

## Article

# Beyond the Grid Connection: Productive Energy Use, Governance Architecture, and the Sustainability of Community Welfare in Semaui Island's Smart Grid Microgrid, Indonesia

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## Abstract

Counting electricity connections is easy. Understanding what those connections actually do for people is harder—and more important. This study examines how a 450 kWp Smart Grid Hybrid Microgrid on Semaui Island, East Nusa Tenggara, Indonesia, shaped the daily lives and economic futures of a community in one of the country's most geographically isolated 3T territories (Frontier, Outermost, Underdeveloped), using a sequential explanatory mixed-methods design (SEM-AMOS,  $n = 123$ ; key informant interviews,  $n = 4$ )—and we find that forty percent of households have shifted from passive consumption to productive agricultural use within five years of grid connection, a rate that challenges common assumptions about rural electrification in eastern Indonesia. The data also reveal a troubling pattern at the heart of Indonesia's subsidy architecture: the 450 VA tier, which absorbs the highest per-kWh State Budget subsidy (IDR 10,518/kWh; 96.2% of Cost of Supply), is associated with the weakest welfare returns. Meanwhile, an estimated IDR 1.87 billion per year in lost capacity—a figure we term the Governance Maintenance Loss (GML)—is linked to governance shortfalls rather than hardware failure. SEM-AMOS results ( $\chi^2/df = 1.613$ ; RMSEA = 0.049; CFI = 0.973; TLI = 0.983; SRMR = 0.043) indicate that, among the constructs examined, Energy Diversification Policy shows the strongest association with community welfare ( $\beta = 0.718$ ,  $p < 0.001$ )—more so than the physical infrastructure itself. In response, this study proposes three governance instruments: the MIDEK framework, a Knowledge Transfer Mandate (KTM), and a Productive Energy Tariff (PET). Together, these tools offer a replicable, low-cost pathway for Indonesia's 1200 planned island installations under Presidential Regulation No. 112/2022—one that is simultaneously revenue-positive for PLN, budget-positive for the State, and welfare-positive for the communities these systems are meant to serve.

Academic Editor: Babatunde Olubayo

Received: 29 May 2026

Revised: 1 July 2026

Accepted: 2 July 2026

Published: 29 July 2026

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**Keywords:** sustainable energy transition; productive energy use; renewable energy governance; smart grid; community welfare; SDG 7; tariff reform; knowledge transfer; polycentric governance; small island developing territories; Indonesia; 3T regions

## 1. Introduction

Energy access reporting counts connections, not what people do with them. The gap between a household light and an irrigation pump is the difference between passive access and productive economic use [1]. In geographically isolated island communities, where supply is costly and unreliable, that distinction matters especially for welfare outcomes [2,3]. Cross-country evidence shows that rural electrification generates lasting welfare gains mainly when households already own productive assets and can reach markets [4,5].

This distinction sits at the heart of the global island energy transition. Small island and remote territories face a structural sustainability dilemma: per-unit generation costs are among the highest in the world, supply chains for fuel and spare parts are fragile, and technical capacity is scarce, yet these same territories are disproportionately exposed to the consequences of continued fossil fuel dependence [6–8]. The transition envisioned under SDG 7 (affordable and clean energy) and SDG 11 (sustainable cities and communities) is therefore not simply a hardware substitution from diesel to solar; it is a governance transition. A growing body of evidence shows that island and mini-grid renewable energy installations frequently underperform their design specifications within a few years of commissioning—not because the technology fails, but because the governance, financing, and maintenance arrangements surrounding it were never designed to sustain it [9–11]. Understanding how to make island energy transitions durable, not merely installable, is therefore a sustainability question as much as an engineering one.

Indonesia provides an unusually rich context for studying this question. Presidential Regulation No. 112/2022 mandates replacement of diesel generators with renewable energy across 3T regions (*Terdepan, Terluar, Tertinggal*—Frontier, Outermost, Underdeveloped), targeting 1200 island installations. Yet the welfare logic embedded in this policy has not been tested empirically. How tariff design, governance quality, and community technical knowledge shape the shift from subsistence to productive electricity use remains largely unexamined in the Indonesian archipelago [12,13].

Indonesia's residential electricity tariff structure is organized around contracted-capacity tiers (*daya tersambung*), historically designed as a social protection instrument: households are assigned to 450 VA, 900 VA, 1300 VA, or higher tiers, with the lowest tiers receiving the deepest State Budget subsidies on the assumption that low contracted capacity correlates with low household income [14,15]. The fiscal stakes of this design are considerable. The 450 VA subsidized tier alone carries a State Budget subsidy of IDR 10,518 per kWh, equivalent to 96.2% of the Cost of Supply (*Biaya Pokok Penyediaan, BPP*) [14,15], while the 900 VA tier carries a comparatively lower, though still substantial, subsidy of IDR 9488 per kWh (86.8% of BPP). At that level of fiscal commitment, whether customers in the most heavily subsidized tier actually use electricity productively is a material policy question: it determines whether billions of rupiah in annual subsidy spending generate measurable welfare returns, or simply maintain a passive grid connection that consumes public funds without producing economic activity in return.

We examine Semaui Island, Kupang Regency, East Nusa Tenggara (NTT), a 3T island that has operated a 450 kWp Smart Grid Hybrid Microgrid since 2020, addressing three research questions: (1) To what extent have households shifted from subsistence to productive electricity use, and what structural conditions enable or limit this transition? (2) How does tariff design affect productive use penetration and welfare outcomes? (3) What

governance provisions, specifically knowledge transfer and maintenance accountability, determine the long-run welfare efficiency of island hybrid energy systems?

Existing studies of island and mini-grid electrification have tended to address productive use, governance quality, and tariff design as separate research streams: productive use studies typically document adoption patterns without quantifying the financial cost of governance shortfalls [16,17]; governance studies document institutional failure qualitatively but rarely translate it into a metric usable in cost–benefit analysis [9,10]; and tariff studies address subsidy incidence at a national scale without connecting it to site-level productive use outcomes [12,18]. This study integrates these three streams within a single bounded case. This study makes four contributions to that gap. First, it provides one of the first SEM-AMOS-based quantifications of productive electricity use penetration for an Indonesian 3T island, benchmarked against Pacific and Sub-Saharan African comparators [6,13,19]. Second, it introduces the Governance Maintenance Loss (GML) as a monetary measure of governance-attributable system degradation, extending qualitative accounts of mini-grid governance failure [9,10,16,17] into a financially actionable metric—a gap also identified in recent SIDS governance reviews [8,11]. Third, it proposes the MIDEK (Integrative Model of Energy Diversification in Island Territories) framework, integrating implementation theory [20], polycentric governance [21], hybrid policy design [22], and contextual adaptation [23] into a single diagnostic-prescriptive tool for island energy governance. Fourth, it reframes tariff design as a welfare governance instrument through the Productive Energy Tariff (PET) proposal, grounded in international subsidy reform evidence [18,24,25].

The remainder of this paper is organized as follows. Section 2 develops the analytical framework, integrating productive-use, tariff-governance, and institutional-design perspectives into the MIDEK model. Section 3 describes the study site, the sequential explanatory mixed-methods design, and the SEM-AMOS and qualitative procedures. Section 4 presents the results: productive electricity use patterns, the structural model, the subsidy efficiency pattern, the financial performance and Governance Maintenance Loss analysis, and the qualitative governance themes. Section 5 discusses these findings in relation to the literature and develops the Knowledge Transfer Mandate and Productive Energy Tariff proposals. Section 6 concludes with limitations and policy implications for Indonesia’s 1200 planned island installations.

## 2. Analytical Framework

Electrification does not deliver welfare in a straight line. The PURE (Productive Use of Renewable Energy) literature shows that welfare gains become nonlinear once households move beyond lighting and phone charging into economically productive applications: irrigation, cold storage, food processing, small enterprise operation [1,26]. In island farming communities, this matters through two concrete channels: irrigation that opens up dry-season cash crop cultivation, and cold storage that allows fishermen to hold product overnight and sell at better prices the next morning.

Sen’s capability approach [2] provides the evaluative anchor. Energy access expands economic facilities (productive asset use), social opportunities (longer study hours, health information access), protective security (income diversification across seasons), and transparency guarantees (documented welfare impacts that create accountability pressure on institutions). Empirical evidence shows that it is productive energy services, not grid connection per se, that are associated with welfare improvements lasting beyond the initial post-connection period [3].

