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Towards energy justice and energy sovereignty: Participatory co-design of off-grid systems in the Brazilian Amazon

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ABSTRACT

Participatory processes that emphasize energy justice and energy sovereignty are essential to provide electricity for those in need in just and sustainable ways. For isolated, off-grid communities, access to electricity remains a significant challenge, especially in the Global South. Participation is critical to ensuring the viability and sustainability of off-grid energy systems in remote areas, as communities need to be self-reliant in managing and maintaining their own systems. However, experiences of participatory co-design of community-owned, off-grid energy systems – including participation in the steps of planning, dimensioning, installation, training, and management – are still underreported in the literature. In collaboration with three off-grid communities in the municipality of Santarém in the Brazilian Amazon, we conducted a participatory co-design process that delivered photovoltaic systems and a hydrokinetic turbine, using microgrids to improve energy access. We describe and discuss how participation was facilitated through transdisciplinary methods, including participatory workshops, surveys, observations, and direct engagement with community members. Our theoretically grounded approach to community engagement advances both the theory and practice of place-based, just energy transitions. Moreover, it also offers a practical example of how energy justice and energy sovereignty could be empirically practiced by academics and practitioners alike.

1. Introduction

Energy justice and energy sovereignty are key concepts that deal with matters of justice, equity, and sustainability of energy systems. Energy justice provides a framework for examining issues of justice within energy systems and ways to mitigate them (1). This framework can be applied as a conceptual, analytical, or decision-making tool, and is typically conceptualized across tenets of distributional, procedural, recognition, and restorative justices (1,2). Energy sovereignty focuses on the rights of communities to make decisions about their energy systems. Grounded in principles of just generation, distribution, and control of energy, energy sovereignty seeks to democratically articulate the rights of communities to decide sources of energy, how much and where to use them, by whom, and for whom (3–7). While these concepts are extensively theorized, they often overlook context-specific, place-based, and culturally sensitive understandings of energy justice and energy sovereignty (7–10). Additionally, their practical application remains underdeveloped (11). Indeed, energy justice and energy sovereignty are often cited as foundational for a just energy transition, but less attention is given to how to operationalize these concepts (12–14).

Participation is central to both energy justice and energy sovereignty. In our study, participation refers to the involvement of communities in decision-making processes related to energy (9). Participation occurs across a spectrum, ranging from degrees of minimum involvement to full community control and ownership. Thus, it is relevant to seek clarity when describing how participation occurs within energy systems (15–17). In the literature, there is a greater focus on using the spectrum of participation as a lens to evaluate people's

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engagement in diverse case studies (e.g., (18 21), with less attention being given to examination of ongoing empirical experiences in electrification (13). While higher degrees of participation contribute to building legitimacy, fairness, and trust, the majority of climate and energy initiatives that conduct participatory projects primarily involve consultation (17).

Multiple traditions, frameworks and methodologies exist to create and inform participatory processes (22 24). Participatory co-design is an engagement approach that directly involves communities (or users) in co-designing artifacts, processes, and technology-enabled systems (25). Within energy systems research, participatory co-design can be used to ensure that projects are responsive to the needs of communities (26). Similar to the concept of participation, participatory co-design operates along a spectrum, ranging from bottom-up to top-down approaches (26). In this paper, we define participatory co-design as an engagement approach that centers community governance and ownership of decentralized energy systems. This includes community engagement throughout steps of planning, dimensioning, installation, training, and management of energy systems. Participatory co-design is an emergent process that involves eliciting the voices, values, needs, and assets of communities, while being attentive to the technical and environmental conditions that influence the array of potential technologies that can be utilized to produce energy. By emphasizing decentralized energy provision and collective forms of governance and ownership of energy infrastructure, participatory co-design can work as an empirical exercise of energy justice and energy sovereignty, thus contributing to the operationalization of a just energy transition (7,27 29).

In Brazil, governmental data indicates that 99.7 % of the national population has access to electricity. However, for the Brazilian Amazon this number is limited to 97.3 %: roughly one million people lack access to electricity (30,31). In parallel, the Amazon region generates nearly 26 % of national electricity, mainly through hydropower, but consumes only 8 % (32). This disparity highlights an unequal distribution of electricity and the imbalance in the costs and benefits of energy production (19,33 39).

In the Amazon, lack of access to electricity is concentrated within isolated Indigenous, riverine, and other traditional communities (31,40). Currently, the populations who live off-grid rely on polluting diesel generators, which provide energy for only 3 4 h at night (usually, from 6 or 7 p.m. to 10 p.m.), and have been increasingly more expensive to run and maintain due to rising costs of fuel (13,32). These individuals reside off-grid not out of preference, but due to their remote location, low income, and limited political influence (13). While geographical isolation is a relevant factor to consider, many communities near hydropower dams still rely on diesel generators (32), often seeing power transmission lines heading to distant areas, while bypassing their own communities.

Efforts to establish technical alternatives for electrification in isolated Amazonian communities have been documented (e.g., (41 45). A comprehensive analysis by Brown et al. (46) suggests that microgrids connected to photovoltaic systems and hydrokinetic turbines, separately or in tandem, offer a viable solution that improves energy access while being financially, socially and ecologically sustainable. In-stream turbines, in particular, differ from other technologies because they can be regionally assembled within the Amazon. Consequently, turbines are less dependent on importations from southern parts of Brazil or other nations (45). However, to meaningfully engage with energy justice and energy sovereignty, there is a need for a systems approach towards off-grid energy planning that balances technical, social, and ecological aspects simultaneously (13,46).

While there is a growing consensus on the importance of participatory processes that engage community members in the implementation of energy solutions, less attention has been given on *how* to effectively conduct community engagement (12 14,21,24,47,48). Particularly in off-grid communities, there is a lack of reported experiences on how participation can be practically implemented, which hinders the operationalization of energy justice and energy sovereignty (17,44,49). Thus, the guiding question for our paper emerges: How can participation be empirically applied in participatory co-design of a local-scale, off-grid energy system? We respond by describing our process to co-create improved energy systems in partnership with three off-grid communities in the Eastern Brazilian Amazon, using solar panels and in-stream turbines as key energy technologies. Our collaborative project is a partnership between a multidisciplinary team of researchers and practitioners, based in universities located both in the Global North (Michigan State University) and the Global South (Federal University of Western Para, University of Campinas, University of Brasília), working alongside three isolated, off-grid, riverine communities in the municipality of Santarem, Brazil. In this paper, we unpack, describe, and discuss the transdisciplinary practices and techniques of participation we utilized in our process. By doing so, we explore how energy justice and energy sovereignty can be practiced on-the-ground, with lessons applicable to other contexts, particularly in the Global South.

The paper is structured in the following way. First, we present a brief panorama of electrification policies and projects in the Brazilian Amazon to contextualize our work and highlight challenges related to electrification of isolated, off-grid communities. Then, we describe the methods we utilized to engage and collaborate with three off-grid communities, focusing on the steps of the participatory co-design process (Methods). We then present our assessment of energy-related characteristics of each community, results from surveys and workshops, technical information, outcomes from the co-installation of energy technologies, and an analysis of the degrees of participation embedded in our work (Results). We discuss our findings in the context of the existing literature on energy justice and energy sovereignty (Discussion) and conclude with our key takeaways (Conclusion).

