Energy Diversification Policy Utilizing Smart Grid Hybrid Solar Power Plants to Meet Electricity Needs in Small Island Areas

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Abstract: ***This article investigates the policy and operational dynamics of deploying Smart Grid Hybrid Solar Power Plants on Semau Island, Indonesia. Using an exploratory qualitative method, the research identifies a critical disconnect between high-end technological installations and the local community's technical readiness. The findings expose a 95.12% public information gap and ongoing dysfunction in the digital control system, undermining the smart grid's automation capabilities. Despite these issues, 74% of the local population supports clean energy, with 40% of farmers transforming electricity access into productive agricultural output. The study introduces the IMEDSI Model, which argues that policy centrality, rather than technical innovation alone, drives successful energy transitions in isolated geographies. It recommends adaptive regulatory frameworks, knowledge transfer mechanisms, and decentralized governance as keys to ensuring sustainable energy access.***

Keywords: energy policy implementation, smart grid solar power, small islands, electricity fulfilment, IMEDSI Model

1. Introduction

Small island regions face absolute geographical barriers that lead to isolation and limitations of energy infrastructure. This condition creates a high dependence on fossil fuels such as oil and diesel, which are expensive and polluting. Fluctuations in global energy prices and supply vulnerabilities are a serious economic challenge for communities on small and remote islands. Complex logistics often lead to a shortage of primary fuels required by non-traditional energy systems [1].

Fossil fuels also produce greenhouse gas (GHG) emissions that significantly accelerate global climate change. On the other hand, the potential of solar energy in the small archipelago of Semau Island, Kupang Regency, East Nusa Tenggara Province, Indonesia, is abundant but has not been utilized optimally. Therefore, the energy transition is not just a technical option but a strategic need for regional independence.

The Government of Indonesia addresses this challenge through Presidential Regulation Number 112 of 2022 on the Acceleration of Renewable Energy Development. This policy sets an ambitious target to achieve Net Zero Emissions (NZE) by 2060 or sooner. One of the main strategies is the program to replace diesel generators with hybrid renewable systems, which replaces around 1,200 PLTD units with a hybrid system based on NRE [2].

The integration of Smart Grid Hybrid Solar Power Plants is designed to improve supply reliability while lowering plant operating costs, [3],[4]. Quantitatively, substituting fossil fuels with solar power plants on Semau Island can save around 540 liters of diesel per day. The resulting reduction in carbon emissions reached 17,548 tons of CO_2 per year, directly contributing to the national decarbonization target. The success of this transition depends heavily on the strength of the regulatory framework and consistent fiscal support.

The implementation of Smart Grid technology on Semau Island reveals a paradox between the system's sophistication and operational reality. It was found that system dysfunction occurs when the computer components controlling the smart grid are damaged, preventing automation from running. The information gap is also very critical, as 95.12% of the public does not understand the concept of smart technology. The lack of knowledge transfer to local engineers puts advanced infrastructure at risk of becoming an abandoned "passive asset". However, people have very strong moral support for clean energy (74%) due to environmental awareness. Electricity has become productive capital, with 40% of farmers using it for pump irrigation in onion orchards. It proves that meeting stable energy needs is an absolute prerequisite for improving real welfare.

The integration of Matland and Ostrom's theories in the Integrative Model of Energy Diversification in the Small Islands (IMEDSI) places Semau Island's policy implementation in the experimental quadrant, where the ambiguity of objectives is very high. However, the level of conflict among stakeholders is relatively low. In this situation, Ostrom's polycentric governance serves as an operational solution by distributing decision-making authority across various centers, from central and local governments to local communities, to prevent technical failures arising from reliance on central technicians. Through this synergy, IMEDSI emphasized that the success of the energy transition on small islands is not determined by technological sophistication alone, but by "Policy Centrality" that is able to synchronize the social capital of the community with adaptive technical regulations, [5]. This approach allows for iterative learning and systematic knowledge transfer so that advanced infrastructure does not become a non-operational asset in the event of technical operational disruptions, [6].

Although this model emphasizes local adaptation, theoretical debates have arisen from adherents of *the top-down* paradigm, such as Pressman and Wildavsky, who view implementation as a structured chain of steps from the center to ensure bureaucratic compliance and policy consistency, [7]. Lindblom, through the "*muddling through*" theory, warns that policymakers tend to act incrementally and make small decisions to avoid significant risks, which often hinder radical innovation in the adoption of renewable energy, [8]. Criticism also came from Sovacool, who highlighted that conservative energy policies that prioritize the status quo of fossil energy could slow down the green transition due to excessive concerns about high investment costs and the uncertainty of new technologies, [9]. However, the IMEDSI model seeks to fill this gap by adopting a hybrid Howlett approach that deliberately synchronizes national regulatory instruments with bottom-up economic initiatives at the village level.

