Analysis of the Impact of Renewable Energy Development, Supporting Infrastructure, and Policy Support on the Sustainability of Rural Areas in Papua

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ABSTRACT

This study aims to analyze the impact of renewable energy development, supporting infrastructure, and policy support on the sustainability of rural areas in Papua. A quantitative approach was applied using survey data collected from 140 respondents through structured questionnaires measured on a five-point Likert scale. Data analysis was conducted using Structural Equation Modeling–Partial Least Squares (SEM-PLS 3) to evaluate the measurement model and structural relationships among variables. The results indicate that renewable energy development and supporting infrastructure have a positive and significant influence on rural sustainability, highlighting the importance of energy access and infrastructure readiness in improving socio-economic and environmental conditions in rural communities. Supporting infrastructure emerges as the strongest predictor, suggesting that connectivity and operational support systems play a crucial role in ensuring long-term development outcomes. Meanwhile, policy support shows a positive but statistically insignificant effect, indicating that existing policies may require stronger implementation and alignment with local needs. The model demonstrates adequate validity, reliability, and predictive relevance, confirming its robustness in explaining sustainability outcomes. This study contributes to sustainable rural development literature by integrating technological, structural, and institutional perspectives, and provides practical implications for policymakers and stakeholders in designing more effective strategies to strengthen rural resilience and sustainability in Papua.

Keywords: Renewable Energy Development, Supporting Infrastructure, Policy Support, Rural Sustainability, Papua

1. INTRODUCTION

Rural sustainability has become a critical issue in many developing regions, particularly in geographically dispersed and resource-rich areas such as Papua. Rural communities often face structural challenges including limited access to reliable energy, inadequate infrastructure, and uneven policy implementation [1], [2], which collectively hinder long-term socio-economic development. In recent years, renewable energy development has been increasingly promoted as a strategic solution to address energy inequality while supporting environmental sustainability [3]. The transition toward renewable energy is not only viewed as an environmental initiative but also as an instrument for improving rural welfare, enhancing productivity, and strengthening community resilience [4], [5].

Papua possesses significant renewable energy potential, including solar, micro-hydro, and biomass resources, yet many rural areas continue to experience energy shortages and infrastructure gaps [6]. These conditions affect economic activities, public services, and social development, thereby limiting the overall sustainability of rural communities. The integration of renewable energy systems in rural areas is expected to reduce dependence on fossil fuels, lower operational costs, and improve access to essential services such as education, healthcare, and digital communication [7], [8]. However, renewable energy initiatives cannot operate effectively without adequate supporting infrastructure and consistent policy support from government institutions.

Supporting infrastructure plays a crucial role in ensuring the effectiveness of renewable energy programs. Infrastructure such as transportation networks, communication systems, maintenance facilities, and technical support services determines whether renewable energy projects can operate sustainably in remote locations [6], [9]. Without sufficient infrastructure, energy projects may face logistical challenges, increased operational risks, and reduced long-term impact. Therefore, the development of infrastructure is often considered a complementary factor that amplifies the benefits of renewable energy initiatives in rural development contexts.

In addition to physical infrastructure, policy support is another essential factor influencing rural sustainability outcomes. Government policies related to energy subsidies, regulatory frameworks, investment incentives, and community empowerment programs shape the success of renewable energy implementation. Effective policy support can encourage stakeholder collaboration, increase investment confidence, and ensure that development programs align with local socio-cultural conditions. Nevertheless, the effectiveness of policy interventions in rural Papua remains a subject of debate, as implementation challenges, administrative limitations, and regional disparities may reduce the impact of existing regulations.

Despite increasing attention to renewable energy and rural sustainability, empirical studies that simultaneously examine renewable energy development, supporting infrastructure, and policy support in Papua remain limited, as prior research tends to focus on single dimensions of sustainability. Therefore, this study aims to analyze the influence of these three factors on rural sustainability using a quantitative approach with SEM-PLS to evaluate the relationships among variables. The results are expected to provide a more holistic understanding of sustainable rural transformation while offering practical insights for policymakers and stakeholders in designing effective and inclusive development strategies.