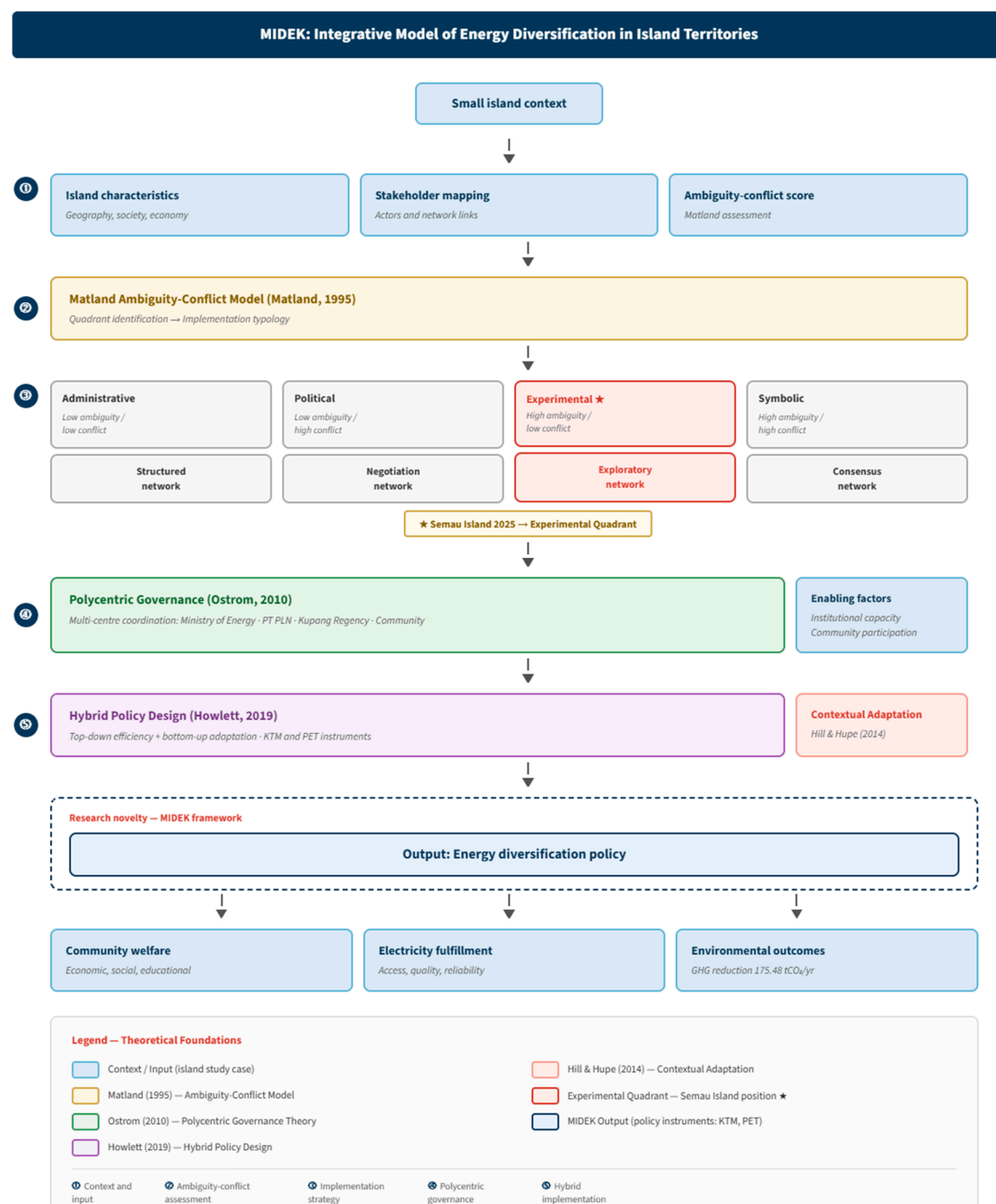
Tariff design in subsidized island contexts is usually treated as a cost-recovery and price-signaling problem [18,24]. That framing misses the point in 3T island settings, where cost recovery requires government subsidization regardless of tariff level. The question

shifts: which tariff structure generates the most welfare return per unit of State Budget subsidy.

Following O'Toole [27] and Hill and Hupe [23], we treat tariff design as a second-order implementation instrument, nested within first-order energy diversification policy and determining whether infrastructure investment actually delivers welfare outcomes. A well-built solar installation paired with a welfare-suppressing tariff will consistently underdeliver. This reframes O'Toole's [27] instrument concept beyond its original administrative domain into energy economics, and underpins the tariff reform proposal developed later in this paper.

MIDEK (Integrative Model of Energy Diversification in Island Territories) integrates four complementary theoretical perspectives, each addressing a different stage of the diagnosis-to-implementation problem: Matland's [20] Ambiguity-Conflict Model to identify the implementation quadrant and its governance prescription (diagnosis—*why* implementation is difficult here); Ostrom's [21] Polycentric Governance Theory for institutional design principles (prescription—*what* institutional arrangements should look like); Howlett's [22] Hybrid Policy Design for instrument-mix logic (integration—*how* multiple instruments combine); and Hill and Hupe's [23] Contextual Adaptation approach for translating generic prescriptions into locally workable arrangements (implementation—ensuring the result fits Semaui Island's specific administrative and cultural setting). Used together, these perspectives move sequentially from diagnosis, to institutional design, to instrument integration, to context-sensitive implementation—the four steps the MIDEK framework operationalizes below.

Semaui Island sits in Matland's [20] Experimental Quadrant, high ambiguity, low conflict. Ambiguity is high because Smart Grid technology is novel in a community with low technical literacy, maintenance protocols are absent from the 3T regulatory framework, and no one has clearly defined where the Ministry of Energy's responsibility ends, and PT PLN's begins, or where PLN's ends and Kupang Regency's begins. Conflict is low because every actor wants the same thing: a functioning electricity supply. That combination calls for adaptive, learning-oriented governance built on bottom-up feedback, which is exactly what the KTM and PET instruments proposed below are designed to create. Figure 1 maps Semaui Island's position in the framework.



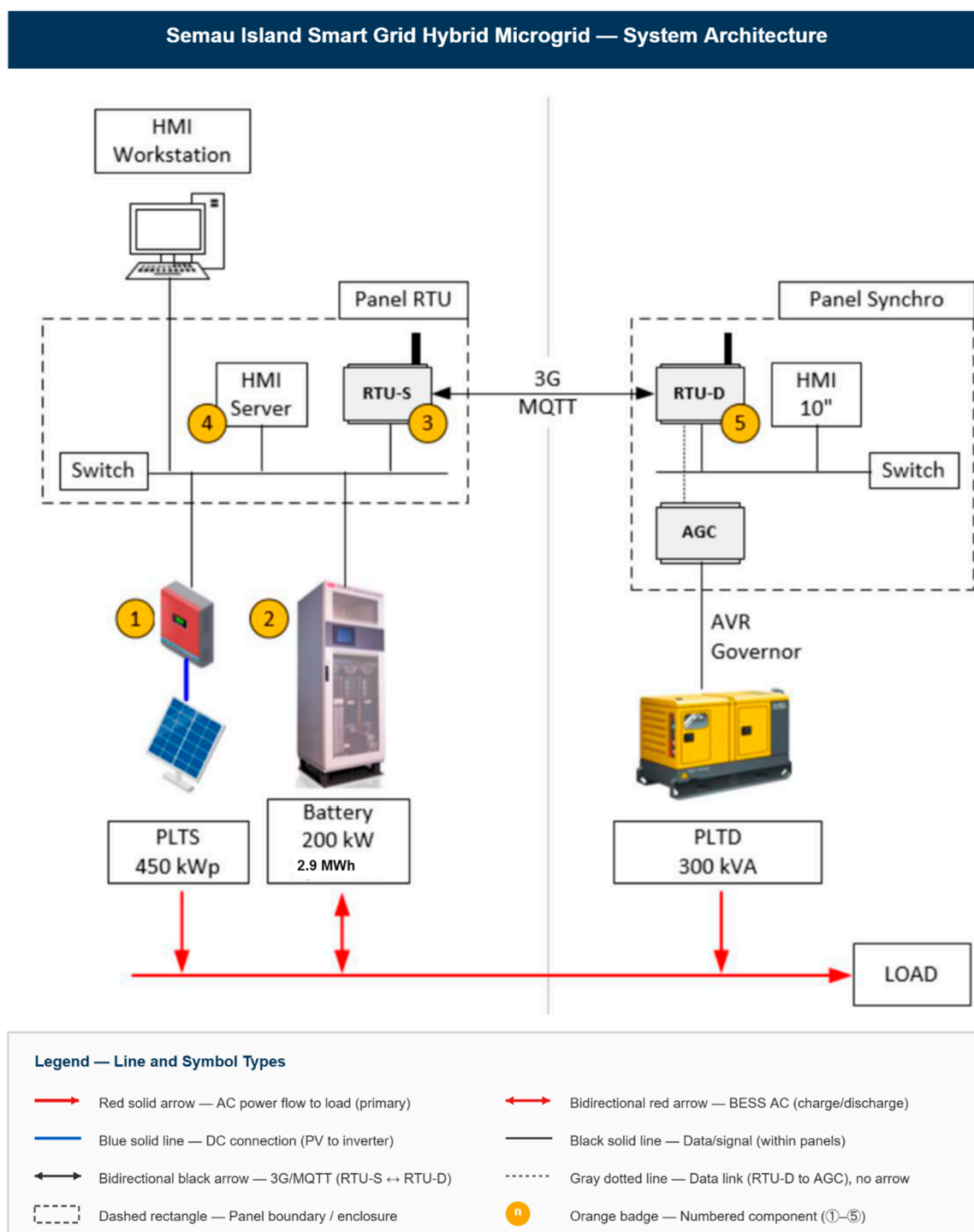
**Figure 1.** MIDEK Framework: Integrative Model of Energy Diversification in Island Territories. ★ = Semaui Island position (Experimental Quadrant). Synthesizing Matland (1995) [20], Ostrom (2010) [21], Howlett (2019) [22], and Hill and Hupe (2014) [23]. Source: Authors (2025).

