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Adaptation to broken climate change mitigation: Exploring social and economic impacts of solar mini-grid electrification in Colombian island communities

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ABSTRACT

Access to reliable electricity remains a central challenge for rural and island communities across the Global South. While solar mini-grids are widely promoted as tools for reducing energy poverty and supporting low-carbon transitions, their long-term social consequences, particularly under conditions of unreliable service, remain insufficiently understood. This study examines the social and economic impacts of mini-grid electrification in three Colombian island communities: Isla Fuerte, Isla Múcura, and Santa Cruz del Islote. Drawing on interviews, focus groups, and census and administrative data, the analysis traces changes in cultural practices, entrepreneurship, gender roles, education, and healthcare. Findings show uneven and conditional development outcomes. Electrification expanded access to modern technologies and supported growth in tourism-related and small-scale businesses. Women gained new income opportunities, and modest improvements occurred in education and health services. However, declining reliability, high operating costs, and limited technical capacity undermined system performance over time. As reliability declined, communities adapted through private diesel generators and informal electricity-sharing networks, increasing costs and reinforcing inequalities. These dynamics constitute what this paper conceptualizes as adaptation to broken mitigation: when renewable energy interventions designed to reduce fossil fuel dependence fail to deliver reliable service, communities reorganize socially and economically to cope with persistent energy insecurity. The findings demonstrate that electrification alone cannot achieve broader development objectives. Sustainable mini-grid transitions require reliable system design, long-term governance capacity, and coordinated investments in social infrastructure.

1. Introduction

Roughly half of Colombia's territory is located in a Non-Interconnected Zone (NIZ),[1] referring to zones of the country that do not have access to the national electricity grid. About 1.83 million people live in a NIZ, encompassing 1565 different locations across Colombia [1]. Despite representing a significant portion of the country (52%), these areas have historically been underserved in terms of infrastructure, including access to electricity. It is estimated that about 34% of the population in NIZs has access to electric power services, compared to the national average of 96.1% electricity coverage. Despite persisting energy poverty in NIZs, access to electricity in these zones has seen gradual improvements over the last decade, due to increased investments in renewable energy projects, particularly mini-grids[2] powered by solar, small hydro, and wind technologies. For example, in 2015, access to electricity in NIZs was estimated to be below 20%, highlighting the progress made through targeted renewable energy initiatives [1]. This aligns with broader global findings that energy poverty is

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[1] Literature in Spanish uses the acronym ZNI from "Zonas No Interconectadas".

[2] While no exact definition of mini-grids exists in terms of its technical capacity, a global review of existing mini-grid systems demonstrates that their installed capacity can range from a couple of kW to multiple MW [3].

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embedded within complex socio-technical and institutional barriers that technology alone cannot solve [2].

The issue of underserved regions in terms of access to electricity is not unique to Colombia, as many countries in the Global South face similar challenges of a slow or never arriving national grid. Thus, autonomous local alternatives, such as Solar Home Systems (SHSs) or mini-grid systems, are widely viewed as important potential solutions to eliminating energy poverty. While SHSs provide an alternative to individual households, mini-grid systems generally aim to power a village with multiple households and businesses, connected by a local grid. Stakeholders increasingly view the mini-grid alternative as a key strategy for electrifying underserved areas because it can serve entire villages and businesses and can scale up supply as demand increases. In fact, mini-grid systems are estimated to provide electricity to about half of the 238 million households in Asia, Sub-Saharan Africa, and island nations across the world that currently lack access to a national electricity grid [3]. Extensive reviews of off-grid systems confirm this trend, showing rapid global growth in hybrid and solar-based mini-grids due to their flexibility and suitability for rural contexts [4–6].

Given the growing prevalence of mini-grid installations across the Global South, numerous studies have analyzed the technical, financial, and socio-cultural aspects of mini-grid system deployment, including ability-to-pay challenges and human capital constraints [7–10]. However, while researchers have extensively studied the diffusion of mini-grids, far less attention has been paid to their broader social and economic impacts on local communities. Although prior research has begun to address these issues, important gaps remain. For example, Carabajal et al. [11] conducted a cohort study in Kenya and Nigeria, identifying significant positive outcomes from mini-grid installations, such as quadrupled median incomes in Kenya and improved gender equality. Additional emerging evidence from Tanzania, Brazil, and Kenya shows that electrification benefits can be significantly constrained by gendered power relations, affordability barriers, and institutional weaknesses [12–14]. In the Latin American context, Feron et al. [15] demonstrate that off-grid PV programs in Chile have faced long-term sustainability challenges linked to institutional design, maintenance uncertainty, and limited user participation. Similarly, studies of rural PV electrification in the Andean region emphasize the importance of governance structures and socio-cultural acceptance in determining long-term system viability [16]. Yet, few studies in Latin America combine longitudinal system performance data with in-depth qualitative analysis of community adaptation, particularly in small island and Non-Interconnected Zone contexts. Nevertheless, previous literature emphasizes the need for further empirical studies that go beyond technical and economic considerations to examine the social and economic consequences for local populations. For example, recent systematic reviews similarly conclude that long-term socio-economic, gendered, and institutional effects of off-grid systems remain understudied, particularly regarding how community participation, governance, and affordability shape sustainability [17–19]. This need is echoed by the World Bank [7], which stresses the importance of deepening empirical insights into the transformative effects of mini-grid systems.

This paper seeks to address this gap by contributing to the understanding of the social and economic impacts of mini-grid installations, with a focus on rural areas. Specifically, the study examines three remote island communities in Colombia that form part of the country's Non-Interconnected Zones (NIZs): Isla Fuerte, Isla Múcura, and Santa Cruz del Islote (hereafter, Islote). These communities have adopted solar PV-based mini-grid systems to address local energy access challenges. Fig. 1 shows the location of the three islands within Colombia and along the Caribbean coast, providing geographic context for the case studies analyzed in this paper.

By exploring a wide range of individual and societal changes, such as cultural shifts, alterations in consumption patterns and diets, and educational, entrepreneurial, and occupational adjustments, the paper provides a holistic perspective on the impacts of electrification. Moreover, the study adds unique value by investigating the implications of mini-grid system failures on local populations and the adaptive strategies employed to cope with unreliable energy delivery. In doing so, the research frames these community responses as an *adaptation to broken mitigation*, illustrating how local populations adjust when a renewable energy intervention strategy intended to mitigate against diesel dependence fails to provide reliable service. This approach resonates with broader literature calling for analyses that integrate energy justice, gender, governance, and community capabilities into assessments of off-grid electrification [20,21].

Accordingly, this study investigates how solar PV mini-grid installations shape social and economic life in three Colombian island

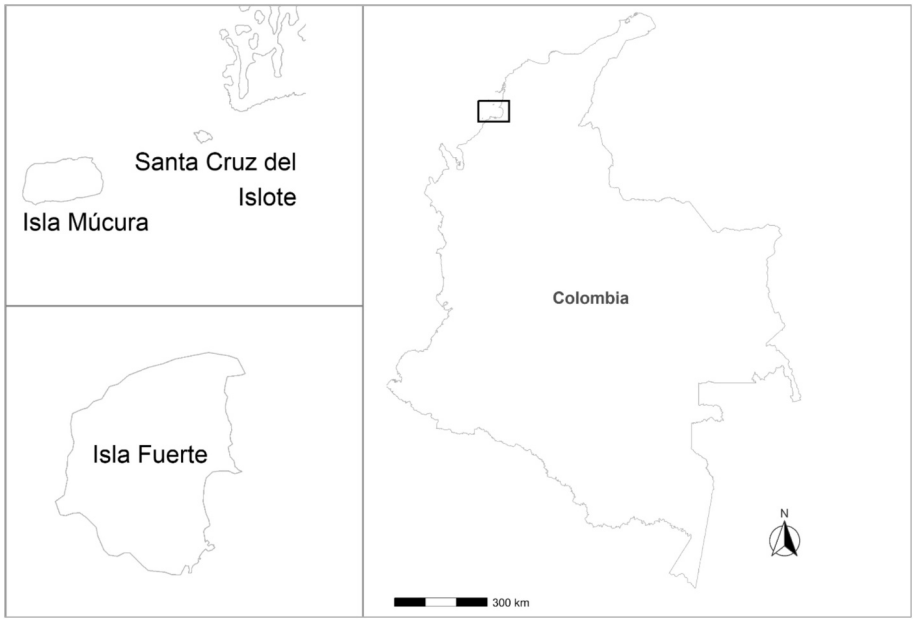

Fig. 1. Geographic location of the three case study islands along the Colombian Caribbean coast, shown in relation to mainland.
Source: Authors' elaboration.

communities. To guide this analysis, we pose the following research questions: (1) How has electrification influenced cultural practices, consumption patterns, and community interactions? (2) In what ways has access to electricity affected entrepreneurial activities? (3) How has electrification reshaped women's daily routines, economic participation, and demographic patterns in the island communities? (4) How has electrification altered educational outcomes (including youth ambitions and choices) and access to health services? (5) What are the social and economic consequences of energy insecurity, and what adaptive strategies have communities employed in response to unreliable electricity delivery? Together, these questions allow us to assess both the transformative potential of renewable energy mini-grids and the forms of *adaptation to broken mitigation* that emerge when such systems fail to deliver reliable service. To address these questions, we first outline the qualitative methodology and case context, then present the results. The discussion connects these findings to broader themes in the literature and concludes with implications for future electrification efforts.

