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Electricity access in the Brazilian Amazon: governance and lived experience

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ABSTRACT

This paper explores the lived experience of top-down universal electricity access governance among three remote communities in the Brazilian Amazon. Through interviews and surveys among participating households, we analyzed and compared access to education, health services, and income through the lens of energy access. While the three case study communities should be beneficiaries of the "Luz para Todos" universal electricity access program, our findings suggest that their remoteness and the lack of incentives for last-mile connection inherent in this governance arrangement have only seen one of them benefit from solar PV and battery provision through this program. While this community fares marginally better in terms of education, health service provision, and income, it still lacks a reliable electricity supply. Among the other communities in the local state of Pará, those with access to locally governed and maintained microgrids, integrating interconnected solar PV and battery systems, display the greatest potential for resilient energy access. This paper concludes with recommendations to shift from a top-down electricity access supply logic to a more decentralized governance logic which supports reliance in access through community embedding.

Introduction

Despite decades of rural electrification programs seeking to achieve universal access to electricity in Brazil, little progress has been made in remote areas of the Amazon in the last decade (Cavalcanti, 2013; ESMAP, 2025; Leduchowicz-Municio et al., 2022; Nerini et al., 2014; Pereira et al., 2011). This is not a result of a lack of policymaking ambition. Decree No. 11,628/2023 provides an update to "Luz para Todos" (light for all), which aims to universalize electricity access throughout Brazil since 2003; the Política Nacional de Transição Energética (PNTE or National Energy Transition Plan) developed by the National Energy Policy Council (CNPE) guides long-term planning; and Normative Resolution No. 1000 of the National Electric Energy Agency (ANEEL) establishes the rules for the provision of the public service of electricity distribution through concessionaries (GFB, 2023; MME, 2024).

These public service concessionaries maintain monopolistic control over the operationalization of "Luz para Todos" in their geographic area (Gomez & Silveria, 2012; Nerini et al., 2014; Slough et al., 2015). As a result of regulated income streams, however, these concessionaires have little to gain from last-mile electrification of remote communities which lack economic integration and economies of scale. Consequently, the inherent top-down governance logic of Brazil's regulated electricity market - which is structured to guarantee the supply of electricity in a safe, reliable and accessible way for all consumers - slows down and ends up blocking the process of universalizing electrical energy service access by denying the inclusion of other business models beyond centralized utility services. This has the contradictory effect of hindering energy access and diversification within a context it purports to support (Leduchowicz-Municio et al., 2022; Slough et al., 2015).

For people inhabiting remote regions of the world, who struggle to maintain energy resilience, but whose livelihoods increasingly depend on reliable energy access, a bottom-up and multifaceted approach is all the more essential, since these societies experience the consequences of energy scarcity more acutely than those inhabiting on-grid environments (Brisbois, 2019; WHO, 2021). The good news is that progress is being made in the development of technical solutions for remote communities which do not hinge on the immediate expansion of national

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grid infrastructure. In Brazil, these solutions mainly compass individual intermittent electricity generation systems (known as SIGFI) or isolated electricity generation and distribution microsystems (known as MIGDI). These comprise solar photovoltaic sources or hybrid systems in combination with another source such as petroleum-based generator systems to power loads such as lighting, refrigeration or agricultural processing equipment (Valer et al., 2014; Valer et al., 2017).

While SIGFI and MIGDI systems are technically decentralized, their governance remains centralized. They are managed by the electricity distribution company (concessionaire of the public service for the supply of electricity; Equatorial Energia S/A in the case of the state of Pará/Brazil; henceforth DSOs – distribution system operators) which is responsible for all energy services in the state, whether on-grid or off-grid services, even though these services are outsourced to other companies in off-grid contexts (Leduchowicz-Municio et al., 2022).

At the same time, significant socio-technical progress and business model innovation accompany the development and diffusion of SIGFI and MIGDI systems in remote locations (Costa & Santos, 2023). Increasingly, these business models and systems challenge the top-down governance logics underpinning universal energy access in Brazil, especially in remote settings. To achieve universal energy access, González-García et al. (2023) argue that a comprehensive governance restructure is required which replaces the top-down centralized model with a multi-level governance approach which supports technological diversification and adaptive business models.

In this paper, we create a better understanding of the juxtaposition of these two logics, the top-down governance logic embodied by "Luz para Todos" and the bottom-up logic building on a nuanced understanding of the consequences of energy scarcity in remote communities. To this end, we seek to answer the following question: *can a more nuanced understanding of the lived experience of energy cultures support better governance and universal electricity access?*

The research underpinning this paper involved an interdisciplinary team of researchers investigating ways in which three remote communities in the state of Pará, Ilha das Onças (Barcarena/PA), Ilha da Pacoca and Sagrado Coração de Jesus (Abaetetuba/PA), and Tucuruí Lake (Tucuruí/PA), who in theory would be beneficiaries of the "Luz para Todos" program, experience energy access. Paradoxically, Pará as a state has the greatest installed electricity generation capacity of all federal states, yet the inhabitants of these communities or experience energy scarcity as part of their daily lives (Thives et al., 2021).

Our research focuses on the arrangements associated with the use of energy sources that become part of the local way of life, directly influenced by, but also influencing, the cultural, social, and kinship context of the three case study communities surveyed, particularly in the absence of (regulated) grid access. Regarding the "Luz para Todos" program, the present work sought to gather evidence that could lead to a better *design* of this public policy, capable of supporting both universal and high-quality energy access in remote areas of the Amazon region and contributing to the delivery of the Sustainable Development Goals (SDGs; UN, 2015).

In the following section, we provide a brief literature review and describe the methodology. Next, we first consider access to energy according to the World Bank (ESMAP, 2015), access to education and health services, and access to income to create an insight into how energy access, or rather energy scarcity, influences the social and economic fabric of these communities. We subsequently link the different energy access scenarios to the (un)availability of basic services and opportunities. Finally, we wrap them up in a discussion and the conclusion in which we share deeper insights and recommendations to foster universal energy access as the basis for sustainable development.

Literature review

As mentioned above, normative Resolution No. 1000 of Brazil's National Electric Energy Agency (ANEEL) establishes the rules for the provision of the public service of electricity distribution and associated remuneration. Article 517 et seq. of this resolution prescribes, among other things, that the DSO must supply the energy necessary to match consumer demand (load) on a monthly basis. In addition, it must respond to any request for a load increase free of charge, subject to specific rules. In accessible and densely populated settings, building the necessary infrastructure for this level of provision will deliver returns through grid charges on bills. In remote, topographically challenging, and less densely populated areas, however, where the economics of grid expansion and operation do not stack up, DSOs are expected to supply electricity through SIGFI (Fig. 1) and MIGDI systems (Costa & Santos, 2023).

Regulations stipulate that the SIGFI must operate autonomously for 36 h using solar sources, and 48 h using wind sources. From a technical standpoint, this autonomy implies that the battery bank is dimensioned to meet the average household load for 1.5 days in the absence of any external power source or solar generation, thereby mitigating supply intermittency during cloudy or rainy periods. Beneficiaries of these programs, however, often suffer from poor quality operation and maintenance services provided by the DSOs, in part because they are far removed from the decision-making processes. Indeed, it is now generally accepted that without correcting pre-existing structural injustices, which often disseminate through markets and socioeconomic arrangements, such regulations can become a further source of injustices and vulnerabilities (Sovacool et al., 2019).

