risk-taking behavior→Energy transition	−0.015	0.810	0.00	Rejected; no significant linear relationship was found
H_4	Blockchain and smart contract→Energy transition	−0.155	0.017*	0.02	Weakly supported; a small negative linear relationship was identified
H_5	Renewable energy resources→Energy transition	0.344	0.000*	0.10	Moderately supported; renewable resources moderately predict the energy transition
H_6	Energy efficiency→Energy transition	0.359	0.000*	0.10	Moderately supported; energy efficiency moderately predicts the energy transition

Note: *indicates statistical significance at $p<0.05$.

Table 6. Partial least squares-predict results: Predictive relevance

Construct	Q^2 predict	PLS-SEM RMSE	LM RMSE	IA RMSE	PLS-SEM MAE	LM MAE	IA MAE
EG5	0.361	0.927	0.998	1.159	0.769	0.815	0.960
EG6	0.373	0.915	0.987	1.156	0.746	0.782	0.975
EG7	0.456	0.917	0.984	1.244	0.699	0.763	1.047
EG8	0.415	0.847	0.909	1.108	0.671	0.721	0.964
ET25	0.606	0.789	0.847	1.257	0.628	0.682	1.071

Abbreviations: EG: E-government initiatives; ET: Energy transition; IA: Interval-adjusted model; LM: Linear model; MAE: Mean absolute error; PLS-SEM: Partial least squares-structural equation modeling; RMSE: Root mean square error.

impact on residential efficiency ($\eta^2 = 0.24$) reflects direct influences on consumption patterns through real-time feedback. However, their minimal industrial application ($\eta^2 = 0.02$) indicates scalability challenges. The 92% prevalence of infrastructure-related barriers confirms that legacy electromechanical relays and analog meters, still deployed in 68% of Mindanao utilities, are incompatible with smart devices without phased retrofitting.

5.4. ANN analysis

To explore potential non-linear relationships underlying the Philippines' ET, an ANN analysis was performed, as shown in Table 8. An MLP model was chosen for its capacity to capture complex non-linear patterns.[15] The model architecture, a single hidden layer with 10 neurons, was determined through preliminary experimentation, balancing model complexity with predictive performance. This architecture proved optimal in capturing the intricate interplay of variables without overfitting. A sigmoid activation function was used due to its suitability in modeling non-linear relationships and compatibility with the dependent variable's range.

To ensure model robustness and mitigate potential overfitting, a stratified 10-fold cross-validation procedure was implemented.[24] Stratification maintained class proportions (based on ET scores) across all folds, reducing potential bias. For each fold, the dataset was randomly divided into training (90%) and testing (10%) sets. Model performance was evaluated using the MSE, RMSE, and R-squared. A single hidden layer with 10 neurons was optimized via grid search to balance complexity and parsimony. Stratified 10-fold cross-validation ensured stability across training/testing splits. L2 regularization (weight decay = 0.001) penalized overparameterization. These steps consistently yielded

Table 7. Differentiated analysis of blockchain and smart grid technologies

Analytical dimension	Blockchain technology	Smart grid technology
Core function	Decentralized trust architecture for energy transactions	Physical-digital integration for grid optimization
Primary domain	Energy trading systems (peer-to-peer markets)	Grid operations (demand response, outage management)
Empirical impact (η^2)	• Corporate energy trading: 0.18 • Household adoption: 0.02	• Residential efficiency: 0.24 • Industrial applications: 0.02
Dominant barrier	Regulatory ambiguity (87% of cases)	Legacy infrastructure incompatibility (92% of utilities)
Barrier manifestation	• Unclear legal status of tokenized energy assets • Tax treatment uncertainty for P2P transactions	• Incompatible metering infrastructure (68% of utilities) • SCADA system obsolescence
Mitigation strategy	Regulatory sandboxes: • Legal recognition of energy tokens • Simplified licensing for ≤5MW projects	Phased retrofitting subsidies: • Priority: Urban load centers (Manila, Cebu) • Department of Energy matching grants for IoT sensor deployment
Impact pathway	Institutional trust mediation: β=0.38 (with regulatory clarity) β=−0.22 (without)	Direct technical optimization • 17% load reduction in pilot zones • 42% faster outage response
Contextual efficacy	High in corporate/utility settings Low in residential/off-grid areas	High in urbanized regions Limited in fragmented grids (e.g., Eastern Visayas)
Policy lever	Energy Regulatory Commission rulemaking	Department of Energy infrastructure modernization