1.1. Overview of electrification policies and projects in the Brazilian Amazon

In Brazil, the largest national effort to provide electricity to rural areas and informal urban settlements began in 2003 with the national policy called Program *Luz Para Todos* (Light For All in English, established by Federal Decree 4.873/03) (40,45,50). This program represented a shift from previous policies and programs because it was grounded on a mandate that the government should provide free connection to electricity to any citizen lacking access and that formally files a request (51). Electricity is delivered through a partnership model between the public and private sectors, in which the federal government funds efforts that are led by companies that are concessionaires and distributors of electricity. Although connection to electricity is a right and it is granted for free, concessionaries profit from tariffs paid by consumers (for a full overview of energy governance in Brazil, see (40,45,52,53).

The Program *Luz Para Todos* was effective in increasing energy access: 17.2 million people have benefited from the policy that had an investment of approximately R$23 billion (~4.6 bi USD) over the 20 years of its existence (54). This nation-wide, top-down program also had other positive beneficial effects, contributing to increases in income, educational level, and literacy rates (51). However, the Program focused on the expansion of the national grid and privileged regions that are geographically easier to connect, thus overlooking the Amazon region (55). Hence, the Brazilian Amazon is the region that still has nearly a million people without access to electricity (31).

A complementary policy targeting the Amazon region was developed in 2020, entitled *Mais Luz para a Amazonia* (More Light for the Amazon , Federal Decree 10,221/20). However, this specific policy has been criticized due to lack of transparency and data sharing that hampers policy evaluation (53). In parallel, the Program *Luz Para Todos* has undergone cycles of termination and relaunching ever since its creation (56). Hence, in August 2023, the Program *Mais Luz para*

Amazonia was terminated and the Program *Luz Para Todos* was relaunched once again with updated deadlines and guidelines, aiming to finally achieve the goal of universal access to electricity for isolated communities within the Amazon by year 2028 (Federal Decree 11,628/23). Although feasible, the operationalization of the program will demand changes in financing, technical, and governance structures (40,45,55). While the positive effects of governmental efforts should be recognized, there are also negative effects of such top-down approaches: reports from communities describe that policy implementers often disregarded community inputs regarding planning, ignored suggestions of locations for technical installation, and presented overall difficulties in communication to ask questions or request maintenance (57).

Given that current policies and programs have not succeeded in reaching the target of universal access to electricity, alternative electrification projects have been conducted by non-state stakeholders. In parallel, research has examined barriers, enablers and impacts of electrification in the region. A key finding is that several initiatives failed due to technical issues at the time or soon after the installation phase; lack of consideration for local socioeconomic and cultural aspects; lack of interface and collaboration with stakeholders in the energy sector; and lack of training for communities to independently maintain and repair the technologies (44). Other experiences report stories of success: Morales et al. (58) describe a case in Amazonas state where after 6.5 years, 20 out of 23 community-managed, photovoltaic systems were still fully operational.

The non-governmental organization World Wildlife Fund for Nature (WWF) documented 20 non-governmental, solar-based electrification projects within the Amazon. Most of them successfully improved quality of life through the electrification of water pumps to source water from wells; refrigeration of food; food processing machinery (e.g., cassava flour, *açaí*); improved conditions of local schools; enhanced public lighting; reduced noise from diesel generators; and decreased the time spent fetching water from rivers (a burdensome task typically performed by women) (59,60). Challenges are also shared, including logistical issues due to geographical isolation; financing the purchase and repairing of equipment; identifying local suppliers for solar technologies (60).

Focusing specifically on the Xingu Indigenous Land, an electrification project led by NGO *Instituto Socioambiental* (ISA) installed 70 photovoltaic systems in 65 communities (61 63). Benefits are similar to the ones reported by WWF (60), with added dimensions of an increased feeling of security in the case of medical emergency services and increases in night lessons at schools. Rather than phasing out the diesel generators, the Indigenous communities preferred hybrid systems to increase available electricity. Among challenges, it is reported that communities struggled to understand the operational limits of how much electricity the solar systems could generate and there was a lack of management strategies to ensure viability and self-funding for the long-term.

Provision of electricity to off-grid communities is directly connected to improvements in quality of life (64). Valer et al. (65) report that electrification of two communities in the Amazon led to improvements in everyday life through increased access to lighting, ventilation through fans, and entertainment (TV, radio). However, pathways to connect electricity to income-generating activities and socioeconomic development are not as direct (66 68). For some isolated communities, as soon as energy access increased, small-scale activities were initiated, such as using lighting to increase work hours during the night to produce handicraft products, cook and bake products to sell, repair and manufacture fishing gears (65). Nonetheless, Brazilian electrification policies have been designed and implemented to provide energy solely for domestic uses and other small-scale activities (40,44,67). Therefore, a key critique of electrification policies is the dimensioning of systems that disregard local development demands, such as building of local, sustainable industries that can support the well-being of communities and conserve forest resources (e.g., processing plants of forest products such as *açaí*, cacao, Brazil nuts) (40,57). Through access to electricity, it can be possible to add value to local products and explore novel models of development beyond exportation of raw materials. Indeed, in a letter signed by social movements led by Indigenous and traditional communities, community leaders demand access to energy that can foster economic activities that are specific to the particularities of each community (69). Creating new models or alternatives to development is a key challenge for the Amazon, and energy access plays a crucial role in shaping future developmental pathways (70).

Although the majority of off-grid electrification projects and policies focus on the utilization of photovoltaic systems, there are other technologies that are feasible and viable for the Amazonian context (44). Sanchez et al. (43) provide an overview of technologies that have been piloted within the Amazon, including biomass, biofuels and vegetable oils, micro-hydropower, hydrokinetic turbines, and other hybrid systems. Among these possibilities, in-stream turbines stand out because they do not require water storage, cost less than conventional hydropower, use only a fraction of the river width, and can harness equivalent amounts of energy as conventional hydropower (71). In fact, in-stream turbines have been previously piloted and successfully implemented, although challenges still persist regarding variations in river level, potential interference with navigation, and river debris (43,72). Even though turbines are not yet produced in a commercial scale, they can be manufactured by local industries within the Amazon (43,46). Follow-up and evaluation of the status of previous projects that utilized hydrokinetic turbines still lack, thus hampering the study of the potential of this energy technology.

A central theme in the literature is the importance of participation in the design, planning, and implementation of electrification projects at off-grid communities (40,53,57,68). Although many non-governmental initiatives embed participation in meaningful ways, the engagement process is often broadly described, with little mention to specific methods or techniques to foster participation and elicit community priorities and aspirational visions (73). Instead, publications predominantly focus on the outcomes of electrification, rather than on the process that led to these results. Given the history of energy injustices and lack of community participation in development projects in the Amazon, operationalizing participation is essential for practicing energy justice and energy sovereignty in a meaningful, on-the-ground way (19,74).