While an unavoidable delay of the clean energy transition is to be expected in the remote areas such as the Amazon forest due to limited formal infrastructure which is still predominantly served by fossil fuel powered machinery, a window of opportunity is opening up to accelerate the transition process. These new opportunities extend far beyond technological solutions using renewable sources, to encompass demand-side actions and new business models, including the vital, but hitherto largely overlooked, aspect of governance (González-García et al., 2023). Such a change demands a decentralized and democratic political approach taking closer consideration of the end user than the current centralized models (Markard, 2018).

Many professionals in the energy sector recognize that achieving such a transition hinges upon a better understanding of underlying injustices and power structures that are invariably intertwined with energy access. It is well documented that these power structures generate barriers to the necessary structural changes for a more just transition which takes into account the needs and requirements of disadvantaged segments of society (Brisbois, 2019; Kuzemko et al., 2016). These barriers are becoming increasingly apparent in the conflict of interest between monopolizing incumbents and decentralizing innovators, a clash between the foundations of the present and future visions which include a growing demand for citizen participation in the public decision-making process (Baldwin et al., 2018; Wieczorek et al., 2024).

Fig. 1. SIGFI installed as part of the "Luz para Todos" initiative.

In this paper, we emphasize the local factors occupying more and more space in the decision-making process, as opposed to solely drawing on authoritarian governance, a concept that Leduchowicz-Municio et al. (2022) deploy when discussing Brazil's last-mile sustainable energy supply. These so-called authoritarian governance approaches limit the participation of the main stakeholders in the construction of an energy transition and impose a heavy burden, particularly in ongoing financial costs and lack of reliability, on the residents of the remote regions such as Amazônia Legal,[1] where residents live with the lowest rates of electricity access in Brazil (Costa & Santos, 2023; Nerini et al., 2014; Slough et al., 2015).

In the face of completely decentralized geospatial arrangements of the Amazônia Legal (i.e. its remoteness), excluding local actors in processes of judging and decision making about energy supply alternatives, is all the more illogical given that the consequences of such choices are so distant from those of the political decision-makers. Additionally, there is no plausible reason to defend a state paternalism utterly alien to the lived reality of people inhabiting forest and rural locales. If it is accepted that governments must support energy transition with tools that speed up the process, then they must start to take seriously the viewpoint and experiences of the end users; and in so doing they also ameliorate further energy injustices.

Methodology

The project aimed to understand the lived experience of energy cultures in remote areas of the Amazon, an very thinly populated area characterized by low Human Development Index and high infant mortality compared to the rest of Brazil (Thives et al., 2021), by examining challenges and vulnerabilities related to energy usage in daily life. We used a multi-modal approach for data collection in three case study forest locales which comprised various communities. This section will introduce our multi-modal methodology and then provide details about the participant communities.

Data collection

This research employed ethnographic approaches, including gathering local perspectives through long-term fieldwork, participant observation, informal conversations with research participants, semi-structured interviews, and life histories (O'Reilly, 2012). Ethnographic research involves the immersion in cultures and the embedding in the lives of research participants to gain insights into their perspective of specific phenomena, local behaviors, characteristics, motivations, and attitudes (Bernard, 2013; Wilson, 1977). This open and adaptable technique facilitates the continual modification of research design during the data collection process, as opposed to manipulating variables to fit a prescribed hypothesis (Tuckman, 1999).

Compared to quantitative approaches, which dominate studies around energy supply and range from supply system engineering to demand forecasting measurements, ethnographic approaches focus on the lived experience of such systems, which goes beyond solely knowledge of technology itself to broader understanding of "energy cultures". In particular, ethnography can provide insights into political allegiances that control access to energy, community tensions that result from such allegiances, and moral interpretations of supply arrangements. Varying local experiences of energy supply, energy failures, energy scarcity, and hopes for the future imparted by research participants informed the research trajectory as the project progressed. Importantly, collaboration was central to the success of the study, with the objectives and methods developed and deployed closely with local actors and institutions whose knowledge, experience, and understanding enabled us to develop an equitable and bottom-up discussion around achievable just energy transition in the region.

Since research explored holistic aspects of "energy cultures" such as the energy supply chain, the use of different energy sources, energy transition, and experiences with public policies and services, our interdisciplinary team also conducted quantitative research using surveys alongside ethnographic data collection. This data supplemented analytical depth with analytical breadth and replicability through comparable community datasets. In total, our Brazilian research team conducted 51 semi-structured interviews and administered 81 structured surveys in the participating communities. Alongside this, they also spend significant periods of time engaging in informal conversation when undertaking energy-related tasks such as installing, using and fixing machinery. It is often during these informal contexts that researchers can obtain the kind of rich data that is difficult to access in formal contexts such as interviews and surveys.[2]

Conducting the field research required navigating complex logistics inherent to the Amazon region, directly reflecting the geographic isolation of each studied profile. Travel to Ilha das Onças relied exclusively on river transport, whereas access to the Sagrado Coração community, Ilha da Pacoca, and the communities surrounding the Tucuruí Lake required a combination of road and river travel. Primary data collection was based on intensive immersion visits to each of the three settings, conducted between 2022 and 2024. The research team spent an average of five consecutive days at each location. This immersion period allowed not only for the application of formal research instruments but also for continuous participant observation of daily routines and the specific nocturnal challenges imposed by energy scarcity across the different governance arrangements.

In addition, regular visits were made to the localities of Ilha das Onças, Ilha da Pacoca, and Sagrado Coração de Jesus throughout the project, with visits to Ilha das Onças taking place every two weeks (one-day visits) and to Abaetetuba approximately every 45 days (visits lasting an average of two days), which enabled continuous monitoring, analytical refinement, and contextual validation of the data. Before the main data collection, a pilot phase was conducted in a community on Ilha das Onças, used to test and refine the research instruments.

Regarding participant selection, a non-probabilistic sampling methodology was adopted, combining purposive, convenience, and snowball sampling techniques. This methodological choice was dictated by the severe logistical and mobility constraints within the territories, where households are highly dispersed and often accessible only via small boats or trails through floodplain areas (*várzea*). Initial contact with these populations was facilitated through a collaborative network of professors and researchers from the Federal University of Pará (UFPA) active in the region. This academic mediation was fundamental in establishing the necessary trust and gaining acceptance from residents prior to the commencement of fieldwork. Subsequently, the residents themselves recommended neighbors and family members who were available and willing to participate. This approach ensured the viability of data collection in remote environments; it enabled the capture of nuanced lived experiences and the diversity of sociotechnical energy arrangements, thereby maintaining ethnographic rigor despite access limitations.

Setting

The research team in Brazil undertook this multi-modal research between 2022 and 2024 as part of a project entitled "*Energy Resilience:*

[1] The Legal Amazon is made up of the states of Acre, Amazonas, Rondônia, Roraima, Pará and Tocantins, all in the North region; in addition to the states of Mato Grosso, belonging to the Midwest region; and part of the state of Maranhão, which belongs to the Northeast region of Brazil.

[2] This project and the forms that guided the field research were approved by the Brazilian Research Ethics Committee, under approval number CAAE 58537222.9.1001.8117.

