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Advancing convergence research: Renewable energy solutions for off-grid communities

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Millions of people across the world live off-grid not by choice but because they live in rural areas, have low income, and have no political clout. Delivering sustainable energy solutions to such a substantial amount of the world's population requires more than a technological fix; it requires leveraging the knowledge of underserved populations working together with a transdisciplinary team to find holistically derived solutions. Our original research has resulted in an innovative Convergence Framework integrating the fields of engineering, social sciences, and communication, and is based on working together with communities and other stakeholders to address the challenges posed by delivering clean energy solutions. In this paper, we discuss the evolution of this Framework and illustrate how this Framework is being operationalized in our on-going research project, cocreating hybrid renewable energy systems for off-grid communities in the Brazilian Amazon. The research shows how this Framework can address clean energy transitions, strengthen emerging industries at local level, and foster Global North–South scholarly collaborations. We do so by the integration of social science and engineering and by focusing on community engagement, energy justice, and governance for underserved communities. Further, this solution-driven Framework leads to the emergence of unique approaches that advance scientific knowledge, while at the same time addressing community needs.

convergence | renewable energy | sustainability science | Amazon | off-grid

Significance

Our team has developed a Convergence Framework where disciplinary boundaries fade and the focus is on creating solutions to society's great challenges. This is done by interweaving of engineering and social science in a novel way that builds on the knowledge of underserved communities in solving problems they face. In this paper, we exemplify the development of this Framework to address the challenge of delivering renewable energy solutions for off-grid communities in the Amazon. This partnership between community members, local stakeholders, scientists, and engineers from both the Global North and South can be applied to address a wide array of sustainability challenges.

An estimated 650 million people globally lack access to clean affordable energy and are not served by their country's national grid (1). These communities are located far from the grid, they are mostly rural and economically poor, and they lack the political clout to have priority in either the public or private energy sector. Because of the large economic and environmental costs to run transmission lines to these communities, they will likely remain off-grid for the foreseeable future–perpetuating a cycle of poverty, inequity, and marginalization. Furthermore, younger generations living in these regions are likely to increasingly seek opportunities in urban areas, putting heightened pressure on cities to provide more jobs and more basic services such as housing and electricity. Bringing innovative and clean renewable energy technologies to people living off-grid is a formidable challenge, yet one that is worth addressing since access to affordable energy has been shown to positively impact economic activity, education, empowerment, standards of living, and overall human well-being (2–4).

Addressing this challenge in a socially, ecologically, and economically just and sustainable manner demands escaping the serial trap of fossil fuels (5–7). In addition, traditional engineering efforts that have attempted to deliver energy technologies to communities without having first gained their trust and without clear communication of the long-term costs of maintenance and other negative unintended consequences, will no longer suffice (e.g., refs. 8 and 9). Key examples of such efforts are nuclear power plants (10) and large-scale hydropower installations (11, 12). Nuclear power initially was billed as a perfect solution, until the long-term risks of radioactive fuel disposal (13, 14) and of catastrophic disasters such as Chernobyl and Fukushima were realized (15). Likewise, large-scale hydropower initially was sold as an optimal solution for energy delivery, especially for rural electrification. Yet, governments and industry later were forced to acknowledge extensive damage to forest cover, fisheries, and river ecosystems more generally, as well as the profound losses experienced by the displaced populations often left worse off than before the dams (12, 16–20). Further, off-grid communities near new hydropower installations often do not even receive improved energy access (21–23). Indeed, recent research reports that large dams have been built without sufficient consultation or participation by communities most directly affected–whether in democratic or autocratic regimes (24, 25).