2. LITERATURE REVIEW

2.1 Rural Sustainability

Rural sustainability refers to the ability of rural communities to maintain long-term economic viability, environmental balance, and social well-being while adapting to changing external conditions, emphasizing inclusive growth, access to basic services, environmental protection, and community empowerment [10], [11]. In remote regions such as Papua, sustainability is closely related to the availability of energy, infrastructure, and institutional support that enhance productivity and quality of life, integrating economic resilience, ecological preservation, and social equity into a comprehensive development framework. From a theoretical perspective, sustainable development highlights the integration of technological innovation, governance structures, and community participation, indicating that sustainability is not determined solely by natural resources but also by effective development interventions [3], [12]. Therefore, analyzing rural sustainability requires considering both physical development factors, such as renewable energy and infrastructure, and institutional aspects, including policy support, to better understand long-term development outcomes.

2.2 Renewable Energy Development

Renewable energy development has gained global attention as a key driver of sustainable development, particularly in rural and remote areas where access to conventional energy remains limited. Renewable sources such as solar, hydro, and biomass offer environmentally friendly alternatives that reduce carbon emissions while promoting energy independence and improving living standards through enhanced access to education, healthcare, and local economic opportunities [13]–[15]. The diffusion of renewable energy technologies, explained through innovation adoption and sustainable development theories, highlights that technological advancements can stimulate socio-economic transformation when supported by appropriate institutional frameworks [16], [17]. Therefore, renewable energy development is expected to contribute positively to rural sustainability by increasing energy access, lowering operational costs, and creating new economic opportunities, leading to the formulation of the following hypothesis.

H1: Renewable energy development has a positive effect on the sustainability of rural areas in Papua.

2.3 Supporting Infrastructure

Supporting infrastructure refers to the physical and technical systems that enable the implementation and sustainability of development initiatives, including transportation networks, communication systems, energy distribution facilities, and technical support services [18], [19]. Infrastructure plays a vital role in improving connectivity, reducing logistical constraints, and ensuring the long-term effectiveness of renewable energy projects in remote areas, as inadequate infrastructure can limit accessibility and hinder operational success. From the perspective of the resource-based view and regional development theories, infrastructure functions as a foundational resource that strengthens economic activities and social progress [10]. In rural Papua, infrastructure development is essential for connecting isolated communities to wider economic systems and maximizing the benefits of renewable energy programs, as previous studies have shown that improved infrastructure enhances mobility, productivity, and access to markets and essential services, leading to the formulation of the following hypothesis.

H2: Supporting infrastructure has a positive effect on the sustainability of rural areas in Papua.

2.4 Policy Support

Policy support encompasses government regulations, incentives, institutional frameworks, and development programs that facilitate the implementation of renewable energy and rural development initiatives [20], [21], encouraging investment, promoting innovation, and ensuring equitable access to resources while aligning national agendas with local needs, particularly in regions with unique geographical and socio-cultural characteristics such as Papua. From an institutional theory perspective, supportive governance structures can enhance development outcomes through clear regulations, financial assistance, and coordinated stakeholder collaboration; however, their effectiveness depends on implementation quality, administrative capacity, and community engagement. When policies are not adapted to local contexts, their impact may become limited, yet strong and well-executed policy frameworks are generally

expected to strengthen sustainability by creating a conducive environment for development initiatives [22], [23], leading to the formulation of the following hypothesis.

H3: Policy support has a positive effect on the sustainability of rural areas in Papua.