Exploring the cultures, politics, and practices of energy access in Amazonia".[3] It involved engagement with three case study communities: two riverside forest locales, each of which comprises a set of clustered communities (known as *Comunidades Ribeirinhas*) that are accessible only by river transport, Ilha das Onças (Barcarena/PA), Ilha da Pacoca and Sagrado Coração de Jesus (Abaetetuba/PA)), in the state of Pará; and the island communities on Tucuruí Lake (Tucuruí/PA), in the state of Pará.

The demographic characteristics of the studied communities and the respective sample sizes for both the semi-structured interviews and structured surveys are summarized in Table 1.

Ilha das Onças

Ilha das Onças, although located only 20 (twenty) minutes by boat from the COP30 hosting metropolis of Belém, benefits neither from access to electricity through the distribution grid, nor from "Luz para Todos". In this community, 10 semi structured interviews and 18 surveys were completed along Rio Piramanha and Landi where most of the population is concentrated.

Ilha Pacoca and Sagrado Coração de Jesus

The communities of Ilha Pacoca and Sagrado Coração de Jesus are both technically part of the city of Abaetetuba, situated on small islands in the Meruú-Açu and Maracapucu rivers, close to Marajó Bay. On the islands – which together comprise a total of 97 households – the team conducted 5 semi-structured interviews and completed 12 surveys.

Tucuruí

After the construction of the Tucuruí Hydroelectric Power Plant (UHT) and the flooding of the hinterland, only islands were left of what was once a rainforest. Former residents of the lowlands populated these islands in Tucuruí lake but never benefited from their proximity to the UHT. Among these island communities, which have benefitted from "Luz para Todos", 36 semi-structured interviews and 51 surveys were completed.

The communities in these territorial areas survive on economic activities related to forest extraction and fishing. Fruits such as taperebá (*Spondias mombin*), andiroba (*Carapa guianensis*) and murumuru (*Astrocaryum murumuru*) are often sold to multinational cosmetic companies. However, among the most profitable activities during harvest periods is the collection of açaí (*Euterpe oleracea*), which traditionally involves the worker, known as "picker", climbing the açaí trees located on their land to collect the fruit. Fish and shrimp are also caught and sold at markets in nearby cities. These are also a core source of income, without which these forest residents would find themselves in severe hardship.

These communities effectively constitute case studies and are referred to as such in this paper. They also represent different energy access scenarios which we explore in greater depth in the discussion. By investigating the daily activities of the residents of these communities, we explored how local arrangements linked to the use of alternative energy sources constituted an integral part of their way of life, directly intertwined with their cultural, social, family, and religious contexts.

Table 1
Community demographics and sample size.

Study area / community	Estimated number of households	Semi-structured interviews	Structured surveys
Ilha das Onças (Piramanha and Landi rivers)	~ 820[a]	10	18
Ilha da Pacoca e Sagrado Coração de Jesus	~ 97[b]	5	12
Lago Tucuruí (Island communities)	N/A[c]	36	51
Total	–	**51**	**81**

[a] Estimate based on data from the Amazon Foundation for Studies and Research of Pará (FAPESPA).
[b] Estimate based on demographic mapping and declarations provided by local interviewees during fieldwork.
[c] Precise demographic data specifically for the insular communities of the Tucuruí Lake are not available (N/A) in official censuses, as government databases aggregate these populations within the broader rural statistics of the surrounding municipalities.

Data analysis

Data was gathered and analyzed by the Brazilian researchers. Their findings were shared with the UK team in a series of details reports, two for each case study area (one qualitative and one quantitative study each), in Brazilian Portuguese. These were translated into English using Microsoft-embedded AI-powered translation software with support from native Portuguese speakers to iron out mistranslations. The qualitative reports are around 20 and pages in length and the quantitative reports are around 50 pages long. As the research was undertaken at different times, by different teams, there is not always a 100% overlap between the reported data categories. In this publication we draw on community-comparable data which also has a national comparator (household composition and educational attainment for example) or an internationally agreed comparator (such as the World Bank's energy access framework – ESMAP, 2015).

The latter categorizes attributes such as capacity, availability, reliability and quality, accessibility, formality, health, and safety into six Tiers (0 to 5) to facilitate comparison (see Table 2 below). Based on specific questions asked in interviews, each attribute was classified into one of these Tiers, resulting in a multi-tier table on access to electricity. Lower Tiers indicate inadequate access to electricity or very low-quality access, while higher Tiers correspond to satisfactory or high-quality access. This approach, developed by Sovacool and Mukherjee (2011), allows for assessing and comparing multiple dimensions of energy supply and (in)security.

This research thus constituted a combination of simultaneous data collection and regular on-site researcher "labs" involving interdisciplinary teams undertaking fieldwork together and discussing findings regularly throughout the process and while new insights were encountered during the data collection process. This "lab" approach evolved from our interdisciplinary methodology, which draws on social analysis, especially ethnography, and the disciplinary backgrounds of the research team, spanning anthropology, law, geography, sociology, history, and engineering.

Findings

This section provides the primary results from quantitative and qualitative evaluations conducted in the abovementioned locations. As part of our multi-modal and interdisciplinary approach, we integrate the quantitative and qualitative findings to establish an organic analytic between the two approaches. This facilitates a set of conclusions that can draw out the diversity and challenges of energy transitioning in remote areas of the Brazilian Amazon.

Access to energy

The evaluation of the data with regards to the Measuring Energy Access framework (Table 1) revealed the following energy access scenarios across the three case studies as shown in (Fig. 2).

Our findings reveal that the communities of Ilha Pacoca and Sagrado

[3] This project was funded by a British Academy Knowledge Friontier grant (2020), KF400220.

Table 2
Measuring Energy Access framework (ESMAP, 2015).

Attributes		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity (W)		< 3	3–49	50–199	200–799	800–1999	≥ 2000
Availability (hrs)	**Day**	< 4	Min 4		Min 8	Min 16	≥ 23
	Evening	< 1	Min 1	Min 2	Min 3	Min 4	
Reliability	**Frequency** (disruptions per week)	> 14				4–14	≤ 3
	Duration (disruptions per week)					> 2 h (if $f \leq 3$)	≤ 2 h
Quality (Voltage problems)		Yes				No	
Affordability (Standard 365 kWh/year)		$\geq 5\%$ household expenditure			$< 5\%$ household expenditure		
Formality (Bill payment)		No				Yes	
Health and Safety (Accidents and risks)		Yes				No	

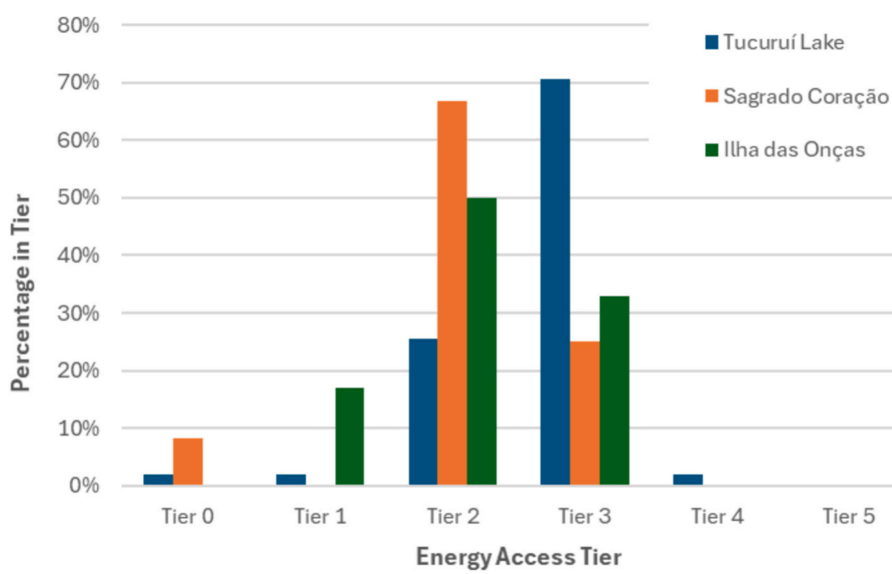

Fig. 2. Multi-tier assessment of the communities in Ilha das Onças, Ilha Pacoca and Sagrado Coração de Jesus, and Tucuruí Lake according to the Measuring Energy Access framework (ESMAP, 2015).