2. Methodology

This paper uses a qualitative methodology to analyze the described research questions. The specific methods for data collection rely on semi-structured interviews and focus groups conducted with the local population in three Colombian islands with installed solar PV mini-grid systems. The qualitative data are complemented by available quantitative data to allow for triangulation or to identify divergences. This mixed-methods design corresponds to broader methodological insights that argue that complex socio-technical systems are best understood through the integration of qualitative and quantitative data, as the combination enhances explanatory depth, enables triangulation, and strengthens the validity of findings [22].

2.1. Qualitative data

Interviews and focus groups involved residents and leaders on the islands, a private company currently responsible for mini-grid management (Soling de Sinu), along with the key central government agency, the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE). In total, 26 interviews and two focus groups took place between March and May 2024. Central actor interviews occurred via video conference, while the remaining interviews and focus groups were completed on-site in Santa Cruz de Lorica with the private management company and on the islands of Isla Fuerte, Isla Múcura and Islote.

All interviews and focus groups were audio-recorded with consent, transcribed verbatim, and analyzed through thematic coding. Coding was conducted using a manually developed Excel-based system informed by the structure of the semi-structured interview guide. Coding categories came directly from the five research questions, focusing on terms related to cultural practices, consumption patterns, community interactions, entrepreneurial activities, gender, educational access and outcomes, youth ambitions, changes in healthcare and adaptive strategies in response to unreliable electricity. This ensured a consistent and transparent alignment between the analytical framework and the empirical material. The semi-structured interview protocol and focus group discussion guide are provided in Appendix A.

2.1.1. Sampling strategy

The recruitment of participants followed a two-stage procedure. Initial access to each community was established through community leaders and system managers, who facilitated entry and provided background information. Beyond this initial contact, participation occurred through on-site solicitation using a form of naturalistic convenience sampling, whereby researchers moved through public areas of the islands and invited residents to take part in interviews or focus groups. This approach aligns with common practice in qualitative fieldwork within remote or hard-to-access communities, where probabilistic sampling is not feasible and trust-dependent recruitment is essential.

Although participation was voluntary and not quota-driven, the process yielded a heterogeneous sample reflecting variation in gender, age, occupations, and social roles. Researchers monitored emerging demographic patterns throughout fieldwork, and targeted recruitment would have been initiated had significant imbalances appeared. However, natural participation patterns produced adequate diversity without intervention.

The final sample consisted of 30 interviews, distributed as follows: Isla Fuerte (17 interviews; 13 women, 4 men), Isla Múcura (3 interviews; all men, reflecting the male dominance among local leaders and system managers), Islote (4 interviews; 2 women, 2 men), Soling de Sinu (3 interviews; 2 women, 1 man), and IPSE (3 interviews; 2 women, 1 man). This represents an overall distribution of 19 women and 11 men across interview participants. Focus group participation further broadened representation: Isla Fuerte (12 participants; 10 women and 2 men) and Isla Múcura (12 participants; 8 women and 4 men). No focus group was held on Islote. These patterns demonstrate substantial female participation, supporting the inclusion of gendered perspectives in the analysis.

While the same semi-structured interview protocol and focus group guide were applied across all study sites, the depth of empirical material varied across themes and locations. In a small number of topic-specific instances, some islands did not yield sufficiently detailed or comparable evidence on a given point (e.g., due to smaller site-specific subsamples or the absence of a focus group), and we therefore report only those cases where accounts were substantively developed. This results in occasional variation in which islands appear across specific analytical subsections, reflecting theme-specific data richness rather than inconsistencies in research design or implementation.

2.2. Case study approach

We chose the case study approach as the most appropriate methodology to answer the research questions, which focus on the social and economic impacts of renewable energy-based mini-grid systems in remote areas. This approach is well-suited for examining complex, context-dependent phenomena, as it allows for an in-depth exploration of the interactions between these systems and the unique characteristics of the communities they serve [23]. Case studies also provide the flexibility to incorporate multiple data sources, including qualitative and quantitative insights, enabling a holistic analysis of the impacts on cultural practices, economic activities, and adaptive strategies [24].

This study selected three island communities with similar structural characteristics as case study sites: Isla Fuerte, Isla Múcura, and Islote. All three are located off the Caribbean coast of Colombia. The selection of Isla Fuerte, Isla Múcura, and Islote is motivated by their shared status as remote island communities within Colombia's NIZs. These areas have no connection to the national grid and therefore rely entirely on locally operated energy systems. All three sites have installed hybrid mini- grid systems that combine solar photovoltaic generation with battery storage and diesel backup, and each system has been operational for several years. These communities offer analytically valuable similarities, such as geographic isolation and dependence on the same national policy framework, while also exhibiting meaningful variation in system performance and reliability. This combination makes them well suited for examining how rural populations adapt to both the opportunities created by electrification and the disruptions associated with system failures. Studying these islands therefore allows for a systematic comparison of socio-economic and institutional dynamics while maintaining sufficient contextual coherence to support an in-depth case study analysis.

2.3. Quantitative indicators

We complement the analysis with secondary quantitative information from the Ministry of Education, the Ministry of Health, and the national censuses of 2005 and 2018. The education data describe educational enrollment and measures of the quality of the education system and help identify correlations between changes in education and electricity access. The healthcare data provide insight into changing practices in healthcare services and use, along with morbidity data over time. Finally, the Census information provides complementary socio-economic data on the islands, such as demographic changes and gender distribution.

3. Case context: energy developments in the Colombian island communities

In Colombia's NIZs, most energy is supplied by diesel, leading to high costs and significant environmental impacts [1,25]. Despite national efforts to promote renewable energy solutions, including initiatives led by IPSE, islands such as Isla Fuerte, Isla Múcura, and Islote remain heavily dependent on fossil fuels. These renewable mini-grid projects were intended to improve energy access and reduce diesel dependence. However, the continued reliance on fossil fuels underscores how such mitigation efforts can falter in practice, thereby requiring local communities to adapt in order to meet their energy needs effectively. Table 1 summarizes key socio-economic and energy characteristics of the three islands to support cross-case comparison.

3.1. Isla Fuerte

Isla Fuerte, located 150 km from Cartagena (a major urban center), has an economy shaped by fishing, tourism, and small-scale agriculture. While tourism has grown rapidly, it was significantly affected during the COVID-19 pandemic [26]. Agricultural production remains constrained by limited technology and insufficient electricity for food storage, alongside continued reliance on firewood and fossil fuels [25].

Table 1
Core characteristics of the case study islands.

Characteristic	Isla Fuerte	Isla Múcura	Islote
Area	3.25 km^2	0.23 km^2	0.01 km^2 (1 ha; densely populated artificial island)
Population	~2000 residents	~100 residents	~1200 residents in 120 homes
Main economic activities	Fishing (50%), tourism (30%), agriculture (20%)	Tourism and fishing (high seasonality)	Tourism and fishing
Average income	Tourism: 400,000–500,000 COP/month (USD 108–135)	380,000–500,000 COP/month; up to 2,000,000 COP in high season	Similar to Múcura; highly dependent on tourism
Mini-grid installation	Hybrid system: 150 kWp solar PV + diesel generators + battery bank (installed 2013)	Hybrid system: 30 kWp solar PV + 116 kW diesel + battery storage (installed 2013)	Hybrid system: 68 kWp solar PV + 116 kW diesel +1324 kWh battery bank
Electricity tariffs	200 COP/kWh residential; 520 COP/kWh commercial	4000–5000 COP/day	Residential: 4000–6000 COP/month. Commercial: 15,000 COP/month
Connectivity to mini-grid	~416 users; 60 families remain unconnected	35 of 45 households connected	80 of 120 homes connected

Source: Compiled by authors using data from Almeida et al. [26].

A hybrid mini-grid system installed in 2013 was designed to provide daytime solar generation with diesel backup [27]. However, telemetry[3] data (Fig. 2) show substantial fluctuations in daily service hours and a gradual decline in supply between 2014 and 2024.

3.2. Isla Múcura

Isla Múcura, located in the San Bernardo Archipelago, has a small, tourism-dependent economy that is highly seasonal. Prior to 2013, the island lacked access to electricity [26]. Following the installation of a hybrid mini-grid system in 2013, electricity access expanded substantially [27,29]. However, affordability challenges led some households to disconnect from the system [24]. Telemetry data (Fig. 3) indicate considerable variation and a declining trend in daily service hours between 2015 and 2024.