2.5 Conceptual Framework

Based on the theoretical background and previous empirical studies, this research proposes a conceptual model that examines the relationships between renewable energy development, supporting infrastructure, policy support, and rural sustainability, where the three first variables act as exogenous factors influencing rural sustainability as the endogenous variable. The model assumes that improvements in energy access, infrastructure quality, and institutional support collectively contribute to sustainable rural development outcomes. By integrating these variables, the framework provides a comprehensive approach to analyzing rural sustainability in Papua, enabling the evaluation of technological, structural, and institutional influences while offering empirical insights into how different development components interact to shape long-term sustainability in rural communities.
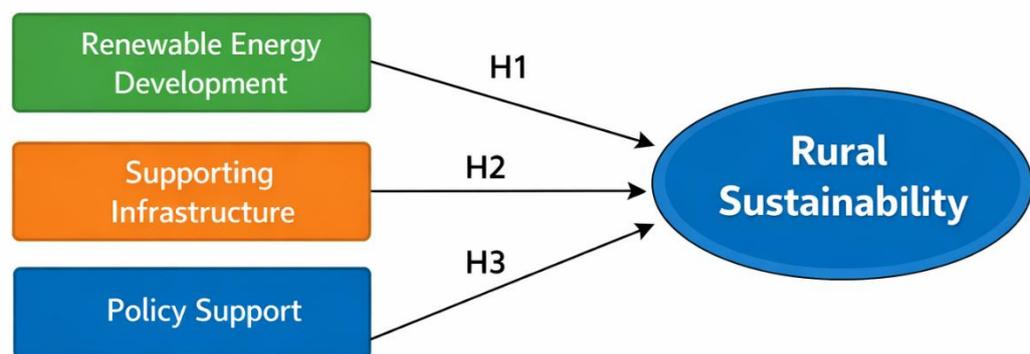

Figure 1. Conceptual Framework

3. METHODS

3.1 Research Design

This study employs a quantitative research approach to examine the relationships between renewable energy development, supporting infrastructure, policy support, and the sustainability of rural areas in Papua. A cross-sectional survey design was used to collect primary data from respondents at a single point in time. Quantitative methods were selected because they enable the measurement of latent constructs and the testing of causal relationships among variables using statistical modeling techniques. The research model was developed based on theoretical frameworks related to sustainable development and rural transformation.

3.2 Population and Sample

The population of this study consists of individuals living in rural areas of Papua who are directly or indirectly affected by renewable energy development and infrastructure programs, including community members, local stakeholders, and individuals familiar with rural development initiatives. A total of 140 respondents were selected using a purposive sampling technique to ensure that participants possess relevant knowledge and experience related to rural sustainability and development programs. This sample size meets the minimum requirements for Structural Equation

Modeling–Partial Least Squares (SEM-PLS) analysis [24], which is appropriate for studies with relatively small to moderate samples and complex models involving multiple constructs.

3.3 Data Collection Technique

Data were collected using a structured questionnaire designed to measure respondents' perceptions of renewable energy development, supporting infrastructure, policy support, and rural sustainability outcomes, with all items assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The instrument was developed based on indicators derived from relevant literature and adapted to the context of rural areas in Papua. Before analysis, all responses were screened to ensure completeness and consistency, and only valid and fully completed questionnaires were included in the final dataset.

3.4 Measurement of Variables

This study involves four main constructs, namely Renewable Energy Development (RED), Supporting Infrastructure (SIF), Policy Support (PSU), and Rural Sustainability (TSU). Renewable Energy Development reflects the extent to which renewable energy initiatives are implemented and perceived to improve rural living conditions through accessibility, reliability, and program benefits. Supporting Infrastructure refers to the availability and adequacy of physical and technical facilities such as transportation access, communication networks, and operational support systems. Policy Support measures the level of government involvement through regulations, incentives, and institutional programs that facilitate rural development and renewable energy implementation. Meanwhile, Rural Sustainability represents the overall perception of long-term economic, social, and environmental outcomes within rural communities. Each construct was measured using multiple indicators, and their validity and reliability were evaluated through measurement model analysis.