Global empirical evidence suggests that the success of energy diversification policies in the Solomon Islands is achieved through a contingency approach that adapts standard technologies to local conditions and leverages innovative financing models, [10] . The Philippines has also achieved success through an experimental approach that involves citizens in the design and trial phases, significantly increasing public acceptance of clean energy by up to 40%. In contrast, failures occurred in the PERMER Program in Argentina because energy policies were not synchronized with other productive sector programs, such as agriculture, and in Mozambique, where the central government forced the procurement of solar street lights despite the community's fundamental need for household lighting, [11]. The case in Semau itself proves that without the integration of maintenance mechanisms and knowledge transfer to local technicians, advanced technologies such as *Smart Grid* are at risk of prolonged technical dysfunction due to unhandled breakdowns of control computer components.

Semau Island in Kupang Regency, East Nusa Tenggara Province (NTT), Indonesia, is a strategic location for the operation of Smart Grid Hybrid Solar Power Plants, designed to improve system reliability through the integration of Solar Power Plants and Diesel Power Plants (DPP). However, on-the-ground implementation shows that the availability of hardware and the use of Smart Grid technology do not automatically guarantee the sustainability and reliability of electricity supply without the support of an adaptive policy framework.

The gap between national policy drafts and local operational realities creates unique challenges in meeting people's energy needs. The focus of this research is to evaluate how the energy diversification policy can meet the electricity needs of the people in the small archipelago of Puau Semau, stably, despite limited supporting infrastructure. Energy development on remote islands should be seen as an instrument of expanding human capabilities through continuous access to basic services.

Limited access to logistics and expert technicians in the archipelago requires a management model that does not rely solely on physical assistance from the center, [12] . The central thesis of this research is that the success of electrification depends on the strength of formal policy structures that can synchronize the community's social capital with adaptive technical regulations. The presence of smart technology must be accompanied by systematic knowledge transfer so that it does not become a underutilized infrastructure when minor technical glitches occur. This transformation requires a paradigm shift from project-oriented management to long-term service-oriented management. Only through strong integration between policies, technology, and social contexts can energy independence in small island regions be achieved sustainably, [13].

2. Methods

This research uses an exploratory qualitative approach that focuses on the depth of the narrative and the field's context, [14]. Data was collected through in-depth interviews with four key actors: the community/customer, technical operators, education leaders, and village authorities. The sampling technique uses *purposive sampling* to ensure the representation of the entire spectrum of stakeholders in the energy ecosystem. Data analysis uses thematic techniques to identify patterns of convergence and divergence in the field's findings, [15]. The validity of the data is maintained through triangulation of sources and methods to verify the consistency of information from different perspectives. The researcher serves as the primary instrument for exploring people's life experiences related to the use of productive energy. Data collection was conducted from May to August 2025 on Semau Island to capture the season's dynamics and peak loads.

The process of data reduction involves iterative coding to organize long narratives into systematic units of analysis, [16]. The primary focus of the analysis is on the mechanisms for meeting electricity needs and the operational constraints faced by local operators. This approach allows researchers to uncover phenomena that are not captured by statistical figures, such as farmers' motives for investing in irrigation pumps. The research ethics procedure is carried out by ensuring *that informed consent is obtained* from all participants voluntarily. The technical documentation of solar power plant operations was also analyzed to validate the informant's claims regarding the frequency of system disruptions. With this method, a holistic picture of the challenges and opportunities for energy policy implementation in the archipelago is produced.

3. Results and Discussion

3.1 The Status of Electricity Needs and the Technological Paradox

The interview results revealed a critical phenomenon: the current Smart Grid system is dysfunctional due to damage to the control computer components. Although physical infrastructure is available, the lack of knowledge transfer hinders improvements due to geographical constraints. The community still welcomes electricity because it supports their children's daily activities and education. However, there are complaints about the quality of the voltage at night, which has the potential to damage household electronic equipment. The high electrification ratio (98.7%) does not guarantee optimal service quality in remote areas. A massive information gap was found, with 95.12% of the public not understanding the automation features of the installed hybrid system.