3.3. Santa Cruz del Islote

Santa Cruz del Islote is a densely populated artificial island neighboring Isla Múcura in the San Bernardo Archipelago, where limited space and resources create structural constraints. Electricity provision initially relied on diesel generators and was later replaced by a hybrid mini-grid system [26]. Despite being designed to provide near-continuous electricity, the system has faced maintenance challenges and high operating costs, contributing to declining reliability. Telemetry data (Fig. 4) show substantial variation and a downward trend in daily electricity availability over the past nine years.

4. Results: observed social and economic changes

4.1. Social and cultural change following electrification

4.1.1. Changes in domestic routines and livelihood practices before and after electrification

Before electricity arrived, life on the islands was vastly different. People used wicks and candles for lighting, and preserving fish was a significant challenge. Fish were salted and dried, while others would transport their catch to the mainland the same day (Islote, Interview 2024). Tasks like laundry were done by hand, and there were only a few television sets on the entire islands, where people gathered to watch news and sports events.

The arrival of electricity was described in interviews as a monumental event, with people too excited to sleep on the first night the lights came on (Isla Múcura, Interview 2024). The joy of waking up to a fan

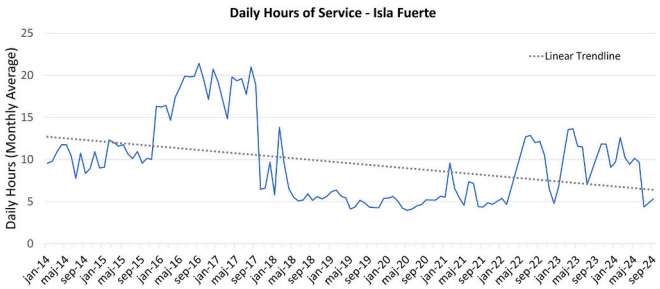

Fig. 2. Monthly average of daily electricity supply hours in Isla Fuerte, 2014–2024.
Source: IPSE telemetry data [28].

[3] Telemetric data refer to remotely collected, time-stamped operational data transmitted from monitoring equipment, used here to track electricity generation and system performance.

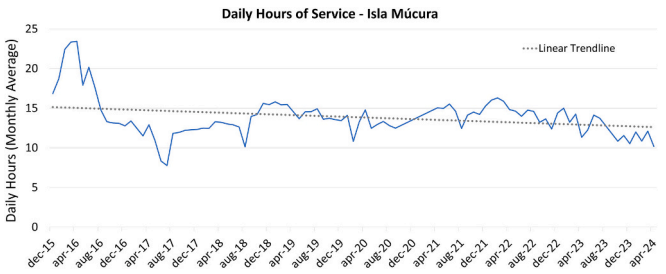

Fig. 3. Monthly average of daily electricity supply hours in Isla Múcura, 2015–2024.
Source: IPSE telemetry data [28].

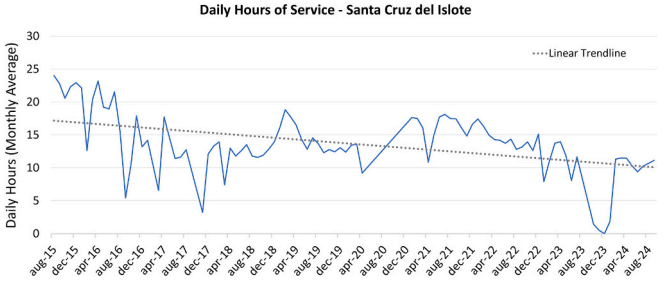

Fig. 4. Monthly average of daily electricity supply hours in Santa Cruz del Islote, 2015–2024.
Source: IPSE telemetry data [28].

and being able to close doors was described as significant. Residents had since become accustomed to these improvements and experienced pronounced discomfort during power outages. Previously, only a few people had generators that powered televisions, allowing them to gather and watch together. Once electricity was available all day and night, residents eagerly bought televisions and fans, enhancing their daily comfort (Isla Múcura, Focus Group 2024).

The first noticeable change when the mini-grid arrived on Islote was the disappearance of larger fishing boats, as local fishermen were now able to freeze their own fish using solar and diesel electricity. This allowed them to sell directly to hotels or to Tolú at better prices than what fishing companies offered. However, many residents bought more freezers than necessary instead of opting for refrigerators, something that happened in all three islands. The community also used many energy-intensive devices, like large speakers.

Limited maintenance capacity and widespread use of energy-intensive appliances contributed to progressive system deterioration across all three islands. Solar PV components were particularly affected; on Isla Múcura, inadequate maintenance resulted in battery failures, including explosions. As a result, solar generation now provides only limited hours of electricity, a pattern reflected in the declining service-hour trends shown in Figs. 2–4, increasing reliance on diesel generators and associated fuel costs and noise. During the hottest months, residents of Islote reported preferring the noise of the diesel plant to sleeping without a fan, while system breakdowns sometimes force people to sleep outdoors (Islote Interview, 2024).

4.1.2. Changes in social interactions

Residents across all three islands describe how the introduction of electricity reshaped cultural practices and community interactions, shifting social life from communal gatherings toward more individualized leisure as televisions and mobile phones became privately owned (Isla Fuerte, Isla Múcura and Islote Interviews, 2024). Across sites, residents described children spending more time indoors watching television rather than participating in shared community activities. On Isla Fuerte, this shift was framed as a loss of intergenerational cohesion, prompting the community council to revive traditional practices such as festivals and dances (Isla Fuerte, Focus Group 2024). In all islands, adult alcohol consumption has increased as refrigeration made cold beer widely available. On the other hand, refrigeration has contributed to improved dietary practices, with reduced consumption of sugary drinks and greater consumption of natural juices enabled by access to refrigerators and blenders.

4.1.3. Demographic change

Locals on the island of Isla Fuerte describe significant demographic changes, with the population growing from 300 families to nearly 700 families in the past decade. This rapid increase has placed considerable strain on local resources, including the electricity plants, which are no longer sufficient to meet the rising demand. The influx of new arrivals, attracted by the island's safety, tranquility, and tourism opportunities, has introduced external influences that have contributed to the excessive use of resources. In response, the community is reviewing its internal regulations to manage the growing population. In addition, the construction of new homes has led to the removal of sand from beaches and stones from the island. As the island has expanded, it has also embraced new cultures and practices brought by outsiders, further shaping its development (Isla Fuerte Focus Group, 2024).

The rapid population increase reported by the locals in the interviews contrasts with the information from the last two censuses conducted by the Colombian National Administrative Department of Statistics (DANE, by its initials in Spanish), depicted in Figs. 5 and 6, highlighting the importance of examining both perceived and recorded demographic change, as perceptions of growth can shape local governance decisions and energy demand even where statistical trends differ. Indeed, between 2005 and 2018, the total population in Isla Fuerte fell by 5.9%. However, the share of the young population (aged below 25) grew from 48.0% in 2005 to 59.1% in 2018 [30,31]. This aligns with qualitative reports of an influx of families with children. The growing number of younger residents may contribute to increased energy consumption for education and household activities.

Contrary to Isla Fuerte, locals on Islote do not describe an increase in population since the arrival of electricity (Islote Interview, 2024). This aligns with census data: between 2005 and 2018, the total population fell by 25.4% [30,31]. However, interviews in Islote describe some noticeable shifts in the community. For example, those who can afford it often send their children to study outside the island. As in Isla Fuerte, the share of the young population grew from 46.5% in 2005 to 59.1% in 2018 [30,31]. Most residents who remain on the island now work in tourism-related jobs, such as in hostels, day trips, and restaurants, with fewer people involved in fishing. The local workforce includes a group of 35 tour guides, along with others who sell art to visitors (Isla Múcura and Islote Interviews, 2024).

4.2. Household consumption and material changes

4.2.1. Energy consumption

In Isla Fuerte, refrigerators and freezers were consistently identified as the primary electricity consumers, followed by fans, televisions, and cell phone charging (Isla Fuerte Interview, 2024). Some households reported disconnecting refrigerators during the day to conserve energy, while others noted that appliances operate only during limited supply windows. Electricity is also used for small-scale income activities such as ice production and nighttime laundry.

4.2.2. Material consumption: first purchases

In Isla Fuerte, the first purchases made by many households after gaining access to electricity were fans, televisions, and refrigerators. Fans were also prioritized because of the intense heat, making them essential for comfort. Televisions followed as a form of entertainment, with refrigerators being added afterward to preserve food and drinks. Additional purchases included appliances like blenders, washing

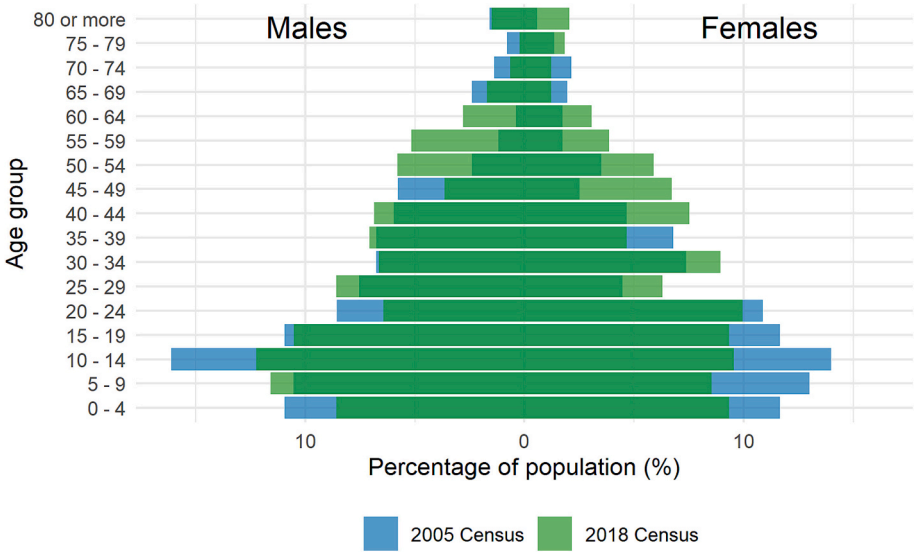

Fig. 5. Population pyramids of Isla Fuerte, 2005 and 2018 census data.
Source: DANE population censuses [30,31].