Employing innovative technologies is necessary but is insufficient to solve the complex problem of providing off-grid populations with renewable energy to substantially improve

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their well-being. A unique approach that respects the physical environment and the social context where people live, and which at the same time is financially viable and just is needed. Such an approach may take the form of transdisciplinary teams of engineers and scientists from the Global North and South working with community members, government energy agency officials, local industry, and other stakeholders. We need cocreation, codevelopment, coimplementation, coevaluation, and community-based governance of the energy system to ensure that technologies can deliver energy, empower communities, and reduce energy and environmental injustices. As our research went forward on identifying the most effective ways to deliver renewable energy to isolated communities in the Amazon, we met numerous challenges. Some were environmental, such as the river's debris, and some were geographical, such as the distance between the communities and population centers—which was also the main reason they had been left out of the grid. Other challenges came from differences between disciplines working together to address an energy delivery system that not only considered, but also integrated technical requirements with local cultural, economic, and ecological characteristics as well as prevalent social norms and needs. Subsequently, during this process of conducting the original research, we developed and have continued to develop a Convergence Framework—a conceptual approach that would facilitate the collaboration of communities, local stakeholders, engineers, social and environmental scientists, and communication scholars from the Global South and the Global North. This paper presents this transformative Framework, characterized by codesign, coimplementation, and comanagement of renewable energy systems. We have also developed ideas of how we may need to transform engineering education—a need that has been noted by a few engineers as well (26). Collaboration of engineers with social scientists is necessary to develop technology in a way that best serves the needs of communities and that recognizes issues of power and justice embedded in socio-technical-ecological systems (27). It is an approach where both assimilate different knowledge and competencies to understand the broad spectrum of sustainability and interdisciplinarity. We built this Framework based on previous efforts carried out by community engagement scholars, diffusion of innovation research, participatory research epistemology, previous work on institutions and governance, and efforts by groups such as Engineers Without Borders.

We are motivated in our research to address the multiple energy injustices facing rural, poor communities in the Global South and North (17, 28–33). Additionally, our research intentionally examines how engineers and social scientists can work collaboratively to learn from people on how to best support them—and deliver technology that addresses their expressed needs and that builds a system they can govern. The knowledge acquired from this collaboration informs the ways social factors shape energy systems and how engineering can be more broadly inclusive of the myriad of nontechnical dimensions present in technological projects. This is not "science-as-usual," but disruptive of the top-down approaches of past energy delivery systems. Our Convergence Framework is scalable, can be modified to different technological specificities, and adapted to various societal contexts. We illustrate in this paper how the Framework came into being from the original research in the Amazon funded by the National Science Foundation (NSF) and the Mott Foundation. We show how it can be operationalized using the experience of delivering in-stream generators and photovoltaic (PV) panels in off-grid communities in the Brazilian Amazon and how the approach might be scaled to other sustainability challenges.

In this paper, we document our research process in delivering energy solutions for communities living off-grid in the Brazilian Amazon. This is an area the size of the continental United States without Alaska that has hundreds of thousands of households that are not connected to the National Integrated Energy System (34). Many communities remain outside the National Integrated Energy System because they are small and isolated and the cost of transmission lines reaching them is viewed by the energy sector as prohibitively expensive. Their source of energy has been diesel generators that are costly to run and maintain, and community dwellers must travel hours to get enough diesel to provide about 4 h of electricity from 6–10 pm due to the high cost (35), allowing them with just enough electricity to accomplish some basic functions such as charging their cellphones and having illumination to eat their evening meal by. This solution has been in place for decades for many of these communities, but the Program "*Mais luz para a Amazônia*" (in Portuguese, "More Light for the Amazon") and the Ministry of Mines and Energy are pushing to replace diesel generators with photovoltaics (PVs) (34). An economic analysis carried out by the energy sector showed the economic feasibility of PVs in isolated communities, relative to the cost of diesel (36). This goal is consistent with a decree regulating Isolated Energy Systems (Decree No. 7 246/2010) that requires players operating such systems to pursue economic and energetic efficiency, mitigation of environmental impacts, and the use of local resources. However, the initial efforts to deliver this PV solution failed because the program was top-down and did not involve the communities in learning how to maintain the system. Within 5 y, 80% of the PVs no longer worked due to lack of maintenance. This failure informs our research and gives us reason to place community engagement and training of community members at the top of our research agenda.