2. Methods

2.1. Identifying and partnering with three off-grid communities in the Brazilian Amazon

Based on available funding for the project, our goal was to identify small off-grid communities (fewer than 30 households) in the Amazon region that would be open to our participatory co-design approach. Given the untapped potential of in-stream turbines for producing electricity, we also aimed to pilot this technology, which is not yet widely adopted. We were particularly interested in experimenting with hydrokinetic turbines because they can be regionally sourced and assembled within the Amazon. Therefore, our choice of focal area was influenced by social dimensions (e.g., communities' openness to collaborate), technical dimensions (e.g., available materials, expertise of engineering team), and ecological dimensions (e.g., river with velocity around 1 m per second to enable utilization of the turbine). To achieve this goal, we utilized geoprocessing tools and hydrologic and climate modeling data (see (13,31,46,71). Our team comprises members with extensive, decades-long experience in the Amazon region. Consequently, we reached out to our contacts within non-governmental organizations and research institutions to identify potential community partners.

After screening off-grid communities in the Amazon and consulting with stakeholders involved in electrification projects, we selected the Extractivist Reserve Tapajos-Arapiuns in Santarem municipality, Para state, as our project site. Para has approximately 400,000 people who have no access to electricity (31). Extractivist Reserves (*Reservas Extrativistas*, or RESEX, in Portuguese) are protected areas designated for sustainable use, aimed at preserving the livelihoods and culture of traditional populations, while ensuring sustainable use of natural resources (75). Land tenure belongs to the government with use granted to traditional populations. At RESEX Tapajós-Arapiuns, community livelihoods are mostly based on agriculture (e.g., cassava, yam, chickens), fishing, and sustainable extraction of forest resources (76). Yearly temperatures average between 26^0 C and 28^0 C. Rainfall occurs throughout the whole year (between 2000 and 2800 mm annually) but is especially concentrated between January and May. River flow fluctuates between the dry and wet season with consequences for navigation and the speed of water (77).

We reached out to three communities within the Extractivist Reserve to collaborate on our project: "Cachoeirinha do Mentai", "Vista Alegre do Maró" and "Porto Rico". The municipal seat, Santarém, is the nearest city. Travel from Santarém to these communities takes between 12 and 20 h by boat, depending on proximity, and there is no direct road access. These communities are located along the Maró and Mentai rivers, tributaries of Arapiuns river, which is part of the Tapajós basin (Fig. 1).

To initiate the collaboration process, members of our group visited the three communities in April 2022. During this visit, we assessed the current energy situation, and we found that two communities (Vista Alegre do Maró and Porto Rico) had limited access to electricity (3-h a day) produced by diesel generators for basic needs such as lamps, cell phone charging, and television. Cachoeirinha do Mentai, on the other hand, had a solar panel and a battery for communal uses (a payphone, a collective cell phone charging station, an internet modem shared by all in the community). Based on this assessment, we invited all residents to a general meeting, where we introduced our project and its aims.

Our group described our views on engagement as a collaborative, two-way process and showed them an animated video illustrating two different technologies (solar systems and in-stream turbines). These technologies had been previously established as being appropriate for the Amazonian region (46), and our engineering team had the expertise to implement. We also emphasized that the energy system would be designed based on our research expertise, the communities' priorities, and local ecological conditions (e.g., the in-stream turbine would require a river with enough water speed). Besides, we made clear the system would be owned by the community and that installing, managing, and taking care of the technologies was part of the collaborative process. We highlighted that we were going to provide the training for all these tasks to community members interested. Community members contributed valuable input, suggesting optimal locations in the river to measure water velocity and recommending suitable sites for future installation of solar panels. After these discussions, we formalized our collaboration by signing an agreement. We continued to stay in touch via WhatsApp, a messaging application commonly utilized in Brazil.

2.2. *Community engagement: Participatory co-design process of an improved energy system*

Fig. 2 provides an overview of the participatory co-design process that has been conducted thus far, as well as ongoing steps. Participatory co-design includes steps of planning, dimensioning, installation, training, and management of the energy system.

In July 2022, we visited the communities again and through mixed methods we started the co-design of the energy system. We surveyed every household in all the communities ($n = 38$ households) and the leader of each community (n = 3 leaders) to comprehend how energy is currently used; what are the perceptions, challenges, and problems that households face regarding energy; what are the community agreements and rules regarding the use of energy; and to have an understanding on the socioeconomic status of each household. These surveys also serve as a baseline that could help us assess how the energy system influenced people's lives in each of the communities over time. Data entry was conducted using ArcGIS Survey123 online platform and analyzed through descriptive statistics.

We conducted a participatory workshop in each community, which lasted between 60 and 120 min (Fig. 3). Every resident over the age of 18 was invited and the workshops were scheduled bearing in mind the regular routines and activities of each community. The workshops had a facilitator, a supporting facilitator, and two note takers. At the first part of the workshop (step 1 in Fig. 3), a brief discussion was conducted on how energy is currently used and what are the challenges residents face in order to build consensus around a shared problem definition. Following that, participants were asked about how they would like to use energy, if more energy was available (step 2). After listing each suggestion in writing, participants ranked priorities through a polling

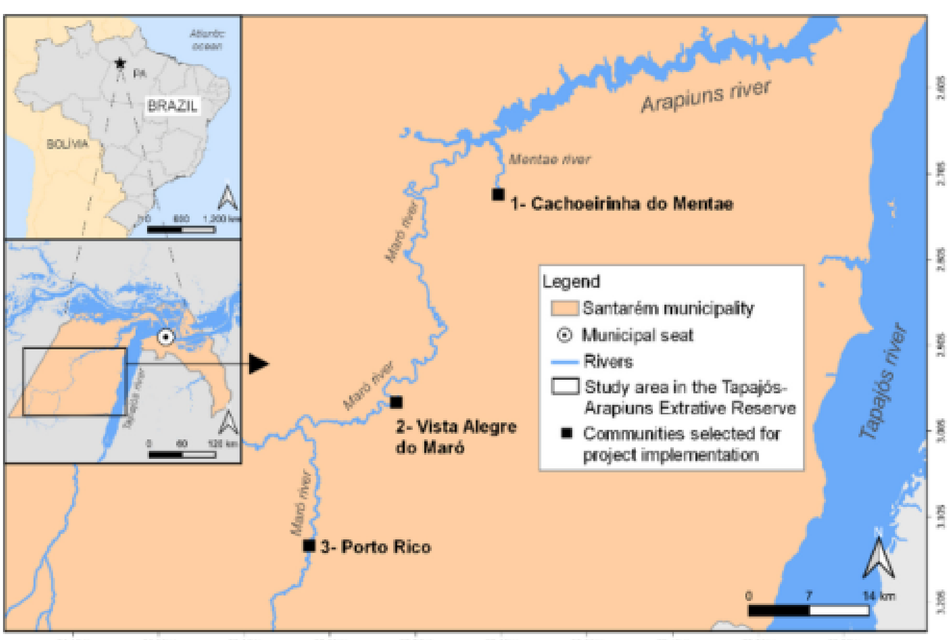

Fig. 1. Location of community partners within Extractivist Reserve Tapajós-Arapiuns, municipality of Santarém, Brazil.

