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Solar eclipse or managerial breakdown? Governance and sustainability of solar mini-grids in colombian island communities

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A B S T R A C T

Despite rapid growth in renewable energy deployment, ensuring the long-term sustainability of off-grid solar mini-grids remains a challenge, particularly in remote and underserved regions. This study examines the decade-long performance of hybrid solar photovoltaic (PV)-diesel mini-grids in three Colombian island communities, Isla Fuerte, Isla Múcura, and Santa Cruz del Islote, where initially successful installations have since experienced declining service quality. Drawing on ten years of electricity provision data, semi-structured interviews, and focus groups, the analysis identifies interrelated technical, managerial, and institutional factors that undermine sustainability. Key drivers include limited community engagement during planning, insufficient operator training, inadequate maintenance, and weak communication between local and central actors. Contrary to common assumptions that professionalized management guarantees reliability, the transition from community to private operation often failed to improve outcomes in the absence of stable financial and regulatory support. The study also reveals how rapid demographic and economic change outpaced systems originally designed for basic residential use. By linking governance dynamics with long-term performance data, the research provides empirical evidence from an under examined Latin American island context. Policy recommendations emphasize the importance of participatory governance, continuous capacity building, and performance-based maintenance frameworks to enhance the resilience and inclusiveness of mini-grids in remote areas.

Introduction

Despite high electrification rates, more than 400,000 residences still lack access to electricity in Colombia. More than half of these homes are situated near the National Interconnected System (SIN), while the remainder are in Non-Interconnected Zones (ZNI),[1] areas that are often remote and costly to serve. A 2020 study estimates that low or absent electricity access affects 223,688 residents living near SIN areas and 207,449 in ZNI regions (Pérez-Arriaga & Ortiz Jara, 2020).

To address energy poverty, Colombia has prioritized renewable energy solutions such as solar photovoltaic (PV) mini-grids and hybrid systems combining solar with battery storage and diesel generators to power isolated communities. These technologies are favored for their cost-effectiveness and low environmental impact in areas where fuel transport is expensive and difficult. The government, through the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE), has supported various solar projects to provide electricity to households and public infrastructure such as schools and health centers (IPSE, 2024).

However, the potential for reducing energy poverty through mini-grid systems in remote rural areas depends on the long-term sustainability and reliability of these systems. In practice, many mini-grids fail to provide continuous service due to technical, financial, and institutional weaknesses. Identifying the drivers of mini-grid malfunction is therefore critical for designing sustainable and resilient energy solutions for populations without access to the national grid.

While existing research on off-grid electrification has focused primarily on technical feasibility and cost efficiency, far less is known about how governance and management practices affect system performance over time, particularly in small-island contexts. This gap is important because island mini-grid systems are especially vulnerable to maintenance delays, logistical bottlenecks, weak institutional coordination, and limited redundancy in service provision. As a result, governance failures in such settings can translate rapidly into prolonged outages and declining service quality. This paper addresses this gap by examining the operational histories of three hybrid solar PV-diesel mini-grid systems installed on remote Colombian islands, all of which have experienced interruptions or collapse since installation.

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[1] SIN refers to areas of Colombia that are connected to the national electricity grid. ZNI (*Zonas No Interconectadas)*—constitutes areas of Colombia that lie outside the reach of the national electricity grid.

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This study asks: How do central and local management *decisions influence the quality and sustainability of hybrid solar PV mini-grid projects?* Specifically, the managerial aspects considered include community participation in project design, local training and system maintenance capacity, monitoring and evaluation of system performance, and communication between local and central stakeholders before installation and during operation.

Methodologically, the paper combines ten years of time-series telemetry data with qualitative interviews and focus groups, offering a unique longitudinal and multi-level perspective on renewable energy governance in Latin America. By linking measured service provision over time with the lived experiences of users, operators, and public officials, the study is able to trace how governance and management dynamics become visible in long-term operational outcomes. The findings contribute to broader debates on the institutional dimensions of energy transitions and energy justice, showing how the interaction between central policy design and local management practices shapes the durability of decentralized energy systems.

This paper makes three main contributions. First, it contributes to the literature on mini-grid sustainability by showing that service decline in remote island systems is not best understood as the result of a single technical breakdown or isolated managerial failure, but rather as the cumulative outcome of interacting planning, maintenance, financial, and governance weaknesses over time. Second, it contributes methodologically by combining longitudinal telemetry data with qualitative interviews and focus groups, allowing for a more robust analysis of how governance failures and user experiences relate to observed performance patterns. Third, it contributes empirically by providing evidence from small-island communities in Colombia's ZNI, a Latin American context that remains underrepresented in the global mini-grid literature and that helps qualify assumptions that professionalized private management necessarily improves system reliability. Taken together, these contributions position the paper not only as a case study of system decline, but as a broader analysis of how governance arrangements shape the long-term durability of decentralized energy infrastructure in remote settings.

The paper proceeds as follows: Section 2 reviews relevant literature on renewable energy transitions in remote communities, emphasizing governance, technical feasibility, and sustainability challenges. Section 3 outlines the methodology and case study selection. Section 4 presents the experiences of the three Colombian island communities following the installation of solar mini-grids. Section 5 analyzes the key managerial, technical, and institutional factors affecting system performance, including community participation, training, maintenance, and communication. Finally, Section 6 discusses the findings and offers policy recommendations, and Section 7 concludes with broader implications for future mini-grid implementations in remote regions.

Renewable energy transitions in remote areas

The expansion of renewable energy mini-grids and off-grid electrification has emerged as a critical response to energy access challenges in remote and underserved regions. Effective management of these systems is essential for ensuring long-term sustainability, economic viability, and integration into local communities. Mini-grids offer a viable alternative to centralized grid expansion, but their success depends on governance structures, institutional arrangements, and community participation. This literature review synthesizes key insights from recent studies on mini-grid management, with a focus on feasibility, sustainability, policy drivers, and best practices for ensuring reliable and inclusive energy access in developing regions.

These challenges are particularly pronounced in small island and other non-interconnected contexts, where geographic isolation, limited institutional redundancy, logistical constraints, and persistent dependence on hybrid diesel–renewable systems amplify the consequences of governance and management failures. In such settings, disruptions in maintenance, financing, or institutional support can translate rapidly into prolonged service interruptions and social impacts, making governance quality a central determinant of system performance (Eras-Almeida & Egido-Aguilera, 2019; Etienne & Robert, 2024).

Feasibility studies play a crucial role in assessing the prospects of solar and hybrid renewable systems. Abo-Zahhad et al. (2024) emphasize the importance of site selection factors such as elevation, land slope, soil texture, and cloud frequency in determining the performance of photovoltaic (PV) systems. By employing multiple meteorological data sources and energy yield estimation methods, this study highlights the variability in energy predictions, demonstrating the necessity of selecting accurate weather data sources. Additionally, a multi-criteria decision-making (MCDM) approach helps balance technical efficiency with economic feasibility, guiding decision-makers based on their priorities. Similarly, Come Zebra, van der Windt, Nhumaio, and Faaij (2021) investigate hybrid renewable energy systems (HRES) for off-grid electrification, demonstrating how government support and community engagement influence their long-term viability. Their findings underscore the cost advantages of solar PV and hybrid PV-diesel systems compared to traditional diesel-powered mini-grids, reinforcing the technical and economic rationale for renewable energy adoption in developing regions.

Governance remains a key determinant of the successful deployment of mini-grids. Berthélemy (2016) discusses governance challenges in electricity access and frames them within Elinor Ostrom's tragedy of the commons, arguing that polycentric governance structures could improve mini-grid sustainability. Lessons from past rural electrification projects suggest that localized, community-driven governance models may mitigate grid inefficiencies and user costs. In the context of Sub-Saharan Africa, Babayomi et al. (2023) highlight the critical role of policy frameworks in shaping mini-grid deployment. Their review of financing models, tariff structures, and decision-making models indicates that energy justice considerations are often neglected, leading to inequities in electricity access. They advocate for an energy justice framework to guide future mini-grid developments, ensuring equitable and sustainable electrification. Eras-Almeida and Egido-Aguilera (2019) extend this discussion to small island energy systems, which face unique governance and financial challenges due to their reliance on non-interconnected thermal power plants. Their study suggests that regulatory frameworks and business models, such as Renewable Energy Service Companies and competitive auctions, are essential for facilitating the transition to hybrid renewable mini-grids.

Building on this governance literature, energy justice scholarship provides a complementary analytical lens for examining how management and institutional arrangements shape energy outcomes in remote contexts. Energy justice frameworks commonly distinguish between three interrelated dimensions: *procedural justice*, concerning who participates in decision-making and how accountability is structured; *recognitional justice*, referring to whether local capacities, needs, and social realities are acknowledged; and *distributional justice*, which focuses on how benefits and burdens, such as reliability, outages, and exposure to costs, are allocated (Jenkins, McCauley, Heffron, Stephan, & Rehner, 2016; McCauley, Heffron, Stephan, & Jenkins, 2013; Sovacool, Heffron, McCauley, & Goldthau, 2016). In remote island mini-grids, these dimensions are closely intertwined with governance and management practices, as decisions about system design, handover arrangements, maintenance responsibilities, and subsidy allocation directly affect service reliability, community legitimacy and community members' ability to pay and benefit from electrification.