Coração de Jesus have the lowest energy access scoring of the three case studies, with around 3/4 of the households engaged in this research below the threshold (Tier 3). This is despite Sagrado Coração de Jesus benefiting from a small extension of the grid infrastructure. This extension, however, is unregulated, unreliable, and expensive, with all interviewees reported spending more than 5% of their family income on electricity, which suggests high levels of energy poverty. At the same time, these islands are administratively part of Abaetetuba, a grid-connected cosmopolitan center. Stark contrasts in energy access at close proximity demonstrate the need to establish specific solutions to meet each community's unique socio-technical profile.

This contrast is even more pronounced in the case of the Tucuruí islands which have been artificially created through the construction and operation of Brazil's second largest 100% national hydroelectric power plant in terms of installed power and one of the most significant engineering works in the Amazon, but do not benefit from grid access. On the other hand, the islands have benefitted from "Luz para Todos" with 2/3rds of interviewees using electricity exclusively from SIGFIs and three quarters of respondents adequately served (Tier 3 and above).

The communities inhabiting Ilha das Onças, meanwhile, fare only slightly better than that the communities of Ilha Pacoca and Sagrado Coração de Jesus, with 2/3rds of the 21 interviewed households below the threshold (Tier 3). These households are all connected to off-grid/isolated systems involving a combination of individual household systems and shared-ownership microgrid systems. 11 of these systems are PV systems and 10 are diesel or gasoline generators which indicates a range of energy sources and ownership models.

Diesel and gasoline systems have been part of the daily lives of the inhabitants of all three communities for many decades, with several of the older interviewees reporting access to generator-powered electric lighting since childhood. But these are expensive to operate as fuel supply is much more costly in these remote areas compared to urban settings which limits continuous operation, restricts the availability of energy, and, consequently, prevents households from reaching higher energy access Tiers (3 or above).

These findings point towards a recurring failure of top-down governance with regards to the 0.5% of Brazil's population who suffer from unreliable electricity access (lower than Tier 5 in the multi-tier framework - GEAPP, 2024; ESMAP, 2025). Since current supply levels among all households in the case study areas do not come close to full energy access as defined by the World Bank's energy access framework (Tier 5), public policy is inadvertently perpetuating energy poverty and vulnerability, thus exposing these communities to energy scarcity as part of their daily experience.

Access to education and health services

Similar to energy, access to education is severely curtailed in remote areas of the Amazon, as our findings in Table 3 suggest.

We find that the values regarding educational attainment across the communities are similar, yet far below the national average. While around 1 in 7 has completed high school or above within the case study communities, over half the population has at a national level (Statista, 2024). In terms of statistical categories, most of the interviewees have received less than 8 years of schooling and fall within the range of "functional illiteracy".

Table 3
Educational attainment by household (own data and Statista, 2024).

	Ilha das Onças		Sagrado Coração		Tucuruí Lake		National
Statistical categories	Count	Percentage	Count	Percentage	Count	Percentage	
Complete High Education	0	0.0%	0	0.0%	1	3.3%	19.0%
Incomplete High Education	0	0.0%	0	0.0%	1	3.3%	4.1%
Complete High School	3	16.7%	1	8.3%	4	13.3%	30.0%
Incomplete High School	1	5.6%	1	8.3%	0	0.0%	5.0%
Complete Elementary School	1	5.6%	1	8.3%	3	10.0%	7.8%
Incomplete Elementary School	11	61.1%	9	75.0%	18	60.0%	28.0%
No Schooling	2	11.1%	0	0.0%	3	10.0%	6.0%
	18		12		30		-

The schools suffer from difficult learning conditions with no air conditioning and only few fans and drinking fountains. The diesel provided for the generator of the school on Ilha das Onças, for example, is insufficient to meet the school's basic needs. The two schools serving the islands on Tucuruí, meanwhile, benefit from solar PV energy systems. Yet the equipment also does not meet the demands of the context, especially the classroom cooling demand from air conditioning at peak times of the day. While the classrooms do have fans, residents have been requesting more powerful solar energy generation equipment to satisfy the demands and thus ensure children have a more comfortable learning environment and are more likely to attend school. According to the interviewees, this impairs the students' performance. Consequently, many residents seek educational alternatives in nearby cities, but the associated expense puts it out of reach for most.

School meals, essential for both the health and educational attainment of low-income students, are rarely available due to the lack of electricity for food refrigeration. Similarly, the lack of access to reliable electricity also affects access to communication and drinking water. Public health and education services are also affected because the community's Basic Health Units (BHU) rely on a diesel generator. Similar to the schools, however, the generators supplying BHUs are often unavailable due to the frequent lack of fuel or mechanical breakdowns, putting the communities' health service at risk. Electricity supply failures also affect the refrigeration of medicines and vaccines. Much like education, residents must travel to nearby cities for primary health care.

Access to income

At a national level in Brazil, there is no centrally compiled statistic on the share of households receiving minimum wage as these are set at federal state level and change with regards to the overall income structure. However, studies undertaken on the Continuous National Household Sample Survey (Pnad) suggest that around 35.6% of households nationally receive only one minimum wage (Carneiro, 2022). The situation among the case study communities is more precarious. On Ilha Pacoca and Sagrado Coração around the same share of the population report household incomes below the minimum wage. On Ilha das Onças this increases to over half the interviewed households (Table 4).

At the same time, our research found that the number of people per household among the three case studies on average exceeded both the national average and the average for Amazon Legal (Table 5). Due to the large number of people per household, the income per person is consequently much lower than the minimum necessary for a dignified life.

Table 4
Household income.

Income structure	Ilha das Onças	Sagrado Coração	Tucuruí Lake	National
	Percentage	Percentage	Percentage	Percentage
<minimum wage	53	33.3	43	35.6

Consequently, one might assume a high dependence on government support, especially the Bolsa Familia program, one of the worlds' oldest and most influential conditional cash transfer programs in the world. It reaches more than 50 m Brazilians and is associated with significantly lower mortality rates compared to scenarios with reduced coverage (Cavalcanti et al., 2025). Nationally, the percentage of households receiving Bolsa Familia fell from 16.6 to 14.3 between 2012 and 2019 before increasing to 18.7% in 2024 as a result of the COVID-19 pandemic (Statista, 2025). Despite average household incomes often below the minimum wage, however, the share of households receiving this support is around the same as the national average with the exception of the Tucuruí communities (Table 6).