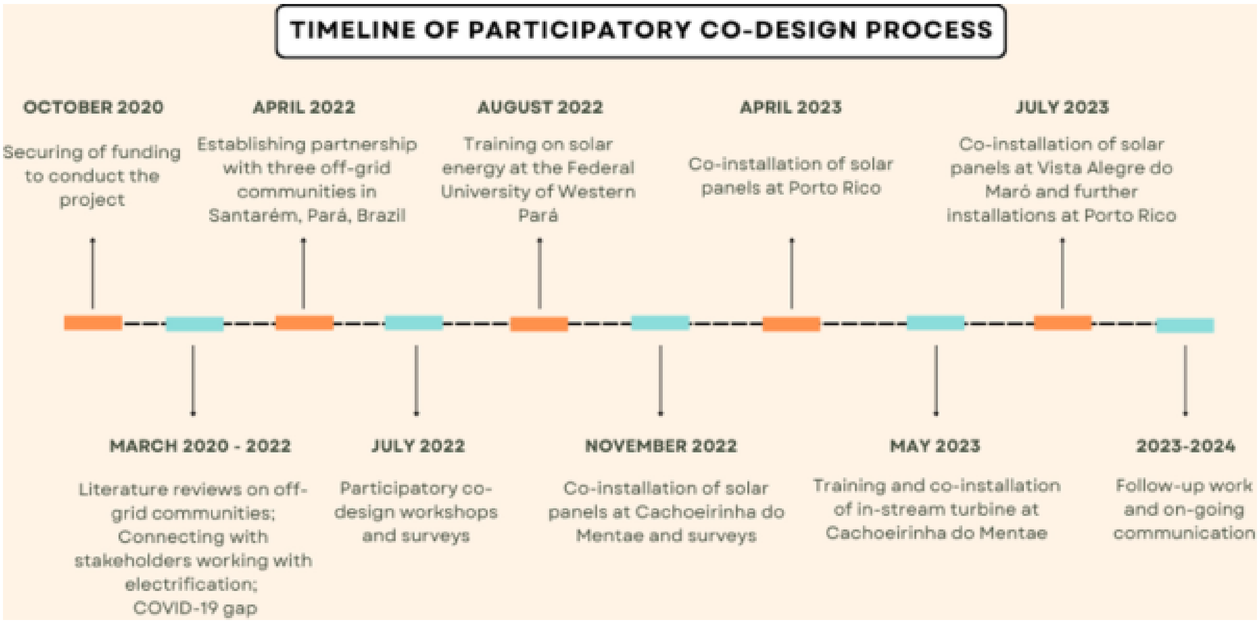

Fig. 2. Timeline of the participatory co-design process in collaboration with three off-grid communities at the Extractivist Reserva Tapajós-Arapiuns, Santarém, Pará, Brazil: Cachoeirinha do Mentai, Porto Rico, and Vista Alegre do Maró.

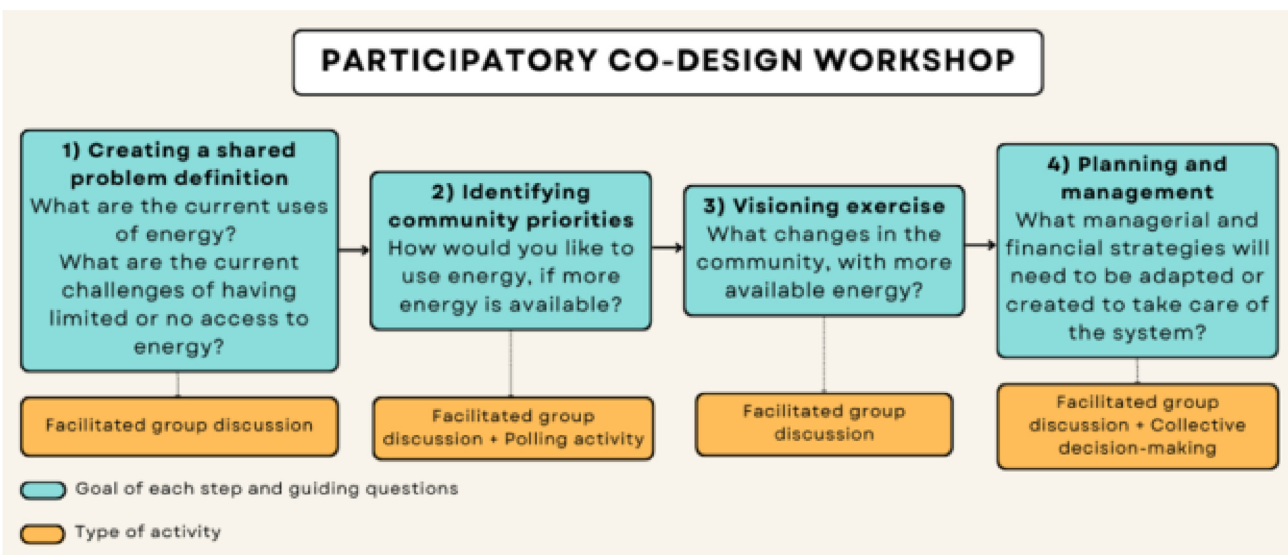

Fig. 3. Participatory workshop process with three off-grid Amazonian communities in Brazil for co-designing an enhanced energy system using solar panels and an in-stream turbine.

activity. Each participant received three post-it sheets that served as votes that could be assigned to the listed energy uses that they perceived as being more relevant. Votes could be distributed among three different energy uses or could be all applied to a single energy use. Community residents that were not comfortable with writing were provided individual assistance to clarify workshop activities. The use of a free listing activity to generate ideas, coupled with a polling activity to enable prioritization, is a facilitation technique that aims at building consensus and facilitating participatory decision-making (78).

The workshop then moved on to the creation of a vision for a desirable future in which energy access is more abundant, using a storyline format to describe everyday life in the community after the effective installation and operation of the energy technologies (step 3). The co-creation of a vision is helpful to guide the participatory co-design process by motivating and evaluating progress towards a collectively developed aspirational goal (79). Indeed, visioning has been established as a key component for success of community energy initiatives (14). Finally, in the last part of the workshop, we held a collective discussion focusing on the management strategies that would have to be adapted or created for the improved energy system (step 4). Because the system would be owned and managed by the community, we discussed the rules currently used to manage the energy system in place and we envisioned some future rules based on the specificities of the technologies that could be installed in each community. Then, the discussion focused on strategies to self-fund the energy system in the long-term since the project would have funding to support maintenance and repairs for only the first year after installation. Notes and transcripts from the workshop were qualitatively analyzed using thematic coding (80).

During our time in each community, we supplemented and validated findings from the surveys and workshop through participant observation and field notes (81). By engaging in daily interactions with residents and experiencing their everyday lives, we gained a better understanding of how the lack of energy impacts the residents in each community. Debriefing sessions during our stay and after the completion of the work were instrumental in aiding the team to reflect on our experiences.

2.3. *Training for solar and hydrokinetic energy production and maintenance*

Given our focus on community ownership of the energy system to promote energy justice and energy sovereignty, building local capacity to independently understand, repair, and maintain the improved energy system becomes essential for its proper functioning and long-term sustainability. The engineering team from Federal University of Western Pará provided a 40-h training course covering the fundamentals of electricity, the process of solar energy production using photovoltaic panels, the operation and setup of control panels, and essential maintenance and repair practices (Fig. 4). Seventeen people from six communities (three of them were our partner communities, and another three were suggested by a local NGO as possible other communities to consider working in upcoming phases of the project) participated in the training. Each community independently selected three people to attend the course, at least one of which should be a woman to promote gender equality and inclusion.