Community engagement is a critical factor influencing the sustainability of mini-grid projects. Gill-Wiehl, Miles, Wu, and Kammen (2022) highlight the importance of early-stage participation, technical capacity-building, and governance structures in enhancing long-term project viability. Katre, Tozzi, and Bhattacharyya (2019) reinforce this by demonstrating that strong institutional, financial, and technical capacities foster project longevity when communities actively govern their systems. Gollwitzer, Ockwell, Muok, Ely, and Ahlborg (2018) further conceptualize mini-grids as Common Pool Resources (CPRs), borrowing insights from natural resource management literature to develop a framework for sustainable governance. Together, the literature highlights that effective governance—characterized by early community involvement, capacity building, locally grounded institutions, and shared management responsibilities—is central to the sustainability of hybrid mini-grids.

Institutional frameworks play a significant role in mini-grid sustainability. Ngoti (2024) examines institutional arrangements for the maintenance of community-based solar mini-grids, finding that reactive maintenance strategies and inadequate maintenance funds undermine long-term viability. The study suggests that enforcement of maintenance rules, accountability structures, and cost-effective adjudication mechanisms could enhance sustainability. Government policies and support structures significantly influence mini-grid deployment. Palit and Kumar (2022) find that in India, while the country has achieved near-universal electrification, barriers to sustaining mini-grid operations persist. Their study ranks policy and economic factors as the most influential drivers, with a strong emphasis on integrating mini-grid development with livelihood programs and agricultural initiatives. Similarly, Nyarko, Whale, and Urmee (2023) propose a greater role for private sector involvement and local manufacturing to address cost constraints.

While mini-grids are widely promoted as solutions for rural electrification, their long-term sustainability is often uncertain. Etienne and Robert (2024) propose a multidimensional sustainability framework encompassing technical, financial, institutional, and socio-cultural factors. Their longitudinal study in Senegal reveals that delays in maintenance trigger cascading sustainability issues, weakening user trust and business models. They argue that mini-grids should not be viewed as fully autonomous systems; instead, sustained external support and funding are required for their long-term success. Boait (2014) focuses on demand management within mini-grids, highlighting the necessity for precise demand forecasting and supply-demand balance, as mini-grids have limited generation capacity compared to centralized grids. Addressing these challenges through smart demand-side management strategies can enhance mini-grid reliability and efficiency.

Economic feasibility remains a central concern for mini-grid implementation. Come Zebra et al. (2021) show that solar PV and hybrid PV–diesel mini-grids are more cost-effective than diesel-only systems based on levelized cost of energy (LCOE), yet high upfront capital costs and limited financing mechanisms continue to constrain large-scale deployment. Evidence from Tanzania indicates that supportive regulatory and financing instruments can mitigate these cost barriers: Edsand and Bångens (2024) find that results-based financing combined with a small power producers regulatory framework has contributed to lower solar panel costs and sustained private-sector investment in PV mini-grids. Similarly, Cerón, Gómez-Luna and Vasquez (2025) argue that policy-supported distributed renewable systems can improve the cost-efficiency of electrification in non-interconnected zones.

Despite these advances, financial sustainability challenges persist. Nyarko et al. (2023) identify limited user ability to pay as a key barrier, while Peters, Sievert and Toman (2019) highlight payment defaults and overestimated demand as major risks to commercial viability. Hazelton, Bruce and MacGill (2014) further show that inappropriate system sizing and poorly matched business models exacerbate financial instability, underscoring the importance of realistic demand forecasting and tailored financing approaches. Collectively, the literature suggests that reducing technology costs must be complemented by regulatory frameworks and financing mechanisms that lower investment risk and align system design with actual demand.

The literature highlights the multifaceted challenges of deploying and sustaining renewable energy mini-grids, requiring coordinated attention to technical, economic, and governance dimensions. Feasibility studies identify key technical and environmental determinants of success (Abo-Zahhad et al., 2024; Come Zebra et al., 2021), while governance and policy frameworks critically shape system viability (Babayomi et al., 2023; Berthélemy, 2016; Eras-Almeida & Egido-Aguilera, 2019). Sustainability analyses further emphasize the interdependence of financial, institutional, and technical factors, underscoring the need for long-term planning and external support (Etienne & Robert, 2024). Economic studies highlight the role of financing mechanisms, cost-effective system design, and alignment with local economic activities in achieving durable outcomes (Cerón et al., 2025; Come Zebra et al., 2021).

From an energy justice perspective, these strands of literature indicate that failures in participation, recognition of local conditions, and continuity of institutional support often translate into unequal exposure to outages, unreliable service, and escalating costs in remote settings. This is particularly salient in island mini-grids, where limited alternatives magnify the distributional consequences of governance breakdowns.

While the existing literature provides a solid foundation for understanding technical feasibility, governance models, energy justice, and economic dimensions of mini-grid sustainability, this study contributes a context-specific and empirically grounded examination of solar mini-grids in small island settings, an area often underrepresented in prior research. The findings confirm widely discussed themes, such as the importance of community participation (Gill-Wiehl et al., 2022; Gollwitzer et al., 2018) and the detrimental impact of inadequate maintenance (Etienne & Robert, 2024), showing how these issues manifest in the Colombian ZNI context. However, this study also reveals critical points of divergence. For example, while professionalized private sector involvement is often seen as a way to improve reliability (Eras-Almeida & Egido-Aguilera, 2019), the transition to private management on the islands resulted in declining service and increased dissatisfaction, highlighting how financial instability and weak institutional support can undermine even technically competent operators. Additionally, although modular mini-grids are frequently promoted for their scalability (Come Zebra et al., 2021), this research shows that without ongoing institutional support and planning, systems designed for household use can rapidly become obsolete under the pressure of tourism and demographic shifts. By capturing the lived experiences of residents and tracing the breakdown of system functionality over time, this paper offers both a validation and a critical rethinking of prevailing assumptions about mini-grid governance, sustainability, and effectiveness in remote regions.

Building on this literature, Fig. 1 presents the conceptual framework that guides the analysis. The framework illustrates how system planning and management inputs, such as local participation, training, maintenance, monitoring, and communication, shape operational outcomes and long-term system sustainability in isolated island contexts. The lower feedback arrow labeled "Institutional Learning" represents adaptive processes through which operational experience and performance outcomes inform governance redesign and management practices.

Methodology

This study employs a qualitative case study approach to examine how governance and management practices influence the long-term performance of hybrid solar photovoltaic (PV) mini-grid systems in remote island settings. Case studies are well suited to complex, context-dependent infrastructure systems by enabling examination of interactions between technical design, institutional arrangements, and local practices(Stake, 1995; Yin, 2018). To strengthen analytical

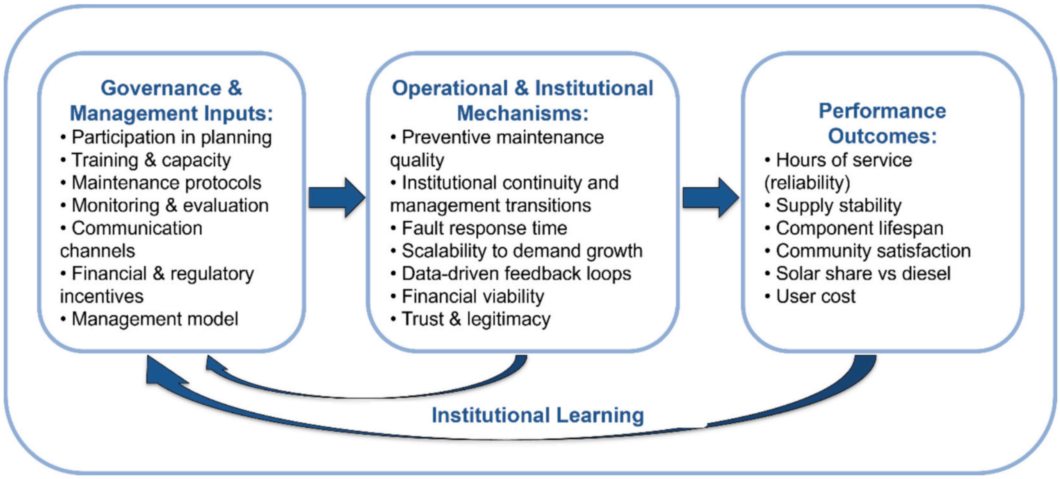

Fig. 1. Conceptual Framework for Mini-Grid System Governance and Performance.

robustness, qualitative data are integrated with quantitative system data, allowing for triangulation across data sources and temporal scales (Timans, Wouters, & Heilbron, 2019). The study draws on IPSE's longitudinal telemetry[2] data of electricity service provision to complement and contextualize the qualitative findings.

Case study selection

The study examines three island communities off Colombia's Caribbean coast: Isla Fuerte, Isla Múcura, and Santa Cruz del Islote (hereforth Islote) (see Fig. 2). All three are located in Colombia's Non-Interconnected Zones and rely on hybrid mini-grid systems combining solar PV generation, battery storage, and diesel backup, installed in 2013. Despite these interventions, the islands have experienced recurrent service interruptions over time, making them appropriate cases for examining the long-term sustainability of renewable mini-grids.