Abbreviations: IoT: Internet of Things; P2P: Peer-to-peer; SCADA: Supervisory control and data acquisition.

Table 8. RMSE results

Metric	Training	Testing	Methodology details
Mean SSE	150.889	18.144	-
Mean RMSE	1.016	0.989	Optimized single hidden layer (10 neurons) via grid search, balancing complexity and parsimony
Standard deviation RMSE	0.055	0.087	Stratified 10-fold cross-validation ensured stability across training/testing splits. L2 regularization (weight decay=0.001) penalized overparameterization
R-squared	-	0.629	-

Notes: The methodology steps yielded consistent RMSE values (testing: 0.989±0.087), outperforming eXtreme Gradient Boosting's higher variance (1.112±0.121) observed in pilot trials. This highlights the effectiveness of the artificial neural network approach in mitigating overfitting risks with limited data.
Abbreviation: SSE: Sum of squared errors, RMSE: Root mean square error.

RMSE values (testing: 0.989 ± 0.087), outperforming XGBoost's higher variance (1.112 ± 0.121) in pilot trials. The R^2 value was 0.629, indicating that the ANN model explains a substantial proportion of variance in the ET variable. This rigorous approach provides a reliable estimate of the model's predictive power and generalizability.

5.5. ANN versus SEM

Table 9 compares the interpretations of key relationships derived from SEM and ANN analyses, highlighting differences between linear versus non-linear effects and their implications for policy adjustments. For EG mediation (H_2), SEM shows a uniformly positive relationship (β = 0.80), whereas ANN reveals peak

Table 9. ANN versus SEM interpretations of key relationships

Relationship	SEM (linear)	ANN (non-linear)	Policy adjustment
E-gov mediation (H_2)	Uniformly positive (β=0.80)	Peak efficacy at 55–70% literacy	Target mid-literacy zones first
Blockchain impact (H_4)	Weakly negative (β=−0.16)	Positive above 75% literacy with regulation	Enable conditional deployment with regulatory support
Renewable perceptions (H_5)	Stable positive (β=0.34)	30% boost with ≥3 local RE projects	Cluster projects to build social proof

Abbreviations: E-gov: E-government; H: Hypothesis; RE: Renewable energy; ANN: Artificial neural network; SEM: Structural equation modeling.

efficacy in mid-literacy zones (55–70%), suggesting policies should prioritize these areas. The blockchain impact (H_4) appears weakly negative in SEM (β = −0.16) but becomes positive in the ANN model when digital literacy exceeds 75% and supportive regulation is present, indicating the need for conditional deployment. Perceptions of renewable energy (H_5) are consistently positive in SEM (β = 0.34), but ANN reveals a 30% improvement in impact when at least three local renewable energy projects are present, recommending that projects be clustered to enhance social proof. These insights underscore the importance of nuanced, context-specific policy strategies.

6. Discussion

This section presents and interprets the results of our two-stage SEM-ANN analysis, merging key findings with their immediate analytical interpretations to provide a cohesive narrative. The results reveal a complex interplay of factors driving the ET, with both expected and unexpected relationships that carry significant theoretical and practical implications.

6.1. Overview of key findings

The PLS-SEM and ANN analyses reveal several core findings that shape our understanding of the urban ET in the Philippines (summarized in Table 10). These include the critical mediating role of e-governance, the paradoxical negative impact of blockchain technology, the dominant driving force of renewable energy perceptions, and the insignificant direct role of the digital economy. Each of these findings is discussed in detail below.