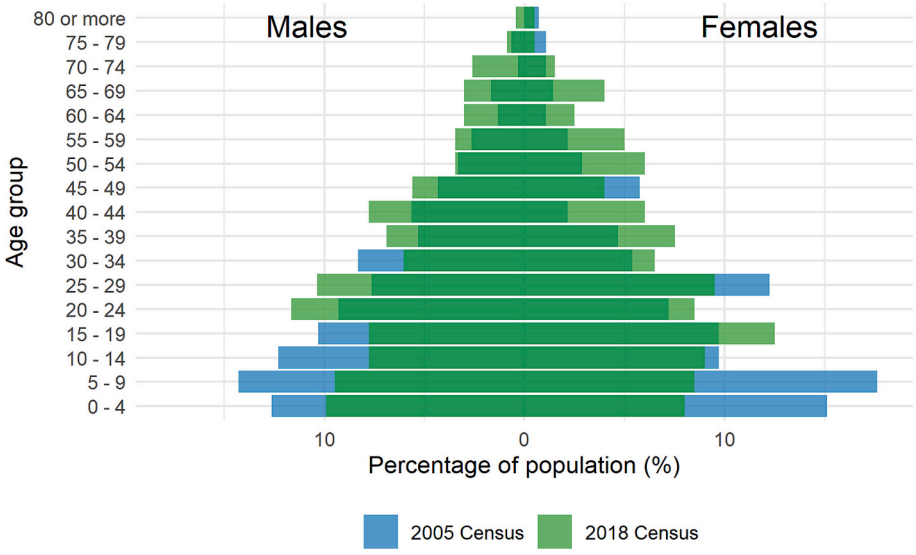

Fig. 6. Population pyramids of Santa Cruz del Islote, 2005 and 2018 census data. Source: DANE population censuses [30,31].
Note: Data for Isla Múcura were only available for 2018.

machines, and even electric styling brushes (Isla Fuerte Focus Group, 2024). When asked about the first purchases across multiple interviews, the refrigerator was the most frequently mentioned appliance (see Table 2). Some homes now have their fridge and freezer running throughout the day, making it easier to store perishable goods and maintain a more comfortable lifestyle. These purchases reflect the gradual improvement in convenience and comfort that access to electricity has brought to the community (Isla Fuerte Focus Group, 2024).

Table 2
First purchases - Electronic appliances (Isla Fuerte).

Appliance	Mentions	Percentage (%)
Refrigerator	9	39
Fan	3	13
Television	3	13
Freezer	3	13
Blender	2	9
Washing machine	1	4
Cooler	1	4
Computer	1	4

Note 1: The percentages are calculated based on the total number of mentions (23). Isla Múcura and Islote were left out of Table 2 due to insufficient data.
Source: Isla Fuerte Interviews, 2024.

On both Isla Múcura and Santa Cruz del Islote, the arrival of electricity prompted rapid household investment in cooling and refrigeration appliances. In Isla Múcura, residents reported purchasing fans, televisions, and refrigerators soon after electrification, enabling continuous lighting, improved thermal comfort, and cold storage of food, fish, and water; blenders were later acquired to support juice preparation and everyday consumption (Isla Múcura Focus Group, 2024). On Santa Cruz del Islote, initial purchases similarly focused on fans and refrigerators, but were more frequently extended to freezers, particularly among residents seeking to start small businesses. These appliances enabled new income-generating activities, such as selling ice cream and beer or operating small shops, echoing the tourism-linked expansion of local enterprise discussed in Section 4.3 (Islote Interview,

2024).

4.2.3. Changes in food consumption

With access to electricity, residents of Isla Fuerte can now blend natural juices and preserve a greater variety of foods, including meats beyond the traditional diet of fish and coconut rice. One interviewee noted that people can refrigerate and store more items, and another observed that fish consumption has increased now that freezers are available. Although one individual felt that the diet remained unchanged, others reported that it has diversified considerably. The ability to enjoy cold beverages like juices and water is a new luxury, but some community members noted that they only buy food as needed, reducing overall variety. Retail dynamics have also shifted in response to changing food storage and purchasing practices: a once large, always-open store has given way to a smaller shop with more limited hours and offerings, reflecting reduced demand for bulk purchases and greater reliance on household refrigeration (Isla Fuerte, Interview 2024).

4.3. Changes in entrepreneurial activities

Across the three islands, respondents described an overall increase in economic activity over the past decade, largely driven by tourism expansion rather than electrification alone. While the introduction of solar mini-grids enabled certain activities, entrepreneurial growth was consistently described as conditional on reliable electricity supply. In practice, unstable service limited investment and often required businesses to rely on diesel generators, constraining the transformative potential of electrification.

On Isla Fuerte, respondents emphasized that unstable electricity discourages investment and keeps some activities dependent on firewood-based cooking (Isla Fuerte Interview, 2024). Where changes occurred, they were typically incremental: households reported selling juices (often switching to diesel generators during outages), offering medicines or lodging, or producing small crafts. One person reported selling merchandise via WhatsApp, though this was not attributed to electrification.

Nevertheless, respondents described an overall increase in economic activity on the island since the system's installation, which they largely attributed to expanding tourism. Growth in visitor numbers was linked to increased ice production, higher sales of juices, chichas, and beer, and the establishment of new hotels by both locals and newcomers. However, many of these enterprises rely on private diesel generation, indicating that the solar mini-grid system has played a limited enabling role rather than serving as the primary driver of business development (Isla Fuerte Interview, 2024).

In addition to challenges related to electricity, other factors that hinder the start of new business activities were raised in interviews with locals in Isla Fuerte. One significant issue is transportation, which complicates operations due to high and multi-layered costs. As one interviewee from Isla Fuerte stated, “Transportation complicates things. It increases pressure. It is unsustainable to have businesses” (Isla Fuerte Interview, 2024). He goes on to explain how it takes four different payments for the merchandise to arrive at its destination (Isla Fuerte Interview, 2024). Additionally, financial constraints make it difficult for individuals to start or sustain ventures. For example, some are burdened by large debts, such as a loan of 10,000,000 pesos taken out for a refrigerator, which limits their ability to invest in other activities (Isla Fuerte Interview, 2024).

Focus group participants on Isla Fuerte reported that the introduction of the solar system enabled new entrepreneurial activities by extending business hours through improved lighting. Whereas businesses previously closed by 7 p.m. due to lack of light, electrification allowed them to operate later, increasing income opportunities. However, participants emphasized that unreliable and insufficient electricity continues to constrain business sustainability. They noted that reliable 24-hour power would reduce spoilage of perishable goods such as fish and enable agricultural activities, including the preservation of produce like guava, thereby strengthening local food stability and resilience.

In a focus group on Isla Múcura, residents reported an expansion of economic activities following the installation of the mini-grid. Access to electricity enabled the production and sale of ice, boli (ice cream), cold water, soda, and freshly made juices, allowing merchants to offer products that were previously unavailable. Participants linked these changes to growing tourism and an increase in hostels, while noting that unreliable electricity remains a challenge when visitors experience nighttime blackouts. Electrification also allowed fishermen to store fish in freezers rather than relying on drying or mainland ice, improving marketing options. Although fishing remains the primary livelihood, declining catches have encouraged many fishermen to diversify their income through new business activities (Isla Múcura Focus Group, 2024).

On Islote, interviews with local residents portray a noticeable increase in businesses on the island after the arrival of electricity. This includes the opening of a pizza place, a bakery, and various fast-food options such as traditional Colombian comida rápida (cornbread). Several businesses catering to locals also emerged, such as those selling natural juices, while for tourists, the primary offerings include fried foods like arepas. Although electricity now powers fridges and ovens, business growth is not solely tourism-driven. Local residents describe how many of the new ventures cater more to the local community than to the influx of visitors, reflecting broader economic growth rather than just a tourism boom.