The cases were selected because they share core structural conditions while differing markedly in local characteristics. All three are geographically isolated, disconnected from the national grid, and governed under the same national policy framework overseen by IPSE. At the same time, they differ substantially in population size, density, and economic structure. Isla Fuerte has approximately 2000 residents and a mixed economy based on fishing, tourism, and agriculture. Isla Múcura has around 100 permanent residents and a highly seasonal tourism-based economy, while Islote is an extreme case of density, with roughly 1200 residents living on an artificial island of about one hectare. These contrasts, combined with broadly similar technological and institutional conditions, enable comparative analysis of how governance and management practices interact with local context to shape the long-term performance of decentralized energy systems (Stake, 1995; Yin, 2018).

Data collection

Fieldwork was conducted between March and May 2024 in the three islands—Isla Fuerte, Isla Múcura, and Islote. Primary qualitative data were collected through semi-structured interviews and complemented by two focus groups conducted on Isla Fuerte and Isla Múcura with community members and local system operators. Participant recruitment followed a flexible snowball and field-based approach appropriate for remote island contexts (Stake, 1995). Initial access was facilitated through community leaders (board members of the Community Action Boards and Community Councils) and system managers, followed by on-site recruitment of additional households across different areas of the islands. Focus group participants were invited through community leaders and open calls during field visits, with the aim of including residents with diverse electricity-use patterns, involvement in local governance, and variation in gender and age. These engagements explored decision-making related to system design, project implementation, training and maintenance arrangements, monitoring practices, and communication between local and central actors. Data collection continued until additional interviews yielded limited new insights into the core governance and management themes, indicating data saturation and sufficiency for the study's analytical objectives.

Additional semi-structured interviews were conducted on-site with representatives of the private management company Soling de Sinú at its offices in Santa Cruz de Lorica on the mainland, followed by remote interviews with central government officials from IPSE, based in Bogotá, involved in project design and monitoring. In total, 30 semi-structured interviews and two focus groups (each involving 12 participants) were completed, capturing perspectives across governance levels and operational roles. All interviews and focus groups were audio-recorded with informed consent and transcribed verbatim. In addition, administrative and policy documents from IPSE and national off-grid and renewable energy policies were analyzed.

Data analysis

Data were analyzed using an iterative thematic coding process guided by the study's research questions. Coding focused on governance and managerial dimensions of mini-grid performance, including institutional coordination, maintenance and oversight, and responses to system failure. Coding and preliminary analysis were undertaken alongside data collection, allowing emerging themes to inform subsequent interviews and to assess data saturation. Quantitative telemetry data from IPSE were used to track long-term trends and fluctuations in service provision and to compare reported experiences with observed performance patterns over time, thereby enabling triangulation between perceived and measured system performance.

Mini-Grid experiences in three island communities

Before the mini-grids were installed in 2013, many islanders relied on limited, individual diesel generators or even candles and lanterns. As one Isla Múcura resident recalled: “Before electricity, people lived with a wick... made with a hammock wick and gas” (Isla Múcura Interviews,

[2] Telemetry data consist of remotely collected; time-stamped operational records transmitted from system monitoring equipment and are used in this study to assess electricity generation and overall system performance.

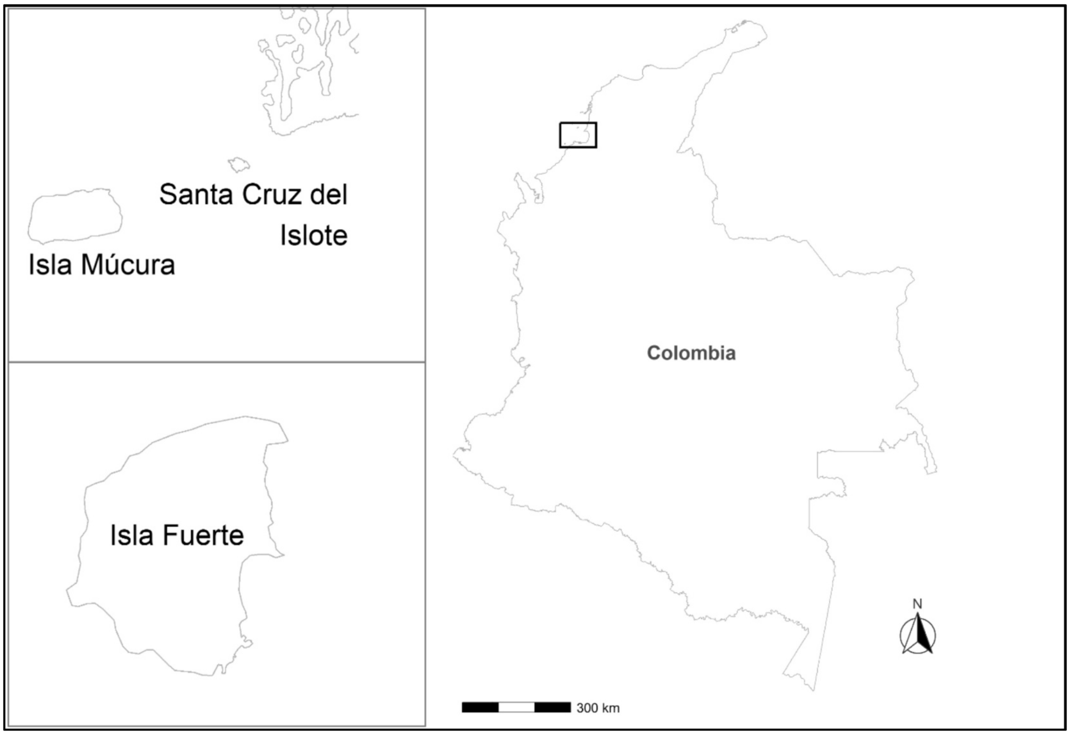

Fig. 2. Location of the case study islands in Colombia's Caribbean region.
(Source: Map created by the authors based on publicly available geographic data.)

2024). When the systems were first installed, there was a sense of excitement and transformation on the islands. The arrival of electricity brought immediate improvements to daily life. "The first night the light came, people didn't want to sleep," remembered one Isla Múcura resident (Isla Múcura Interviews, 2024). In Islote, the system initially allowed for 24-h electricity, transforming local businesses and daily practices. People began storing fish, juices, and other goods, leading to the growth of bakeries and fast-food stalls.

However, the systems quickly became overburdened by increased in household electricity demand, growing populations and the rise of tourism-related businesses, such as eco-hostels and restaurants, driving demand beyond installed capacity. A resident of Isla Múcura explained, "The system required more load than recommended. This influenced the wear and tear of the system" (Isla Múcura Interviews, 2024). "Electrification results in more people arriving in the area, the population grows," added one government official, pointing to how the increased migration further strained the system (IPSE Interviews, 2024). On Isla Fuerte, this imbalance was also evident, as residents reported that the solar panels initially provided around five hours of power, which soon diminished to just one to one and a half hours per day during certain periods due to system degradation (Isla Fuerte Interviews, 2024).

The energy challenges were exacerbated by technical failures, particularly with the battery storage systems. "The current issue is battery storage. People are depending on the diesel plant," one IPSE staff emphasized (IPSE Interviews, 2024). On Isla Múcura, the battery bank eventually exploded after overheating due to inadequate preventive maintenance, leading to further instability in the power supply. "Since 2022, signs began that the system was being damaged, but prevention was lacking," noted a local operator (Isla Múcura Interviews, 2024). Residents of Isla Múcura were already aware of the system's limitations from the start, with one resident recalling, "When they installed it, the engineer said that the system was going to have a useful life of 5 years" (Isla Múcura Interviews, 2024). Similarly, on Islote, the solar system stopped working due to battery life expiration and electronic misconfigurations (Islote Interviews, 2024).

As the solar components of the systems deteriorated, diesel generators became the primary source of power, increasing the cost of electricity for residents. On Isla Fuerte, for example, residents faced frequent blackouts and had to rely on costly diesel fuel, which only provided power for approximately 18–20 days per month (Isla Fuerte Interviews, 2024). Many communities resorted to purchasing their own small generators and sharing fuel, reflecting a growing dependence on expensive and unsustainable energy solutions. In the words of a local resident of Islote, "When the plant was damaged for about a month, many people bought small plants" (Islote Interviews, 2024).

Across all three islands, the energy systems, once a source of joy, have experienced frequent outages, unreliable solar energy, and an increasing reliance on diesel power. Fig. 3 presents telemetry data from the installed IPSE equipment (hybrid solar PV with batteries and diesel generators) illustrating long-term trends in electricity supply across the islands.[3] As shown by the dotted trendline, all islands experienced a continued reduction in daily hours of service. Another notable feature is the severe fluctuations in energy supply, particularly in Isla Fuerte and Islote. Isla Fuerte shows a significant downward trend in service hours, with initial peaks reaching above 20 h during 2016 and 2017, followed by a sharp and sustained decline beginning in October 2017, with monthly averages frequently at four to six hours per day. Islote exhibits considerable variability with extreme peaks and valleys. Service hours on Islote frequently fluctuate between lows near 5 h and highs at 17–18 h, reflecting a high degree of inconsistent energy supply. Isla Múcura also demonstrates a declining trend but in a more gradual manner, as depicted by the flatter trendline. After the lowest monthly average of 7.8 h in July 2016, the mini-grid has continuously supplied roughly 10–16 h per day on average.

[3] The data depicts a monthly average of daily service delivery. Daily service delivery refers to the number of hours in day that the system provided electricity to its citizens. The data do not disaggregate electricity by generation source (solar versus diesel), but instead report total electricity provision from the hybrid system.