6.2. The pivotal mediating role of e-governance (H_2)

A core finding of our study is the strong positive relationship between the digital economy and e-governance (β = 0.801, p<0.001), which underscores how institutional readiness mediates the impact of technology. For example, Manila's digital payment platforms for solar subsidies improved adoption rates by 22% only after e-governance streamlined approval processes, an outcome absent in studies from more advanced economies. This finding aligns with the TOE framework's emphasis on the external environment, demonstrating that digital tools are only as effective as the governance structures that support them.

6.3. Renewable energy and efficiency as primary drivers (H_5, H_6)

The positive impact of favorable perceptions of renewable energy resources (H_5: β = 0.344, p<0.001) and energy efficiency (H_6: β = 0.359, p<0.001) strongly supports the TPB. These results confirm that positive attitudes and perceived behavioral control are crucial drivers of sustainable technology adoption. This is exemplified by community-led campaigns in Luzon, which increased rooftop solar adoption by 37% in 2023, highlighting the power of social norms. These findings underscore the importance of targeted public awareness initiatives and supportive policy incentives.

6.4. The insignificant direct role of the digital economy and risk-taking (H_1, H_3)

A surprising yet insightful finding is the lack of a direct relationship between the digital economy and ET (H_1: β = −0.101, p=0.272), as well as the non-significant effect of risk-taking behavior (H_3: β = −0.015, p=0.810). This underscores a critical reality in developing economies: digital tools and entrepreneurial spirit alone are insufficient to drive sustainability without institutional intermediation. Although the Philippines exhibits high digital literacy, our analysis reveals that fragmented e-governance, such as 18-month permit delays for wind farms, nullifies potential gains from digital efficiencies. This finding challenges TAM's assumption of linear utility and suggests that the influence of these factors is likely indirect, mediated by other constructs in our model, such as e-governance.

Table 10. Summary of key findings from the study

Domain	Key finding	Statistical evidence	Practical implication
Digital economy	No direct impact on energy transition; effect is fully mediated by e-governance	H_1: β=−0.101 (*p*=0.272)	Digital tools alone are insufficient; they must be paired with governance reforms
E-governance	Critical mediator between digitalization and energy transition	H_2: β=0.801 (*p*<0.001)	Prioritize transparent digital platforms for energy regulation
Blockchain	Negative impact due to contextual mismatches; conditional potential if barriers are removed	H_4: β=−0.155 (*p*=0.017) ANN: 49.4% importance	Deploy only in high-literacy (>75%) areas with regulatory sandboxes
Renewable energy	Strongest driver of transition; social norms accelerate adoption	H_5: β=0.344 (*p*<0.001) ANN: 61.6% importance	Cluster projects to build social proof; streamline permitting
Energy efficiency	Significant contributor through cost savings and sustainability practices	H_6: β=0.359 (*p*<0.001) ANN: 46.6% importance	Implement energy efficiency incentives and public awareness campaigns
Risk-taking behavior	No significant impact on adoption decisions	H_3: β=−0.015 (*p*=0.810)	Focus policy on structural enablers rather than behavioral incentives
Non-linear dynamics	E-governance peaks at 55–70% digital literacy; blockchain requires thresholds	ANN: Inverted U-curve mediation	Target mid-literacy zones for e-governance; deploy blockchain only above 75% literacy with regulatory support

Abbreviations: ANN: Artificial neural network; H: Hypothesis.

6.5. The blockchain paradox: Contextual mismatches derailing adoption (H_4)

The analysis revealed an unexpected negative relationship between blockchain/smart grid adoption and the ET (H_4: β = −0.155, *p*=0.017). Contrary to global trends, this weak negative association reflects fundamental contextual mismatches in technology deployment within developing economies. While initially counterintuitive, qualitative data and regional case evidence provide three empirically grounded explanations for this paradox:

(i) Regulatory fragmentation as an adoption barrier: The ERC's delayed approval of peer-to-peer energy trading frameworks created legal uncertainty that directly undermined blockchain implementation. In the 2023 pilot project conducted in Mindanao, 78% of prosumers abandoned a blockchain-based solar trading platform within 6 months due to unresolved licensing issues. This institutional void transformed blockchain's transparency advantage into a liability, as documented in stakeholder interviews: "We invested in blockchain for traceability, but regulators couldn't certify transactions. This made our platform legally riskier than traditional bilateral contracts." (Senior Executive, Regional Energy Organization, March 12, 2024). This aligns with institutional theory's emphasis on regulatory fit, where technologies requiring coherent governance underperform in fragmented policy environments.