4.4. Gendered impacts of electrification

4.4.1. Female demographic changes during electrification

Census data on sex ratios in Isla Fuerte and Islote show different trends (Figs. 5 and 6). In Isla Fuerte, there were 102.4 females for every 100 males in 2005, and the ratio increased to 105.6 by 2018. As this ratio reflects the entire population rather than only the working-age group, it cannot be attributed to a single factor. This trend may reflect a combination of influences, including a growing influx of families and women drawn to opportunities in tourism-related activities, suggesting a potentially more inclusive labor market. Conversely, in Islote, there were 92.4 females for every 100 males in 2005, and the ratio declined further to 86.2 by 2018 [30,31]. While not solely driven by employment dynamics, this decline could suggest challenges in the local labor market's ability to absorb female workers, potentially due to the dominance of male-oriented jobs such as fishing or limited diversification of economic activities. As a result, women may feel compelled to migrate to other regions for better opportunities, leaving behind a more male-dominated population.

4.4.2. Changes in daily routines and economic activities

In interviews with female residents of Isla Fuerte, the arrival of electricity was depicted as impactful and as an improvement in quality of life. Comparing overlapping periods of the census data with the daily hours of electricity (see Fig. 2), a correlation can be observed between increased access to electricity and the female-to-male ratio rise from 102.4 to 105.6 (2005–2018). This correlation may reflect several factors, including increased working opportunities for women on the island, among other possible explanations. Unfortunately, more recent census data are not available, resulting in an inability to compare changes in female-to-male ratios post 2018, during which period the daily hours of electricity were reduced significantly.

Across both Isla Fuerte and Isla Múcura, women reported that reliable daytime electricity initially produced significant improvements in daily routines and domestic labor. On Isla Fuerte, interviews indicated that access to daytime power allowed women to wash clothes and prepare juices earlier in the day, reducing workload intensity, enabling daytime refrigeration for juice storage, and freeing evenings for rest (Isla Fuerte Interview, 2024). Similarly, focus group participants on Isla

Múcura described how daytime electricity from the solar PV mini-grid improved women's ability to manage household tasks, prepare juices for sale, and stay cool using fans. In both cases, however, declining reliability of solar generation, consistent with the system deterioration described in Section 4.1.1 and Figs. 2–4, forced women to reorganize these activities around limited supply, often shifting laundry and food preparation back to the evening and relying on diesel-generated electricity. In contrast, men in Isla Múcura—who typically fish during the day—experienced fewer daytime benefits from electrification but gained improved nighttime comfort through the use of fans, television, and leisure activities, with only limited increases in male participation in household tasks (Isla Múcura Focus Group, 2024).

In Islote, interviews with local residents revealed an increase in economic opportunities and activities for women. Many women now engage in economic activities such as making items like pens, paddles, and buckets. The use of washing machines has become common, with some women claiming to have "forgotten" how to wash by hand. One woman explains how her children help with household tasks such as washing, cooking, and ironing, though it is rare for men to do these chores on the island. Men typically dive from 7 am and return by 10 am and then spend time playing dominoes. A decade ago, women did not work and were dependent on men. Now, however, many empowered women work in hotels or run their own businesses, marking a significant shift in gender roles and economic participation. The census data, however, diverge from the description provided in the interview data, as Islote's female-to-male ratio fell from 92.4 to 86.2 between 2005 and 2018. Consistent with the observation in Isla Fuerte where the census depicted an increase in the female-to-male ratio during a period of improved electricity access, conversely, energy access experienced a consistent reduction in daily hours of electricity during the available overlapping period (see Fig. 4). While limited data do not allow for drawing final conclusions, the census data suggest women's out-migration, which can possibly be explained by limited job diversification, thus contradicting the interview data [30,31].

4.5. Changes in education and health services

4.5.1. Changes in educational access and outcomes on the islands

In line with Research Question 4, this section examines how electrification and the reliability of electricity supply have shaped educational access, learning conditions, and outcomes on the islands. While institutional reforms, such as the expansion of secondary schooling and the introduction of school transportation, have shaped enrollment and attainment patterns, the analysis below focuses specifically on how electricity access and reliability affect learning conditions and educational quality. Local inhabitants in Isla Múcura portray significant changes in the education system over the past few years. Students now have the ability to do their homework online, a development enabled by electricity access, though access to reliable internet remains a challenge due to fluctuating and weak connections. About eight years ago, the educational system was much more limited, with no connection to schools on the island due to the lack of transportation, leading to high dropout rates. Some students even had to use their own boats to attend school. In 2016, school transportation was introduced, connecting Isla Múcura and Islote, which greatly strengthened their access to education. Until 2016, schooling on Isla Múcura only went up to ninth grade, but in 2017, high school education was established, leading to an increase in high school graduates. Consequently, according to data from the Ministry of Education, school enrollment increased from 515 students in 2015 to 636 in 2022 (Fig. 7). This increase occurred alongside expanded schooling levels, improved transportation, and electrification, making it difficult to isolate the causal role of electricity in shaping enrollment trends.

Consistent with the increased enrollment, census data reveal that between 2005 and 2018, educational outcomes improved significantly in Isla Fuerte and Islote, particularly among females. The percentage of the population aged 15 and older with at least 9 years of education increased from 31.9% to 39.9% in Isla Fuerte and from 6.2% to 28.3% in Islote. In Isla Fuerte, the increase for females was 10.5 percentage points

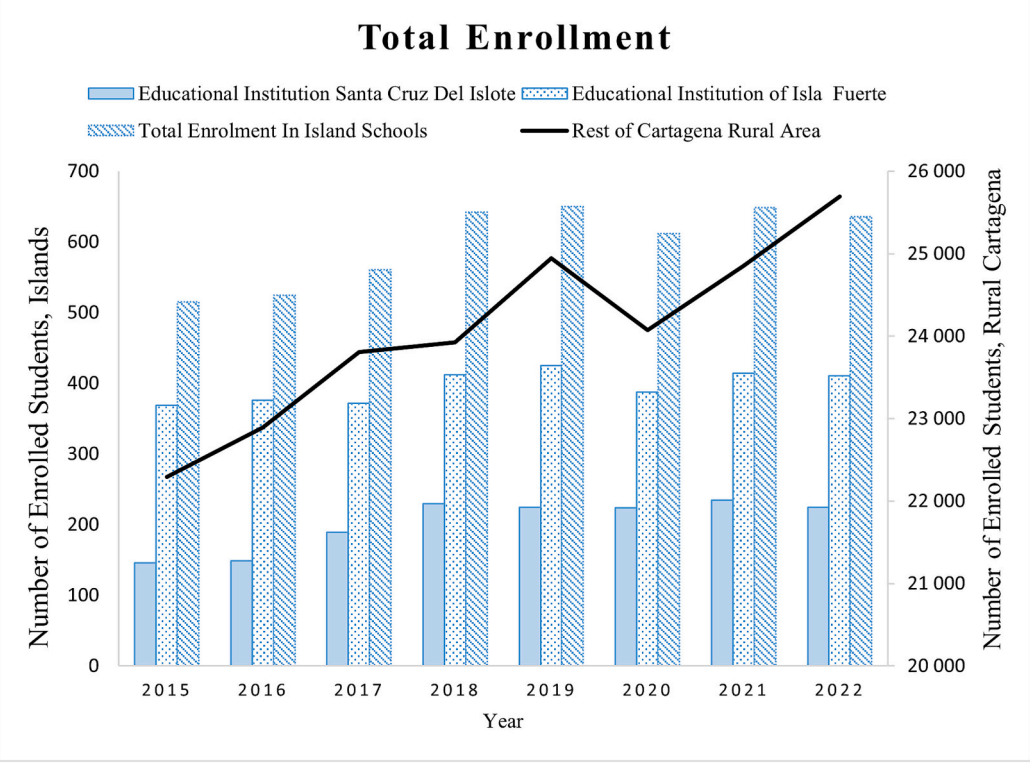

Fig. 7. Total school enrollment in Santa Cruz del Islote and Isla Fuerte, 2015–2022.
Source: Ministry of Education administrative data [32], authors' tabulation.

higher than for males, and in Islote, it was 4.1 percentage points higher [30,31]. Illiteracy also decreased notably in Isla Fuerte and Islote, particularly among males. In Isla Fuerte, illiteracy fell from 16.2% to 11.0% between 2005 and 2018, and in Islote, it decreased from 15.2% to 12.0% for the same period.

The standardized Colombian national test, *Saber 11*, reiterates the discrepancy between the test scores on the islands and the national average (see Fig. 8). The test scores indicate that this discrepancy is not isolated to the island communities but rather reflects a wider rural issue in the quality of education compared to the national average. In interviews, the effect of the pandemic was raised as a concern, reflected in increased inconsistencies in teacher attendance and students having to rely on WhatsApp for their studies (Isla Fuerte Focus Group, 2024). However, the data for Saber 11 do not show a clear correlation in the test results for the national average, Isla Fuerte, nor the rural average, which all demonstrate a pre-pandemic decline. In fact, the Isla Fuerte scores show an improvement in the test scores during the pandemic, i.e., from 2019 onward. The exception can be seen in Islote, which shows a sharp decline in the test score between 2020 and 2021, followed by a quick recovery between 2021 and 2023 [32].