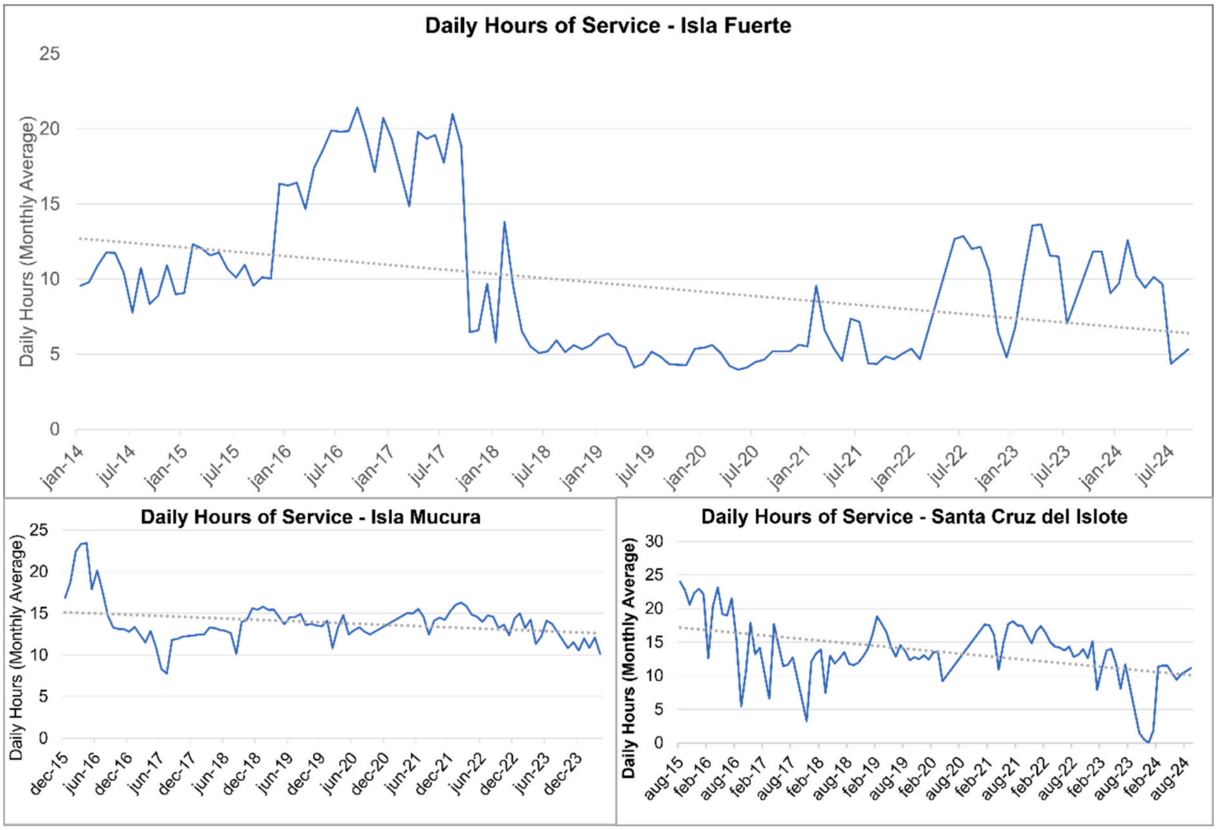

Fig. 3. Daily Hours of Electricity in Island Communities 2014/15–2024. Source: (IPSE Interviews, 2024).
Note: Telemetry data for Isla Fuerte was available from January 2014, for Isla Múcura from December 2015 and for Islote from August 2015.

In summary, the telemetry data indicate significant issues with the mini-grid systems providing reliable electricity supply to the three islands. The next section analyzes multiple planning and management aspects to identify possible explanations behind the fluctuating energy supply. Building on these findings, the subsequent section offers targeted policy recommendations to inform future energy implementation strategies in remote communities.

System planning and management: Findings

This section presents the empirical findings on system planning and management across the three island cases, grounded in triangulated evidence from longitudinal telemetry data, IPSE documentation, and primary qualitative data. Together, these sources provide corroborating quantitative and qualitative evidence on how governance, management practices, and institutional arrangements have shaped system performance over time on the three islands. Guided by the conceptual framework in Fig. 1, the analysis examines how key governance and management dimensions, including participation in planning and handover, local capacity and training, maintenance practices, monitoring and evaluation, communication between local and central actors, and financial and regulatory support, have influenced operational outcomes and the long-term sustainability of the mini-grid systems.

IPSE role and renewable strategy

The Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE) plays a central role in addressing energy poverty in Colombia's non-interconnected zones (ZNI) through the development of sustainable and hybrid energy solutions. IPSE finances these initiatives through a combination of local and international funding sources. The *Fondo de Apoyo Financiero para la Energización de las Zonas No Interconectadas* (FAZNI) provides the primary financial support for regional projects. Additionally, IPSE secures substantial international funding from entities such as the Inter-American Development Bank (IDB) and the Global Environment Facility (GEF) (Eras Almeida, Vásquez, Merlyn, Hurtado Coordinador, & Egido, 2020).

At the national level, Law 1715 of 2014 serves as a key legislative framework promoting the integration of non-conventional renewable energy sources into the national energy system. It establishes fiscal incentives and regulatory mechanisms to support renewable energy projects across Colombia, especially in isolated, non-interconnected zones, that traditionally rely on diesel generation (CMS, 2024). In practice, Law 1715 provides public funding and tax incentives, mandating that IPSE promote renewable energy and efficiency initiatives aimed at expanding energy access in remote ZNI areas such as Isla Fuerte, Isla Múcura, and Islote (Eras Almeida et al., 2020).

System ownership and management transition

The implementation of energy systems on Isla Fuerte, Isla Múcura, and Islote initially followed a hybrid management model, with IPSE responsible for system design and installation. During this phase, IPSE facilitated the creation of local cooperatives intended to assume responsibility for system management after handover. Interviewees reported that training of local personnel was brief—lasting no more than two weeks—and that communities were given limited time to establish cooperatives, a first-time endeavor requiring the creation of boards, operating rules, and payment-collection mechanisms. Despite this substantial transfer of responsibility, respondents emphasized that post-handover technical and administrative support from IPSE was minimal (Interviews Isla Fuerte, Isla Múcura and Islote, 2024). Over time, these constraints contributed to mounting operational and governance challenges, and in 2021 the community-based management model was replaced by an external contractor, Soling del Sinú (IPSE Interviews, 2024).

Throughout the study period, asset ownership, tariff regulation, and subsidy frameworks remained public and unchanged; the empirical analysis therefore focuses on changes in management and governance practices rather than on ownership transitions.

Importantly, this management change did not constitute a transfer of asset ownership or a shift toward a fully market-based electrification model. In both periods, the mini-grids remained publicly owned infrastructure implemented within Colombia's national policy framework for ZNI. Government support primarily took the form of capital investment and financial support for diesel generation, while long-term operational support for the renewable (solar and battery storage) components of hybrid systems remained more limited. The transition in 2021 therefore primarily altered the locus of operational responsibility and formal decision-making authority, rather than the underlying policy or subsidy framework.

Within this institutional continuity, community operators reported that their rapid assumption of management responsibilities, coupled with limited understanding of the subsidy framework, prevented them from effectively accessing available government support. On Isla Múcura, for example, during community management the system relied almost entirely on household electricity payments, which were limited and uneven given the island's restricted income base. When Soling del Sinú assumed control, operations became heavily dependent on fuel subsidies from the central government; however, delays in subsidy disbursement introduced additional financial uncertainty.

In line with the governance dimensions outlined in Fig. 1, the shift from community-led to private management primarily affected decision-making authority, accountability structures, and the interface with national support mechanisms, rather than asset ownership or tariff regulation.

Community-owned systems

Initially, at IPSE's initiative, the systems on Isla Fuerte, Isla Múcura, and Islote were owned and managed by local cooperatives or community councils. From a governance perspective, local cooperatives and councils functioned as the primary decision-making arenas for day-to-day operational issues, including allocation of service hours, responses to outages, and prioritization of minor repairs. These decisions were locally embedded but weakly formalized, and accountability mechanisms relied largely on community norms and leadership rather than codified procedures or performance benchmarks.

On Isla Fuerte, a cooperative named Copercusi managed both the energy system and other public services such as trash collection. However, financial difficulties severely constrained operations between 2018 and 2021, and residents recalled this period as one in which electricity supply had effectively ceased (Isla Fuerte Interviews, 2024). Telemetry data qualify this perception, showing not a complete stop but a sharp and prolonged reduction in supply, with monthly averages typically between four and six hours per day. The prolonged instability created significant hardships for the community.

On Isla Múcura, the system was also managed by a local cooperative in charge of both Isla Múcura's and Islote's system but faced challenges from the outset due to insufficient preparation. The cooperative was established only 20 days before handover, leaving members unclear about their roles. As one focus group participant stated, “The cooperative was set up only 20 days before the handover, so people did not know their role within it” (Isla Múcura Interviews, 2024). This lack of preparation led to immediate operational difficulties. Another resident noted, “The cooperative's problem was that the majority were from Islote, and the priority was Islote, and what was left over was for Múcura” (Isla Múcura Interviews, 2024). This uneven allocation of resources generated frustration among Múcura residents, who felt that the system did not adequately serve their needs.