In the low-education-low-income *Comunidades Ribeirinhas* of Ilha das Onças, Ilha Pacoca and Sagrado Coração, in contrast, most households supplement their incomes with the extraction of açaí between May and November, while others also carry out activities related to fishing and services offered to the community (see the range of income generating activities among the households of Ilha das Onças in Table 7).

It is notable that most of these activities depend entirely on human labor. Given the limits to productivity such labor entails, it is unlikely that the households will be able to receive more income and access better educational and health services without access to reliable energy sources.

Energy access scenarios

Our findings regarding energy access enable us to differentiate the consequences of energy scarcity among entirely unregulated off-grid (Ilha das Onças and Ilha da Pacoca), unregulated on-grid (Sagrado Coração de Jesus), and regulated off-grid (Tucuruí) electricity (in-)

Table 5
Inhabitants per household.

People per household	Ilha das Onças		Sagrado Coração		Tucuruí Lake		Amazon Legal	National
	Count	Percentage	Count	Percentage	Count	Percentage		
1 to 3	9	50%	5	42%	19	63%		
4 to 6	8	44%	6	50%	10	33%		
7 to 9	1	6%	1	8%	1	4%		
Average	3.66		3.83		3.47		3.33	2.79

Table 6
Financial support among households.

Financial aid	Ilha das Onças		Sagrado Coração		Tucuruí Lake	
	Count	Percentage	Count	Percentage	Count	Percentage
Bolsa Familia	4	19%	2	15%	12	32%
Retirement	1	5%	2	15%	6	16%
Closed insurance	3	14%	1	8%	10	27%
Public aid	1	5%	0	0%	2	5%
None	12	57%	8	62%	7	19%

Table 7
Household income-making activities on Ilha das Onças.

Activity	Ilha das Onças
Acai picking	15
Fishing	4
Shrimp	3
Heart of palm	2
Mechanical workshop	1
Lumberyard	1
Gasoline trade	1
Student transportation	1
Unspecified	1

accessibility scenarios as follows (Table 8):

The more off-grid and unregulated the electricity supply scenario, the greater the repercussions, cascading effects, and self-reinforcing feedback loops: unpredictable and insufficient energy access results in inadequate education and health service provision. This in turn reduces educational attainment and household income. Consequently, the households in these communities lack the resources to establish sufficient systems of energy supply.

Unregulated off-grid supply

The good news is that even in the most deprived and inaccessible case study community surveyed, Ilha das Onças, most residents have sufficient resources to acquire solar PV energy systems privately, often in combination with batteries for storage. In this *unregulated off-grid supply scenario*, these systems meet the households' basic electricity needs given the absence of regulated grid access. Investment costs, however, can consume a large share of family income and place people in a situation of evident poverty and energy insecurity. Nevertheless, despite the significant upfront cost and lack of access to bank credit, families continue to invest in solar PV equipment using their hard-earned savings to improve their quality of life and, in the long term, reduce the amounts spent on operating and maintaining the electricity supply system, when compared to fossil fuel-based systems.

Private equipment traders are the only people responsible for sales and installation, and in most cases, acquisition and service provisions are made without contracts or warranties. Furthermore, without a formal contract, maintenance is unregulated. Consequently, maintenance is undertaken informally, often by nearby relatives or acquaintances and frequently without the required technical qualifications. In response to the inherent intermittency and low power output of solar PV systems and infrequent availability of technical assistance, it is typical for interviewees to combine PV systems with diesel or gasoline generators to improve the reliability and security of their power supplies. However, this emergency hybrid solution implies a significantly high total cost of acquisition and operation, making access to electricity an expense that consumes a large portion of household income. This critical scenario highlights an immeasurable technical and institutional gap in support, which could be mitigated through structured collaboration between communities and public and private institutions.

Generators are still used to power equipment with higher load requirements, such as pumping, freezing, and pulping machines (see also Costa & Santos, 2023). On the other hand, equipment with lower loads, such as fans, cell phone chargers, sound equipment, and lighting, are powered by PV solar energy. As a general observation, this implies a more significant expenditure of family income to guarantee a minimum electricity supply, as two systems need to be purchased, installed and maintained. In both cases, the maintenance and part replacement costs are high, while fossil-fuel systems also require continuous fuel input.

Additionally, fossil fuel generators cause numerous local environmental impacts, including air and noise pollution that community members often state have negative impacts on their everyday lives.

Unregulated grid supply

Community residents of Sagrado Coração de Jesus benefit from a small extension of the electricity grid through which they have tariff-free access to electricity. However, it is unregulated and unreliable, thereby constituting an *unregulated grid-supply scenario*, referred to as "bush energy." This term is used because the interviewees either do not know or chose not to reveal the origin of the grid extension. This informal grid, the installation of which was led by a former service provider of the electricity distribution concessionaire, benefited from financial contributions by members of the community to develop the electrification project in the area. The installation process also drew upon local labor to open swaths (deforestation) to make space for the power line.

Following this initiative, however, a recurring concern of the residents is deforestation, which threatens one of the primary sources of income for *Comunidades Ribeirinhas* families, the collection of açaí. While electricity supply from the distribution grid promises security in

Table 8
Energy access matrix.

	Regulated	Unregulated
Grid supply	Belém etc.	Sagrado Coração de Jesus
Off-grid supply	Tucuruí Lake	Ilha da Pacoca and Ilha das Onças

principle, in practice, it does not generate the necessary security in terms of access. Based on the interviews, it was found that the electricity supply is frequently interrupted for days, weeks, and even months at a time. This is due to improper wiring that does not meet professional installation standards. In addition, heavy rainfall, which is common in the region, often causes trees to fall on the power lines which also causes significant power outages.

As a result, this tariff-free access to electricity does not improve household incomes. Similar to residents of Ilha das Onças, these communities need to purchase fuel (diesel or gasoline) to power generators as a backup. Consequently, these communities end up spending more on their unreliable power supply with fuel prices reaching up to 200% the cost in urban environments, even though they are hypothetically entitled to discounts worth up to 100% for a reliable supply (claimants of social benefits – Bolsa Familia - depending on the user's monthly consumption and socioeconomic profile - Brasil, 2025) if they were operating in a regulated environment.

The situation on nearby Ilha da Pacoca is similar to the situation on Ilha das Onças. The families living on the island are entirely cut off from services and infrastructure, due to the low demand and high costs for the irregular grid extension, which must be shared among residents. In contrast to the Ilha das Onças community, however, occasional tariff-free electricity access in Sagrado Coração and regular access to generator fuel in both communities results in apathy towards solar PV systems, batteries, and inverters. Only one of the Ilha da Pacoca's residents uses a solar PV system, purchased online from an online retailer. Because the design was not properly sized, the equipment's performance suffers, failing to deliver the electricity it was designed for, and even making it impossible to access the supplier's warranty.

In these communities, high equipment costs are cited as the main barrier to access to renewable energy. Likewise, there are no lines of financing, nor do residents have the ability to present guarantees that prove income for the acquisition of equipment. Much of the land where they live also lacks documentation of ownership, so does not serve as collateral for loans, for example. Add to this the insecurity brought about by the inability to safeguard possessions in dark homes - houses lacking lighting close to waterways are easy targets of theft during the night – then one can see how forest inhabitants suffer from multiple risks when denied adequate energy.