The dysfunction of *the Smart Grid* system at the Semau Solar Power Plant is caused by damage to the control computer components, reflecting a "*missing link*" between the physical development phase and long-term operational management. Although the physical infrastructure was fully available, the lack of technical knowledge transfer to the local operator led the system to lose its intelligent automation function and to revert to an inefficient manual mode of operation [17]. The archipelago's absolute geographical constraints complicate the system recovery process due to the very high dependence on experts from the center or from outside the island, which is difficult to access quickly, [18]. This phenomenon shows that advanced hardware alone does not ensure the sustainability of energy supply without the support of preventive maintenance standards tailored to the characteristics of remote areas. The lack of technical capacity at the local service unit level results in high-risk, high-tech investments becoming "passive assets" that are abandoned due to technical glitches in small digital components. Changing the management paradigm from project-oriented (development) to service-oriented (sustainable benefits) is an absolute prerequisite for maintaining the functionality of *this smart grid* technology. Therefore, this study emphasizes that the formalization of knowledge transfer must be a mandatory clause in every energy technology procurement contract for Semau Island, a small archipelago, to mitigate the risk of similar technical failures in the future.

In general, the people of Semau Island strongly support (74%) the provision of electricity because of its role as an enabling factor for daily activities and for the quality of children's education. Electricity provides stable lighting that allows children to learn at night and facilitates modern school administration through the use of laptops, printers, and LCD devices [19]. However, this positive reception was overshadowed by serious complaints about the unstable voltage at night and the potential to damage residents' household electronic equipment, [20]. This condition shows that a high Electrification Ratio (98.7%) does not necessarily guarantee optimal service quality in the field. These impressive electrification figures often mask reliability issues, as routine monthly outages continue due to technical glitches in the companion diesel-generating unit. The use of energy, which is still dominated by household consumptive needs (91.87%), also indicates that electricity has not been fully transformed into an equitable economic production capital in all villages. The community really expects an energy service that is not only "connected to the grid" but also reliable, stable, and able to support the economic productivity of dry land sustainably, [21], [22].

The discovery of a huge information gap, in which 95.12% of the public does not understand the automation features of the Smart Grid, places the implementation of this policy in the "Experimental Quadrant" of the Matland matrix. The high ambiguity of information at the grassroots level hinders the conversion of community moral support into active participation in maintaining the security and sustainability of these energy assets. Without an interactive communication strategy, these smart technologies will continue to be seen as alien and passive by local users, which, in turn, lowers a sense of community ownership. Polycentric governance is needed to involve various decision-making centers, including community committees, to monitor the physical infrastructure and detect disturbances early. Low technology literacy is a key predictor of long-term operational failure of new and renewable energy projects in isolated areas [23]. Synchronization between *top-down national targets and* bottom-up *local adaptation initiatives* is key to eliminating this critical information gap [24]. The findings of this study conclude that the success of the clean energy transition in the archipelago is determined more by "Policy Centrality" than by mere sophistication of physical technology, [25].

This condition puts policy implementation in the "Experimental Quadrant," where technical ambiguity is very high but social support remains strong. The solar power plant operator confirmed that technical failures originated primarily in diesel-based units, not from the solar panels themselves. The malfunction of these smart features forces the system back to less economically efficient manual operation, demonstrating that hardware sophistication will fail without structured maintenance management support.

The energy literacy gap is the primary predictor variable for low public active participation in asset supervision. Interactive education is needed to turn community moral support into preventive measures in maintaining network security. Without the synchronization of policy instruments, high-tech investments will continue to face the risk of becoming abandoned passive assets.

3.2 Productive Economic Transformation and IMEDSI Model Synthesis

The study's unique findings show that 40% of customers in South Semau have invested in electric irrigation pumps on their own. Electricity has transformed from a consumptive necessity to the main production capital for onion and watermelon farming. This phenomenon strengthens the Policy Centrality Thesis in the IMEDSI Model, where policy serves as a lever for welfare. The IMEDSI model brings together Matland's thinking about adaptation in experimental quadrants to navigate technological ambiguity.

The integration of Ostrom's theory offers a polycentric governance framework for engaging local communities in the long-term maintenance of assets. Michael Howlett's hybrid approach is used to synchronize national targets with *bottom-up economic initiatives* at the village level [26]. Hill and Hupe's views emphasize the importance of contextual adaptation so that policies do not mismatch the geographical characteristics of dry islands, [27].