The course was conducted on campus at Federal University of Western Pará, in the city of Santarém, and was taught by our team members who are engineering professors. By learning about how the system works, community members gained the necessary technical skills to be able to fix the technologies on their own. Travel-related expenses (e.g., transportation, food) were covered by the project. The attendees also became our key points for contact with the research team and they understood that they would be expected to help install the system and be responsible to help maintain and repair it. At the end of the course, participants received a diploma for having successfully completed 40 h of training in electrical systems, which may also help some of them have employment opportunities to work in the energy sector.

Additionally, colleagues from the University of Brasília conducted a separate training session to instruct community members on assembling, installing, and maintaining the hydrokinetic turbine. The turbine, built in Santarém, was transported by boat to the community in three separate pieces, requiring a delicate process of reassembling on-sites. Then, the turbine was mounted on floating pontoons and tested to ensure proper functioning.

3. Results

3.1. *Assessment of the status of current energy uses, rules, and challenges in the communities*

Energy-related characteristics of each community reveals the energy insecurity that communities face and provides a panorama of overall community characteristics (Table 1). Broadly, the communities can be described as small and poor, relying on activities such as agriculture, occasional freelance work, and government-assistance programs as sources of income.

Regarding energy challenges within the communities, 57 % of households across three communities report not having sufficient energy for their needs, and 33 % indicate that diesel is prohibitively expensive. Additionally, 72 % of households express complete dissatisfaction with the current energy situation, 13 % report being somewhat satisfied, and only 6 % say they are satisfied. No household reports being fully satisfied.

Community residents share that key challenges include the fact that they are unable to preserve food (salting is the only option), lack of access to cool water and juice to cope with heat, and limitations on income-generating activities in the evening, such as sewing hammocks for sale. Productivity is also impacted by the lack of electricity-powered equipment, such as grinding machines for cassava flour.

A major issue regarding the local energy system is the reliability of the diesel generator. In Vista Alegre, the community had no energy for two consecutive months due to technical issues. To fix a generator, the communities have no other alternative than crowdsourcing funds and taking it to the city of Santarém for maintenance, which poses logistical challenges and financial burdens. Further, fuel price has been increasing in recent years, making the diesel generator an increasingly inaccessible source. Fuel is either received via donations, purchased at the city, or it can be bought from merchants that travel the river visiting communities. Overall, this means that diesel prices vary, with price that range between R$ 9–12 (1.6–2.4 USD) per liter at the communities in 2022, in comparison with a cost of R$ 7.50 (1 USD) per liter in Santarém. Some households have independently invested in small generators or solar panels, but reliability remains an issue: of the four households with private solar panels, only two are working properly. Therefore, it is possible to observe the interplay between social, economic, and technical aspects influencing the capacity and reliability of the energy system.

Fig. 4. Community training in solar energy at Federal University of Western Pará campus: Participants learn control panel operation basics (Left); Participants receive certificates for completing 40 h of training (Right) (Photos: Gabriel Yúri Campos Lacerda).

Table 1
Baseline community characteristics: key demographics and energy conditions prior to system installation.

	Vista Alegre do Maro	Porto Rico	Cachoeirinha do Mentai
Number of households	25	4	7
Number of residents	97	19	28
Collective sources of energy	Diesel generator (2)	Diesel generator (1)	Solar panel (1) and battery (1)
Sources of fuel (diesel)	8 L per month per family (R $80, 14.5 USD)[1]	10 L per month per family (R$120, 21.8 USD)	
Average hours of communitarian energy per day	3 h	3 h	0 h
Collective uses of energy	Lamps Cell phone chargers TV Water pump to refill community water reservoir	Lamps Cell phone chargers TV Community internet modem Sound speakers	Solar panel and battery exclusively used for a payphone, internet modem and cell phone charging station
Days without energy over a three-month period (91 days in total; April June 2022)	60 (65.9 %)	5 (5.5 %)	91 (100 %)
Longest consecutive period without energy over the previous year (June 2021 June 2022)	30 consecutive days	5 consecutive days	Whole year with no energy
Private households' sources of energy	Small gasoline generator (1 household) Solar panels (3 households, but only functional in one)	No private sources of energy	Small gasoline generator (1 household) Solar panels (1 household)
Internet access	Privately owned by community leader, who charges internet use for R$5 (~ 0.9 USD) per hour	Communitarian: service is intermittent and paid by a cooperative, of which the families are members	Communitarian: monthly costs shared among all residents (R$650, 130 USD)
Water sources	Water well with electric pump River	River	River
Available food preservation techniques	Salting	Salting	Salting
Key community activities and sources of income	Agriculture Freelance work Fishing Government assistance programs	Freelance work Fishing Government assistance programs	Agriculture Fishing Government assistance programs

[1] Diesel price varies per community, ranging from R$9 12 at the time of data collection. Dollar conversion used values for August 2022

3.2. *Selection of technologies and assessment of community priorities for the improved energy system*

The energy system that is being co-designed uses solar panels and in-stream turbines as key technologies for the generation of renewable energy, associated with a diesel generator back-up (46). Whether the two technologies can be installed in each community depends on their local biophysical characteristics. For example, in Cachoeirinha do Mentai, where river velocity is suitable for hydrokinetic turbine, solar panels and a turbine were both used to generate power. In contrast, in Vista Alegre do Maro and in Porto Rico, the river flow is insufficient for turbine use, so solar panels are the sole energy source.

The assessment of community priorities for the improved energy systems revealed that for the ones that rely on the diesel generator, their foremost concern is to alleviate the cost of diesel. There was broad consensus on how increasingly unaffordable diesel is becoming. Therefore, as part of the polling activity, we did not include alleviating the costs of fuel expenses as an energy use, in order to enable the exploration of other energy uses that are less dependent on external factors. It is possible to observe that collective uses for the improved energy system were privileged, although varying across the three communities (Table 2). Differences in priorities were also identified. For instance, in communities without access to water wells, electrifying a water pump became a top priority.

3.3. *Visioning exercise*

Communities were invited to imagine potential future changes they might experience with a more reliable and extended energy supply. Based on the workshop and observation data, the research team wrote a vision statement that describes the positive changes that energy could bring to the communities, potential unintended consequences, and strategies to mitigate such outcomes (Box 1). This vision serves as both an aspirational goal and a source of indicators to evaluate project progress. For instance, the vision statement describes access to clean and safe water as a desired outcome that could be generated by improved access to electricity. Therefore, availability and quality of water can be used as metrics for evaluation to determine whether our project is achieving the desires and aspirations voiced by community members. The vision statement also reveals the interconnections between energy and other aspects of the community, such as water, food, communication, and income-generating activities.

Importantly, the vision statement also highlights unexpected implications of electrification that may lead to negative outcomes for the community. For instance, it is possible to observe in Box 1 that community members expressed concerns about more people moving to their villages due to increased access to energy compared to neighboring areas, youth spending too much time on phones due to increased internet access, and apprehension about whether the community would be able to effectively manage and repair the system. The visioning exercise thus provided an opportunity to conceptualize a desirable future for the communities, while recognizing that even positive changes might lead to new challenges that need proactive consideration.