3.5 Data Analysis Technique

Data analysis was conducted using Structural Equation Modeling–Partial Least Squares (SEM-PLS 3), which involves two main stages: evaluation of the measurement model (outer model) and evaluation of the structural model (inner model) [24]. The measurement model assessment includes tests of convergent validity, discriminant validity, and reliability, where convergent validity is evaluated through factor loadings and Average Variance Extracted (AVE), while reliability is assessed using Cronbach's Alpha and Composite Reliability. The structural model evaluation examines the relationships among latent variables by analyzing path coefficients, R-square values, predictive relevance (Q^2), and hypothesis testing through bootstrapping procedures, along with model fit indices such as SRMR and NFI to determine model adequacy. The SEM-PLS approach was selected because it is suitable for exploratory and predictive research, capable of handling complex models, and does not require strict data normality assumptions, allowing this study to provide empirical evidence on the influence of renewable energy development, supporting infrastructure, and policy support on rural sustainability in Papua.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics

This study involved 140 respondents from rural areas in Papua, and their demographic characteristics were analyzed to ensure adequate representation of individuals familiar with rural development conditions, including gender, age, education level, and occupation.

Table 1. Demographic Characteristics of Respondents

Demographic Variable	Category	Frequency	Percentage (%)
Gender	Male	82	58.6

	Female	58	41.4
Age	18–25 years	28	20.0
	26–35 years	46	32.9
	36–45 years	39	27.9
	>45 years	27	19.2
Education Level	High School	52	37.1
	Diploma	26	18.6
	Bachelor Degree	49	35.0
	Postgraduate	13	9.3
Occupation	Farmer/Fisherman	34	24.3
	Local Entrepreneur	29	20.7
	Government/NGO Staff	41	29.3
	Community Member/Other	36	25.7

Based on Table 1, the demographic profile of respondents shows that the majority are male (58.6%), while female respondents account for 41.4%, indicating relatively balanced participation. In terms of age, most respondents fall within the productive age range of 26–35 years (32.9%), followed by 36–45 years (27.9%), suggesting that the data largely reflect perspectives from active community members involved in development activities. The education level is dominated by high school graduates (37.1%) and bachelor degree holders (35.0%), showing that respondents generally possess sufficient educational background to understand issues related to rural sustainability. Regarding occupation, government or NGO staff represent the largest group (29.3%), followed by farmer/fisherman (24.3%), community members (25.7%), and local entrepreneurs (20.7%), indicating that the sample includes diverse stakeholders with varying roles in rural development and renewable energy initiatives.

Descriptive statistical analysis was conducted to examine respondents' perceptions of renewable energy development, supporting infrastructure, policy support, and rural sustainability, using minimum values, maximum values, mean scores, and standard deviations.

Table 2. Descriptive Statistics of Research Variables

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Renewable Energy Development (RED)	140	2.10	5.00	4.12	0.63
Supporting Infrastructure (SIF)	140	2.25	5.00	4.05	0.68
Policy Support (PSU)	140	1.90	5.00	3.74	0.72
Rural Sustainability (TSU)	140	2.30	5.00	4.18	0.59

The descriptive results indicate that respondents generally perceive renewable energy development and rural sustainability positively, reflected in mean values above 4.00, while supporting infrastructure also receives a relatively high evaluation, suggesting noticeable improvements within the study area. In contrast, policy support shows a slightly lower mean score (3.74), indicating that its implementation is perceived as moderate and less effective compared to technological and infrastructure development. The standard deviation values ranging from 0.59 to 0.72 demonstrate relatively consistent responses, overall suggesting that renewable energy and infrastructure initiatives are viewed favorably by rural communities, whereas policy support may still require stronger implementation to enhance sustainability outcomes.

4.2 Measurement Model

The measurement model evaluation was conducted to assess construct reliability and validity through convergent validity, internal consistency reliability, and discriminant validity, using loading factors and Average Variance Extracted (AVE) for validity, and Cronbach's Alpha and Composite Reliability for reliability testing.