### 3. Materials and Methods

#### 3.1. Study Site

Semaui Island (10°04′–10°20′ S; 123°22′–123°32′ E; ~236 km<sup>2</sup>; ~21,000 residents; 3542 registered electricity customers as of December 2024) is accessible only by ferry, 25 km southwest of Kupang City. Its economy is built on subsistence dry-land agriculture—red onion, watermelon, stone fruit, and artisanal fisheries. The island’s energy system comprises a 450 kWp Smart Grid Solar Power Plant (SPP) commissioned in 2020, operating alongside five diesel plants (1600 kW total; 405 kW peak load) managed by PT PLN Oesao ULP. The SPP has an installed peak capacity of 450 kWp. When we collected data (May–August 2025), its available capacity, the maximum output the system could sustain given

its degraded state, was approximately 250 kW, 44% below the installed specification, because battery capacity and the monitoring system had degraded. Figure 2 illustrates the system architecture, comprising the 450 kWp PLTS (solar array and inverter), a 200 kW/2.9 MWh battery energy storage system, the PLTD synchronization unit (300 kVA), and the supervisory control layer (RTU-S and RTU-D remote terminal units linked via 3G/MQTT, HMI workstations, and the automatic generation controller, AGC) through which monitoring-system inoperability (Theme 3, Section 4.5) occurred.



**Figure 2.** Electrical system architecture of the Semau Island Smart Grid Hybrid Microgrid. The PLTS (450 kWp) and battery energy storage system (200 kW/2.9 MWh) supply the load directly; the PLTD shown (300 kVA) is the diesel unit integrated into the smart grid synchronization layer, operating under AVR-Governor control via the AGC. Supervisory monitoring (Panel RTU: HMI server and

RTU-S; Panel Synchro: RTU-D and HMI) communicates over a 3G/MQTT link. Numbered components (1\20135) correspond to PLTS inverter, battery bank, RTU-S, HMI server, and RTU-D, respectively. This architecture represents the Semau Island system as a whole; the remaining diesel capacity referenced in Section 3.1 (1600 kW across five units) operates as conventional backup outside the smart-grid-integrated synchronization layer shown here. Source: Authors (2025), based on as-built system documentation.

### 3.2. Research Design

We used a sequential explanatory mixed-methods design (QUAN  $\rightarrow$  qual) [28]: SEM-AMOS first to identify structural pathways, then qualitative thematic analysis to explain what the statistics show but cannot explain in isolation. The design follows Yin's [29] bounded single-case logic.

Semau Island qualifies on three grounds: it has defined geographic and institutional boundaries; it shares key structural features with hundreds of other 3T island installations across Indonesia (PLN utility management, ferry-only access, subsistence agricultural base, low technical literacy); and it presents a quasi-experimental condition, functional productive electricity use and documented concurrent governance challenges in the same system, at the same time. Consistent with Yin [29], the goal is analytical generalization, from case evidence to theory, not statistical generalization to a population.

### 3.3. Quantitative Component: SEM-AMOS

#### 3.3.1. Sample Size and Respondent Profile

We set sample size using SEM-specific criteria rather than general population formulas, which do not guarantee adequate power for latent variable estimation [30,31]. Hair et al. [30] recommend a minimum of 100–150 observations;  $n = 123$  meets this. Westland [31] requires a minimum observation-to-parameter ratio of 2:1; our 34 free parameters yield 3.6:1. Monte Carlo simulation shows that  $n \geq 100$  achieves power of  $1 - \beta \geq 0.80$  for path coefficients of  $\beta \geq 0.30$  [32]. Post hoc analysis (G\*Power 3.1) confirmed  $1 - \beta = 0.82$  at  $\alpha = 0.05$ . We drew a cluster random sample across six villages, stratified by contract tier (450 VA, 900 VA, 1300 VA+), using the PT PLN customer register. The resulting sample of 123 respondents comprised 67.48% male and 32.52% female participants, with a mean age of 42.08 years ( $SD = 13.40$ ; range 20–79). Contract tier distribution was as follows: 900 VA (53.66%), 450 VA (22.76%), and 1300 VA+ (23.58%). A complete village-by-tier-by-gender sampling breakdown is provided in Supplementary Table S2.

#### 3.3.2. Constructs and Measurement

We measured five latent constructs through 20 five-point Likert items: Smart Grid SPP (X1; 5 items covering system reliability, capacity, and technological effectiveness), Energy Diversification Policy (X2; 5 items covering policy awareness, implementation quality, and governance responsiveness), Electrification Ratio (X3; 5 items on electricity access coverage), Electricity Needs Fulfillment (X4; 5 items on supply adequacy for productive and subsistence needs), and Community Welfare (Y; 5 items on perceived improvements in income, health, education, security, and social participation since grid connection). Content validity was assessed by an expert panel ( $n = 5$ ). It is important to note that the Community Welfare construct (Y) is based on respondents' self-reported perceptions rather than objective socioeconomic indicators such as measured household income, expenditure records, or health and education outcome data. While perception-based measures are a well-established approach in capability-based welfare assessment [2], they reflect how respondents experience and evaluate change rather than independently verified material outcomes. This distinction is revisited in the Limitations.

### 3.3.3. Discriminant Validity of X3 and X4

The HTMT ratio between Electrification Ratio (X3) and Electricity Needs Fulfillment (X4) was 0.887 near the 0.90 threshold, but statistically acceptable [33]. Retaining two separate constructs is justified by the rejection of the constrained CFA model ( $\Delta\chi^2 = 8.34$ ,  $df = 1$ ,  $p = 0.004$ ). Conceptually, the distinction is real: X3 measures the presence of physical infrastructure (system performance indicator), while X4 measures the subjective adequacy of that supply for productive purposes (service quality indicator). Collapsing them would make the governance mechanism through which coverage translates into welfare analytically invisible. The near-threshold value is acknowledged as a limitation requiring replication across multi-island settings.

### 3.3.4. Analytical Procedure

SEM-AMOS v26.0 (IBM) followed Anderson and Gerbing's [34] two-step procedure: CFA first to establish measurement model validity, then structural model estimation with 2000-iteration bootstrap resampling (95% BCa) [35]. Fit thresholds applied [36,37]:  $\chi^2/df \leq 3.0$ ;  $RMSEA \leq 0.08$ ;  $CFI \geq 0.90$ ;  $TLI \geq 0.90$ ;  $SRMR \leq 0.08$ . Discriminant validity was assessed using the HTMT ratio [33].