3.4. *Management of the improved energy system*

Establishing and reinforcing agreements regarding energy use and management is essential for the local stewardship of the energy system. Residents from each community were invited to anticipate what are the strategies and rules that must be created or modified to ensure that the improved energy system is properly taken care of (Table 3). All communities agreed that the trained people should be in charge of repairs and ensuring proper use in each household that matches the capacity of the system. Different arrangements were suggested, but an overall agreement was that most of the proposed rules should be adjusted after the first months of technology installation, while taking advantage of their tradition of pursuing collective work to attend to demands at the community level. So called *puxirums* are a form of collective action in which all adults collectively collaborate in addressing a given problem during a shared day of work, such as cleaning and weeding of the community, construction and repairing of sheds, sourcing of wood to construct poles for wiring. To store the batteries and other equipment

Table 2
Assessment of priorities for electricity use with the improved energy system. Numbers indicate the percentage of votes assigned to each of these priorities through the polling activity during participatory workshops.

Priorities for the new energy system	Relevance and examples	Type of use	Vista Alegre (%)	Porto Rico (%)	Cachoeirinha do Mentai (%)
Community internet or more hours of internet access	Improve communication with emergency services, communication with relatives, coordination of logistics	Collective	23.1 %	38 %	15 %
Community freezer	Preserve food, cool water and juice, diversify diet	Collective	20.7 %	24 %	20 %
School improvements	Improvements of infrastructure, such as buying of fans and computers, lightening for night classes for adults	Collective	20.7 %		17.5 %
Improved or new business	New sources of income could be enabled or improved, such as carpentry (e.g., manufacturing boats, oars and furniture), sewing machines for craftwork (e.g., hammocks), freezing and selling of fruit pulp, cassava crusher for making flour	Collective or individual	13.4 %		5 %
Electric pump for water well	Acquiring and installing an electricity pump to source better quality water from wells, in comparison with rivers	Collective	12.1 %	38 %	25 %
TV and speakers	News and entertainment	Individual	7.6 %		2.50 %
Household improvements	Acquiring of home appliances such as fans, computers, blenders, drills	Individual	2.4 %		
Lightning outside the houses	Improved feeling of safety during the evening	Collective			15 %

Box 1
Vision statement written by the research team based on data collected in the workshops. The vision describes future changes that energy can bring to off-grid communities.

What changes in the community with more available energy?

With a more reliable source of energy that provides more hours of energy a day, the community can develop and improve the quality of life of residents. With refrigerators and a community freezer, food will be better, more diversified, and preserved for a longer time. Salting of food will decrease, thereby improving the quality and flavor of food, while reducing the negative health impacts of salting. Children and adults will have access to safe, healthy water with an electric pump to get water from a well, instead of relying on water from the river that can be dirty and contaminated. Residents, particularly women, will spend less time having to source water from the river for domestic uses. Residents will be able to refrigerate water and drink cool water and juices to ward off the heat. Communication will improve with more hours of internet a day, allowing for families to be able to communicate with emergency services in case of accidents; coordinate logistical efforts to request, purchase and have produce from the city delivered to the community; and keep in touch with relatives in the city. The learning conditions in the school will improve due to internet access for online searches, infrastructure improvements (e.g., fan, computer), and potential night classes for adults. Savings actualized on reduced spending on fuel can be reinvested by families into new sources of income, such as electric sewing machines for craftwork (e.g., hammocks), equipment for carpentry (e.g., manufacturing of boats, oars, and furniture), freezing and selling of native fruit pulp (e.g., *açaí*), increasing cassava flour production with an electric grinder. Families will be able to have more entertainment and be better informed about the news with more hours of TV. Finally, there are also a few negative impacts that will require attention: more people could be interested in moving to the community, youth might start spending too much time on the internet and on phones, and the community may fail to manage and repair the energy. However, there are also strategies that could be set in place to prevent that, all of which being related to the establishment of rules and community agreements around energy.

safely from environmental conditions, there is a need to store them in sheds. All communities agreed on conducting a day of collective work to build sheds and also make them child-proof for safety reasons. Financial sustainability emerged as a critical issue. While the research project has allocated budget for follow-up repairs for the first year, the communities will be independent in the long-term. The research team shared with the communities our estimations of costs: based on a 3-year durability for batteries, between R$ 72 78 (13 14.1 USD) will need to be saved each month by each family so there is enough cash in stock to replace a battery. Communities discussed various fundraising strategies, including monthly contributions from households, organizing bingo games and soccer tournaments.

3.5. Co-installation of the energy technologies

A key step in our participatory co-design process involved collaborating with communities during the installation phase. Community members and research team worked together in building a shelter to cover the panels and batteries associated with the solar system. In November 2022, the first installation of the technologies occurred in Cachoeirinha do Mentai (Fig. 5). The goal was to power the communitarian internet system and to light the school, the church, and a community meeting building, aligned with previously identified needs that had been voiced by the community in the workshop (Table 2). A follow-up installation provided electricity for all 13 households within the community, enabling the use of electricity within households for the first time in the community. The entire system delivers 2000 W and encompasses a photovoltaic generator (4.7 kWp), batteries (3520 Ah), and two inverters (3 kW each) that generate electricity for up to 4-h a day. The in-stream turbine was installed in May 2023, and it is still being monitored for performance (expected power of 300 W).

In the community of Porto Rico, the photovoltaic system provides 2010 Wp (six 335 Wp solar panels, eight batteries, two charge controllers, and one frequency inverter), powering all households and community buildings (church, school) with the capacity to supply electricity for up to 4 h per day (82). In Cachoeira do Mentai, the photovoltaic system delivers 4690 Wp (14 panels, 335 Wp each, 16 batteries, two charge controllers, two frequency inverters) (83). The system is divided in a circuit that is exclusive for shared community buildings (school, church, community sheds) and another that is exclusive for domestic uses. A community freezer was also provided by the project and was placed by community members in a protected, shared community space. The hydrokinetic system, consisting of a floating device, the in-stream turbine, a bridge rectifier, a generator, and a motion transmission system, is still being piloted and is directly connected to a separate battery that is charged by it. In Vista Alegre, the system is also divided in two circuits due to a river that separates two parts of the community. The section of the community with the largest number of households has a photovoltaic system that delivers 1340 Wp (four panels, 335 Wp, four batteries, one charge controller, one frequency inverter). Both photovoltaic systems are connected to shared community buildings (school, church, community sheds) and a community freezer, the smaller section has a system that delivers 670 Wp (two panels, 335 Wp each, two batteries, one charge controller, one frequency inverter), and another system exclusively electrifies a water pump with 2010 Wp (six panels, 325 Wp each, one charge controller, one frequency inverter). Diesel generators are now used as back-ups or can be used on demand. The community members who participated in the training sessions were key in collaborating with the installation.

Community members who participated in the training sessions play a

Table 3
Current energy management rules and community agreements, along with proposed new rules and modifications for the improved energy system.