Table 3. Measurement Model

Variable	Code	Loading Factor	Cronbach's Alpha	Composite Reliability	Average Variant Extracted
Renewable Energy Development	RED.1	0.853	0.912	0.938	0.791
	RED.2	0.933			
	RED.3	0.897			
	RED.4	0.872			
Supporting Infrastructure	SIF.1	0.874	0.856	0.912	0.776
	SIF.2	0.871			
	SIF.3	0.899			
Policy Support	PSU.1	0.862	0.848	0.908	0.767
	PSU.2	0.908			
	PSU.3	0.856			
the Sustainability	TSU.1	0.869	0.895	0.927	0.761
	TSU.2	0.867			
	TSU.3	0.886			
	TSU.4	0.867			

Source: Data Processing Results (2026)

The results in Table 3 show that all indicator loading factors exceed the recommended threshold of 0.70, indicating strong relationships between indicators and their latent constructs, with Renewable Energy Development ranging from 0.853–0.933, Supporting Infrastructure from 0.871–0.899, Policy Support from 0.856–0.908, and Sustainability from 0.867–0.886, confirming good convergent validity. In terms of reliability, all constructs demonstrate Cronbach's Alpha values above 0.80 and Composite Reliability above 0.90, while AVE values exceed 0.50, indicating strong internal consistency and that each construct explains more than half of the variance of its indicators, thus confirming that the measurement model meets the required validity and reliability criteria.

4.3 Discriminant Validity

Discriminant validity was evaluated using the Fornell–Larcker criterion, which compares the square root of AVE values with inter-construct correlations.

Table 4. Discriminant Validity

	PSU	RED	SIF	TSU
Policy Support	0.876			
Renewable Energy Development	0.785	0.890		
Supporting Infrastructure	0.813	0.739	0.881	
the Sustainability	0.692	0.685	0.723	0.872

Source: Data Processing Results (2026)

Based on Table 4, the discriminant validity results indicate that each construct has adequate conceptual distinction, as shown by the diagonal values (square root of AVE) being higher than the correlations with other variables. Policy Support has a value of 0.876, Renewable Energy Development 0.890, Supporting Infrastructure 0.881, and Sustainability 0.872, all exceeding their inter-construct correlations. Although some correlations among variables are relatively high, such as between Policy Support and Supporting Infrastructure (0.813), they remain below the respective diagonal values, confirming that each construct measures a different concept. Overall, these findings demonstrate that the model meets the Fornell–Larcker criterion and possesses satisfactory discriminant validity.

The overall measurement and structural relationships among variables are illustrated in Figure 2 (Model Results), which presents the SEM-PLS path model used in this research. The figure shows the relationships between Renewable Energy Development, Supporting Infrastructure, Policy Support, and Rural Sustainability, including indicator loadings and path coefficients.
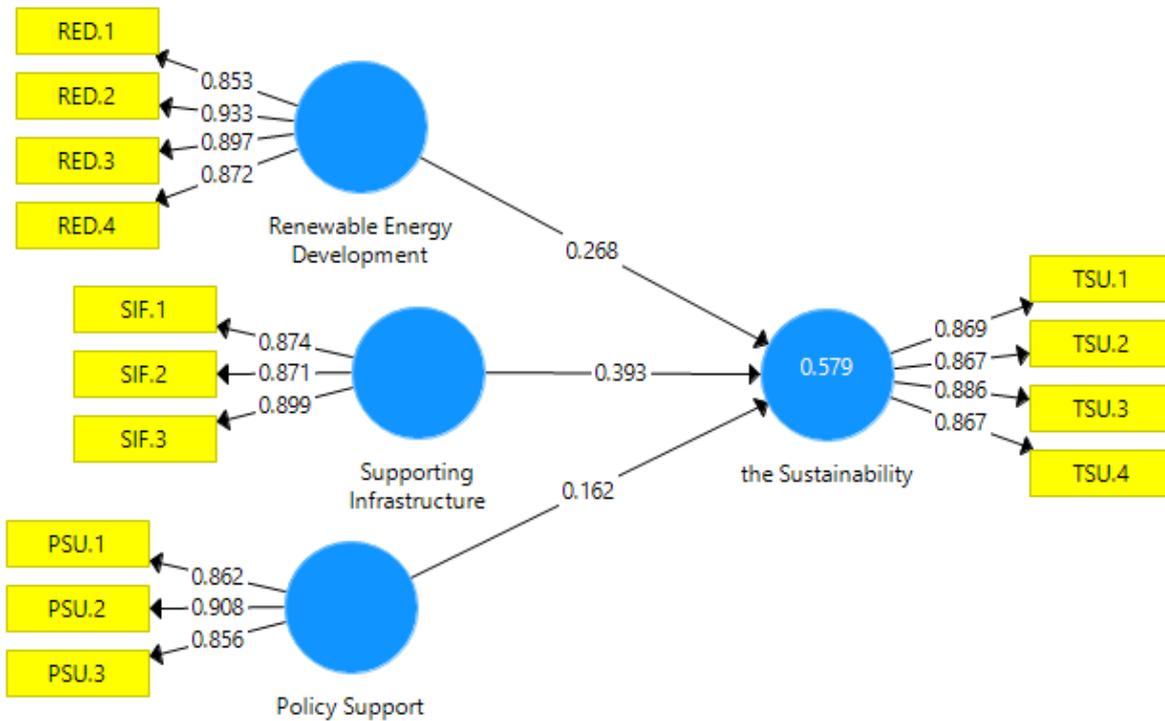