## 3.4. Qualitative Component

We purposively selected four key informants to cover the four institutional roles in Semaui Island's energy governance: community leaders (CL-01, CL-02), PLN system operator (OP-01), and a government education/health officer (TH-02). This meets Malterud et al.'s [38] information power criteria; the theoretical framework is established, the case is bounded and specific, and four informants exhaust the complete institutional landscape without redundant perspectives.

The sampling logic follows Yin's [29] bounded single-case design: saturation here means boundary exhaustion, not thematic replication across an open-ended sample [39]. Interviews averaged 75 min, were conducted in Bahasa Indonesia, audio-recorded with written consent, and transcribed verbatim. Thematic analysis followed Braun and Clarke's [40] six-phase procedure. Two independent coders computed inter-rater reliability on 30% of the corpus:  $\kappa = 0.81$  [41]. Perspectives from female-headed households and commercial customers (1300 VA tier) are absent from the qualitative data—a recognized gap. A complete summary of each informant's role, interview date, institutional affiliation, and relevance to the three research questions is provided in Supplementary Table S4.

## 3.5. Financial Analysis

We ran three complementary financial analyses alongside SEM-AMOS: productive electricity use penetration by village and tier; a comparative tariff welfare analysis across the 450 VA and 900 VA configurations; and a financial performance model computing Payback Period and 25-year ROI under pessimistic, base, and optimistic scenarios, incorporating fuel savings ( $SFC = 0.3$  L/kWh, based on the PLTD technical specification at Semaui Island), PLN revenues, and carbon incentives (USD 10–30/tCO<sub>2</sub> [42]). We use GML (Governance Maintenance Loss) rather than GDP throughout to avoid confusion with the standard macroeconomic abbreviation. GHG emission reductions were calculated per the IPCC [43] energy substitution methodology.

# 4. Results

## 4.1. Respondent Profile and Productive Electricity Use

Among this sample, 40% of South Semaui customers use electricity productively for agricultural irrigation within five years of grid connection. This concentrates in Huilelot

and Utiuthtuan, where agro-ecological conditions support irrigation-based cash crop cultivation. Almost all productive users are on the 900 VA tier. The reason is technical: irrigation pumps draw 750–1500 W, which exceeds the 450 VA contract capacity outright. Table 1 presents the full breakdown.

**Table 1.** Productive electricity use patterns, primary users, and economic outcomes: Semaue Island, 2025.

| Productive Use Category             | Penetration | Primary Users          | Key Economic Outcome                                                   |
|-------------------------------------|-------------|------------------------|------------------------------------------------------------------------|
| Agricultural irrigation (pump)      | 40% ★       | Smallholder farmers    | Net income multiplier: 10–21× electricity cost (red onion, watermelon) |
| Fisheries refrigeration             | ~15% †      | Artisanal fishermen    | Reduced perishability losses; temporal arbitrage in fish sales         |
| Nocturnal small enterprise          | ~20% †      | Seaweed/net processors | Extended working hours; increased weekly output                        |
| Subsistence only (lighting + phone) | ~60% ★      | 450 VA households      | Educational lighting, mobile communication, safety                     |

★ Survey-derived ( $n = 123$ ). † Indicative from field observations and PT PLN records. Sources: Field survey (2025); PT PLN Persero (2025) [14].

#### 4.2. SEM-AMOS Results

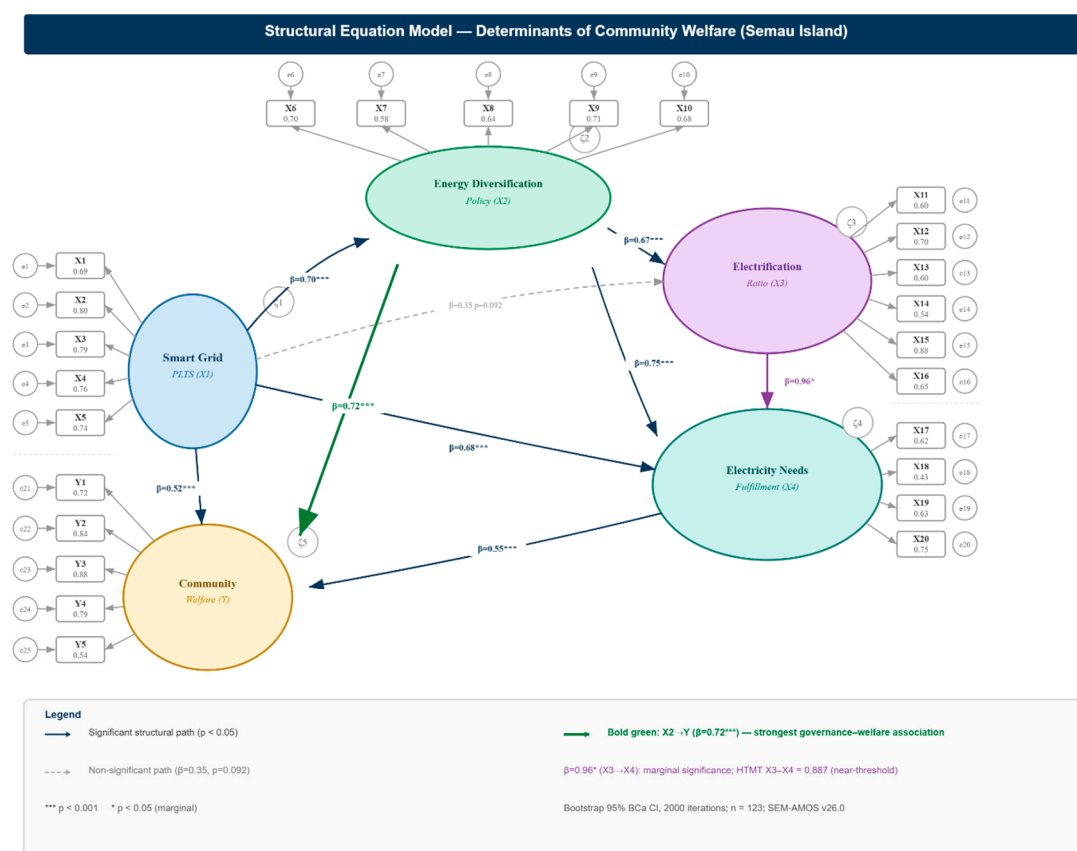
The structural model achieved satisfactory fit across all five indices ( $\chi^2/df = 1.613$ ; RMSEA = 0.049; CFI = 0.973; TLI = 0.983; SRMR = 0.043), meeting or exceeding all threshold criteria of Hu and Bentler [36] and Kline [37]. Convergent validity held: AVE exceeded 0.50 (range: 0.591–0.668) and CR exceeded 0.70 (range: 0.874–0.909). Table 2 presents measurement model statistics and structural path results. Figure 3 displays the standardized structural model.

**Table 2.** Measurement model validity (a) and SEM-AMOS structural path results (b).

| (a)                                                                                     |       |          |            |                                 |          |
|-----------------------------------------------------------------------------------------|-------|----------|------------|---------------------------------|----------|
| Construct                                                                               | Items | $\alpha$ | CR         | AVE                             | Max HTMT |
| Smart Grid SPP (X1)                                                                     | 5     | 0.868    | 0.883      | 0.612                           | 0.743    |
| Energy Diversification Policy (X2)                                                      | 5     | 0.891    | 0.909      | 0.668                           | 0.801    |
| Electrification Ratio (X3)                                                              | 5     | 0.851    | 0.874      | 0.591                           | 0.887 +  |
| Electricity Needs Fulfillment (X4)                                                      | 5     | 0.874    | 0.895      | 0.634                           | 0.887 +  |
| Community Welfare (Y)                                                                   | 5     | 0.882    | 0.901      | 0.649                           | 0.801    |
| (b)                                                                                     |       |          |            |                                 |          |
| Hypothesized Path                                                                       |       | $\beta$  | $p$ -value | Decision                        |          |
| H1: Smart Grid SPP (X1) $\rightarrow$ Electricity Needs Fulfillment (X4)                |       | 0.681    | <0.001     | Supported                       |          |
| H2: Energy Diversification Policy (X2) $\rightarrow$ Electricity Needs Fulfillment (X4) |       | 0.748    | <0.001     | Supported—strongest association |          |

|                                                                     |       |              |                                                     |
|---------------------------------------------------------------------|-------|--------------|-----------------------------------------------------|
| H3: Electrification Ratio (X3) → Electricity Needs Fulfillment (X4) | 0.956 | 0.048        | Supported (marginal; see Section 3.3.3)             |
| H4: Electricity Needs Fulfillment (X4) → Community Welfare (Y)      | 0.547 | <0.001       | Supported                                           |
| H5: Smart Grid SPP (X1) → Community Welfare (Y)                     | 0.524 | <0.001       | Supported                                           |
| H6: Energy Diversification Policy (X2) → Community Welfare (Y)      | 0.718 | <0.001       | Supported—strongest association                     |
| H7: Electrification Ratio (X3) → Community Welfare (Y)              | 0.676 | <0.001       | Supported                                           |
| Exploratory: X1 → Electrification Ratio (X3)                        | 0.351 | 0.092 (n.s.) | Not significant—see Discussion 5.1                  |
| Exploratory: X2 → Electrification Ratio (X3)                        | 0.667 | <0.001       | Largest association among governance-mediated paths |