	Vista Alegre	Porto Rico	Cachoeirinha do Mentai
Current energy rules for each community's diesel generator	Designated person responsible for turning the generator on and off Crowdsourcing funds for eventual repairs	Designated person responsible for turning the generator on and off Crowdsourcing funds for eventual repairs	No diesel generator
Proposed new set of rules for the improved hybrid energy system	Trained individuals will form a commission to ensure proper use and maintenance of the system An energy treasurer will be appointed Collective work ("*puxirum*") for building a storage facility for the batteries	Trained individuals will ensure proper use and maintenance of the system An energy treasurer will be appointed and funds will be stored in a safe Collective work ("*puxirum*") for building a storage facility for the batteries Monthly contribution of R $20 per family directed to the energy fund	Trained individuals will ensure proper use and maintenance of the system, with an appointed coordinator An energy treasurer will be appointed and funds will be stored in a safe Collective work ("*puxirum*") for building a storage facility for the batteries Monthly rate to be determined based on battery replacement costs Fundraising events such as bingos and soccer tournaments Meetings to create rules for energy use

crucial role in the installation process. Choosing the optimal location for the technologies withing the community was also a significant part of the process. In Cachoeirinha do Mentai, community members indicated an appropriate site for installing the in-stream turbine so that it would not negatively affect boat transportation and areas that children use for leisure. The turbine was built in Santarém by a local industry, and it was installed in May 2023 with the assistance of community members, especially the ones who participated in previous training (Fig. 6). For both research team and community members, the co-installation process is a mutual learning experiences about how the system empirically works and how it will serve the local context. While evaluating the ongoing installations are still underway, preliminary observations suggest that communities are experiencing improvements in their quality of life.

3.6. *Aligning and managing roles and responsibilities throughout the participatory co-design process*

An overarching theme of any participatory process is the negotiation and management of expectations, roles, and responsibilities within a project (16,84). Fig. 7 outlines the key steps and degrees of participation in our participatory co-design process (inspired by the abacus tool proposed by (84)). Aligned with the perspective that participation is a spectrum that should be specified for any project, we aim to elicit how we have effectively collaborated and centered the voices and perspectives of off-grid communities within the participatory co-design process. In doing so, we respond to calls in community engagement literature on the relevance of specifying how degrees of participation vary through different project stages (84).

4. Discussion

A key aspect that informed our participatory co-design process is the relevance of being attentive to the local context. Although all our community partners are located within a similar forest ecosystem and within a sustainable-use protected area, they differ in their priorities for energy use, biophysical characteristics, and their initial conditions of access to electricity. Furthermore, prior to engaging with the communities, it was imperative to contextualize the social and historical background that has shaped energy access. Universal conceptions of justice that stem from Western-based forms of knowledge may overlook the specific details and particularities that are critical to the success of an electrification project aiming for a just, place-based energy transition (7,8,10). Therefore, our mixed-methods approach and community engagement through the participatory co-design process were key for a contextualized, situated articulation of energy justice and energy sovereignty.

The practical applications of energy justice and energy sovereignty scholarship remain underdeveloped (8,11). Through our project, we have demonstrated how participation can be operationalized to co-design an off-grid energy system. In doing so, we empirically contribute to the concrete achievement of a place-based energy transition that is grounded on energy justice and energy sovereignty. Jenkins et al. (1) define energy justice across tenets of distributional, procedural, and recognition justice. Because of the history of energy injustices in the

Fig. 5. Co-implementation of the solar panels at Cachoeirinha do Mentai. Left: Solar panels and other components of the technical system, with community members and research team in the background. Right: Community members and the research team use solar energy to power a TV and watch the national soccer team score the first goal of the 2022 World Cup live! (Right) (Photos: Renato Chalú, left; Wesley Braun, right).

Fig. 6. Process of co-implementation of the in-stream turbine at the community of Cachoeirinha do Mentai. Researchers and community members worked together to assemble, test and install the turbine (Photos: Karina Ninni).

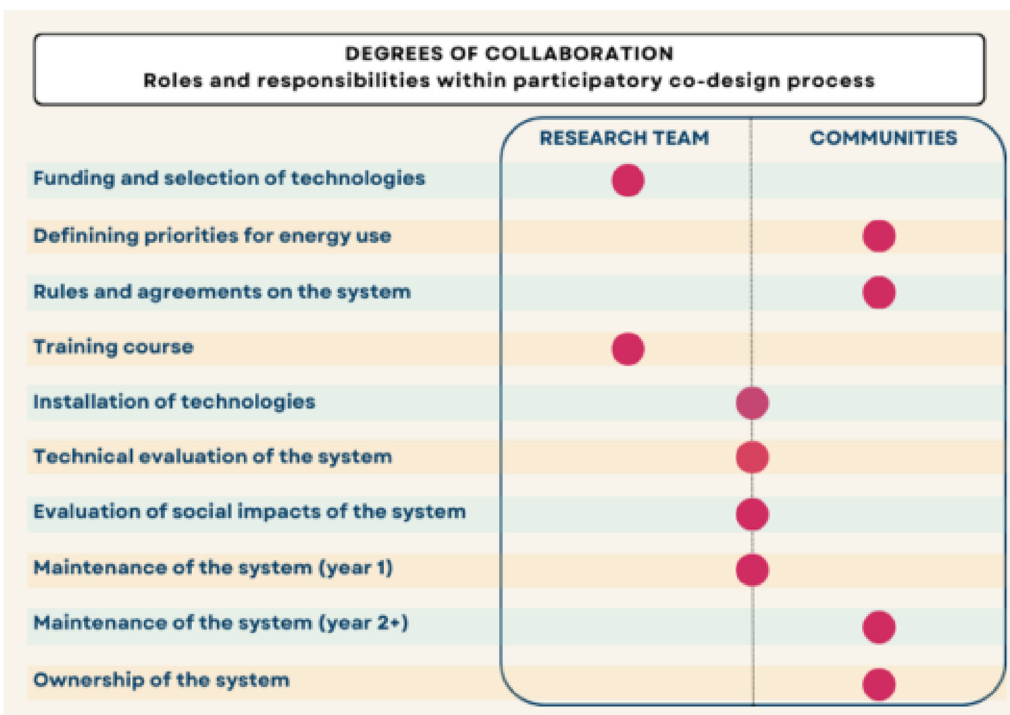

Fig. 7. Degrees of collaboration between research team and off-grid communities during key phases of the participatory co-design process. Roles and responsibilities are negotiated between collaborators, with tasks conceptualized as either independently pursued (red dot on the far right or left side) or collaboratively pursued (red dot along the traced line between the research team and communities) (Modified from Doberneck & Dann (84)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Amazon caused by dams, and due to the fact that we co-designed the system in a collaborative way, we paid attention to consider and embed each of these tenets along the process. In the case of *distributional justice*, this system is enclosed in a place where the production and consumption of energy occurs in the same location, so the ills and benefits of the system are all in the same location (as opposed to dams). The system was designed in a way that ecosystem disruptions were minimum: solar panels were and are being installed in vacant areas within the community, and the in-stream turbine does not cause any changes to the river.

Regarding *procedural justice*, our collaborative approach emphasizes decision-making that is fair, equitable and participatory. Our approach allowed for collective agreement among community members on how the system should be governed. Procedural justice was also woven into all aspects of the project, including activities such as measuring water velocity, training community members to repair and maintain technologies, ensuring community ownership of the system. In doing so, we prioritized community voices through the participatory co-design process.

In terms of *recognition justice*, we acknowledge the historical oppressions faced by these communities, particularly in relation to their lack of access to energy in a region impacted by large-scale hydropower dam construction. By improving the energy conditions of communities that have been historically neglected by governmental policies, while recognizing the traditional ways of living and local knowledge when co-designing the system, we embedded recognition justice into our process. Further, we invited all community members to participate in the design of the new system, further liking recognition justice with procedural justice.