Regulated off-grid supply

Communities on Lake Tucuruí inhabit islands owned by the Federal Government. They previously inhabited the lowland territory before the construction of the dam. These islands also attracted people who wanted to live in places further away from the region's main urban center, the city of Tucuruí. Until recently, many of these new settlements did not have access to electricity even though they lived near a hydroelectric plant with one of the largest installed energy generation capacities in the world. In contrast to the other communities surveyed, most of the homes in Lake Tucuruí have small individual power generation systems with intermittent sources, with a minimum monthly energy availability of 45 kWh using photovoltaic solar energy and battery storage (SIGFI 45).

As these systems were set up as part of the Brazilian government's "Luz Para Todos" program, these communities constitute a *regulated off-grid supply scenario*. Despite these improvements, some residents, especially those who recently moved to the islands, do not have access to the SIGFI systems. There also exists a degree of cynicism surrounding the political promises regarding improved energy access, which are repeated every election cycle but not always fulfilled, which is also evident across the other case studies. Negative perceptions regarding the operation and maintenance service provided by the electricity distribution company (who install and maintain the SIGFI, along with all other energy services) also proliferate (Gomez & Silveria, 2012; Nerini et al., 2014).

In addition to traveling to Tucuruí to schedule the service, the time it takes to complete the service can vary between 5 and 21 days. When residents are faced with a lack of proper maintenance by their electricity distribution company, they often seek self-sufficiency, but they do not always have the necessary training to handle electrical equipment safely. This poses serious risks to equipment and the lives of people in the area. Maintenance is far from straightforward, and residents consider the technology of these systems to be complex, and the knowledge opaque.

The operation and maintenance of equipment on Lake Tucuruí, like in the other case study communities, require greater effort due to difficult access and logistics, the lack of specialized professionals capable of installing and maintaining systems in compliance with best practices; extreme environmental conditions; the lack of availability of spare parts; and, of course, solid knowledge of electrical energy, photovoltaic systems and batteries, and safety protocols. Yet the specialized nature of the technologies is what also makes them so valuable. As a result, communities in Lake Tucuruí report theft of solar PV energy generation equipment, which incentivizes residents to make changes to the subcontractor installations to keep the equipment safe. These modifications include repositioning the PV modules to less visible areas, placing the system cabinet inside the house, and building walls or fences around the installation to deter theft attempts. However, the installation contractors often refuse to carry out maintenance, as the original standard or location of the PV system installation has been altered, reducing the resilience of the system.

Discussion

Our case study research has identified three energy access scenarios in the Brazilian Amazon, *unregulated off-grid supply*, *unregulated grid supply*, and *regulated off-grid supply* which closely map onto the World Bank's (ESMAP, 2015) energy access framework (Table 1). *Unregulated off-grid supply* often aligns with Tiers 1–2 of the framework; *unregulated grid supply* with Tiers 2–3, and *regulated off-grid supply* at mostly Tier 3. In terms of energy access, the findings above suggest that *regulated off-grid*, of all three, yields the greatest benefits. Residents of Tucuruí island report that the quality of life in the region has improved since the installation of this solar PV SIGFI systems (see also Valer et al., 2014). As a result of this improvement in energy supply, the residents have acquired modern conveniences and benefit from slightly higher educational attainment, slightly better access to health services, and to income support they are entitled to. Unlike the other communities surveyed as part of this project, the residents of the communities of Lake Tucuruí also demonstrate confidence in expanding the power supply, despite cynicism regarding the underlying political process.

Among the unregulated scenarios of Ilha das Onças, Ilha Pacoca and Sagrado Coração de Jesus, on the other hand, households have benefit from increasing availability of evermore powerful electricity generation equipment since the early 1990s, which enables them to power more equipment than ever before. Alongside this, users are adept in adapting to these generator systems as well as fixing common technical issues. However, our findings indicate that remote Amazon forest communities such as the ones presented here still predominantly rely on fossil fuels such as diesel and gasoline for energy access in general and electricity service provision in particular. This is complicated by the increasing numbers, diversity and complexity of equipment supported by such generators. Fans, blenders, televisions, computers, sound systems, refrigerators, freezers, phone chargers, and routers now accompany lightbulbs and radios. Rapid change in lifestyles - similar to other communities across the tropics – run parallel to rapid changes in energy demand profiles.

What is most concerning, however, is the health and safety of these electricity access arrangements. The lack of technical standardization has led to many accidents, some of which have been fatal. Among those interviewed, 58% have suffered or know of people who have been victims of electricity-related accidents. This compares to a total of 2354 recorded incidents of injury due to electrical systems in the whole of

Brazil, which equates to electricity-related accident rate of 0.0001% (Martinho et al., 2025). Accidents occur due to falling or tripping due to lack of lighting and electric shock. While there is inevitably a huge number of such accidents that go unreported at national level, this discrepancy is still one of several orders of magnitude, demonstrating that insecurity in supply is not just a matter of comfort, but also of life safety and public health.

Furthermore, while *regulated off-grid*, from a technical point of view, presents the best indicators as stated above, even models such as SIGFI and MIGDI installed on the islands of Tucuruí, although created for remote areas, fail institutionally by keeping their operation and management fully linked to the concessionaire. Such arrangements, instead of fostering autonomy, treat autonomous systems as mere extensions of the hierarchical *status quo*. This design flaw prevents the development of autonomous and adaptive institutional governance arrangements which are crucial for operational resilience. Consequently, these models perpetuate injustices by burdening these communities with intermittency and technical insecurity that could be mitigated by a decentralized and collaborative governance structure.

Additionally, announcements to secure *regulated grid* connections, as mentioned above, tend to coincide with election cycles but fail to materialize subsequently. When they do arrive, the connections are not necessarily maintained due to their remote locations and, as a result, they suffer from the same fate as these *regulated off-grid* systems which do not necessarily improve the resilience of these communities, as is the case in Sagrado Coração de Jesus. Furthermore, the environmental destruction accompanying associated infrastructural development might also put livelihoods at risk, as evident in interviewees' concerns about the removal of açai trees.

Under these circumstances, a combination of clean energy sources through *unregulated off-grid supply*, despite the comparative shortfalls across the case studies, can allow residents and entire communities at least to mitigate against the inadequacy of energy service provision stemming from fossil fuel generators. Since the mid-2015s, clean energy sources, especially solar PV in combination with one or more batteries and an inverter, have been supplying alternative forms of modern energy services (Costa & Santos, 2023). Yet the adoption of clean energy sources is hindered by a chicken-and-egg situation. While many people understand the benefits of PV systems, the high initial costs mean people must show proof of income and have a bank account to acquire them, often with limited opportunities to build a credit history. The lack of warranties also means that skilled individuals are required to perform maintenance, as electrical engineering knowledge required for PV systems is less common than knowledge of mechanical engineering required for generators (Nerini et al., 2014).