On Islote, the community council initially managed the mini-grid and took responsibility for ensuring fair electricity distribution. However, the council struggled to sustain the solar system due to a lack of technical expertise and proper maintenance routines. These challenges made it difficult for the community to keep the system operational, setting the stage for a transition to external management. A resident expressed frustration about IPSE's lack of ongoing support, stating, “IPSE installed the project and then washed their hands” (Islote Interviews, 2024).

Across the three cases, the relationship between local and national levels during the community-led phase was characterized by high decentralization in practice and limited institutional support. Although national agencies financed and initiated the projects, interviewees consistently described follow-up as episodic and largely reactive, typically taking place only after major system failures rather than through continuous supervision or structured technical and administrative assistance.

Transition to private management (Soling del Sinú)

Financial and operational difficulties across all three islands eventually led to the replacement of local cooperatives and community councils with Soling del Sinú, a private company contracted to manage the systems. Under this arrangement, Soling del Sinú assumed operational responsibility through contractual agreements while ownership, tariff regulation, and subsidy eligibility remained under state control. This shift aimed to professionalize operations, ensure more reliable performance, and improve maintenance (IPSE Interviews, 2024). However, new challenges emerged, especially regarding financial sustainability and system upkeep.

On Isla Fuerte, Soling del Sinú took over the energy system in 2021, inheriting infrastructure that had deteriorated after years of neglect. The company now faces significant financial strain, as it must cover the costs of diesel when government subsidies run out—which have a monthly cap—placing a burden on both the operator and the community due to rising energy prices (Isla Fuerte Interviews, 2024).

On Isla Múcura, residents became increasingly dissatisfied with the company's management. Although the transition was intended to professionalize operations, many community members felt that the system had functioned better under local control. One resident commented, “Soling made mistakes – they didn't know how to use the hybrid system and they didn't know how to do the readings” (Isla Múcura Interviews, 2024). Another resident explained that “When they managed it as a community it worked better, they maintained it, they did security maintenance, they kept spare parts.” Yet another resident echoed the same sentiment more succinctly: “When they managed it as a community, it worked better” (Isla Múcura Interviews, 2024). Collectively, these accounts suggest that despite its limitations, the cooperative model was perceived as more responsive to local needs than the private contractor. To avoid conflating perceptions with measured performance, we treat these accounts as evidence of experienced responsiveness and legitimacy, while assessing reliability trends primarily through telemetry.

On Islote, Soling del Sinú also faced difficulties improving the situation. Despite taking over the mini-grid, the company lacked the resources necessary to provide adequate maintenance and meet growing energy demands. A resident expressed concern, noting that “Soling does not have the capacity to install the new project that is coming” (Islote Interviews, 2024), referring to a new and bigger system that IPSE has committed to install.

Regulatory barriers—particularly those affecting hybrid energy systems—limited Soling del Sinú's access to government subsidies for solar generation, as existing support mechanisms apply only to diesel fuel and are capped at a maximum monthly amount. As a result, the company faced persistent financial constraints that reduced the effective contribution of solar energy to the islands' power supply (Interviews, Soling del Sinú, 2024). While diesel subsidies provided partial relief, they were insufficient to cover the costs of maintaining aging infrastructure and, in practice, tended to favor reliance on diesel generation.

Across all case study sites, the transition from local management to private ownership introduced new challenges. Financial difficulties, inadequate maintenance, and limited responsiveness to community needs have left many residents convinced that the system performed better under local control.

Telemetry evidence around the 2021 management change. To assess whether service provision worsened following the transition to private management, we compare monthly average daily hours of service before (from first available telemetry through December 2020) and after (January 2021 onward).[4] On Isla Fuerte, mean daily service hours declined from 10.22 h/day before the transition to 8.46 h/day after it ($\Delta = -1.76$ h, −17%), while Islote declines from 14.60 to 12.52 h/day ($\Delta = -2.08$ h, −14%). Isla Múcura shows little change (14.07 to 13.64 h/day; $\Delta = -0.44$ h, −3%).[5] For both Isla Múcura and Islote, the post-2021 period includes a short-term rebound in service provision during 2021 and early 2022, with monthly averages temporarily exceeding late-2020 levels. These improvements were not sustained, however, and were followed by renewed decline from mid-2022 onward. Within the post-2021 period, trendlines diverge: Isla Fuerte exhibits a partial recovery (upward slope) despite high volatility, whereas Isla Múcura and Islote continue to soften (see Fig. 4). These patterns suggest that the management change did not have a uniform effect across islands and likely interacted with pre-existing maintenance backlogs, battery end-of-life, growing demand, and subsidy design.

The partial post-2021 recovery observed on Isla Fuerte warrants specific attention. Unlike Isla Múcura and Islote, Isla Fuerte entered the management transition following an extended period of extremely low service provision, associated with severe operational breakdowns under the cooperative model. The subsequent improvement therefore reflects a rebound from an unusually degraded baseline rather than a clear structural performance gain. Interview evidence suggests that this recovery was supported by short-term operational stabilization, including more regular diesel operation, improved communication channels with IPSE and the contractor, and ad hoc corrective maintenance, rather than by fundamental resolution of underlying issues related to aging components, limited renewable support, or long-term financing. The high volatility observed in the telemetry data indicates that these gains remain fragile and contingent.

Importantly, these pre–post comparisons indicate that performance decline was already underway prior to 2021, and that the transition occurred within an existing trajectory of component aging and deferred maintenance rather than initiating system deterioration.

Local Participation in project planning and implementation

The participatory involvement of local communities in the design and implementation of the mini-grid systems was generally limited, though interviews revealed some differences in community engagement across the islands. On Isla Fuerte, residents had minimal input in the planning process and felt that decisions were largely dictated by the government. “The government has been telling us how the project should be set up; no input from the community has been sought” (Isla Fuerte Interviews, 2024). According to IPSE, “The initial project was made only for providing basic electricity supply to private household for the 3 islands” (IPSE Interviews, 2024), and there was little consideration of the local population's input regarding future expansions.

Similarly, on Isla Múcura, the community had limited involvement during the installation of the mini-grid system. “The community did not pay attention to how much money was available for the project; the community focused only on the opportunity to have light” (Isla Múcura Interviews, 2024). IPSE did conduct limited community outreach about the intended use of the system, but since the cooperative established to manage the system was organized hastily, residents were left unprepared for its operation and management. Nevertheless, the selection of members for the cooperative was somewhat participatory. As a resident explained, “It was open to the entire community to be part of the cooperative and people volunteered” (Isla Múcura Interviews, 2024).

In contrast, the community council on Islote played a more active role in decision-making. The council advocated for the extension of the mini-grid project to Isla Múcura, as it was initially planned only for Islote. As one participant recalled, “Islote fought with the government to expand the project” (Islote Interviews, 2024). Established in 2003, this council also advocated for broader needs such as water, electricity, and healthcare, providing a platform for residents to influence decisions.

Overall, the lack of meaningful consultation during project planning resulted in a disconnect between the designed capacity of the systems and the community's evolving needs. This top-down approach led to frustrations and a misalignment between system capabilities and the actual demands of the populations, particularly as population grew, tourism increased and as residents expanded electricity use to support household needs and small-scale economic activities.

System demand and adaptability

Initial system design

The primary objective of the mini-grid projects on the three islands was to provide basic energy needs for residential households, enabling essential appliances like refrigerators, fans, and televisions. IPSE noted, “The energy systems were built for basic loads, specifically household use” (IPSE Interviews, 2024). However, the initial projections failed to fully anticipate the growing energy demand on the islands.

Increasing demand and system overload

On Isla Fuerte, the system was initially designed for 300 families, but by 2024, nearly 700 families lived on the island, placing a significant strain on the system (Isla Fuerte Interviews, 2024). Tourism growth further exacerbated the situation as businesses required more electricity for appliances like freezers.

Similarly, on Isla Múcura, higher than planned demand overwhelmed the system. As one resident noted, “the photovoltaic system was designed for residential use only… but people started looking for tourism and business opportunities” (Isla Múcura Interviews, 2024), indicating how as tourism increased, new businesses emerged that required higher loads of electricity. This increased pressure contributed to accelerated battery degradation, ultimately leading to battery failure.

Islote also experienced rapid changes in energy consumption habits following the arrival of electricity. A resident shared, “I didn't have a freezer, a TV, a fan; I started buying my fan, then the neighbor saw and bought two, then the other bought a fridge” (Islote Interviews, 2024). Despite warnings by the community council against purchasing too many appliances, demand continued to grow, contributing to mismanagement and further deterioration of the system.

In all cases, the inability to scale system capacity in line with growing population, household, and livelihood demands resulted in system strain and frequent power outages, underscoring the need for more adaptable energy planning. This is particularly relevant in low-income island communities that rely heavily on tourism and fishing, where the introduction of electricity is widely expected to support livelihood diversification and income enhancement.

[4] We compute monthly averages and compare pre (≤2020) vs post (≥2021) means. Because 2016–2019 already show deterioration in Isla Fuerte, we avoid attributing causality solely to the 2021 handover; the analysis identifies temporal correspondence, not causal effects.

[5] Source: Authors' calculations from IPSE telemetry, 2014/2015–2024.