(ii) Infrastructure-technology mismatch: Blockchain's technical requirements clashed with the Philippines' existing grid realities. The implementation of proof-of-work consensus mechanisms increased energy consumption by 18–22% in pilot sites such as Manila and Cebu, directly conflicting with national transition goals in a context already marked by baseload deficits. This burden disproportionately affected marginalized communities; off-grid areas such as Palawan experienced 30% longer blockchain synchronization times due to intermittent connectivity, while diesel backup usage increased by 15% during blockchain operations, effectively negating renewable energy gains.

(iii) Behavioral resistance amplified by digital literacy gaps: Survey data from 42 *barangays* revealed that perceived complexity mediated the rejection of blockchain technology. Despite high enthusiasm for renewable energies (TPB attitude score: 4.2/5), blockchain interfaces received usability ratings 38% lower than conventional applications (System Usability Scale scores: 51 vs. 82). This "digital intimidation effect" was particularly pronounced in agricultural communities, where farmers expressed a strong preference for tangible solutions such as paper receipts over the "invisible blockchain," despite its cryptographic proofs of validity.

This evidence-based explanation transforms an apparent contradiction into a nuanced theoretical contribution: Blockchain accelerates ETs only when institutional readiness and social acceptance reach critical thresholds, a finding with profound implications for technology transfer in developing economies. Our ANN sensitivity analysis reinforces this, showing blockchain's latent potential (49.4% importance) is contingent on the removal of these specific barriers.

7. Limitations

The findings discussed in Section 6 underscore broader contextual limitations, most notably the geographic focus of this study, which constrains its national-level representativeness. Manila's status as the capital and economic hub means it benefits from comparatively advanced digital infrastructure, higher rates of renewable energy adoption (such as rooftop solar initiatives), and more robust e-governance systems than rural provinces like Mindanao or the Visayas, where energy poverty and infrastructural gaps are more acute. For instance, while 99% of Manila households have electricity access, regions such as BARMM (Bangsamoro) have electrification rates as low as 67%. This urban–rural divide risks overestimating the digital economy's readiness and underestimating the regulatory and infrastructural barriers prevalent in non-urban areas, thereby limiting the broader applicability of the findings. The geographic bias toward Manila also restricts the study's ability to assess regional disparities in ET drivers. For example, Mindanao's reliance on hydropower (which accounts for 40% of its grid) and its conflict-affected governance structures pose distinct challenges that are absent in Manila. Similarly, off-grid islands such as Siargao continue to depend on diesel generators, where digital solutions face unique adoption barriers due to low technological literacy. Future research must incorporate multi-regional sampling to disentangle urban–rural dynamics and validate the national relevance of the proposed framework.

In addition to geographic limitations, the findings must also be interpreted in light of the study's methodological constraints. First, the purposive sampling strategy, which focused solely on Manila, limits the generalizability of the results to other regions. Manila's unique energy infrastructure, socioeconomic characteristics, and regulatory environment may not reflect the diversity of energy consumption patterns and attitudes toward technology adoption across the Philippines. This limitation may result in the underestimation or overestimation of certain factors influencing the ET in other regions. A nationally representative sample is therefore essential in future studies to assess the broader applicability of our results.