(a) Criteria:  $\alpha > 0.70$ ; CR > 0.70; AVE > 0.50 [44]; HTMT < 0.90 [33]. + Near-threshold; constrained CFA rejected ( $\Delta\chi^2 = 8.34$ ,  $df = 1$ ,  $p = 0.004$ ); two-construct retention supported (Section 3.3.3). (b) Bootstrap-corrected 95% BCa CIs (2000 iterations). n.s. = not significant. Source: SEM-AMOS v26.0; primary data (2025).



**Figure 3.** SEM-AMOS structural model: standardized path coefficients ( $n = 123$ ; Bootstrap 2000 iterations; 95% BCa CI). Bold arrows = governance-mediated pathways with the largest standardized coefficients. Dashed arrow ( $\beta = 0.351$ ,  $p = 0.092$ ) = statistically inconclusive exploratory path. \*\*\*  $p < 0.001$ ; \*  $p < 0.05$ . Source: SEM-AMOS v26.0; primary data (2025).

Among the structural paths estimated, Energy Diversification Policy (X2) shows the strongest associations: it is linked to the largest standardized path coefficients for Community Welfare ( $\beta = 0.718, p < 0.001$ ) and Electricity Needs Fulfillment ( $\beta = 0.748, p < 0.001$ ). Smart Grid SPP (X1) shows a significant direct association with Electricity Needs Fulfillment ( $\beta = 0.681, p < 0.001$ ) and Community Welfare ( $\beta = 0.524, p < 0.001$ ).

An exploratory path from Smart Grid SPP to Electrification Ratio yielded a positive but statistically inconclusive coefficient ( $\beta = 0.351, p = 0.092$ ), contrasting with the strongly confirmed governance-mediated pathway (Energy Diversification Policy  $\rightarrow$  Electrification Ratio:  $\beta = 0.667, p < 0.001$ ). This pattern suggests that physical infrastructure alone does not appear sufficient to explain variation in electrification coverage, while governance-related factors show a stronger association with this outcome; the implications of this distinction are developed further in the Discussion.

#### 4.3. Tariff Architecture: The Subsidy Efficiency Pattern

Table 3 reveals the subsidy efficiency pattern: the 450 VA tier is associated with the highest per-kWh State Budget subsidy (IDR 10,518/kWh; 96.2% of BPP) while delivering the lowest welfare return. The structural pattern appears to operate through two interconnected mechanisms. The first is technical capacity suppression: productive devices such as irrigation pumps exceed the 450 VA contract capacity, making productive use technically infeasible at that tariff tier. The second is a financial barrier: connection upgrade costs (IDR 1.5–2.5 million) represent 30–83 months of typical 450 VA monthly expenditure, prohibitive for subsistence households even when income returns would recoup the investment within one agricultural cycle.

**Table 3.** Comparative tariff analysis: subsidy efficiency pattern across 450 VA and 900 VA tiers, Semaui Island, 2025.

| Parameter                      | 450 VA Subsidized                  | 900 VA Tier                     |
|--------------------------------|------------------------------------|---------------------------------|
| Registered customers           | ~835 (23.57%)                      | ~1900 (53.66%)                  |
| Customer tariff (IDR/kWh)      | 415                                | 1444.70                         |
| State Budget subsidy (IDR/kWh) | 10,518 (96.2% BPP)                 | 9488 (86.8% BPP)                |
| Annual subsidy burden          | ~IDR 6.85 billion                  | ~IDR 17.31 billion              |
| PLN annual revenue             | IDR 270.1 million                  | IDR 2649.0 million              |
| Productive use penetration     | ~5% (capacity constrained)         | ~40% (survey-derived)           |
| Net income multiplier          | None documented                    | 10–21 $\times$ electricity cost |
| Connection upgrade barrier     | IDR 1.5–2.5 million (30–83 months) | Not applicable                  |

BPP = *Biaya Pokok Penyediaan* (Cost of Supply). Sources: Ministry of Energy [45]; PT PLN [14]; field survey (2025).

#### 4.4. Financial Performance and the Governance Maintenance Loss

Table 4 presents financial performance across three scenarios. Under optimal (450 kWp) capacity, the SPP generates a combined-revenue Payback Period of 1.8 years (CAPEX midpoint IDR 9.04 billion, range based on [15] adjusted for 2025 construction costs) and a 25-year ROI of 892%. The GML of IDR 1.87 billion per year quantifies the

annual financial cost of the 200 kW available capacity shortfall, which we associate with procurement design weaknesses: the absence of maintenance standards and Knowledge Transfer provisions in the original contract corresponds with monitoring system inoperability since mid-2023 and 35–40% battery degradation (confirmed by OP-01). The full GML calculation—formula, input parameters, and sensitivity to diesel price assumptions (range: IDR 0.9–1.9 billion/year)—is provided in Supplementary Table S3. At a KTM cost of IDR 150–200 million, the payback period is <40 days under base-case assumptions.

**Table 4.** Financial performance analysis and Governance Maintenance Loss (GML) sensitivity, Semaui Island SPP (CAPEX midpoint IDR 9.04 billion).

| Performance Metric                                   | Pessimistic                       | Base Case     | Optimistic    |
|------------------------------------------------------|-----------------------------------|---------------|---------------|
| CAPEX (IDR billion)                                  | 11.46                             | 9.04          | 6.63          |
| Diesel price (IDR/L)                                 | 10,000                            | 12,900        | 15,000        |
| Available capacity (kW)                              | 250 (degraded, vs. 450 installed) | 450 (optimal) | 450 (optimal) |
| PBP—combined revenue (years)                         | 5.8                               | 1.8 ★         | 1.1           |
| 25-year ROI (%)                                      | 198%                              | 892% ★        | 1847%         |
| Annual CO <sub>2</sub> reduction (tCO <sub>2</sub> ) | 97.49                             | 175.48        | 175.48        |
| Carbon revenue (IDR million/yr)                      | 16.47                             | 29.65         | 29.65         |
| Governance Maintenance Loss—GML (IDR billion/yr)     | 1.21                              | 1.87 ★        | 2.34          |
| KTM payback period (days)                            | 60                                | <40 ★         | 31            |

★ Base-case highlighted values. KTM investment: IDR 150–200 million. GML = annual financial loss from 200 kW available capacity shortfall (vs. 450 kWp installed peak capacity). Sources: Giwangkara & van Campen [15]; IPCC [43]; IRENA [46]; Ministry of Energy [45]; field data (2025).

#### 4.5. Qualitative Findings: Four Governance Themes

The SEM-AMOS results reported in Sections 4.2–4.4 establish that governance variables (Energy Diversification Policy) outperform technical infrastructure variables (Smart Grid SPP) as predictors of welfare and electrification outcomes, and that the SPP’s available capacity was 44% below its installed specification at the time of data collection. These statistical patterns describe what is happening but not why. Thematic analysis of four key informant interviews ( $\kappa = 0.81$ ) was therefore conducted to explore plausible explanations for the quantitative finding that governance variables show the strongest associations, generating four convergent themes that map directly onto the SEM-AMOS results: Themes 1 and 2 offer contextual interpretations of why the technology-to-coverage path ( $X1 \rightarrow X3$ ) was statistically inconclusive, Theme 3 identifies a contributing factor to the 44% capacity shortfall underlying the Governance Maintenance Loss reported in Section 4.4, and Theme 4 illustrates how Energy Diversification Policy relates to Community Welfare.