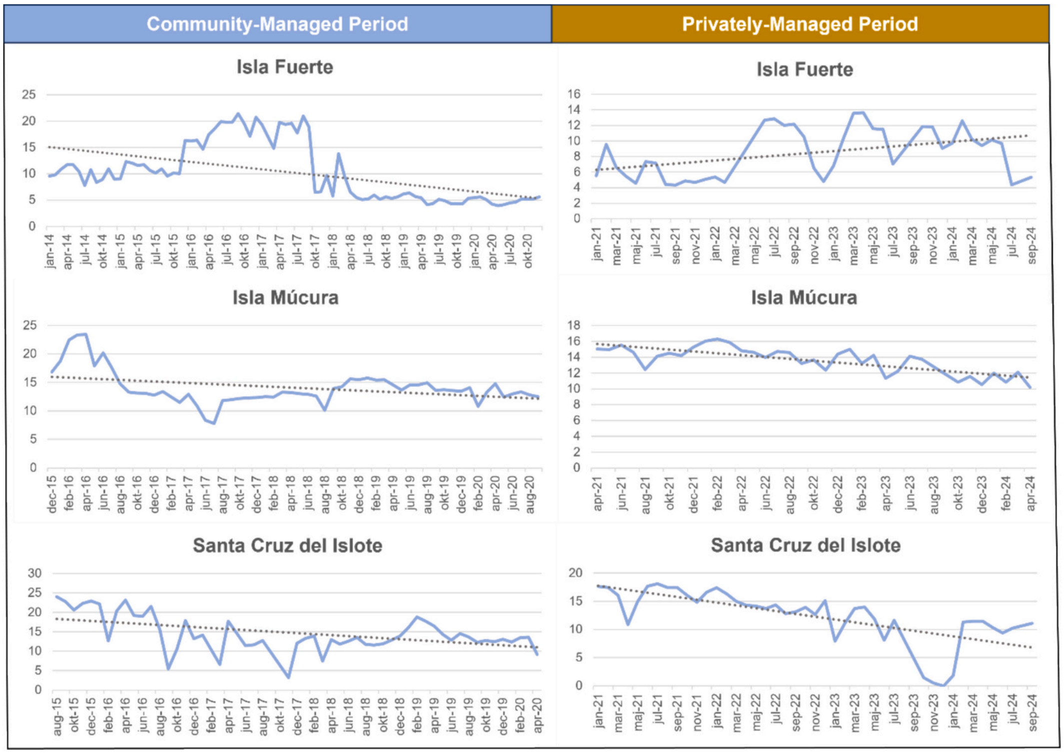

Fig. 4. Transition to private management: Service provision before and after 2021.
(Source: Authors' tabulation from IPSE telemetry (2014/2015–2024).)

Training and maintenance

Local capacity building

IPSE provided basic training to local personnel on operating the energy systems, mainly through booklets, instructions, and operating manuals. "This does not mean that IPSE ignores its monitoring role once the training was completed," according to IPSE (IPSE Interviews, 2024). Despite these efforts, the training was inadequate for handling technical failures, particularly related to battery storage and maintenance. This lack of comprehensive, ongoing training contributed to the system's gradual degradation, particularly the solar panels and batteries, as local operators lacked the expertise to perform preventive maintenance on critical components, eventually leading to increased reliance on diesel generators.

On the three islands, training provided was minimal, and this lack of technical expertise played a significant role in the systems' decline. As noted by one Islote inteviewee, "IPSE only came once at the beginning of the project to train… subsequent operators learned by observing others" (Islote Interviews, 2024). The account from an Isla Múcura echoes the limited training, "the community attended the trainings but without sufficient technical experience. And that is why today we are paying the consequences of our inexperience in the technical management of the panels" (Isla Múcura Interviews, 2024). While basic instruction was offered, it was insufficient to prepare the communities for long-term maintenance and management.

Training limitations extended beyond technical aspects to system management, where capacity-building was even more insufficient. As discussed in the Isla Fuerte focus group, the cooperative initially responsible for managing the system lacked both the financial resources and sustained training required to keep it operational. Participants emphasized that there was no long-term effort to equip local actors with the skills needed for ongoing maintenance and management, ranging from day-to-day operations to payment collection and processing government subsidy requests (Isla Fuerte Focus Group, 2024).

Challenges in system maintenance

Maintenance of the hybrid solar-diesel systems on the islands became a critical issue as the systems aged. Initially, the diesel plants provided sufficient backup energy to cover solar power gaps, but over time, "there was a lack of maintenance, so the diesel plant does not give 100%," leading to energy shortfalls and system breakdowns (IPSE Interviews, 2024). Limited preventive maintenance by the communities, and later by the private operator, resulted in frequent system failures and an increased reliance on diesel fuel.

On Isla Múcura, maintenance was insufficient from the start. Preventive maintenance was rarely carried out, leading to a major system breakdown, including an explosion of the battery bank. "Since 2022, signs began that the system was being damaged, but prevention was lacking," a resident explained (Isla Múcura Interviews, 2024).

In Isla Fuerte, maintenance posed significant challenges as well. The solar panels degraded quickly, and high maintenance costs further burdened the community. "The useful life of the panels has been reached," noted a resident, who added that government subsidies covered only part of diesel expenses, leaving the community to manage the rest when the system failed (Isla Fuerte Interviews, 2024). Frequent voltage fluctuations also caused damage to appliances, with repair costs falling on the residents (Isla Fuerte Interviews, 2024).

On Islote, maintenance was minimal and largely neglected. Although locals were trained to operate the system, they received no instructions on performing routine maintenance on solar panels or batteries. "The solar panels have never had maintenance done by the natives, only the diesel power plant," a resident observed (Islote Interviews, 2024). Two years ago, Soling del Sinú changed the water in the batteries, but no further maintenance was done, leading to system failure and forcing residents to rely on diesel plants (Islote Interviews, 2024).

Since assuming system management in 2021, Soling del Sinú has struggled to maintain already degraded solar and diesel components, and preventive maintenance has remained limited. While the company has carried out routine tasks—such as cleaning solar panels and servicing diesel generators—more complex technical work involving transformers and battery systems requires specialized expertise sourced from cities including Barranquilla, Cartagena, Lorica, Cali, and Bogotá, making such maintenance both costly and subject to delays (Soling del Sinú, 2024). No major upgrades have been undertaken to renew the solar generation component, and the battery systems in particular have aged substantially, severely constraining performance of the solar system and limiting its electricity provision to only a few hours per day across the three islands.

The stepwise drops and prolonged low plateaus that can be seen in the telemetry data (see Fig. 3), particularly Isla Fuerte (2018–2020) and Islote (2023) are characteristic of deferred maintenance and component end-of-life, corroborating interview accounts of battery degradation and irregular preventive work.

System monitoring and evaluation

Since taking over the management of the mini-grids, Soling del Sinú, in collaboration with IPSE, has been responsible for monitoring and evaluating the system. On Isla Fuerte, while operators have been able to report technical issues to mainland specialists, island residents claim that prior to the takeover routine monitoring was limited (Isla Fuerte, Múcura and Islote Interviews, 2024). This view is reiterated by Soling del Sinú, who describes a lack of regular maintenance and system upgrades through the system's operational life, which reflects failed long-term evaluation efforts (Soling del Sinú, 2024). However, IPSE points to its efforts to monitor the performance of the system, such as installing telemetry equipment in 2014–2015 to measure energy delivery and quality (IPSE Interviews, 2024).

Residents' accounts, however, diverge sharply from IPSE's portrayal of ongoing system monitoring. Across the three islands, residents emphasized the absence of sustained follow-up and effective communication from IPSE after system installation. On Isla Múcura, interviewees described limited channels for reporting failures or seeking guidance from either IPSE. As one resident explained, “we were not given any contact details for IPSE, and therefore we had no way of communicating with them” (Isla Múcura Interviews, 2024). Similarly, on Isla Fuerte, a resident noted, “the system has failed because there has been no monitoring by the state” (Isla Fuerte Interviews, 2024). The lack of follow-up and timely technical support left communities coping with unreliable electricity, and over time the system—originally designed to alternate between solar and diesel generation—became increasingly dependent on diesel as solar components deteriorated.

On Islote, the absence of monitoring and evaluation from IPSE or other authorities forced residents to take significant action, including filing lawsuits, to gain the government's attention. As one frustrated resident expresses, “They don't give us any explanations. IPSE staff come, take their notes, asks a few things, and they leave” (Islote Interviews, 2024). Although IPSE returned recently to collect data, no concrete steps have been taken to repair or upgrade the system, leaving the communities dependent on diesel power and personal generators.

As telemetry data presented in Figs. 3 and 4 indicate, electricity provision was continuously monitored by the central government and clearly documents both a long-term decline in service and pronounced fluctuations across the three islands. The core issue, therefore, was not the absence of monitoring infrastructure, but rather the lack of systematic data analysis and feedback mechanisms capable of alerting central authorities to declining performance and triggering timely support. From IPSE's perspective, its mandate was largely limited to system installation and handover to communities; however, given the communities' constrained technical, managerial, and financial capacity, more regular post-handover support—at least in the form of technical and financial guidance—would have been necessary. In addition, interviewees pointed to the need for adjusted subsidy schemes that support the maintenance and repair of solar components, rather than focusing exclusively on diesel fuel.