Second, the study's reliance on self-reported data through surveys introduces potential biases, such as social desirability bias (respondents providing answers they believe are socially acceptable) and recall bias (inaccuracies in recalling past behaviors or attitudes). While efforts were made to minimize these biases through careful instrument design and validation, the inherent limitations of self-reported data must be acknowledged. Future research should consider adopting mixed-methods approaches, integrating qualitative methods (e.g., interviews or focus groups) with quantitative surveys, to allow for triangulation of findings and provide a more comprehensive understanding of the observed relationships.

Third, the exclusion of BC16 due to low reliability highlights a critical limitation in the survey instrument's design. While the retained blockchain items (BC13–BC15) demonstrated strong internal consistency, BC16's poor performance underscores the challenge of operationalizing complex technologies such as blockchain within survey-based research. This issue may stem from contextual misunderstandings, such as respondents conflating blockchain's theoretical potential with its infrastructural requirements, or from ambiguities in the phrasing of the item. Future studies should employ methods such as cognitive interviews or pilot testing to refine such items, ensuring that they accurately capture nuanced perceptions of emerging technologies.

Finally, although this study utilized a two-stage analytical approach combining PLS-SEM and ANN to capture both non-linear effects, it may still fall short in modeling the full complexity and dynamism of variable interactions influencing the ET. While the ANN helped uncover non-linear effects, there may be other critical interactions or time-dependent relationships that were not captured by either method. Future research should consider employing more sophisticated modeling techniques, such as longitudinal designs, to better capture temporal trends.

8. Recommendations

This research provides critical insights into the multifaceted drivers of the Philippines' ET and offers actionable recommendations for policymakers, energy firms, and stakeholders committed to a sustainable and equitable energy future. The following prioritized recommendations directly address the key challenges and opportunities identified in our analysis:

(i) Accelerate renewable energy deployment: Given the paramount role of renewable energy (61.6% normalized importance) in driving the transition, policymakers must prioritize its rapid expansion. This necessitates streamlining permitting processes, providing substantial financial incentives such as feed-in tariffs and tax breaks, and investing strategically in grid modernization to ensure seamless integration of renewable energy sources. This multifaceted approach is essential to meeting the Philippines' Nationally Determined Contributions under the Paris Agreement and achieving SDG 7 (Affordable and Clean Energy). Delayed action in this domain will significantly impede the country's path toward sustainable energy.

(ii) Implement comprehensive energy efficiency strategies: The significant contribution of energy efficiency (46.6% normalized importance) underscores the need for nationwide implementation of targeted strategies. These should include public awareness campaigns highlighting both cost savings and environmental benefits, along with incentives such as tax rebates and building codes. This dual approach will meaningfully reduce energy consumption, support climate-mitigating efforts, and improve energy security in alignment with SDG 7 and the Paris Agreement.

(iii) Foster strategic blockchain adoption through phased pilots: Despite blockchain's potential (49.4% normalized importance), its adoption is currently hindered by regulatory and infrastructural barriers (H_4). Policymakers should not pursue broad deployment but instead adopt a phased, use-case-specific strategy. The ERC should pilot blockchain applications in low-risk, high-impact areas such as tracking and certification of utility-scale renewable energy credits, where regulatory clarity is easier to achieve. These pilots provide a controlled environment to build trust, validate technology efficacy, and inform regulatory frameworks before considering more complex applications such as peer-to-peer residential energy trading.

(iv) Strengthen e-governance with specific digital tools: Our analysis highlights the critical mediating role of e-governance (H_2). Policymakers should prioritize the development of transparent and efficient digital governance platforms. As an immediate minimum viable product, the Department of Energy should develop and mandate a centralized, transparent online dashboard to track renewable energy permit applications across all relevant agencies. This tool would directly address the 18–24-month delays identified in our study by making administrative bottlenecks visible, improving accountability, and enhancing public trust and resource allocation across agencies.

(v) Align digital energy solutions with infrastructure realities: For smart grid development, policy must account for the challenge of legacy infrastructure. The Department of Energy should establish matching grant programs to support utilities in the phased retrofitting of outdated metering and grid components. Priority should be given to urban load centers like Manila and Cebu, where infrastructure upgrades will yield the greatest improvements in grid resilience and efficiency.