**Theme 1—Structural Knowledge Deficit.** Despite five years of SPP operation, 95.12% of community members cannot describe system functions beyond identifying solar panels. CL-02 (July 2025) stated: “The solar panels have been here since 2020, but we do not know how the system works inside”. This knowledge deficit severs the demand-side accountability mechanism through which Ostrom’s [21] Principle 4 (monitoring by users) operates.

**Theme 2—Governance Architecture Disconnect.** All community informants learned of Presidential Regulation No. 112/2022 through television rather than official socialization. TH-02 (July 2025): “The Presidential Regulation is good on paper, but here we only learned about it from television news.” This disconnect directly triangulates with the technology-governance complementarity pattern found in the quantitative data.

**Theme 3—Procurement Design as a Contributing Factor.** OP-01 (June 2025) confirmed: “Battery capacity has dropped by about 35–40 percent from the initial specifications”. Analysis of the procurement contract indicates that it contains no maintenance standards, Knowledge Transfer clauses, spare parts inventory requirements, or interagency accountability mechanisms—a gap in contractual governance design that plausibly contributed to the capacity shortfall, though we cannot rule out additional technical, environmental, or operational factors not captured by this single-case qualitative design.

**Theme 4—Productive Energy as Welfare Ladder.** CL-01 (July 2025): “If electricity runs continuously, I can store fish in the refrigerator and sell them the next day at a better price”. TH-02 (August 2025): “Since electricity became stable, my children can study until nine or ten at night. Their exam scores have improved”.

## 5. Discussion

### 5.1. Productive Energy Threshold, Tariff Architecture, and the Welfare Mechanism

The 40% productive electricity use penetration (Section 4.1) substantially exceeds subsistence-dominated assumptions for eastern Indonesian 3T islands [12] and aligns with the upper range Dornan [6] documents in Pacific Island programs (35–45% adoption within comparable timeframes). The divergence from Sub-Saharan African programs, where Blimpo and Cosgrove-Davies [13] and Wassie and Adaramola [19] document typical rates of 10–20%, reflects Semau Island’s agro-ecological specificity: dry-season red onion and watermelon cultivation creates a binding demand-pull for irrigation electricity. This finding is consistent with Peters and Sievert [5], who demonstrate that rural electrification welfare effects depend on complementary productive asset ownership.

The SEM-AMOS results are consistent with the implementation theory prediction: Energy Diversification Policy shows a stronger direct association with welfare ( $\beta = 0.718$ ,  $p < 0.001$ ) than Smart Grid infrastructure alone ( $\beta = 0.524$ ,  $p < 0.001$ ). This technology-governance complementarity pattern is consistent with Gollwitzer et al.’s [9]. Nature Energy finding that governance architecture is strongly associated with mini-grid performance, and extends this line of inquiry to the Indonesian 3T island context with SEM evidence.

The statistically inconclusive path from Smart Grid SPP to Electrification Ratio ( $\beta = 0.351$ ,  $p = 0.092$ ) provides a useful theoretical insight: advanced technology alone is insufficient to explain variation in electrification coverage in 3T territories. This finding is consistent with the stronger association of governance variables observed in this study, where Energy Diversification Policy (X2) is associated with both physical infrastructure and coverage outcomes in ways that suggest it may play a mediating role, though formal mediation testing was beyond the scope of this study. It suggests that without the *governance infrastructure*—clear maintenance protocols, knowledge transfer mandates, and interagency accountability—the physical infrastructure remains a dormant asset with limited transformative potential. This reframing converts an apparent statistical result into a theoretically meaningful contribution: the non-significance of the direct technology-to-coverage path is not a model deficiency but an empirical confirmation that hardware deployment without governance architecture is insufficient for welfare transformation in remote island contexts.

The subsidy efficiency pattern has direct implications for Indonesia’s national energy subsidy architecture. Evidence across 49 developing countries shows that uniform volumetric subsidies systematically benefit higher-consumption wealthier households [18]; In-

Indonesia's 450 VA tier is a paradigmatic instance. The PET reform addresses this pattern through three mechanisms: a subsidized connection upgrade pathway (each migrating household reduces State Budget burden by IDR 1030/kWh while generating IDR 8.83 million additional PLN annual revenue); a transitional PET tier (IDR 800–1000/kWh); and an agricultural sector tariff classification under Law No. 30/2009 Article 34(4). This reform aligns the interests of smallholder farmers, PLN, and the Ministry of Finance simultaneously, satisfying Matland's [20] condition for improved implementation prospects. The closest international parallels are Rao's [25] analysis of Indian kerosene subsidy reform and Dornan's [6] Pacific Island tariff design initiatives. Two operational questions are central to making this proposal workable. The first concerns financing: under the current connection arrangement, the cost of upgrading from a 450 VA to a 900 VA contract (IDR 1.5–2.5 million, Section 4.3) is borne by the household itself, which, as discussed above, is precisely the barrier that keeps many subsistence households from accessing the productive-use tariff in the first place. Whether this self-financing requirement should be retained, subsidized, or replaced with a deferred-payment mechanism tied to the PET's projected revenue gains is a policy design question this study does not resolve, but flags as a precondition for the PET to reach the households it is intended to benefit. The second concerns eligibility verification: PT PLN's existing field verification procedure, in which technical officers inspect registered productive facilities (agricultural, plantation, or fishery sites) and confirm that connected equipment such as water pumps or drive motors matches the declared load capacity, provides a workable basis for verifying PET eligibility without requiring new administrative infrastructure. Extending this existing procedure to productive-tariff classification would be more administratively feasible than designing a new verification system from scratch.

These findings speak directly to the global sustainability agenda. SDG 7.1 calls for universal access to affordable, reliable, and modern energy services by 2030; SDG 7.2 targets a substantial increase in the share of renewable energy in the global energy mix. Semaui Island's experience shows that meeting both targets simultaneously is possible in remote island contexts, but only when the governance architecture keeps pace with the hardware. A grid connection without a functioning maintenance system, without community technical literacy, and without a tariff structure that rewards productive use is not, in any meaningful sense, "modern energy access"—it is infrastructure waiting to degrade. The 40% productive use rate documented here, achieved within five years and concentrated among smallholder farmers who use electricity to multiply their incomes tenfold, is precisely the kind of welfare transformation SDG 7 is designed to measure. The MIDEK framework, KTM, and PET together constitute a governance package that translates SDG 7 from an access metric into a welfare outcome—replicable across Indonesia's 1200 planned installations and, with appropriate contextual adaptation, across the broader landscape of small island developing territories worldwide.

### *5.2. Governance Challenges, the Knowledge Transfer Mandate, and Functional Polycentricity*

The GML of IDR 1.87 billion per installation per year (Section 4.4; Supplementary Table S3) operationalizes governance-related system degradation as a financially actionable construct, extending qualitative documentation of mini-grid governance challenges [9,10] into the domain of quantitative cost–benefit analysis. At a KTM implementation cost of IDR 150–200 million, the estimated payback period falls below 40 days (see Supplementary Table S3).

The KTM is designed to address three interrelated governance gaps. First, it resolves the principal-agent problem: the installing contractor retains informational advantages and has a commercial incentive to withhold technical knowledge, since ongoing service contracts are foreclosed by knowledge transfer. Mandatory KTM provisions, a minimum

of three locally certified technicians (80-hour curriculum; Tier-2 certification before final payment), local spare parts inventory, Bahasa Indonesia maintenance manual, and quarterly interagency meetings address this misalignment. Second, the KTM operationalizes Ostrom's [21] Principle 4 by creating the community-level technical literacy prerequisite for demand-side accountability. Third, evidence from East African off-grid programs [47] documents significant capacity-building gaps and the critical role of local technical knowledge in sustaining energy system performance, providing comparative support for the KTM design principles proposed here.

Diagnostic application of Ostrom's [21] eight design principles reveals the structural-functional polycentricity divide: structural elements are formally present (Ministry of Energy, PT PLN, Kupang Regency, village institutions), but functional coordination linkages are absent (interagency meetings fewer than twice per year; no community feedback channels; undefined maintenance accountability). The Semaui Energy Governance Committee simultaneously operationalizes Ostrom's [21] Principles 3, 5, 6, and 7 through a formally convened coordination body—consistent with Howlett's [22] Hybrid Policy Design prescription.