In the field, we started our research by identifying potential off-grid communities that are not going to be part of the "*Mais luz para a Amazônia"* in the foreseeable future, and we established relations with local universities and NGOs that have experience working with communities in the area. In this paper, we describe a hybrid energy technology, combining in-stream generators and PVs not as a ready-made solution, but one that can be scaled to the size of communities and modifiable to meet community-identified needs and desires. Communities are offered either, or both, of these renewable approaches to energy generation as well as the training to install, maintain, and repair them. They can choose to combine the two technologies with existing diesel, or choose to stay with the diesel generators they currently have, or make small modifications like using biodiesel instead of traditional diesel fuel. The communities participate in scaling the solution to the community or individual household units and work together to ensure that the technology can be maintained sustainably for years to come. Due to the high energy density of solar irradiation in the region (35, 37), PVs are a sensible renewable energy alternative, and the in-stream generators are a good complement as the Amazon has a very dense riverine water system with many streams having adequate speed to produce hydrokinetic power (38, 39).

A Convergence Framework

The NSF defines convergence as problem-driven research that fosters deep integration across disciplines, highlighting the key role convergence can have in trying to solve the world's most urgent and formidable challenges. We expand this definition by insisting that it is essential to change the top-down paradigm often found in development programs, and instead use an approach in which scientists work with community members experiencing these challenges firsthand in solving their problems. Using concrete examples from our ongoing research in the Amazon, we advance this

Framework to meet the energy needs of populations worldwide who are not served by national electric grids and must use unreliable and polluting diesel generators (e.g., riverine communities in the Brazilian Amazon). As stated earlier, millions of people across the world live off-grid not by choice but because they live in rural areas and have low income (40–43). In disadvantaged communities in the United States, residents pay as much as 25% of their low income for electricity, making it very hard to meet other basic needs, such as food, health care, and housing costs (44).

Our framework is inspired by the diffusion of innovations theory proposed by Rogers (45) that has been widely used in rural sociology and communication research (46). At its core, this theory predicts that the newness of an idea, regardless of its merits, creates uncertainty, and actors either seek information as a means of reducing it or decide to reject it altogether. In doing so, stakeholders seek and share information and knowledge about innovation through various communication channels. The diffusion of innovations is a complex process that involves interaction between media messages, interpersonal communication, prior experience or legacy effects, and compatibility with the existing societal structures (45). It is a time-dependent process which allows communication and multiple iterations between communities and those who propose possible solutions, whether they are government, NGOs, or private corporations. In doing so, diffusion of innovation theory (45) explores social acceptability and adoption of innovations usually as a one-way process: an innovation is first developed, and then communication is used to implement it, with rejection often seen as the forecasting failure. However, this approach does not consider the active participation and engagement of civil society across the design, development, and implementation of technology.

In the 21st century, we can no longer offer, or impose, a one-size-fits-all top-down solution for communities. They differ even within one community in how they see the problem and what their needs, values, and capabilities are. They have different information about previous technologies that tried to solve a similar problem, they differ in their openness to a given type of solution, and they differ in how much trust they have in those offering the solution. Arnstein (47) proposes a ladder of participation that spans from nonparticipation to citizen control. Thus, in our case, it means that civil society has the power to decide whether the technology will be developed and how the system will operate. Energy projects usually occur with either nonparticipation or low participation levels (24, 25). Therefore, we consider community engagement a central aspect of the Convergence Framework to ensure community participation and empowerment (47, 48). We understand community engagement as the process that allows participation, leadership, and ownership by communities usually neglected in energy projects.

We developed the Framework in the process of carrying out our NSF project (Fig. 1). Our Framework began first with the work of Rogers discussed above and it also follows the work of Chambers and other participation-oriented researchers, including the human-centered design approach (49–52), in having communities engage in the issue being studied so that solutions and their design are developed in a democratic and participatory manner. Our approach follows a "research-to-action" approach in a collaboration between communities facing lack of electricity, other stakeholders in the area, and researchers both from the Global North and the Global South. We engage with communities in all steps of the process from the identification of the problem and the design of the system and its evaluation, to the cocreation of the governance of the energy system. Central to our approach is the governance and sustainability of the system that includes not only the set of rules to manage the system to allocate the energy produced, but also the responsibilities in terms of its maintenance and repairs. Elinor Ostrom's design principles (53–55) for the governance of community-based natural resources are used as an initial step in the cocreation of these systems. Because the social-ecological characteristics of each community are different, as well as its needs, values, and capabilities, we expect that each community will have a different energy system. In addition, the systems need to minimize any impact on the natural resources upon which people's income and livelihoods depend and avoid placing unnecessary burdens on the community regarding maintenance, labor, and ongoing cost. Having a transdisciplinary team allows us to collaboratively codesign each one of these systems.