This model proves that electricity fulfillment is not just about infrastructure, but about the sustainability of productive economic benefits. The increase in power status from 450 VA to 900 VA is a clear indicator of rising purchasing power driven by energy stability. Multi-actor collaboration is an absolute prerequisite to prevent the failure of technical facilities in the 3T region. IMEDSI offers a new framework that prioritizes strengthening regulatory structures over just the physical procurement of technology. With this model, the energy transition can run in harmony with inclusive improvements in the welfare of the archipelago's people.

4. Conclusion

The success of meeting electricity needs on small islands depends on the strength of an adaptive formal policy structure. Smart Grid technical dysfunction and low energy literacy pose significant risks that must be mitigated through systematic knowledge-transfer programs. This study recommends a regulatory transformation towards technocracy by requiring post-construction maintenance standards.

Local governments need to leverage community support to establish a community-based energy management committee. Tariff incentives for productive energy use must be formulated immediately to support the 40% of farmers who already use electricity for irrigation. Digitization of monitoring through *Smart Meters* is crucial to ensure targeted subsidies in the village's leading sectors.

The sustainability of the energy system depends on the center's ability to decentralize technical authority to local operators. The IMEDSI model has proven to be valid in explaining the dynamics of the energy transition in remote island regions.

Further research is needed to quantify the long-term impact of GHG emission reductions following system restoration. The transition to green energy is a moral obligation to preserve the ecosystem of small islands in Indonesia. Synergy between technology, policy, and social capital is the primary key to national energy independence.

5. Policy recommendations

Based on the findings regarding technological dysfunction and critical information gaps on Semau Island, this study formulates strategic policy recommendations for key stakeholders:

5.1 Recommendations for the Central Government

The central government, through the Ministry of Energy and Mineral Resources, needs to transform regulations from a physical procurement paradigm to a sustainable, technocratic operational management model. The expansion of regulatory scope, as in Presidential Regulation No. 112 of 2022, is required to include post-construction maintenance management standards for infrastructure in the 3T area to prevent assets from becoming passive. In addition, the central government must issue a mandate requiring that every high-tech procurement contract include formal training clauses for local technicians, thereby breaking the reliance on outside experts. The restructuring of the fiscal incentive scheme is also urgent to make renewable energy more competitive with fossil energy for the private sector in small islands.

5.2 Recommendations for Local Governments

Local governments must immediately mitigate information ambiguity through interactive socialization to overcome the energy literacy gap that reaches 95.12% at the grassroots level. High public support for smart grids (74%) should be leveraged to promote active participation by educating the public about their functional capabilities. In accordance with Ostrom's polycentric theory, local governments should facilitate the formation of community-based energy management committees that involve local figures in the physical oversight of infrastructure. In addition, it is necessary to synchronize energy planning with regional leading sectors, such as integrating electricity as an enabling factor for agricultural irrigation pumps on dry land.

5.3 Recommendations for PT PLN (Persero)

PLN, as the leading operator, must prioritize restoring the Smart Grid system's functionality by repairing the control computer components and replacing the degraded battery bank. Strengthening inter-organizational coordination between Customer Service Units (ULPs) and control centers is crucial to ensure voltage stability at night. PLN also needs to optimize the use of Smart Meters (AMI) to separate consumptive household electricity use from productive use, ensuring the accuracy of tariff subsidies. Finally, PLN should adopt preventive maintenance practices rather than only responding to failures.

References

[1] K. Mudhoffar and L. Magriasti, “Ekonomi Politik Energi Terbarukan: Peluang dan Tantangan di Indonesia,” *Multiverse: Open Multidisciplinary Journal*, vol. 3, no. 1, pp. 47–52, 2024, doi: 10.57251/multiverse.v3i1.1382.

[2] PLN, “Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) 2021-2030.,” 2021.

[3] C. K. Rao, S. K. Sahoo, and F. F. Yanine, "Development of a smart cloud-based monitoring system for solar photovoltaic energy generation," *Unconventional Resources*, vol. 6, no. September 2024, 2025, doi: 10.1016/j.uncres.2025.100173.

[4] M. Kinzie, "Small Seasons," *Chicago Review*, vol. 34, no. 1, p. 51, 1983, doi: 10.2307/25305228.

[5] B. E. Ostrom, "Beyond Markets and States: Polycentric Governance of Complex Economic Systems †," vol. 100, no. June, pp. 641–672, 2010.

[6] R. E. Matland, "Synthesizing the Implementation Literature: The Ambiguity-Conflict Model of Policy Implementation," *Journal of Public Administration*

Research and Theory, vol. 5, no. 2, pp. 145–174, Apr. 1995, doi: 10.1093/oxfordjournals.jpart.a037242.