Communications between local leaders and central government agencies

Across Isla Fuerte, Isla Múcura, and Islote, communication between local leaders and IPSE has remained a persistent challenge. While IPSE maintained direct oversight during the early phases of the energy projects, communication deteriorated after the systems were installed. Residents from all three islands reported difficulty contacting IPSE for technical support once problems arose.

On all islands, communication remained limited for years, despite ongoing challenges with the systems' operation. Residents felt disconnected and abandoned by the central government and forced to manage the systems' problems on their own. On Islote, the situation was particularly strained. The community council made multiple attempts to advocate for improvements and repairs, but government responses were slow and largely ineffective. As one resident explained, “For being an isolated island, government response usually takes a long time. The community has to sue the government to get their attention” (Islote Interviews, 2024).

The arrival of Soling del Sinú brought some changes in communication, particularly in Isla Múcura, where the company acted as a bridge between the community and IPSE. “Now the community has direct communication with some people from IPSE thanks to Soling,” said one resident (Isla Múcura Interviews, 2024). Interviews with Islote residents suggest that communication challenges with the central government remained significant, even after Soling del Sinú took over. The company was unable to fully address the community's needs, and many residents still found themselves resorting to legal action to get government attention. On Isla Fuerte, the introduction of a WhatsApp group with 549 users marginally improved communication, helping residents with basic tasks like meter readings (Isla Fuerte Interviews, 2024). While the group helped create a more efficient way to share information, the overall feeling of exclusion from decision-making persisted. Residents across all islands still felt that the larger, more important decisions about their energy system were made without their input, particularly around the selection of the private operator (Soling del Sinú) and the operation and maintenance of the systems.

Only recently has the central government, through IPSE and the Ministry of Mines and Energy, re-engaged with the island communities to introduce the *Comunidades Energéticas*[6] a nation-wide initiative, which is presented as a pathway for the three islands toward upgrading local electricity systems. Interviews with IPSE staff suggest that the initiative places greater emphasis on socio-economic considerations, alongside technical design, and acknowledges the need to better support communities in establishing effective management and operational arrangements. However, respondents did not indicate a clear commitment to sustained post-installation follow-up or ongoing technical and administrative support (IPSE Interviews, 2024). Moreover, substantial uncertainty remains regarding the timing of implementation, as well as the financing of system installation, operation, and maintenance.

As of December 2025, follow-up communication with community leaders indicated that no new systems had been installed and that energy provision remained severely constrained. On Isla Múcura and Islote, the solar components were no longer operational, while on Isla Fuerte solar-powered electricity supply was limited to no more than two hours per day, leaving communities largely dependent on diesel generation and exposed to fluctuating fuel prices. Community members expressed concern that, if new systems are installed, earlier patterns of limited institutional support may be repeated. At the same time, the acute need

[6] *Comunidades energéticas* (energy communities) are an initiative of the Gustavo Petro government aimed at improving community energy access at lower cost while supporting the energy transition. Under this framework, energy users or prospective users may form collective, community-based organizations to jointly produce, manage, commercialize, and use energy, with a focus on non-conventional renewable energy sources.

for electricity places communities in a position where rejecting new projects, despite their shortcomings, is not a viable option, a situation exacerbated by their limited political leverage as small, low-income, and remote island communities.

Analysis and policy suggestions

This section analyzes the principal findings from an energy justice perspective and presents integrated policy recommendations to strengthen the sustainability of solar mini-grid systems in Colombia's island communities. Drawing from qualitative data and stakeholder insights, the study revealed a complex interplay of issues, ranging from limited community involvement to initial design limitations and maintenance constraints that undermined the sustainability of these systems. The convergence between telemetry data and residents' perceptions echoes findings by Gill-Wiehl et al. (2022) and Gollwitzer et al. (2018), who stress that combining technical indicators with governance and participation insights produces a more complete understanding of mini-grid resilience. The alignment between the time-series telemetry data and local narratives enhances confidence in these findings, showing that perceptions of decline are substantiated by objective performance records. These challenges correspond to the governance and operational dimensions outlined in the conceptual framework (Fig. 1), which provides the analytical structure for interpreting how these factors interact to shape system performance.

This study shows notable fluctuations in energy supply across the solar mini-grid systems in Isla Fuerte, Isla Múcura, and Islote, as shown in Fig. 3. The data highlights a steady decline in service hours over time, with sharp variations in availability between the islands. On Isla Fuerte, service hours dropped sharply from over 20 to just 4–6 h daily, while Islote showed extreme variability, and Isla Múcura experienced a more gradual decline. Importantly, the telemetry data indicate that declining service provision was already underway prior to the 2021 management transition, reflecting cumulative equipment aging and deferred maintenance. Telemetry data further indicate that after the 2021 transition to private management, mean daily service fell modestly across all sites, by 17% on Isla Fuerte, 14% on Islote, and 3% on Isla Múcura before diverging thereafter, with partial stabilization only on Isla Fuerte. These quantitative patterns broadly mirror residents' accounts: communities perceived continued deterioration in reliability following the management change, though the degree varied by island.

Importantly, the analysis does not show that community-led management outperformed private operation in aggregate performance terms; rather, both qualitative and telemetry evidence indicate that service decline was cumulative rather than abrupt, predating the management transition and continuing thereafter, shaped by aging infrastructure, deferred maintenance, and persistent financial and institutional constraints across governance models. This trajectory aligns with Etienne and Robert's (2024) sustainability framework, which emphasizes how delayed maintenance triggers cascading failures and erodes user trust over time. These fluctuations highlight underlying systemic issues in addressing energy poverty on the islands. From an energy justice perspective, this cumulative decline manifests as a distributional justice concern, reflected in unequal and unreliable access to electricity services over time (Jenkins et al., 2016; McCauley et al., 2013).

One prominent issue identified was the limited engagement of local communities during the planning stages of the mini-grid systems. Decisions about the design and implementation of these systems were often dictated by central authorities, with little to no input from the communities they were intended to serve. This mirrors patterns noted in the broader literature, where top-down governance frameworks—contrary to Ostrom-inspired polycentric models—tend to weaken long-term collective management and accountability (Berthélemy, 2016). This dynamic reflects a procedural energy justice deficit, where affected communities have limited influence over decisions that shape their energy futures (Jenkins et al., 2016; Sovacool et al., 2016). This top-down approach led to systems that were poorly aligned with local needs, particularly as energy demands grew due to population increases and tourism. Furthermore, the lack of consultation left many residents feeling excluded, eroding their sense of ownership and accountability. In addition, the absence of meaningful consultation resulted in low-income communities being tasked with managing and operating complex energy systems despite having limited prior experience, constrained technical knowledge, and insufficient financial capacity to sustain effective operation and maintenance.

To address this challenge, policymakers could adopt a more structured and inclusive participatory planning approach. Involving communities from the outset would ensure that their energy needs, aspirations and capacities are better reflected in system designs. Consistent with Katre et al. (2019), durable participation also enhances local legitimacy and the adaptive capacity of energy systems. Establishing regular consultations and follow-ups might provide a platform for meaningful engagement, helping to align technical and managerial solutions with the realities of community life.

Another critical challenge was the inadequate training provided to local operators, which left island residents ill-equipped to manage the systems effectively. Training efforts were often limited to basic operational instructions, which proved insufficient as the systems aged and became more complex to maintain. Ngoti (2024) similarly finds that weak institutional arrangements for maintenance and training undermine system longevity and foster reactive rather than preventive maintenance cultures. This gap highlights a recognitional justice concern, insofar as local capacities, knowledge systems, and long-term operational realities were insufficiently acknowledged in system design and handover processes (Jenkins et al., 2016; McCauley et al., 2013). A potential solution would be to develop robust and continuous training programs. Such programs could include hands-on technical workshops, periodic refresher courses, and long-term mentoring to ensure operators are equipped to handle both routine and unexpected challenges. Regular training should also address managerial and governance functions, including cooperative administration, monitoring of energy supply and demand, fee collection, and communication with users regarding payment obligations. Capacity-building in administrative processes—such as subsidy applications—and in operational decision-making, including diesel procurement strategies, would strengthen accountability between operators and communities across both community- and privately operated energy systems. By reinforcing local governance capacity, such training could reduce operational disruptions, improve financial sustainability, and foster a greater sense of self-reliance and accountability within the community.

The systems also suffered from a lack of scalability, as they were initially designed for basic residential use without accounting for future growth in population or livelihood-driven energy demand. As a result, the systems became overloaded, leading to frequent outages and accelerated degradation of components. This outcome reflects challenges identified by Come Zebra et al. (2021), who note that mini-grids often fail when initial design assumptions ignore demand evolution and productive energy use. This misalignment between system capacity and actual needs exacerbated frustrations in the island communities and further strained already limited resources. From a justice standpoint, this design rigidity exacerbated distributional inequalities by unevenly constraining access as demand expanded (Sovacool et al., 2016). To address this, it is crucial to incorporate growth forecasts and modular scalability into system designs. By prioritizing adaptable solutions, policymakers can ensure that systems remain capable of meeting evolving demands. Integrating demand-side management (DSM) and modular design principles, as recommended in Boait (2014), could also enhance efficiency and system stability. Flexible funding mechanisms could also support incremental expansion, enabling communities to scale their energy systems as their needs grow.