We prioritized community agency over the decisions regarding the project, in which community members were able to decide if they want to participate in the project. Together with the communities, we considered different technical solutions that suit their energy needs; the characteristics of their environment (river stream flow, amount of solar insolation, type of river sediments) and how they use it for their livelihoods, their capabilities (e.g., what is needed for them to learn to maintain and repair the technology); and their economic constraints (e.g., their level of poverty or income that can be devoted to this energy technology). We also considered their capacity to self-organize to govern the new energy system (e.g., determine who has access at what cost, for how many hours, who maintains the technology, power dynamics in the community) and their social norms (e.g., understand the social rules and institutions that limit or enhance aspects such as social equity and justice). These elements act as "initial conditions" that precede any work. Because it is essential for communities not to depend on external people to repair the system, given their relative isolation and long distances to any nearby city, we offer workshops for community members in learning how to install, maintain, and repair the technology. These community members can then become a core group in each community to ensure the functioning and governance of the system installed.

Our approach tries to make the design of the system, implementation, and governance processes more democratic and focuses primarily on community well-being, justice, and equity. Therefore, our Convergence Framework is one in which communities exercise agency in the creation of the energy system they will later use (48). In other words, they make choices they have been denied in the past, such as being collaborators in the design and implementation, as well as crafting the rules for the governance of the energy systems once installed.

In our Framework, we see adoption of innovation as a two-way iterative communication process, where the engagement and contributions of community members are crucial to improving the innovation itself and developing communication strategies that better fit the needs of that specific community. We pay close attention to power dynamics, ensuring that decision-making is shared between researchers and participants, and that the communities are involved in the entire process (51). In that sense, the starting point is to create trust between community members and the transdisciplinary team by including their knowledge and perspectives and ensuring the communities' leadership and ownership of the process and of the energy system. Highlighting community engagement in our Framework emphasizes the engagement process rather than merely the outcomes. Ensuring agency to the communities over the energy system is fundamental to sustainability. A Convergence Framework such as we have developed here pushes scientists and engineers to go beyond the NSF Convergence Ladder (columns 1 and 2 in Table 1) toward establishing ways to deliver sustainable energy solutions for communities and to do