### 5.3. Theoretical Contributions and National Policy Implications

Before turning to these contributions, it is worth clarifying the epistemic status of the four constructs introduced in this paper, since they differ in how directly they are tied to the empirical evidence. The GML is the most directly empirical: it is a calculation derived from measured parameters (the 200 kW available capacity shortfall, PSH, SFC, and diesel price), and its formula and sensitivity range are reported in Supplementary Table S3. The MIDEK framework is best understood as a conceptual synthesis: it organizes existing implementation, governance, and policy design theories [20–23] around the Semaui Island case, and its value lies in offering a structured way of thinking about island energy governance rather than in being a statistically tested model in its own right. The KTM and PET are policy proposals: they are grounded in the patterns observed here and in the broader literature [18,24,25,47], and their projected costs and returns are calculated from the data presented, but they have not themselves been implemented or evaluated, and should be read as recommendations for piloting rather than as validated interventions.

Returning to the three research questions posed in Section 1, the Semaui Island case speaks to all three: productive use is achievable but capacity-constrained by tariff tier (RQ1); tariff design is materially associated with productive use penetration and welfare outcomes, as illustrated by the subsidy efficiency pattern (RQ2); and knowledge transfer and maintenance accountability—operationalized through the GML—appear to be the governance provisions most strongly associated with long-run welfare efficiency (RQ3). The MIDEK framework makes three theoretical contributions. First, it provides a diagnostic-prescriptive model integrating implementation theory [20,27], institutional design [21], hybrid policy design [22], and contextual adaptation [23]. Comparison with patterns reported in Pacific [6], African [9,47], and Southeast Asian island cases [17,48], and consistent with Kuang et al.'s [7] global synthesis across 47 island territories, suggests three transferable governance lessons worthy of further testing: governance architecture appears more strongly associated with outcomes than technical quality alone, knowledge transfer is among the highest-return governance instruments identified, and tariff architecture functions as a welfare governance instrument in subsidized island contexts.

Second, the GML operationalizes governance-related system degradation as an economically quantifiable variable amenable to cost–benefit analysis. At the national scale, a comparable shortfall pattern across 1200 planned installations would imply an aggregate fiscal exposure approaching IDR 2.24 trillion per year—a figure that, while illustrative,

points to a category of risk that current project appraisal frameworks do not systematically capture.

Third, the reconceptualization of tariff design as a second-order welfare governance instrument extending O'Toole's [27] implementation instrument concept into energy economics generates the PET framework grounded simultaneously in implementation theory, welfare economics [2], and international subsidy reform evidence [18,24]. Universal PET implementation across 1200 planned installations could generate aggregate annual PLN revenue increases of IDR 10.6 billion while reducing State Budget subsidy burden by IDR 12.4 billion per year—revenue-positive, budget-positive, and welfare-positive, requiring no new legislation.

The findings from Semau Island are the first output of a broader research program on governance sustainability in Indonesia's 3T island energy systems. Three studies are currently in preparation as direct extensions of this work. The first will replicate the MIDEK diagnostic across five NTT islands—Rote, Sabu, Alor, Lembata, and Flores Timur—representing the full range of agro-ecological conditions and PLN institutional arrangements in the province, to test whether the pattern of stronger governance-related associations observed here holds across different island typologies. The second will conduct gender-disaggregated productive use analysis, addressing the absence of female-headed household perspectives from the current qualitative data and responding directly to the SDG 5–SDG 7 intersection in island energy governance. The third will evaluate the PET pilot, if implemented, as a natural policy experiment, tracking welfare outcomes before and after tariff reclassification in a quasi-experimental design. Together, these studies will transform the single-case findings reported here into a multi-site evidence base capable of informing national policy at the scale Presidential Regulation No. 112/2022 demands.

## 6. Conclusions

### 6.1. Summary of Key Findings

This study set out to understand what actually happens when electricity arrives on a remote island—not simply whether households are connected, but whether that connection changes how people live and work. Three principal conclusions emerge from the evidence gathered at Semau Island. We present them here as findings grounded in one specific place and time, acknowledging from the outset that the precise figures—the 40% productive use rate, the IDR 1.87 billion Governance Maintenance Loss—belong to Semau Island and require replication before they can serve as benchmarks for the 1200 island installations Indonesia is planning under Presidential Regulation No. 112/2022.

First, productive electricity use is achievable, and it happens faster than conventional wisdom suggests. Within five years of grid commissioning, 40% of surveyed households ( $n = 123$ ) had shifted from passive consumption—lighting and phone charging—toward productive applications, principally irrigation pumps for dry-season red onion and watermelon cultivation. This rate substantially exceeds what has been documented in comparable Sub-Saharan African off-grid programs [13,19] and aligns with the more optimistic outcomes observed in Pacific Island settings [6]. The implication is straightforward: when agro-ecological conditions support productive demand and governance arrangements do not suppress it, communities can and do make transformative use of grid electricity within a single policy cycle.

Second, how electricity is priced matters as much as whether it is available. The tariff structure that Indonesia uses to protect its most vulnerable households—the 450 VA subsidized tier, which carries a State Budget subsidy of IDR 10,518 per kWh, equivalent to 96.2% of the Cost of Supply—appears to be working against the very welfare gains it is meant to enable. Because productive equipment such as irrigation pumps exceeds the 450

VA capacity ceiling, the households receiving the deepest subsidy are structurally excluded from productive use. The Productive Energy Tariff (PET) proposal developed in this study offers a way to resolve this tension: a dedicated productive-use tier at IDR 800–1000/kWh, grounded in Law No. 30/2009 Article 34(4), that would simultaneously reduce the State Budget burden, increase PLN revenue, and give smallholder farmers and fishermen the contractual capacity they need to run productive equipment.

Third, the single highest-leverage governance intervention identified in this study costs relatively little and addresses a gap that currently goes unaccounted for in procurement design. The Governance Maintenance Loss—IDR 1.87 billion per year in foregone output from the 200 kW available capacity shortfall at Semau Island—is recoverable through a Knowledge Transfer Mandate (KTM) that would cost between IDR 150 and 200 million to implement. The implied return ratio of approximately 120:1 in annual terms is not a projection from a financial model; it is derived directly from the measured capacity gap and published fuel and diesel price data. If a comparable governance shortfall were to characterize even a fraction of the 1200 planned installations, the aggregate fiscal exposure could approach IDR 2.24 trillion per year—a risk that current procurement frameworks do not require contractors to disclose or address.

## 6.2. Limitations and Boundary Conditions

Honest reporting of what a study cannot establish is as important as reporting what it can. Six boundary conditions shape how the findings above should be read.

First, this is a single-island study, and that choice was deliberate. Following Yin's [29] bounded case logic, the goal was never to sample representatively across Indonesia's 3T island portfolio; it was to test whether a specific theoretical prediction—that governance quality would show a stronger association with welfare outcomes than technical infrastructure quality alone—holds under real-world conditions on a real island. It does, and that consistency with implementation theory [20], polycentric governance theory [21], and the PURE literature [1] is precisely what justifies extending the research to additional sites. The present study is the starting point of that program, not its conclusion.

The specific numbers reported here—the 40% productive use rate and the IDR 1.87 billion GML—are Semau-specific and should be treated as provisional reference points pending replication across islands with different agro-ecological profiles, institutional arrangements, and levels of PLN operational support. Additionally, the qualitative sub-study involved four key informants, selected to cover all distinct institutional roles in Semau Island's energy governance. While this breadth served the study's diagnostic purpose, it inevitably means that some household-level experiences—particularly those of smallholder farmers in more remote villages—are not directly represented in the qualitative data.

Second, the qualitative component has a notable demographic gap: neither female-headed households nor larger commercial electricity customers (1300 VA tier) are represented among the four informants. This matters because women and commercial users often have distinct relationships with productive energy—women as managers of household food security and small enterprises, commercial users as early adopters whose behavior shapes community norms around electricity use. Future work should treat gender-disaggregated and commercial-customer perspectives not as optional additions but as core components of any replication study.