Maintenance practices were another area of concern. The systems faced infrequent preventive maintenance, which contributed to rapid degradation and increased reliance on diesel generators. Financial constraints, coupled with a lack of spare parts and trained personnel, left many communities unable to address these technical failures effectively. This pattern directly reinforces Etienne and Robert's (2024) argument that institutional and financial weaknesses, rather than technological limits, are often the true determinants of mini-grid failure. Training local technicians to conduct preventive and corrective maintenance might further ensure that systems are kept in good condition. To improve maintenance outcomes, clear and structured maintenance protocols, affordable access to spare parts, and access—whether in person or virtual—to specialized technical support could be implemented. Regular inspections and accountability mechanisms could extend the lifespan of critical components and reduce dependence on diesel generators.

Weak communication channels between local communities and central authorities were frequently cited as a major issue. Residents often reported difficulties contacting the relevant agencies to report technical problems or request assistance, both technical and financial. Such communication failures parallel findings by Palit and Kumar (2022) and Nyarko et al. (2023), who emphasize that the absence of institutional feedback loops undermines trust and slows system recovery. This lack of responsiveness delayed repairs and contributed to a sense of neglect among the affected populations. These breakdowns further compound procedural and recognitional justice deficits by limiting accountability and responsiveness. Improving communication frameworks, such as establishing dedicated hotlines or digital reporting systems, could ensure more timely responses to community needs. Such measures would also help foster greater transparency, accountability, and collaboration between stakeholders, ultimately strengthening institutional trust and community engagement.

Finally, financial and regulatory barriers posed significant obstacles. Hybrid systems were hampered by inadequate subsidies and restrictive regulations, which increased operational costs and limited the ability of communities to maintain their systems sustainably. The high costs of diesel and replacement components further strained limited local resources. A subsidy system limited to diesel fuel may also create incentives that favor diesel generation over solar, as the solar component of the hybrid system receives no dedicated financial support for operation or maintenance. This finding supports Eras-Almeida and Egido-Aguilera (2019), who argue that without regulatory mechanisms and financing structures tailored to island contexts, hybrid systems remain economically fragile. Policy reforms, such as restructuring subsidy frameworks to support hybrid systems and introducing incentives for renewable energy projects, could alleviate some of these pressures. Simplifying regulatory processes for hybrid solutions, as recommended in Table 1, would further encourage investment in cleaner, more sustainable energy systems, reducing reliance on fossil fuels over the long term.

Taken together, these findings reaffirm several principles identified in the broader literature on mini-grid sustainability while extending them to the specific context of small islands. Consistent with Etienne and Robert (2024), the results show that technical failures are rarely isolated events but instead reflect cumulative governance and institutional weaknesses that intensify over time. The Colombian islands cases, however, reveal an important qualification to prior work: although private or hybrid management arrangements are often associated with improved efficiency and reliability (Eras-Almeida & Egido-Aguilera, 2019), the observed management transitions did not reverse declining performance in the absence of stable financing, adaptive regulation, and sustained institutional support. Framed through the procedural, recognitional, and distributional dimensions of energy justice, the findings demonstrate that governance and management practices shape not only technical performance but also the perceived fairness, legitimacy, and durability of energy service provision in remote island settings (Jenkins et al., 2016; McCauley et al., 2013).

The policy recommendations outlined in Table 1 aim to address the governance and management challenges analyzed in relation to the conceptual framework (Fig. 1), offering targeted, context-sensitive solutions across key dimensions such as participation, training, maintenance, monitoring, communication, and financial and institutional arrangements. By integrating longitudinal telemetry data with qualitative accounts, the study provides empirically grounded evidence that complements existing theories of community participation, maintenance governance, and institutional continuity, and translates them into concrete governance and management lessons for renewable energy transitions in other remote, non-interconnected, and island contexts. Collectively, the findings and recommendations point toward pathways for building more resilient, community-centered, and adaptive energy systems for remote island populations.

Table 1
Governance Challenges and Policy Recommendations.

Framework Dimension	Description	Recommended Policies
Participation in planning	Limited consultation during planning misaligned system design with local needs.	Expand participatory planning so communities help shape system design and capacity planning.
Management model / institutional continuity	Rushed cooperative formation and unclear responsibilities weakened long-term operation and management.	Introduce phased handover with readiness checklists, clear role definitions, and time-bound follow-up.
Training and capacity	Basic training left local operators unable to manage technical failures or preventive maintenance.	Provide continuous training, refresher support, remote technical assistance, and dedicated capacity-building budgets.
Scalability and demand growth	Systems designed for basic household loads were quickly outgrown by rising population, tourism, and productive use.	Incorporate demand-growth forecasts, DSM measures, and expansion funding into system design.
Maintenance protocols / preventive maintenance quality	Limited preventive maintenance and delayed repairs accelerated component degradation and diesel dependence.	Establish routine maintenance schedules, local spare-parts inventories, rapid procurement arrangements, and periodic audits.
Communication channels	Communities faced persistent difficulties contacting central authorities for support.	Create clear fault-reporting channels and public outage-and-repair tracking systems.
Financial and regulatory incentives	Limited support for hybrid systems increased costs and prolonged reliance on diesel.	Reform subsidy schemes and introduce incentives that better support hybrid renewable systems.
Monitoring and evaluation / data-driven feedback loops	Weak follow-up and lack of response mechanisms allowed technical problems to persist.	Implement regular monitoring, independent review, and telemetry-based response protocols.
Management model / institutional continuity	The shift to private management occurred under legacy degradation and weak cost recovery, with uneven results across islands.	Provide targeted financial and technical support for private operators and enforce performance benchmarks.

Source: Authors' elaboration based on primary data analysis.

Conclusions

This study examined how central and local management decisions shape the performance and durability of solar PV mini-grids in three Colombian island communities, Isla Fuerte, Isla Múcura, and Islote. Triangulating ten years of electricity provision data with interviews and focus groups, we find that declining and volatile service is not the result of a single failure but of cumulative, mutually reinforcing weaknesses in governance, maintenance, and planning. Limited early-stage participation, inadequate operator and management training, weak monitoring and communication channels, and systems sized only for basic household loads, despite rapid growth in population and tourism, produced predictable strain on the hybrid energy systems (particularly, batteries and controls) and a steady fallback to diesel generation. We also demonstrate that the transition from community to private management did not uniformly improve outcomes.

The findings affirm that sustainable off-grid electrification depends on governance arrangements that embed participation, accountability, and adaptive learning. This echoes earlier calls for polycentric and community-based governance (Berthélemy, 2016; Gill-Wiehl et al., 2022) and aligns with studies emphasizing preventive maintenance and institutional stability as preconditions for durable energy access (Etienne & Robert, 2024; Ngoti, 2024). Designing systems that evolve with local demand, both demographic and economic, require continuous interaction between central authorities and communities, supported by stable subsidy frameworks and enforceable maintenance regimes. In this regard, hybrid solar and diesel systems will remain vulnerable unless backed by long-term technical, financial and regulatory commitments that secure both technical upkeep and managerial accountability.

Empirically, this research provides new evidence from small island contexts in Latin America, a setting rarely examined in the global mini-grid literature. By combining telemetry data with qualitative narratives, it illustrates how quantitative performance decline mirrors local perceptions of governance breakdown, offering a multidimensional view of sustainability. The findings challenge assumptions in prior work (Come Zebra et al., 2021; Eras-Almeida & Egido-Aguilera, 2019) that professionalized private management inherently improves reliability. The findings are best interpreted as showing that professionalized private management alone was insufficient to reverse declining reliability in these cases, given aging infrastructure and constrained institutional support. Instead, they suggest that without institutional continuity and local legitimacy, such transitions can deepen system fragility. Theoretically, this study reinforces that governance reform, not technological innovation alone, is central to equitable and durable energy transitions. More broadly, the findings suggest that mini-grid failure is best understood not as the result of isolated technical or managerial breakdowns, but as a cumulative governance process unfolding across system design, handover, maintenance, and financing stages. This process-oriented perspective contributes to a more dynamic understanding of mini-grid sustainability, particularly in small-island contexts where limited redundancy amplifies the effects of governance misalignment.

A limitation of this study is that asset ownership, tariff regulation, and subsidy frameworks remained constant across cases and over time, precluding direct analysis of ownership effects. The findings therefore speak to variation in management and governance practices within a single public ownership regime, rather than to comparative performance across ownership models.

While the analysis is limited to three island cases, the methodological approach, linking institutional diagnostics with longitudinal performance data, offers a transferable framework for studying similar systems in other non-interconnected zones. For policymakers, the central message is that energy governance architecture should be treated as infrastructure: it requires maintenance, adaptation, and investment. Implementing the policy measures identified in this paper, including enhanced participation, capacity building, and consistent technical, financial and regulatory support, can help reverse the cycle of decline observed in many decentralized systems. Looking ahead, future research should explore cross-country comparisons and longitudinal evaluations to better understand how governance models, financing arrangements, and local engagement interact over time. Such evidence is essential for designing energy systems that are not only technically reliable but also socially resilient and institutionally sustained.

CRediT authorship contribution statement

Hans-Erik Edsand: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sandra C. Valencia:** Writing – review & editing, Data curation, Conceptualization. **Andrés Aleán-Romero:** Writing – review & editing, Data curation. **Tania Jiménez Castilla:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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