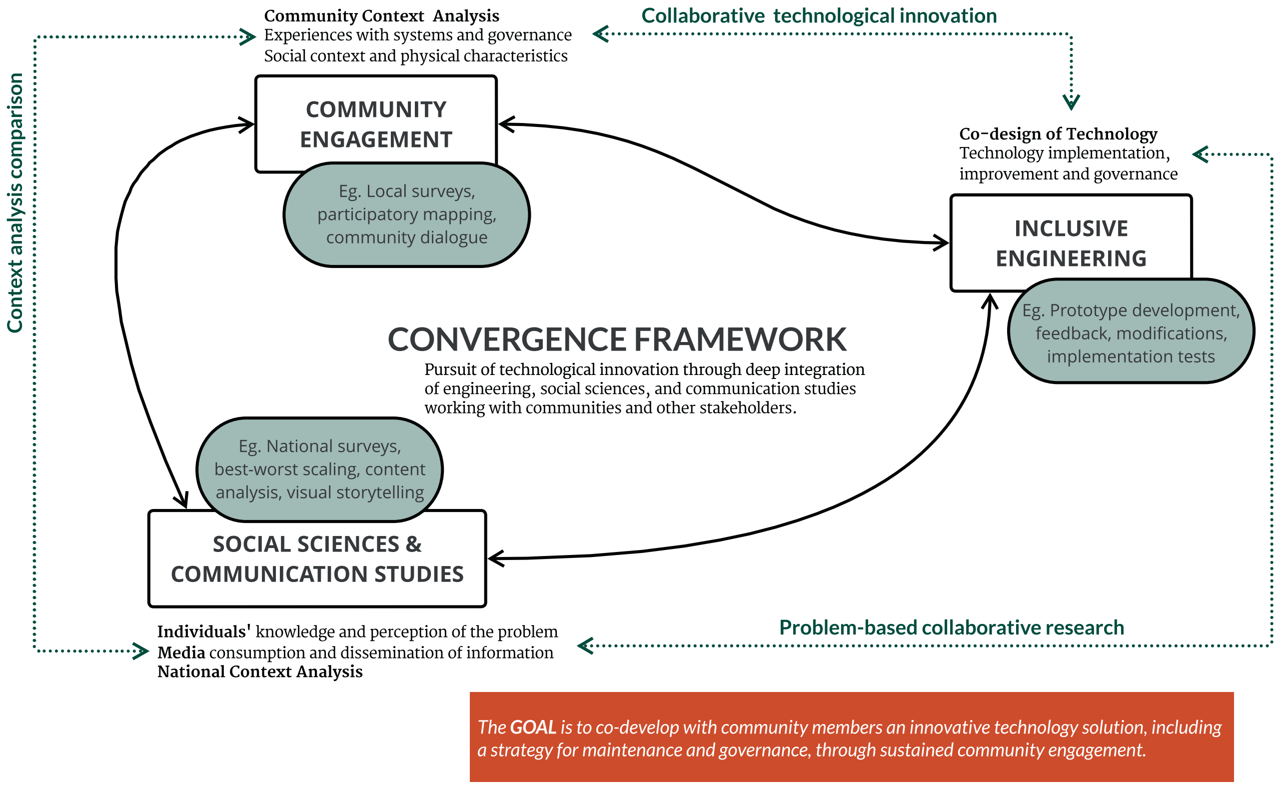

Fig. 1. The Convergence Framework is an approach for codevelopment of innovative technological solutions through deep integration of community engagement and disciplines to address sustainability challenges.

science that is coproduced, ensuring lasting positive impacts on communities' well-being. In column 3, we discuss how we have given substance to the ladder and discovered ways of communicating as a team.

Because of the nature of the problem we aim to solve, and the way we intend to coproduce solutions, it is central to our Convergence Framework to gradually morph our disciplinary backgrounds into a unified solution-driven process unimaginable at the outset. We discovered during our research that there is steady movement from individual disciplines toward collaborative transdisciplinarity, gradually creating a language to solve the problem together. This approach can revolutionize engineering (26), natural science, and social science education by not placing theory, methods, or mathematics first. Instead, starting with the process of defining practical problems faced by citizens and communities that need to be addressed (56) and engage multiple fields of knowledge to work together to find sustainable solutions—into which they can bring their epistemologies, theories, methods, and math—together with the communities facing the problems. It is, ultimately, a human-centered approach.

The collaborative perspective is not only at the disciplines' level, but also across geographies (e.g., Global North and South scientists) and stakeholders (e.g., academia, local communities, NGOs, private businesses, government). Therefore, our Convergence Framework moves beyond transdisciplinary research by simultaneously coupling community engagement in all stages of the process, explicitly centering on energy justice, collaborating across disciplines in a way that enables novel theoretical discoveries, utilizing mixed methods, fostering partnerships between the Global North and South, and having a focus on capacity building and development of a new generation of convergence-savvy scholars. Moreover, we exemplify how this framework has been operationalized for off-grid communities in the Brazilian Amazon, while still having a scalable approach that produces lessons that can be broadly applicable to other contexts and other challenges, such as ensuring water quality and quantity, sewage disposal, food production and distribution, and carbon sequestration through afforestation. These problems often involve trade-offs and are interconnected: water recycling can support agricultural production which in turn connects to community agriculture and food security, and sewage can be used to enrich soils with nutrients for agricultural production. Like energy, these are complex interconnected problems calling for a convergence framework.