Figure 2. Model Results
Source: Data Processed by Researchers, 2026

Based on the results above, it can be concluded that all constructs meet the criteria for convergent validity, discriminant validity, and reliability. Therefore, the model is suitable for further analysis in the structural model evaluation stage.

4.4 Structural Model (Inner Model Evaluation)
The structural model evaluation was conducted to analyze the relationships between renewable energy development, supporting infrastructure, policy support, and rural sustainability by assessing model fit, predictive capability, and hypothesis testing using SEM-PLS, including model fit indices, R^2, Q^2, and bootstrapping path coefficients.

4.4.1 Model Fit Evaluation
Model fit evaluation aims to determine whether the proposed model adequately represents the empirical data. The results of the model fit test are presented in Table 3.

Table 3. Model Fit Results Test

	Saturated Model	Estimated Model
SRMR	0.059	0.059
d_ULS	0.366	0.366
d_G	0.287	0.287
Chi-Square	198.705	198.705
NFI	0.857	0.857

Source: Process Data Analysis (2026)

The Standardized Root Mean Square Residual (SRMR) value of 0.059 indicates a good model fit because it is below the recommended threshold of 0.08. The Normed Fit Index (NFI) value of 0.857 reflects an acceptable level of model adequacy, suggesting that the structural model sufficiently explains the observed relationships among variables. Meanwhile, the d_ULS and d_G values also indicate that the discrepancy between the empirical data and the proposed model is within acceptable limits. Overall, these results confirm that the model demonstrates satisfactory goodness-of-fit.

4.4.2 Coefficient of Determination and Predictive Relevance

The coefficient of determination (R^2) measures the proportion of variance in the endogenous variable explained by the exogenous variables. In addition, predictive relevance (Q^2) assesses the model's ability to predict observed data.

Table 4. Coefficient Model

	R Square	Q2
the Sustainability	0.579	0.568

Source: Data Processing Results (2026)

The R^2 value of 0.579 indicates that renewable energy development, supporting infrastructure, and policy support collectively explain 57.9% of the variance in rural sustainability. This level of explanatory power can be categorized as moderate to substantial, suggesting that the selected variables play an important role in determining sustainability outcomes in rural Papua. Furthermore, the Q^2 value of 0.568 demonstrates strong predictive relevance, indicating that the model has good predictive capability in explaining sustainability performance.

4.4.3 Hypothesis Testing

Hypothesis testing was performed using bootstrapping analysis in SEM-PLS to evaluate the significance of path coefficients. The results are presented in Table 5.