School infrastructure was described in interviews as facing challenges. Classrooms on Isla Múcura and Islote have been damaged by sea salt corrosion, and the Cartagena education department declared the classrooms in Islote unsafe due to structural cracks. It is important to mention that the children from Isla Múcura attend school in Islote because Isla Múcura offers education for 4th and 5th grades, while in Islote, education is available from preschool through high school. Local residents on Isla Múcura also describe a change in the relationship between teachers, parents, and students. “Teachers can no longer enforce rules or assign homework as they once did, and respect has diminished. Parents no longer support the teachers, and in some cases, when a teacher disciplines a child, the student reports it to their parents, leading to conflicts” (Isla Múcura Focus Group, 2024). Interviews with parents and teachers further partly link classroom management issues to heat and overcrowding during hours without electricity, stating that “when fans are off, attention drops and tolerance for discipline wanes” (Isla Múcura Focus Group, 2024).

The lack of consistent electricity on Isla Fuerte is described by locals as negatively impacting children's education and opportunities. At an island-based child development center, children are released early due to the heat, as there is no electricity to power fans. “If electricity were available 24 hours a day, the cooler environment would improve concentration and extend study hours” (Isla Fuerte Focus Group, 2024). There was a proposal to delay turning on the town's diesel plant until 9 p.m., but the school principal advocated for an earlier time to allow students to study in the evening, now starting at 6 p.m. (Isla Fuerte Focus Group, 2024).

Taken together, the quantitative and qualitative evidence suggests that electrification has not been the primary driver of increased enrollment or formal educational attainment on the islands, which instead reflect institutional and policy changes such as expanded schooling and transportation.

However, interview material indicates that declining and unreliable electricity (Figs. 2–4) increasingly constrains learning conditions, particularly through heat exposure, reduced study hours, and limited use of digital tools. In this sense, electricity access shapes the quality and effectiveness of education rather than participation alone, influencing students' ability to concentrate, complete homework, and benefit from expanded educational opportunities. These findings directly address Research Question 4 by highlighting electricity as an enabling condition for educational outcomes rather than a sole determinant of schooling trajectories.

4.5.2. *Opportunities and educational ambitions of youth*

Children's ambitions across the islands were described as mixed and increasingly shaped by local economic and social conditions. While improved access to education has expanded opportunities, residents reported declining motivation among some youth, with traditional livelihoods such as fishing losing appeal and parental behaviors, including alcohol consumption, negatively influencing aspirations. Interviewees linked the growth of tourism on Isla Fuerte and Isla Múcura to reduced incentives to pursue education, as many young people opt to earn income at an early age. At the same time, residents emphasized that reliable 24-hour electricity could enable remote technical or university education, which remains largely unrealized due to current conditions (Isla Fuerte Focus Group, 2024; Isla Fuerte and Isla Múcura Interviews, 2024). In response, some parents have sent their children to Cartagena to improve educational prospects (Isla Fuerte Interview, 2024).

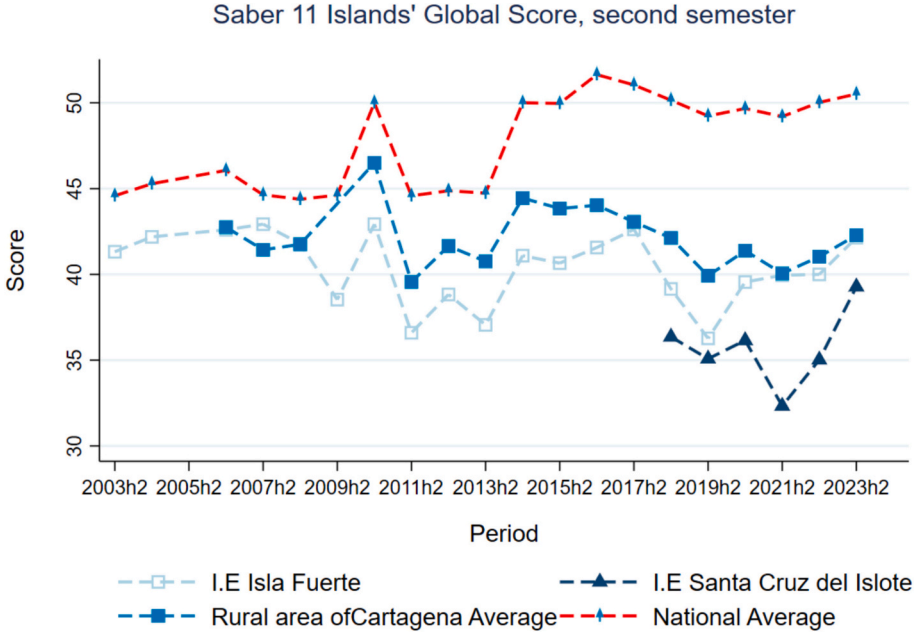

Fig. 8. Saber 11 global average scores in Santa Cruz del Islote and Isla Fuerte, 2003–2023.
Source: Ministerio de Educación Nacional [32] with author tabulation.

Interviews on Santa Cruz del Islote indicated that electrification significantly altered youth engagement with the internet and education. With community electricity from the mini-grid, internet access expanded beyond households with private generators, allowing more young people to go online at home, while the school, powered by a diesel generator, provides free internet to students. Residents and local leaders linked improved internet access to increased educational aspirations and a rise in college graduates (Islote Interview, 2024). Census data support this trend, showing that between 2005 and 2018 the share of adults with higher education increased from 0.4% to 3.7% on Islote and from 3.1% to 9.3% on Isla Fuerte, with gains driven disproportionately by women [30,31].

Residents of Isla Múcura noted that few young people pursue professional careers, even among those who have completed secondary or higher education. Despite rising educational attainment reflected in census data, interviewees identified several barriers to continued education, including limited access to scholarships, declining interest in teaching careers initially promoted by the local school system, and the growing availability of local employment in tourism-related sectors such as hotels and tour guiding. The immediate appeal of earning income often outweighs incentives to continue studying, a trend reinforced by limited parental encouragement for long-term educational goals (Isla Múcura Focus Group, 2024). Structural constraints further undermine educational pathways, as weak internet connectivity limits access to virtual education and teacher shortages contribute to poor performance on the Saber 11 standardized test (see Fig. 8).

Overall, the opportunities and further education for youth in the island communities demonstrate both positive and negative trends. The role of electricity access has simultaneously provided new employment opportunities, a development that in turn was described to negatively incentivize continued education. While additional electricity supply through the mini-grids introduced the possibility for online study, unreliable service delivery was argued to negatively affect study results in the absence of fans to reduce extreme heat for students.

4.5.3. Changes in health care

The construction of healthcare centers in 2022 by the ESE Hospital Local Cartagena de Indias marked a significant improvement in health service provision on Isla Fuerte, Isla Múcura, and Islote. Prior to this, residents relied largely on temporary health brigades due to the absence of permanent medical infrastructure, often traveling long distances to Cartagena or nearby municipalities for more complex care [33,34]. Nevertheless, 2018 census data indicate that access to professional medical treatment remained limited, with only 33.9% of sick residents on Isla Fuerte, 28.6% on Isla Múcura, and 25.9% on Islote receiving care, compared to 60.9% in other rural areas of Cartagena. The data also reveal gender disparities: women reported slightly higher sickness rates on Isla Fuerte, while men did so on Isla Múcura and Islote; women accessed medical treatment more frequently on Isla Múcura (by 30 percentage points), whereas men dominated access on Isla Fuerte and Islote by at least 11.9 percentage points. As health data for the islands are limited to the 2018 census, longitudinal analysis of health outcomes is not possible.

However, interview data reveal several trends across the islands regarding access to health services following electrification. On Isla Fuerte, residents highlighted tangible positive effects of electricity access and new healthcare infrastructure. The installation of vaccine refrigerators, although powered by an independent generator, has enabled the storage of essential vaccines and medications that were previously unavailable due to the lack of refrigeration. The health center, staffed by doctors and dentists commuting from Cartagena, now provides basic services. Nonetheless, serious emergencies still require travel to mainland hospitals in cities such as Moñitos or Lorica, as no dedicated medical transport is available to the island. The center's operations remain constrained by limited availability of medical professionals, insufficient equipment (e.g., defibrillators), and restricted access to online healthcare resources (Isla Fuerte, Interview 2024).

The introduction of electricity has also positively impacted health and living conditions on Isla Múcura. Residents report a significant improvement in air quality, noting that before electrification, they often woke up with ash and smoke in their noses due to wood-based cooking practices (Isla Múcura, Interview 2024). This highlights how infrastructural developments in electricity and healthcare are interconnected and can contribute to overall well-being.

4.6. Consequences and adaptive measures of energy insecurity

The local community in Isla Fuerte raises several problems due to the lack of consistent energy and frequent power fluctuations. As a consequence, individuals are generally forced to plan their activities around the limited availability of electricity, which creates conflicts between those managing the electricity and the broader community (Isla Fuerte Interview, 2024).