Working with Communities: Inclusive Engineering, Social Sciences, and Communication Studies. Inclusive engineering (see Fig. 1) is understood as an approach that does not begin with a company or government deciding when, how, and where to install a technology, without engaging with the population that will be impacted by its installation. Rather, it is problem driven and engages scientists and engineers with communities and/or society, whose members actively participate in the process by voicing their needs; assessing the affordability of the technology; and participating in the testing, (re)design, implementation, and evaluation phases. These steps ensure that the technology positively contributes to their well-being, rather than negatively impacts their quality of life. Inclusive engineering is a different approach to overcoming the theoretical and methodological difficulties in defining the role of social science knowledge in engineering. In the first presentations of our proposed in-stream turbine, local people showed concern with what the generator blades might do to the fish, so our team gave priority to looking into how to design the generator in a way that would minimize such damage to the fisheries, which was a key concern to people who depend on the fisheries—i.e., in other words, it changed the engineering priority of optimizing energy production to making sure that the turbine

Table 1. Our approach to advancing convergence research and convergence activities

Stage	NSF description	Our approach	Specific indicators
Unidisciplinarity	Working with people who speak our dialect	Prior to grant	Engineering, social sciences, and communication researchers working in their own disciplines
		Working in siloed discipline arenas	
Sequential multidisciplinarity	Communicating our insights to other disciplines and groups so that they can pick up where we left off	Communication process to bring team together	Preproposal meetings with Co-PIs
Collaborative multidisciplinarity	Thinking things through with other disciplines and groups, understanding each other well enough to pool expertise.	Identification of key concerns guiding the project and how selected disciplines can address the problem	Multidisciplinary writing of proposal
			INFEWS, Food–energy–water nexus program at NSF
			Three different hydrologic models that included an engineering design team and a social science team
Emerging convergence	Starting to create frameworks, processes, and a unified language (glossary) to understand and solve problems together. Jargon goes away	Mapping project inputs, processes, and outputs to achieve specific goals	Input–Processes–Output model (IPO)
		Defining group norms—how we work together, processes, and shared language	Project's organizational structure moves from multidisciplinary to convergent output areas
		Identifying community stakeholders	Formalized codes of conduct
		Building a website together	Formalized norms of authorship
		Implementing project management	Community identification (maps, networking)
Consolidating convergence	Productive, convergent teams, clearly greater than the sum of their parts	Research subgroups formed around outputs and goals, not disciplines, national surveys for Brazil and the United States, content analyses, community engagement	Convergent research outputs: papers and conference presentations
		Collaborative creation of instruments for self-assessment of convergence (Toolbox)	Consolidation of convergence subgroup and measures (team surveys, analysis of meetings)
		Gathering community feedback	Forming partnerships with community leaders and members
			Forming partnerships with Brazilian universities and US education groups
			Forming partnerships with local industries
Deep convergence	Breakthrough insights and solutions not possible without deep convergence	Research without disciplinary focus, rather on solving the problem	Convergent publications on research outputs
		Dissemination of our convergence framework for energy solutions	Publications presenting our Convergence Framework as a way of doing science and engineering
		Focus on delivery of energy solutions to communities, ensuring that trained people from community can maintain the technology	Delivering innovative solutions that are cocreated with communities to address the project's original problems

blades do not harm the fish in the process of energy production. The motto "we do not want to make sushi" with which we began our monthly meetings highlighted the priority the team gave to livelihoods rather than energy production. It differs from the existing approaches such as Engineers Without Borders, which has not shown collaboration with disciplines outside of engineering, much less work closely with social scientists and local communities to have those concerns be inherent in the technological problem-solving. It differs as well from "humanistic engineering" advocated by the Colorado School of Mines, which has engineers consider the ethical obligations when working with communities but does not integrate social science in the practice of engineering. An early consideration of our Framework was to establish trust with the community and local experts (universities and local organizations) and then to identify social norms, previous experiences with other technologies, preexisting knowledge, and behaviors that would favor or oppose a change in the energy system. Further, we coidentified attitudes toward energy solutions, how salient it is for communities to find a solution to their energy needs, who can benefit the most from the technology due to daily activities, and the competing interests involved in decision-making for adoption. By integrating social science and engineering knowledge with communities and local experts, we were able to identify situations that could affect technology implementation.