Our efforts to provide technical training on maintenance and repair of energy technologies were a fundamental part of our participatory co-design process. Through the training sessions, we aimed to increase the ability of community members to self-manage community-owned systems. Self-reliance is crucial for off-grid communities due to logistical challenges associated with isolation from urban areas that concentrate a broader array of resources. While technical training is essential for long-term sustainability of the off-grid systems, it is important to recognize that knowledge sharing is not merely a one-way transfer. As Robinson et al. (26) suggest, our approach is better described as capacity sharing, rather than capacity building. Hence, community members shared their knowledge and lived experiences related to local conditions, assets, and problems, while the research team provided resources and expertise on energy technologies. Moreover, from a justice perspective, access to knowledge can expand the array of available activities and opportunities that an individual can access. According to Sen (85), this is crucial for enhancing the capabilities of individuals or a communities to achieve their self-defined goals. For example, other electrification projects indicate have shown that technical training can broaden employment opportunities (86). In this sense, our project's focus on both energy access and training aligns with the principles of *capabilities justice* (87,88).

Castan Broto et al. (8) argue that energy justice scholarship can be enriched by perspectives stemming from energy sovereignty, which emphasizes autonomy and self-determination regarding decisions on energy. Three key tenets of energy sovereignty responsible social-ecological relationships, self-determination in business models and technologies, and participation in decision-making (3,8) are all reflected in our project. By including locally manufactured renewable energy technologies, we emphasize responsible social-ecological relationships. We center our process in community ownership and self-governance of the energy system, instead of community acceptance of an energy technology. Therefore, we stand to advance practical applications of energy justice and energy sovereignty.

We highlight the relevance of participatory workshops as a way to facilitate collective discussions that can connect access to electricity to local development pathways. Through the workshops, we identified that communities prioritize the use of electricity for more immediate necessities (e.g., alleviating fuel costs, water pumps, or community freezers), but they also aspire to use it as a way to diversify and increase sources of income (65). In particular, we highlight the relevance of visioning exercises during workshops to build shared aspirational goals regarding the use of electricity and identify potential unexpected outcomes (14,89). For instance, through the visioning exercise, we were able to elicit some of the concerns that community members expect after access to energy is improved. Indeed, the visioning exercise reveals how different people with differences in positionalities and identities (e.g., differences in age) may experience access to energy in different ways, which has also been observed by other scholars investigating development interventions (90). Therefore, it is relevant to build mechanisms for sustained engagement during off-grid electrification projects to ensure that injustices are not reinforced or perpetuated, even if a project centers energy justice and energy sovereignty as key values. Combining sustained engagement with diverse evaluation techniques, including participatory workshops and visioning exercises, may be of help to anticipate potential unintended consequences and build mechanisms to address novel injustices that may emerge (91).

While the participatory workshops were instrumental in creating management rules and agreements, we emphasize that planning and implementation must remain flexible to accommodate unforeseen changes. For example, in Amazonas state, Penteado et al. (68) report on an experience of implementing solar ice machines with a traditional community and highlight how collective organization surrounding a new technology is dynamic. In this regard, we emphasize the relevance of reporting on project *process*, in order to detail the specific challenges influencing the practicalities of off-grid electrification. Through reporting on process, it is also possible to better understand potential tools, actions and strategies that can help navigate potential challenges. For instance, in Chile, Palma-Behnke et al. (92) and Valencia et al. (93) detail a participatory co-design process with an off-grid community and present a five-step process for planning and monitoring a community microgrid, grounded on the use of a collaboration tool titled Metalogos (94). Therefore, we highlight the relevance of reporting on the practicalities of project process as a way to identify relevant lessons, tools and strategies that can be applicable across different contexts.

Another key challenge lies in the transferability of the insights we describe in this paper to other forms of energy development. Our study examines communities of place that are geographically bound. However, in renewable energy development, other studies examine communities of interest that are geographically distant but united by shared interests (95). While some of our findings might not be immediately transferable to communities of interest, we argue that our study still generated insights that can be broadly applicable. For instance, we have shown the relevance of sustained community engagement, the role of eliciting community needs and assets to inform energy planning, the importance of visioning exercises to anticipate potential injustices, and techniques to build consensus around management strategies.

Finally, beyond energy, our findings carry implications for other issues and systems in the Amazon. An Amazonian bioeconomy that is based on the sustainable use of ecosystems to support human well-being of Indigenous and traditional communities necessarily implies providing communities with access to energy (70). Place-based initiatives such as sustainable management of fisheries, community-based ecotourism, and agroforestry benefit from having sustainable energy infrastructure (70,74). Hence, access to electricity can amplify the transformative potential of place-based initiatives that are grounded on bioeconomy principles.

5. Conclusion

Participatory approaches are fundamental for a just energy transition towards reliable and sustainable electricity for off-grid communities. While participation can serve as a catalyst for transformative change in energy systems, it is not a silver bullet (17). Managing expectations, timelines, roles, and responsibilities are some of the challenges in community-engaged processes (84). In the Amazon, these challenges are further compounded by logistical issues and legacy of energy injustices caused by previous projects (60,73,96).

In our study, we implemented a participatory co-design process to develop an improved energy system with three off-grid communities. Our process centered on community ownership of a decentralized microgrid powered by photovoltaic panels and in-stream turbines as key technologies. We demonstrate how to effectively operationalize participation across the stages of planning, dimensioning, implementation, training, and ongoing management of the local energy system. In doing so, we show how our project puts into practice the concepts of energy justice and energy sovereignty, which remains a key challenge for energy research (11).

Before crafting an energy system, we emphasize the importance of actively engaging with the local communities to identify their needs and assets. This collaborative process involves co-creating a system that not only meets current needs but is also scalable to accommodate future growth. Additionally, developing strategies that enable communities to maintain and repair the technology is crucial. This holistic approach ensures that energy infrastructure remains adaptable and aligned with the community's evolving needs while fostering self-sufficiency.

By converging engineering, social sciences and community engagement, we argue that alternative, desirable approaches to designing energy systems for off-grid communities are possible (13). Our innovative project offers a practical example of how create transformative change towards just and sustainable social-ecological systems (74,97). As a university-led initiative facilitating a participatory co-design process for off-grid energy, our project makes tangible contributions to community partners while advancing the academic literature on participation as a pathway to enacting energy justice and energy sovereignty.

CRediT authorship contribution statement

Rafael Lembi: Writing review & editing, Writing original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Claudia Lopez:** Writing review & editing, Writing original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Karina Ninni Ramos:** Writing review & editing, Validation, Project administration, Methodology, Investigation. **Igor Cavallini Johansen:** Writing review & editing, Writing original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Lazaro Joao Santana da Silva:** Writing review & editing, Validation, Project administration, Methodology, Investigation. **Manoel Roberval Pimentel Santos:** Writing review & editing, Validation, Project administration, Methodology, Investigation. **Gabriel Yúri Campos Lacerda:** Writing review & editing, Methodology, Investigation. **Gisele Souza Neuls:** Writing review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emilio Moran:** Writing review & editing, Writing original draft, Validation, Supervision, Resources, Project administration, 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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Data availability

The data that has been used is confidential.

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