Nevertheless, there is no doubt that independence from the most socioeconomically critical fossil fuel generators improves overall resilience and safety while facilitating diversification of economic activity through temporally and spatially expanded communication networks. There is a clear trend among forest community residents to respond to this by acquiring privately owned solar PV systems to mitigate some of the energy service shortfalls they encounter daily. The possibility of supplying electricity through microgrids based on distributed energy resources, incorporating solar PV systems, batteries, and inverters, implies that they are unlikely to break down simultaneously. Crucially, however, they facilitate a shift away from the top-down governance logic (González-García et al., 2023). With power quality and availability increasing, and the range of processing technologies suitable for these arrangements increasing, these communities are shifting from powering only low-power energy services such as lighting, television, fans, sound systems, and phone charging to an increasing range of high-value processing activities. These range from pumping, freezing, and pulping to butchery and meat processing while improving the quality of light, convenience, safety (fewer accidents involving generation equipment), and lower indoor air pollution.

Study limitations

While this study provides essential insights into energy governance in remote areas of the Amazon region, particularly in the state of Pará, it is important to acknowledge its methodological and practical limitations. The primary constraint stems from the extreme logistical challenges inherent to fieldwork in the remote Amazon. Complex access to riverine and island communities, reliant on fluvial transport, mixed routes, and subject to weather and tidal conditions, limited the viable time window for primary data collection to immersions averaging five days in each location. This timeframe may limit the continuity typical of extended ethnographic studies, although this was mitigated by periodic returns to the field, particularly in the localities of Ilha das Onças, Ilha da Pacoca and Sagrado Coração de Jesus, and by the conduct of a preliminary pilot phase, which contributed to the refinement of the research instruments.

Consequently, access difficulties and the high geographic dispersion of households necessitated a methodological approach based on building trust and relying on local referrals. In practice, participant selection began with initial contacts who then introduced or recommended neighbors and family members willing to collaborate with the researchers. Although this organic network of contacts was the only viable way to conduct research in this environment, it resulted in an absolute sample size that inherently restricts the capacity for large-scale statistical generalization of the quantitative data.

However, from a qualitative and ethnographic perspective, these numerical constraints are largely mitigated by the research's ecological validity. The three study areas were carefully selected and share deep socioeconomic, cultural, and geographic characteristics, alongside technical limitations regarding electricity access, with most isolated riverine communities across the Legal Amazon. Therefore, we argue that the dynamics of energy poverty, technical improvisation, and governance documented in this study are not local anomalies, but rather accurate reflections of a much broader regional reality, granting the findings significant theoretical and practical representativeness.

Conclusion

The reasons for the lack of universal energy access among the case study communities are manifold: centralization in the design and execution of energy governance, inaccessibility, difficult terrain, low population density, and poor economic integration of remote communities. In this paper, we analyze the consequences thereof on the resilience, diversity, and justice of electricity supply, which in turn significantly affects the economic integration of remote communities. Despite unfavorable circumstances, we identify a diverse range of approaches used in different communities, depending on local conditions, to overcome adversity.

Overall, however, the level of energy service provision among the case study communities is far below what is necessary for a dignified human life. Residents of these communities consequently maintain low trust in the institutions responsible for providing electricity. These circumstances confine these remote forest communities to living in energy poverty (SDG7) and insecurity with inadequate education facilities (SDG4), restricted access to health facilities (SDG3), and limited opportunities for energy-intensive economic activity (SDG8). Average educational attainment and average incomes reflect this lack of access to energy services. Furthermore, many community residents do not receive the full benefits they are entitled to, such as financial incentives to deter overfishing during the breeding season, which means that they must rely on other sources of income, but these tend to be limited to human labor-related activities due to energy scarcity. Consequently, their circumstances confine their economic activities to primary production with few opportunities for capturing more of the value chain through processing and distribution.

Yet governance of energy access is still mainly approached through a top-down, one-size-fits all approach reflecting a world of property rights, bank accounts, regular income, and taxation. It is evident that this approach has its limitation in remote locations, especially along the Brazilian Amazon. Ensuring access to reliable energy systems and the education and health services and income opportunities they support requires a better understanding of how governance and public policy align with social and cultural realities. It is essential to consult and engage with communities not directly involved in crafting public policy to understand the day-to-day challenges they face and the resilience they strive for.

Consequently, governance responsibility for energy access should be shared among entities with a duty of care for the communities involved. By establishing better communication between the realities on the ground and public policy decisions, we can promote the adoption of clean energy solutions, improve educational attainment, increase access to health services, help lift households out of poverty, and facilitate a shift towards sustainable and resilient living. Support for community self-organization governance models to provide the service of access to electricity on one hand, and new energy service business models involving long-term loans and service contracts on the other are necessary to increase the generation capacity of such distributed clean energy systems and challenge the stranglehold of dangerous and costly fossil fuel generators.

While such generators will continue to provide essential energy backup for the foreseeable future, their dominance in the advancement of economic livelihoods creates an unsustainable interdependence. With the introduction of interconnected PV energy systems with better batteries and inverters, this interdependence can be challenged. One way to address this issue is for public policies to move beyond the logic of universal access to the grid embodied in top-down programs such as "Luz para Todos". Politicians also need to stop using this logic as a political trump card and instead fully reflect the energy cultures of remote forest communities in the provision of public services, including the possibility of developing new concession models that can integrate those directly interested in the decision-making process, decentralizing governance and management, and expanding the supply of electricity to a achieve sustainable development and a just transition also in the remotest reaches of the Amazon.

Based on the presented results, this study proposes that robust bottom-up alternatives, in response to centralized top-down models, can contribute to reaching the 'last mile' in the Amazon. At a broader policy scale, Brazil can draw inspiration from the success of Southern Rural Electrification Cooperatives, such as CRELUZ, located in the state of Rio Grande do Sul. However, the scalability of such models depends on fostering a culture of cooperation and establishing regulatory frameworks specifically tailored to the Amazonian reality.

At a local level, with the precise objective of addressing the structural failures of government electrification programs in the 'last mile' highlighted earlier in this article, the transition to decentralized models requires the development of prototypes capable of directly responding to the vulnerabilities identified in the research. A practical example of this approach is the community association established in 2025 in Ilha da Pacoca, resulting from collaborative governance between residents and university researchers. This initiative aims to transform the vulnerability scenario, evidenced by field data, into a resilient bottom-up management model. From a technical standpoint, the solution is structured around the implementation of a direct current (DC) microgrid, ensuring efficiency and robustness through decentralized photovoltaic generation and battery storage systems, overcoming the typical instability of informal grids. While the university provides technical expertise, institutional mediation, and continuous capacity building, the community assumes direct governance of the infrastructure. This local management goes beyond the physical equipment, encompassing the autonomous definition of tariffs, sharing rules, and preventive maintenance managed by the association itself. By linking local empowerment to the overcoming of concrete technical challenges, such initiatives represent viable and scalable alternatives to the centralized, top-down logic of traditional programs, promoting inclusion, autonomy, and energy sustainability.

CRediT authorship contribution statement

Ricardo Caçapietra: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wilson Macêdo:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Colin Nolden:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Marcos Galhardo:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amy Penfield:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Sam Williamson:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization.

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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References

Baldwin, E., Rountree, V., & Jock, J. (2018). Distributed resources and distributed governance: Stakeholder participation in demand side management governance. *Energy Research & Social Science, 39*, 37–45. https://doi.org/10.1016/j.erss.2017.10.013

Bernard, H. (2013). *Social research methods: Qualitative and quantitative approaches*. London: Sage.

Brasil. (2025). *Law No. 12.212. Precidency of the Republic, L12212*.