Table 5. Hypothesis Testing

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics	P Values
Policy Support-> the Sustainability	0.162	0.154	0.115	1.406	0.160
Renewable Energy Development-> the Sustainability	0.268	0.270	0.100	2.664	0.000
Supporting Infrastructure-> the Sustainability	0.393	0.398	0.102	3.858	0.000

Source: Process Data Analysis (2026)

The results indicate that renewable energy development has a positive and significant effect on rural sustainability (β = 0.268; t = 2.664; p < 0.05), while supporting infrastructure shows the strongest positive and significant influence (β = 0.393; t = 3.858; p < 0.05), highlighting the critical role of infrastructure in enabling sustainable rural transformation. In contrast, policy support demonstrates a positive but statistically insignificant effect (β = 0.162; t = 1.406; p > 0.05), suggesting that existing policies may not yet produce tangible impacts at the community level due to implementation challenges or contextual limitations.

Discussion

The results of this study provide important insights into the factors influencing the sustainability of rural areas in Papua. The findings reveal that renewable energy development and supporting infrastructure significantly contribute to rural sustainability, while policy support shows a positive but statistically insignificant effect. These outcomes illustrate the complex interaction between technological, structural, and institutional dimensions in shaping sustainable development, particularly in remote regions with unique geographic and socio-economic characteristics [22].

The significant positive relationship between renewable energy development and rural sustainability confirms the role of renewable energy as a key driver of socio-economic transformation in rural communities. Access to renewable energy sources such as solar and micro-hydro systems enhances electricity availability, reduces dependence on fossil fuels, and creates opportunities for local economic activities. Improved energy access also enables communities to adopt digital technologies and improve services in education and healthcare, supporting the broader objectives of sustainable development through technological innovation [1], [2].

Supporting infrastructure emerges as the most influential factor affecting rural sustainability, indicating that infrastructure development functions as a fundamental enabler that strengthens renewable energy programs. Adequate transportation systems, communication networks, and maintenance facilities allow energy initiatives to operate effectively and reach wider communities. This finding suggests that sustainability is not only determined by energy availability but also by the supporting ecosystem that ensures development initiatives can operate consistently [7], particularly in geographically challenging areas like Papua.

In contrast, the insignificant effect of policy support highlights a gap between regulatory frameworks and practical outcomes in rural development. Although policies are designed to encourage renewable energy adoption and infrastructure expansion, their impact may be limited by implementation challenges, administrative constraints, or misalignment with local community needs. This indicates that policies require stronger execution, greater community involvement, and more adaptive strategies that consider local socio-cultural contexts to produce measurable sustainability outcomes.

Overall, the combined findings suggest that tangible development components such as renewable energy and infrastructure tend to generate more immediate impacts than institutional mechanisms alone. From a theoretical perspective, this study contributes to the literature by integrating technological, structural, and institutional variables into a unified empirical framework, reinforcing the multidimensional nature of sustainability. Practically, the results emphasize the need for policymakers and stakeholders to prioritize infrastructure investment alongside renewable energy expansion while strengthening policy implementation to foster a more resilient and sustainable rural development pathway in Papua.

CONCLUSION

This study concludes that renewable energy development and supporting infrastructure play significant roles in enhancing the sustainability of rural areas in Papua, where renewable energy improves energy access, economic activities, and environmental balance, while supporting infrastructure provides a critical foundation that enables development programs to operate effectively and reach wider communities, with infrastructure showing the strongest influence on sustainability outcomes. In contrast, policy support demonstrates a positive but statistically insignificant effect, indicating that existing regulatory frameworks may not yet produce tangible impacts at the community level and require more adaptive, locally oriented implementation strategies. Overall, sustainable rural development requires a balanced integration of technological advancement, infrastructure improvement, and effective governance, suggesting that future development efforts in Papua should prioritize infrastructure investment and renewable energy expansion alongside stronger policy execution to achieve long-term sustainability and community resilience.

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