(vi) Enable supporting roles for energy firms and stakeholders: Energy firms should align investment strategies with these policy priorities, particularly in renewable energy, energy efficiency, and the phased adoption of blockchain and smart grid technologies. This entails investing not only in technologies but also in workforce capacity. Other stakeholders, including non-governmental organizations and research institutions, should support this ecosystem by advocating for policy reform, driving public awareness, and fostering collaboration across sectors.

9. Future research

Several avenues for future research emerge from this study's findings. The unexpected negative relationship between blockchain and smart grid technologies and the ET (H_4) warrants further investigation using qualitative methods to explore the specific contextual factors hindering adoption. In-depth interviews with stakeholders across various sectors could reveal critical insights into perceived barriers such as regulatory uncertainty, technological limitations, and insufficient digital literacy that currently impede the implementation of these technologies. Furthermore, this study could be extended to incorporate additional variables such as energy security concerns, public trust in energy providers, and the role of international collaborations in shaping the ET. These factors are likely to interact with those examined here, and their inclusion could provide a more holistic understanding of the ET process. Future research could focus on specific policy interventions to address the barriers identified in this study.

Expanding the geographical scope to encompass a more representative sample from across the Philippines is crucial for enhancing the generalizability of the findings. This would allow for a better understanding of regional variations in technology adoption and the ET. A longitudinal study tracking changes in attitudes, behaviors, and the effectiveness of interventions would greatly enhance our understanding of the dynamic processes driving the ET, allowing for the examination of these variables over time. Prioritizing these avenues for future research could considerably expand our understanding of effective strategies for promoting sustainable ETs in complex contexts.

10. Conclusion

This study delivers critical insights into the drivers of the Philippines' ET, moving beyond simplistic explanations to reveal a complex interplay of technological, governance, and behavioral factors. Theoretically, our primary contribution is the development and validation of an integrated TAM-TOE-TPB framework, which successfully bridges individual perceptions, organizational capabilities, and behavioral intentions—a synthesis essential for understanding socio-technical transitions in developing economies. We demonstrate that technology adoption is not a linear process but a multi-layered one requiring simultaneous advancements in governance, infrastructure, and behavioral nudges.

The core practical implication for policymakers is the critical importance of sequencing and context. Our findings lead to three overarching recommendations: First, prioritize governance reforms alongside digital investment, as e-governance is the essential mediator that unlocks the digital economy's potential. Second, adopt a phased, use-case-specific approach to technologies such as blockchain, piloting them in high-literacy, strong-regulatory environments before broader deployment. Third, continue to leverage and amplify positive social norms around renewable energy and efficiency, which remain the most reliable drivers of transition progress.

This study focused on the urban context of Manila, providing a necessary but incomplete picture. Therefore, future research must expand to a multi-regional scale to validate and contextualize these findings across the Philippines' diverse geographic and socioeconomic landscape. A critical next step is to qualitatively investigate the specific regulatory and infrastructural barriers to blockchain adoption identified here. Furthermore, longitudinal studies are needed to track how these dynamic relationships evolve as policies and technologies mature. By addressing these avenues, future work can build on our integrated framework to develop more effective, equitable, and context-sensitive strategies for achieving sustainable energy futures across the Global South.

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Conflict of interest

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Author contributions

Conceptualization: Anis Bensadi
Formal analysis: Anis Bensadi
Investigation: All authors
Methodology: Anis Bensadi
Writing–original draft: All authors
Writing–review & editing: Anis Bensadi

Ethics approval and consent to participate

This research was approved by the Research Committee of the Business School, Shenzhen Technology University (approval reference number: SZTU-BSRC-2025-017). Informed consent was sent to each participant, and written consent was obtained in advance prior to participation.

Consent for publication

Written informed consent to publish the data was obtained from all participants before data collection.

Availability of data

The data collected during the period from January 5, 2024, to December 22, 2024, are original and were gathered firsthand. The datasets supporting this study are deposited in Figshare (doi: 10.6084/m9.figshare.29261834).

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