[7] K. Wegrich, "Jeffrey L. Pressman and Aaron B. Wildavsky, Implementation," Mar. 26, 2015, *Oxford University Press*. doi: 10.1093/oxfordhb/9780199646135.013.10.

[8] C. E. Lindblom, "The science of 'muddling through,'" *Foundations of the Planning Enterprise: Critical Essays in Planning Theory: Volume 1*, vol. 19, no. 2, pp. 337–355, 2017, doi: 10.4324/9781315255101-29.

[9] K. E. H. Jenkins, B. K. Sovacool, N. Mouter, N. Hacking, M. K. Burns, and D. McCauley, "The methodologies, geographies, and technologies of energy justice: A systematic and comprehensive review," *Environmental Research Letters*, vol. 16, no. 4, 2021, doi: 10.1088/1748-9326/abd78c.

[10] UNDP, "United Nations Development Programme: People, purpose. progress.," pp. 2–25, 2020.

[11] S. Best, *Remote access Expanding Energy Provision in Rural Argentina Throught Public Private Partnership and Reneable Energy*. International Institute for Environment and Development (UK) in 2011., 2011.

[12] A. Primadi, S. Y. Yosepha, U. Dirgantara, and M. Suryadarma, "Logistica: Journal of Logistic and Transportation," no. 3, pp. 177–188, 2024.

[13] J. P. Praene, M. Payet, and F. Bénard-Sora, "Sustainable transition in small island developing states: Assessing the current situation," *Util. Policy*, vol. 54, pp. 86–91, 2018, doi: https://doi.org/10.1016/j.jup.2018.08.006.

[14] G. A. Bowen, "Document analysis as a qualitative research method," *Qualitative Research Journal*, vol. 9, no. 2, pp. 27–40, 2009, doi: 10.3316/QRJ0902027.

[15] J. Wessels and X. Thani, "Research methods in Public Administration," *Reflective Public Administration*, pp. 156–178, 2022, doi: 10.25159/118-9.012.

[16] J. Fereday and E. Muir-Cochrane, "Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development," *International Journal of Qualitative Methods*, vol. 5, no. 1, pp. 80–92, 2006, doi: 10.1177/160940690600500107.

[17] I. Alotaibi, M. A. Abido, M. Khalid, and A. V. Savkin, "A comprehensive review of recent advances in smart grids: A sustainable future with renewable energy resources," *Energies (Basel).*, vol. 13, no. 23, pp. 1–43, 2020, doi: 10.3390/en13236269.

[18] Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications," *Results in Engineering*, vol. 20, no. November, p. 101621, 2023, doi: 10.1016/j.rineng.2023.101621.

[19] A. Ross, S. Hollingworth, N. Rollock, K. Allen, and T. C. Garcia, "Technology and school improvement: reducing social inequity with technology? Report to Becta April 2008 I nstitute for Policy Studies in Education (IPSE) London Metropolitan University," no. April, pp. 1–124, 2008.

[20] S. Matthewman and H. Byrd, "Blackouts: A sociology of electrical power failure," 2014.

[21] D. Atsu, I. Seres, and I. Farkas, "The state of solar PV and performance analysis of different PV technologies grid-connected installations in Hungary," *Renewable and Sustainable Energy Reviews*, vol. 141, p. 110808, 2021, doi: 10.1016/j.rser.2021.110808.

[22] Y. Cao, T. Xiao, and Y. Liang, "Analysis on the development of modern rural power grids with low carbon serving rural revitalization from the," no. November 2023, pp. 1445–1452, 2024.

[23] International Reneable Energy Agency (IRENA), *Renewable Energy For Remote Communities*. 2023.

[24] A. M. Minas *et al.*, "Advancing Sustainable Development Goals through energy access: Lessons from the Global South," *Renewable and Sustainable Energy Reviews*, vol. 199, no. January, p. 114457, 2024, doi: 10.1016/j.rser.2024.114457.

[25] D. Demortain, *The Science of Bureaucracy*. The MIT Press Cambridge, Massachusetts, 2020. doi: 10.7551/mitpress/12248.001.0001.

[26] M. Howlett, *Designing Public Policies*, Second., vol. 1, no. 1. Routledge, 2019.

[27] Michael Hill and Peter Hupe, *Implementing Public Policy Governance in Theory and in Practice*, First publ. London: SAGE Publications London • Thousand Oaks • New Delhi, 2002.

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