Brisbois, M. C. (2019). Powershifts: A framework for assessing the growing impact of decentralized ownership of energy transitions on political decision-making. *Energy Research & Social Science, 50*, 151–161. https://doi.org/10.1016/j.erss.2018.12.003

Carneiro, L. (2022). *Two-thirds of workers make up to two minimum wages*. Valor International. Two-thirds of workers make up to two minimum wages | Economy | valorinternational.

Cavalcanti, D. M., et al. (2025). Health effects of the Brazilian Conditional Cash Transfer programme over 20 years and projections to 2030: A retrospective analysis and modelling study. *The Lancet Public Health, 10*(7), e548–e558. https://doi.org/10.1016/S2468-2667(25)00091-X

Cavalcanti, H. P. M. (2013). O acesso à energia elétrica no Brasil sob a ótica do desenvolvimento como liberdade. *Revista Direito Econômico E Socioambiental, 4*(2), 58–86. https://doi.org/10.7213/rev.dir.econ.socioambienta.04.002.AO04

Costa, T., & Santos, R. (2023). Sizing and deploying an off-grid energy system for rural electrification in an Amazonian remote community. *IEEE Explore*. https://doi.org/10.1109/INDUSCON58041.2023.10374621

ESMAP. (2015). *Beyond Connections – Energy Access Redefined. Energy Sector Management Assistance Program, World Bank Document*.

ESMAP. (2025). *2025 Tracking SDG7 report. Energy Sector Management Assistance Program, Downloads | Tracking SDG 7*.

GEAPP. (2024). *Electrification of Brazil – Deep-Dive Analysis. Global Energy Alliance for people and Planet, LAC-UAC-Brazil-Deep-Dive-1.pdf*.

GFB. (2023). *Light for all program: Decree no. 11,628/23*. Governo Federal do Brasil. https://www.gov.br/mme/pt-br/destaques/Programa%20Luz%20para%20Todos/normativos/arquivos/mme_decreto-no-11-628-de-4-de-agosto-de-2023.pdf.

Gomez, M., & Silveria, S. (2012). Delivering off-grid electricity systems in the Brazilian Amazon. *Energy for Sustainable Development, 16*(2), 155–167. https://doi.org/10.1016/j.esd.2012.01.007

González-García, A., Diaz-Pastor, S. J., & Moreno-Romero, A. (2023). A comprehensive approach to the governance of universal access to sustainable energy. *Sustainability, 15*(22), Article 15813. https://doi.org/10.3390/su152215813

Kuzemko, C., Lockwood, M., Mitchell, C., & Hoggett, R. (2016). Governing for sustainable energy system change: Politics, contexts and contingency. *Energy Research & Social Science, 12*, 96–105. https://doi.org/10.1016/j.erss.2015.12.022

Leduchowicz-Municio, A., López-Gozález, A., Domenech, B., Ferrer-Martí, L., Udaeta, M. E. M., & Gimenes, A. L. V. (2022). Last-mile rural electrification: Lessons learned from universalization programs in Brazil and Venezuela. *Energy Policy, 167*, Article 113080. https://doi.org/10.1016/j.enpol.2022.113080

Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy, 3*, 628–633. https://doi.org/10.1038/s41560-018-0171-7

Martinho, E., De Souza, D. F., Martinho, M. B., Morita, L. H. M., & Maionchi, D.d. O. (2025). *Anuario Estatistico de Acidentes de Origem Eletrica 2025 – Ano base 2024*. Salto: Abracopel. Anuario-2025.pdf.

MME. (2024). *Política Nacional de Transição Energética irá contribuir para maior articulação entre outras políticas de Governo*. Ministério de Minas e Energia. https://www.gov.br/mme/pt-br/assuntos/noticias/politica-nacional-de-transicao-energetica-ira-contribuir-para-maior-articulacao-entre-outras-politicas-de-governo.

Nerini, F., Howells, M., Bazilian, M., & Gomez, M. (2014). Rural electrification options in the Brazilian Amazon: A multi-criteria analysis. *Energy for Sustainable Development, 20*, 36–48. https://doi.org/10.1016/j.esd.2014.02.005

O'Reilly, K. (2012). *Ethnographic methods* (2nd ed.). Abingdon: Routledge.

Pereira, M. G., Sena, J. A., Freitas, M. A. V., & da Silva, N. F. (2011). Evaluation of the impacts of access to electricitiy: A comparative analysis of South Africa, China, India and Brazil. *Renewable and Sustainable Energy Reviews, 15*, 1427–1441. https://doi.org/10.1016/j.rser.2010.11.005. https://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Lei/L12212.htm

Slough, T., Urpelainen, J., & Yang, J. (2015). Light for all? Evaluating Brazil's rural electrification progress, 2000-2010. *Energy Policy, 86*, 315–327. https://doi.org/10.1016/j.enpol.2015.07.001

Sovacool, B. K., & Mukherjee, I. (2011). Conceptualizing and measuring energy security: A synthesized approach. *Energy, 36*(8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043. ISSN 0360-5442.

Sovacool, B., Martiskainen, M., Hook, A., & Baker, L. (2019). Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Climatic Change, 155*, 581–619. https://doi.org/10.1007/s10584-019-02521-7

Statista. (2024). *Education level among residents over 25 years old in Brazil in 2024, by gender. Education level in Brazil by gender 2024*. Statista.

Statista. (2025). *Share of households receiving family benefits in Brazil 2012–2024. Brazil: Share of households part of Bolsa Família 2024*. Statista.

Thives, L. P., Ghisi, E., & Thives Junior, J. J. (2021). Regional inequalities in electricity access versus quality of life in Brazil. *Ambiente Construído, 22*(3), 47–65. https://doi.org/10.1590/s1678-86212022000300609

Tuckman, B. (1999). *Conducting educational research*. Orlando: Harcourt Brace College Publishers.

UN. (2015). *Sustainable Development Goals. United Nations, THE 17 GOALS | Sustainable Development*.

Valer, L. R., Manito, A. R. A., Selles Ribeiro, T. B., Zilles, R., & Pinho, J. T. (2017). Issues in PV systems applied to rural electrification in Brazil. *Renewable and Sustainable Energy Reviews, 78*, 1033–1043. https://doi.org/10.1016/j.rser.2017.05.016

Valer, L. R., Mocelin, A., Zilles, R., Moura, E., & Nascimento, A. C. S. (2014). Assessment of socioeconomic impacts of access to electricity in Brazilian Amazon: Case study in two communities in Mamirauá Reserve. *Energy for Sustainable Development, 20*, 58–65. https://doi.org/10.1016/j.esd.2014.03.002

WHO. (2021). *Measuring energy access: A guide to collecting data using the core questions on household energy use*. International Bank for Reconstruction and Development. https://www.who.int/publications/i/item/WHO-HEP-ECH-AQH-2021.9.

Wieczorek, A., Rohracher, H., Bauknecht, D., Kubeczko, K., Bolwig, S., Valkering, P., Belhomme, R., & Maggiore, S. (2024). Citizen-led decentralized energy futures: Emerging rationales of energy system orientation. *Energy Research & Social Science, 113*, Article 103557. https://doi.org/10.1016/j.erss.2024.103557

Wilson, S. (1977). The use of ethnographic techniques in educational research. *Review of Educational Research, 47*, Article 245265. https://doi.org/10.2307/1170130