Food, particularly meat, often spoils, and appliances are damaged due to power outages. Because of the inconsistent electricity supply, locals resort to short-term storage only for items such as fish and fresh meat to avoid the risk of spoiling. Another inhabitant chose to avoid refrigeration altogether and instead purchased only for immediate needs. Others rely on coolers to sell chichas, ice, and water rather than using refrigerators. One person mentioned having separate refrigerators for home and business use, though they currently only have one available. Additionally, some use refrigerators in local stores to store food, while noting the risk of spoiling food due to the unreliable power supply (Isla Fuerte Interview, 2024).

The poor quality of electricity on the island of Isla Fuerte has had a significant impact on businesses. It has made it difficult for businesses to operate sustainably, especially those that rely on preserving perishable goods. For instance, fish sellers must rush to sell their stock early in the morning to prevent it from spoiling due to the lack of consistent refrigeration. This instability creates a sense of urgency and limits business growth, as reliable power is crucial for maintaining food quality and expanding operations (Isla Fuerte Focus Group, 2024).

When the electricity cuts off in the middle of the night, residents must seek out fuel sellers to keep their lights and appliances running. Additionally, adults who study online are significantly affected by the unreliable power supply, which disrupts their virtual learning sessions (Isla Fuerte Focus Group, 2024).

To adapt to the unreliable energy system, many people on Isla Fuerte have started purchasing their own generators, as they now desire 24-hour electricity. Once the electricity comes on at 6 p.m., residents often rush to complete tasks like washing clothes. Given the system's unreliability, some neighbors have established a shared network where those with generators share electricity with others. For example, neighbors might provide half a gallon of diesel to power basic appliances like lights, fans, and televisions, typically enough to last from 6 p.m. to 6 a.m. However, the responsibility for repairing personal equipment remains with the owner. These solutions are generally adopted by those who are more financially solvent (Isla Fuerte Focus Group, 2024).

Similarly, on Isla Múcura, the lack of reliable energy and frequent power fluctuations present several challenges for the community. People describe the intense heat as unbearable without consistent electricity, and when the diesel plant breaks down, there is no backup from the solar panels. Residents of Isla Múcura stress a particular problem for businesses, especially in tourism, as tourists often leave or refuse to stay in hostels without reliable light during the day and night. As on Isla Fuerte, they also note that food spoils quickly due to the inability to keep it refrigerated, leading to financial losses. People feel a sense of hopelessness, and household appliances frequently become damaged due to lack of use, corrosion from salt, and the instability of the power supply (Isla Múcura Focus Group, 2024).

To accommodate the low reliability of the energy system in Isla Múcura, the community has made several adjustments. When appliances

are damaged, people replace them, though such instances are not very frequent. In cases where the plant breaks down, the community collectively contributes money for repairs, with businesses typically contributing more and households less, depending on their financial capacity. Additionally, four individuals have their own energy sources and provide power to one to two neighboring houses when needed. These adaptations have helped mitigate some of the challenges caused by the unstable energy supply (Isla Múcura Focus Group, 2024).

On Islote, one inhabitant described how businesses have been significantly affected by poorly functioning solar panels. A seafood business owner, for example, reported that when receiving electricity from the solar and diesel generated communal grid, his monthly electricity costs were around 150,000 Colombian pesos (COP; approximately USD 39), which is roughly one third of the average income on the island. However, without access to this electricity, his expenses soared to 1.5 million pesos per month to keep seafood fresh. He had to purchase two gallons of diesel daily. Currently, with only community diesel-based electricity available at night, he must minimize the use of his fridges during the day. He avoids opening them from 12 p.m. until the power plant is turned on again in the evening, and he only opens them sparingly throughout the day to conserve the cool air and reduce energy consumption.

Another local resident of Islote reiterates that local residents are forced to purchase small diesel generators to cope with the unreliable energy supply of the mini-grid. These small plants are often shared among neighbors to ensure access to light. Additionally, over recent decades, both the temperature and tides have increased, exacerbating the difficulties associated with unreliable power. Despite the unreliable power supply, local residents have continued to buy freezers, which adds to demand and, in turn, reduces the share of energy available from the local mini-grid for each islander.

Table 3
Summary of findings on social and economic outcomes of mini-grid electrification.

Research area	Findings
Cultural practices & social interactions	Increased individualization of social interactions; reduced communal gatherings; improved access to entertainment but increased social isolation.
Household consumption & diet	Increased use of refrigerators led to improved dietary diversity, but affordability constraints limit widespread adoption.
Economic impact & entrepreneurship	Growth in tourism and small businesses, but high electricity costs and unreliable supply limit expansion. Dependence on diesel generators remains.
Gender & labor market	More economic opportunities for women, but continued gender disparities in income and job stability. Women remain largely in informal sectors.
Education & human capital development	Higher school enrollments and improved access to learning materials; teacher shortages and poor infrastructure persist.
Youth ambitions and choices	Youth in the island communities face mixed and often limited educational ambitions, shaped by new opportunities enabled by electrification, such as internet access and remote learning, yet constrained by unreliable service, local labor market pull factors, economic barriers, and weakened motivation and support for continued education.
Healthcare services	Improved vaccine storage and medication refrigeration, but limited access to healthcare professionals and emergency transport.
Energy reliability & adaptation	Power outages lead to reliance on diesel generators and private electricity-sharing networks, increasing costs and uncertainty.

5. Discussion of findings and pathways for improving energy security

This study advances the literature on off-grid electrification by demonstrating that service reliability, rather than access alone, mediates the social, economic, and institutional outcomes of mini-grid deployment in small island contexts. Drawing on mixed qualitative and quantitative evidence from three Colombian islands, the analysis shows how electrification interacts with tourism expansion, governance capacity, gender dynamics, and public service provision. Rather than treating electrification as a singular causal driver, the findings highlight its conditional and system-dependent character. This section synthesizes the findings presented in Section 4 (summarized in Table 3) and situates them within the broader scholarly literature to highlight points of convergence, divergence, and contribution.

Our findings largely agree with previous literature on economic impacts of mini-grid installations, e.g., the income gains reported by Carabajal et al. [11]. While our study did not measure changes in income specifically, but rather changes in entrepreneurial activities, it is plausible that income improvements accompanied the observed expansion in entrepreneurial activity. Our study found that tourism-related businesses have benefited from the installation of the mini-grid systems, as improved access to electricity enabled refrigeration of beverages and food, as well as extended operating hours for local businesses. Moreover, small-scale ventures, including ice production and beverage sales, have flourished, reflecting a positive economic shift. These findings align with broader reviews showing that mini-grids, particularly hybrid systems, often stimulate local productive uses where supply is reliable, though affordability and tariff structures remain major constraints [5,6,12].

However, the claims of entrepreneurship expansion with electrification [3] are only partially borne out. The instability of the energy supply in the Colombian cases demonstrates a major impediment to sustained entrepreneurial growth. Inconsistent power availability forces many businesses to rely on diesel generators, which increases operational costs and limits business scalability. Although a detailed technical assessment of system underperformance falls outside the primary scope of this paper, the qualitative and quantitative evidence from the islands nevertheless points to several design and implementation shortcomings that help contextualize the observed socio-economic effects. The interview and telemetry data suggest limitations in the design of the Colombian systems, where both a plan to address expected increases in demand and sufficient training of local inhabitants to maintain the systems were lacking. These gaps contributed to premature degradation of key components, such as battery banks, which reduced the performance of the solar PV portion of the hybrid systems and thereby increased community reliance on diesel generation over time. This reinforces scholarship emphasizing that long-term mini-grid success depends not merely on installation but on anticipatory planning, monitoring capacity, and sustained governance structures [17,18,35]. Future mini-grid investments would benefit from a well-defined preparatory and planning stage, where both adequate technical training of local operators as well as future scaling of the system to follow demand growth are fully addressed.

Regarding gender impacts, our findings echo broader electrification literature, both by the increasing participation by women in hospitality, as shown by the data, and in terms of the reverse effect, i.e., stagnant or reverse progress shown because of the inconsistent service delivery of electricity on the islands. Gender disparities in the labor market can be addressed through vocational training programs aimed at increasing women's participation in skilled professions, including renewable energy management and entrepreneurship. Encouraging women to take on leadership roles within mini-grid governance structures could further improve their economic standing and influence over community development initiatives. This is consistent with feminist energy-transition scholarship calling for intersectional, gender-responsive, and community-inclusive approaches [21].

One of the most notable social changes resulting from electrification has been its impact on cultural practices, consumption patterns, and

community interactions. Prior to the arrival of electricity, social gatherings were an integral aspect of island life, with community members congregating at central locations to share limited access to television and other forms of entertainment. With the widespread availability of personal televisions, mobile phones, and internet access, communal socialization has decreased, and individual consumption of digital media has risen. This shift, while representing an increase in access to modern technology, has also introduced a sense of social isolation, particularly among younger generations. Additionally, the availability of refrigeration has led to subtle changes in dietary habits, with an increase in the consumption of fresh juices and stored foods. However, economic constraints have prevented many families from fully capitalizing on these benefits, limiting the extent of dietary diversification.