For example, decades of having diesel-generated energy for 4 h in the early evening may have led to accommodation to this solution that could result in resistance to change from an established routine around which their lives' schedules are structured. There could also be any number of community members whose livelihoods may be tied to buying, selling, or distributing diesel to the community. In addition, introducing a new energy technology is a challenge in any setting (39) and much more so when it has not been field tested in a difficult environment such as that of a hyperhumid and hot weather and in rivers that carry formidable amounts of suspended organic matter. Our work began with engaging the community in the project in late 2020 to codesign the energy systems. In collaboration with local people, we gained broad and deep knowledge of the social-ecological context such as the riverine aquatic environment, its hydrological characteristics (depth of channel, water velocity, annual fluctuation in river level) and fishing and other activities that lie at the base of the community's livelihoods. Through multiple field visits, we have used a mixed-methods approach combining quantitative and qualitative data collection and analysis to understand the community's energy needs, the limitations of the current energy system, their previous experiences with other technologies, what local norms may stand in the way of a new energy system, and the possibilities of adoption. In addition, through a series of ongoing community-engaged workshops, we are learning their existing community rules and norms and how they manage other resources, such as those coming from the forest. We have used a visioning approach in workshops that enables us to identify what are desirable future states (visions) for the energy system. Visioning is a key method in sustainability science that combines systems thinking and community engagement to elicit stakeholders' preference for the future of energy (57). The visioning workshops have strengthened our results by exploring desirable states for the energy system and offered possibilities to adapt and address concerns and needs. Finally, workshops to facilitate the codesign of community energy agreements and rules are being conducted as we begin installation. The coupling of different methods deepens our understanding of the community's views, needs, abilities, and preferences. They have also participated in a training course taught by our colleagues in a local university to help them repair and maintain the system after installation.

A step we took during the first year of the project, and before going to the communities in the spring and summer of 2022, was to delve deeply into the messages that community members have acquired from national media. The public in Brazil, even in the Amazon, is very well connected via television and radio (and now social media) to what is going on socially, politically, and economically in the rest of the country and in that region. Over 80% of households in Brazil watch the national news each evening and they get their news from a highly centralized national news media via satellite. These mediated narratives interact with lived experiences, both directly and indirectly, via interpersonal communication and social movements around energy generation technology (58). Even the most isolated communities in the Brazilian Amazon watch national TV and use social media to communicate rapidly (59). This raises some crucial questions: Under which conditions do mass-mediated messages matter? How does proximity to dams—an energy generation technology that has impacted the lives of thousands in the region—affect people's perceptions of the technologies proposed? Under which conditions do lived experiences shape attitudes and behaviors? How do these forces combine to shape the social acceptability of an innovation?

In Brazil, most studies about the development of mass media have identified the government as one of the main economic forces behind the growth of the communication apparatus by giving economic and technical incentives and providing the necessary infrastructure for broadcast expansion. In the past, the military governments (1964–1985) used these channels to promote key priorities, which included a push to make hydropower a major driver of economic development. It is, thus, crucial to understand how news portrayals of hydropower evolved after censorship ceased at the end of the military regime. These mediated narratives combine with people's personal experiences and interpersonal communications to create schemata about hydropower in their minds, facilitating or hindering the adoption of energy alternatives. Brazil's media markets are dominated by a few conglomerates that have benefited from the politics of quid-pro-quo privatizations postmilitary regime (59). We have conducted quantitative and qualitative content analyses of news articles posted by the three most-circulated newspapers in Brazil, all part of large conglomerates that have a major presence online and offline: Folha de São Paulo, O Estado de São Paulo, and O Globo. Together, these organizations are pivotal in defining the news that people receive in the country. These communities rely on national newscasts for their information and even in isolated regions this government perspective is influential. The media analysis also helped us design a survey instrument carried out at national scale through a national representative sample of the Brazilian population, which included examination of the reach of social media and print media in shaping attitudes about possible energy solutions. What we found in the national sample seems to hold at local Amazon communities' level, since media discourses consistently promote the views of government and the hydropower sector and avoid discussion of negative impacts.