Third, all five constructs were measured through a single self-administered questionnaire administered at one point in time. This creates the possibility that responses on different constructs are correlated for reasons of measurement rather than for the substantive reasons the model proposes—a problem known as common method bias. A Harman's single-factor test (reported in Supplementary Materials) suggests this is unlikely to be a

severe confound: the first unrotated factor accounts for just 22.46% of total variance, well below the 50% threshold of concern. Nevertheless, the cross-sectional single-source design is a genuine limitation, and longitudinal or multi-informant designs would strengthen confidence in the structural relationships reported here.

Fourth, two statistical features of the SEM-AMOS results require careful interpretation. The HTMT discriminant validity ratio between the Electrification Ratio (X3) and Electricity Needs Fulfillment (X4) constructs is 0.887, close to the 0.90 warning threshold, which means the distinction between infrastructure presence and service adequacy in this context is real but empirically narrow. Separately, the path from Smart Grid infrastructure to Electrification Ratio produced an inconclusive coefficient ( $\beta = 0.351$ ,  $p = 0.092$ ), suggesting that the physical system alone does not reliably explain variation in coverage outcomes—a finding that is substantively interesting but requires replication before strong conclusions can be drawn. Both observations reinforce the case for multi-island replication rather than placing sole weight on the Semaui Island findings.

Fifth, the Community Welfare construct is built from respondents' own assessments of how their lives have changed since grid connection—their sense of whether income, health, education, physical safety, and social participation have improved. These perception-based measures are well established in capability-based welfare research [2] and capture something genuinely important: how people experience change, not only what administrative records say has happened. At the same time, perceptions are not the same as independently verified material outcomes. Readers should treat the welfare findings as evidence of how 123 Semaui Island households perceived their situation in mid-2025, not as externally validated proof that incomes rose or health outcomes improved by measurable amounts.

Sixth, the comparison between the 450 VA and 900 VA tariff tiers in Section 4.3 treats tariff category as the variable of interest, but the survey did not collect data on household wealth, land ownership, asset holdings, occupation, or family size. It is entirely plausible that wealthier or larger-landholding households are more likely both to hold a 900 VA contract and to engage in productive electricity use, which would mean the tariff-welfare pattern reflects household characteristics rather than the tariff tier itself. The relationship between tariff tier and productive use reported here is a descriptive association, and controlling for these confounders is an essential priority for the replication program described in Section 6.4.

### 6.3. Policy Implications

The central lesson of this study is not that Indonesia's island energy installations need more capital—they need better governance of the capital they already receive. Two low-cost regulatory instruments, both within the existing legal framework, could meaningfully address the gaps identified here.

The first is a mandatory Knowledge Transfer Mandate embedded in Smart Grid procurement contracts. At a minimum, this would require the installing contractor to train and certify at least three local technicians (80-hour curriculum, Tier-2 certification as a condition of final payment), provide a maintenance manual in Bahasa Indonesia, and establish a local spare-parts inventory adequate for one year of routine maintenance. The estimated cost of IDR 150–200 million per installation is recovered in under 40 days from avoided Governance Maintenance Loss—making this one of the highest-return governance investments available to the Ministry of Energy and Mineral Resources.

The second is a Productive Energy Tariff tier, introduced under Law No. 30/2009 Article 34(4) without requiring new legislation. A tariff in the range of IDR 800–1000 per kWh—above the subsidized household rate but well below the full Cost of Supply—would create a dedicated connection pathway for smallholder farmers, fishermen, and

small enterprises that currently cannot access productive-use capacity under a 450 VA contract. Every household that migrates to a PET connection reduces the State Budget subsidy burden by IDR 1030 per kWh while generating IDR 8.83 million in additional PLN annual revenue—making the reform simultaneously budget-positive, PLN revenue-positive, and welfare-positive for island communities.

Both instruments are modest in cost, grounded in existing law, and pilotable at Semaui Island before any decision about national rollout. We recommend that the Ministry of Energy consider incorporating KTM provisions into the next round of Smart Grid procurement contracts for NTT island installations as an immediate, low-risk first step.

#### 6.4. Future Research

The limitations described in Section 6.2 are not reasons to discount the findings reported here; they are a precise research agenda for what comes next. Three lines of inquiry follow directly from the gaps identified in this study. Multi-site replication is the most urgent priority. The governance-outcome associations observed at Semaui Island need to be tested across islands that differ in agro-ecological profile—dryland agriculture versus coastal fisheries versus mixed economies—and in their institutional arrangements with PLN and regional government. Five NTT islands—Rote, Sabu, Alor, Lembata, and Flores Timur—offer contrasting conditions that would allow meaningful comparative analysis within a geographically coherent setting. Gender-disaggregated and commercial-user data collection should be built into any replication design from the start, not added as an afterthought. Women farmers and fisherwomen are among the most likely beneficiaries of productive-use tariff reform, and their perspectives on energy governance barriers are essential for designing interventions that actually reach them. Similarly, 1300 VA commercial customers represent an underexplored but potentially important diffusion pathway for productive electricity norms. A natural experiment around the PET reform, if implemented, would allow researchers to compare productive use outcomes before and after tariff migration using a difference-in-differences design. This is the most methodologically direct way to disentangle the causal contribution of tariff design from the household-level wealth and asset characteristics that the present study could not control for. Collecting baseline data on asset ownership, land access, and household composition now—before any reform is implemented—would make such an evaluation feasible and credible. Semaui Island is one small island in one of the world's most geographically complex archipelagos. What it has shown is that the question of whether electricity transforms lives in remote island communities is not primarily a question about solar panels and batteries. It is a question about how institutions are designed, how knowledge is transferred, and how tariffs are structured—in short, about governance. That is a question worth pursuing seriously across many more islands.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157709/s1>, Table S1. Standardised factor loadings for all 25 indicator items across five latent constructs (SEM-AMOS measurement model,  $n = 123$ ). Table S2. Survey sample distribution by village, contract tier, and gender ( $n = 123$ ). Table S3. Governance Maintenance Loss (GML): formula, input parameters, and sensitivity analysis across four diesel price scenarios. Table S4. Key informant profile summary: institutional role, interview date, and relevance to research questions.

**Author Contributions:** Conceptualization, F.J.L.; methodology, F.J.L. and J.A.C.L.; software, F.J.L.; validation, F.L.B., P.K. and P.E.d.R.; formal analysis, F.J.L.; investigation, F.J.L.; resources, F.L.B.; data curation, F.J.L.; writing—original draft preparation, F.J.L.; writing—review and editing, F.L.B., P.K., P.E.d.R. and J.A.C.L.; visualization, F.J.L.; supervision, F.L.B. and P.K.; project administration,

F.J.L.; funding acquisition, F.J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki. Ethical review and approval were waived for this study in accordance with national and institutional requirements, on the basis that the research posed no more than minimal risk to participants, involved no sensitive personal, medical, or financial data, and was conducted under official research permission granted by the Investment and One-Stop Licensing Service Agency (Dinas Penanaman Modal dan Pelayanan Terpadu Satu Pintu) of Kupang Regency, East Nusa Tenggara, Indonesia (Research Permit No. 074/210/DPM-PTSP/V/2025, dated 6 May 2025). Survey respondents were informed of the study's purpose and voluntary, anonymous nature prior to participation; key informant interviewees additionally provided written consent, as described in Section 3.4.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions concerning identifiable household-level survey responses; however, the anonymized dataset underlying Tables 1–4 may be submitted to the editorial office for verification purposes upon request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|       |                                                                     |
|-------|---------------------------------------------------------------------|
| 3T    | Terdepan, Terluar, Tertinggal (Frontier, Outermost, Underdeveloped) |
| BCa   | Bias-Corrected and Accelerated (bootstrap CI method)                |
| BPP   | Biaya Pokok Penyediaan (Cost of Supply)                             |
| CFA   | Confirmatory Factor Analysis                                        |
| GML   | Governance Maintenance Loss                                         |
| HTMT  | Heterotrait-Monotrait Ratio                                         |
| KTM   | Knowledge Transfer Mandate                                          |
| MIDEK | Integrative Model of Energy Diversification in Island Territories   |
| PET   | Productive Energy Tariff                                            |
| PLN   | PT Perusahaan Listrik Negara (State Electricity Company)            |
| PURE  | Productive Use of Renewable Energy                                  |
| SEM   | Structural Equation Modeling                                        |
| SPP   | Solar Power Plant/Sistem Pembangkit Photovoltaic                    |

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