With regard to education and human capital development, mini-grid electrification has contributed to higher school enrollments and enhanced access to digital learning tools. The ability of students to complete assignments online has improved, and educational infrastructure has expanded to accommodate secondary education. However, the educational system continues to struggle with teacher shortages, inadequate infrastructure, and limited internet connectivity, which hinder the full realization of electrification's potential. Consistent with existing literature [12], our findings suggest that electricity access alone is insufficient to produce measurable improvements in education unless paired with institutional investments, reliable service, and affordability mechanisms. Schools on the islands suffer from poor building conditions, exacerbated by environmental factors such as sea salt corrosion. Furthermore, while electricity has enabled nighttime study opportunities, the intermittency of power supply has created new constraints on academic performance.

Electrification has also brought modest improvements to healthcare services, particularly in vaccine storage and the refrigeration of essential medicines. The establishment of local healthcare facilities represents a critical advancement in improving access to primary medical care. However, major challenges persist, particularly the lack of consistent medical personnel and the absence of emergency transport services to mainland hospitals. While electricity has facilitated better healthcare provision, the infrastructural and institutional constraints of the healthcare system remain largely unaddressed. Similar to findings in Africa and Latin America, electricity improves basic health service capacity but cannot overcome systemic healthcare limitations without parallel investments [12,19].

The unreliability of energy provision remains one of the most critical issues identified in this study. Across all three islands, frequent power outages and fluctuations have led to adaptive coping strategies, such as the purchase of private generators and informal power-sharing arrangements among neighbors. The unreliability of power has negatively impacted businesses, household planning, and public services, limiting the overall success of mini-grid electrification. Consequently, while electricity access has significantly improved living conditions, the instability of supply threatens its long-term sustainability and effectiveness. These community-driven coping mechanisms exemplify the adaptive response required when a mitigation initiative fails to deliver as intended.

Finally, this study has revealed both the possibilities and the limitations of energy supply investments to address the social dimensions of development. While access to electricity provides a fundamental aspect of improving several social and economic indicators, explicitly incorporating social dimensions into the planning of mini-grid projects would likely enable enhanced progress toward social goals held by many governments in the Global South. For example, accompanying a mini-grid project with investments in teacher training programs and digital infrastructure may prove essential to sustaining the progress made in school enrollments in the Colombian case. Providing financial incentives for teachers to work in remote areas would help alleviate staff shortages. Additionally, strengthening internet connectivity would enhance access to digital learning resources, further expanding educational opportunities for island students. Likewise, energy projects that include health objectives could consider simultaneous improvements of local healthcare facilities, including support with consistent staffing and training programs to reduce dependence on mainland hospitals. Furthermore, investments in emergency transportation infrastructure, such as medical boats or airlift services, would improve response times in critical cases. These align with recent literature recommending integrated social-energy interventions and long-term system planning to ensure that mini-grid systems enable broader socio-economic development [6,36,37]. In conclusion, a hybrid intervention model, where energy infrastructure is deployed alongside complementary social and institutional investments, offers a more viable pathway for translating mini-grid electrification into sustained social development outcomes.

6. Conclusion

This study highlights the social and economic changes resulting from mini-grid electrification in the Colombian island communities of Isla Fuerte, Isla Múcura, and Islote. While the introduction of solar PV mini-grids has improved household comfort, education, healthcare, and entrepreneurial activities, the findings underscore persistent challenges in energy reliability, affordability, and governance that limit the full realization of electrification's potential.

Despite progress in economic opportunities, particularly in tourism and small-scale businesses, high electricity costs and unreliable supply remain major constraints to the further growth in economic activities on the islands. Moreover, while women have gained new economic opportunities, persistent gender disparities continue to shape labor market outcomes.

A critical takeaway from this study is that energy access alone is insufficient to drive sustainable development in isolated communities; rather, electrification efforts must be accompanied by institutional support, infrastructure investments, and financial mechanisms that address local social and economic constraints. Future mini-grid projects must prioritize improved energy storage, renewable energy scaling to meet increased demand, and dynamic pricing models to ensure equitable access and long-term viability. Additionally, policy interventions aimed at strengthening public services, vocational training, and local governance structures are essential for maximizing the socio-economic benefits of electrification.

The design of the paper as a single-country, multi-case study, and the difficulty of disentangling electrification effects from contemporaneous changes (e.g., tourism growth), constitute limitations of this research. Future research should extend to longitudinal mixed-methods approaches and comparative island systems. However, the experiences of these Colombian island communities offer valuable insights into the opportunities and limitations of decentralized energy solutions in rural regions of the Global South, particularly other island communities with electricity access constraints, such as archipelagic Southeast Asia and comparative island systems. While mini-grids hold significant potential for alleviating energy poverty and fostering local economic resilience, their success ultimately depends on the integration of technological advancements with socio-economic policies that promote inclusive and sustainable development. Addressing these challenges will be crucial in shaping the future of off-grid electrification and ensuring that energy transitions effectively support broader goals of social development and economic opportunities.

CRediT authorship contribution statement

Hans-Erik Edsand: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrés Aleán-Romero:** Writing – review & editing, Writing – original draft, Data curation. **Jhorland Ayala-García:** Writing – review & editing, Writing – original draft, Data curation. **Tania Jiménez Castilla:** Writing

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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.

Appendix A. Semi-structured interview protocol

This appendix reports the subset of interview questions used to analyze the socio-economic impacts of electrification in three island communities.

A. Semi-Structured Interview Protocol

A.1 Life Before and After Electrification
- What was everyday life like on the island before electricity arrived?
- What were the most important changes after electricity became available?

A.2 Electricity Use and Daily Routines
- How do you typically use electricity in your household?
- Which appliances consume the most electricity in your household?
- How is electricity used during the evening or night?

A.3 Consumption and Material Change
- What was the first purchase you made after electricity became available? Why?
- What other purchases or household changes followed?

A.4 Social and Cultural Change
- How have social interactions within the community changed since electrification?
- Has the use of television or mobile phones changed how people spend time together?

A.5 Food, Cooking, and Diet
- Has access to electricity changed food storage or diet (e.g., refrigeration, cold drinks, juices)?
- Has cooking practice changed since electrification (e.g., use of firewood or charcoal, indoor air quality)?

A.6 Economic Activities and Entrepreneurship
- Have you or others started new income-generating activities since electrification?
- How have local economic opportunities or livelihoods changed since the mini-grid was installed?
- Have new businesses emerged on the island?
- How would livelihoods or business activities change if reliable 24-h electricity were available?

A.7 Gendered Impacts
(Asked primarily to women respondents)
- What has changed in women's daily routines since electricity became available?
- Has electricity affected women's participation in paid work or income-generating activities?
- Have demographic patterns (e.g., migration or new arrivals) changed, and how does this relate to local opportunities?

A.8 Education, Youth, and Internet Use
- Have children's study habits or school outcomes changed since electrification?
- How does unreliable electricity or heat (e.g., lack of fans) affect studying and concentration?
- Do children or youth use the Internet for schoolwork or learning?
- Have youth ambitions or education and career plans changed?

A.9 Health and Well-Being
- Has access to health services changed in recent years?
- Has electricity affected refrigeration for medicines or vaccines?
- Are there remaining barriers to healthcare access?
- Have living conditions or health practices changed since electrification?

A.10 Energy Insecurity and Adaptive Strategies
- Do you experience blackouts or electricity fluctuations?
- How does unreliable electricity affect daily life in the household or community?
- What social or economic consequences result from unreliable electricity (e.g., food spoilage, damaged appliances, lost income)?
- What adaptations have households made to cope with unreliable electricity?
- How has unreliable electricity affected household or business expenses?

A.11 Future Aspirations and Perceptions
- What changes would you make if reliable and affordable 24-h electricity were available?
- How do you perceive solar power as an energy source for the community?

B. Focus Group Discussion Guide

Focus group discussions were conducted in two study sites to explore shared experiences and collective perceptions of socio-economic change following electrification.

B.1 Life Before and After Electricity
- What was life like before electricity, and what changed most after electrification?

B.2 Household Practices and Consumption
- What were the first changes households made after electricity arrived?
- How is electricity typically used during the day and at night?

B.3 Social Life and Community Interaction
- How have social interactions within the community changed since electrification?
- Has the use of television or mobile phones affected social life?

B.4 Economic Opportunities
- What new economic activities or businesses have emerged since electrification?
- What limits economic activity when electricity is unreliable?
- How would economic activities change with reliable 24-hour electricity?

B.5 Education, Youth, and Internet
- How has electrification affected studying, school outcomes, and youth aspirations?
- How do heat and lack of electricity affect learning environments?
- How is the Internet used for education or learning?

B.6 Food, Health, and Well-Being
- How has electrification affected food storage, diet, cooking practices, or well-being?
- Has access to health services or medicine storage changed?

B.7 Energy Insecurity and Adaptation
- What problems do people experience due to unreliable electricity?
- What coping strategies and adaptations are used by households or the community?

B.8 Closing Question
- Overall, would you say life on the island has improved or worsened since electrification? Why?

Data availability

Data will be made available on request.

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