Our content analysis found that most stories carried by the media focused on the process of approval and construction of hydropower projects and on the benefits that hydropower brought to national economic development (60). Despite significant opposition to some hydropower projects, few stories covered these critical views, relying instead on voices from official sources and construction companies. Consequently, news has neglected the struggles faced by people and the environment impacted by large energy projects, such as hydropower dams. These results speak to the findings from an earlier household survey conducted by our team in the region, which revealed that the community residents affected by dams were mostly unfamiliar with the information about their impact. In fact, respondents seemed to directly reproduce the discourse from mainstream media, lamenting the negative outcomes from dams in their community, but believing that they are needed to make sacrifices for the larger good of the country (17). These findings indicate that there are information deficits, and that media consumption might directly influence people's attitudes about energy alternatives to hydropower.

We are also generating considerable creative visual work around the project and its Framework. Our team members collaborated on an animated video to explain the in-stream generator technology and PVs to the communities. The short 90-s film outlines the project and emphasizes our desire to engage with them to help alleviate at least a portion of their energy needs. It was effective in generating questions and creating interest in the proposed energy system. More profound will be a longer documentary film encapsulating our processes and experiences, our relationships with each other and the communities, and important moments along the way that were defining in creating a new way to do the science. The videos will serve to communicate the critical aspects of our approach and the role that community members play in discovery and finding solutions that work for them.

Our Suggested Solution: In-Stream Generators and PVs for Off-Grid Communities. Given that communities in the Amazon commonly rely on diesel generators, in-stream generators integrated with PVs can be an attractive sustainable solution with considerable efficiency, reliability, and lower costs for communities. Before arriving at this solution, our team examined other possibilities. Wind proved not to be a good option in this region of the Amazon, as opposed to the Atlantic Coast, and would be insufficient to efficiently generate energy (35, 61). Geothermal technology also proved nonfeasible. For an affordable off-grid system, the in-stream generator(s) matches local demand when the sun is down, and the integrated PV solar panels accommodate the difference between the in-stream turbine power and the day peak load. Both solar and hydrokinetic sources are highly available in the Amazon region. Chaudhari et al. (38) demonstrated that in-stream generators could generate up to 62% of all the power that planned dams are expected to generate. In other words, in-stream generators would be an effective alternative to dams at meeting planned energy demand, without the social and environmental negative impacts. When used in combination with PVs, they offer reliability and efficiency, demonstrated in a recent paper by Brown et al. (39). Below, we present the hybrid technology at its current stage (see Fig. 2), but we highlight that this is an open, iterative process in which the technology will be adapted based on community concerns, needs, capabilities, and desirable features. For example, through participatory workshops, the first community where we are installing the hybrid system has opted for a community microgrid with batteries to serve community-defined goals (e.g., school, Internet), rather than the individual solar panels on house rooftops illustrated in Fig. 2. We expect each community to arrive at different configurations for their energy system as a product of the community engagement process. This is the opposite of the top-down, one-size-fits-all energy solutions that have been used in the past and that have resulted in many energy injustices in Brazil and elsewhere.

In-stream generators are preferable to dams in several key respects. Unlike dams, in-stream generators require no reservoir and cause no deforestation, flooding, population resettlement, and major changes to the surrounding landscape (62). Further, in-stream generators cause little to no blocking of rivers, so sediments and other river-borne materials can flow naturally (see Fig. 2). Especially important for local communities dependent upon fisheries, in-stream generators can be designed to cause no fish mortality, and therefore will not affect this key food source and livelihood (39). Their relatively small blockage ratio, low-pressure ratio, low solidity, and low rotational speed allow

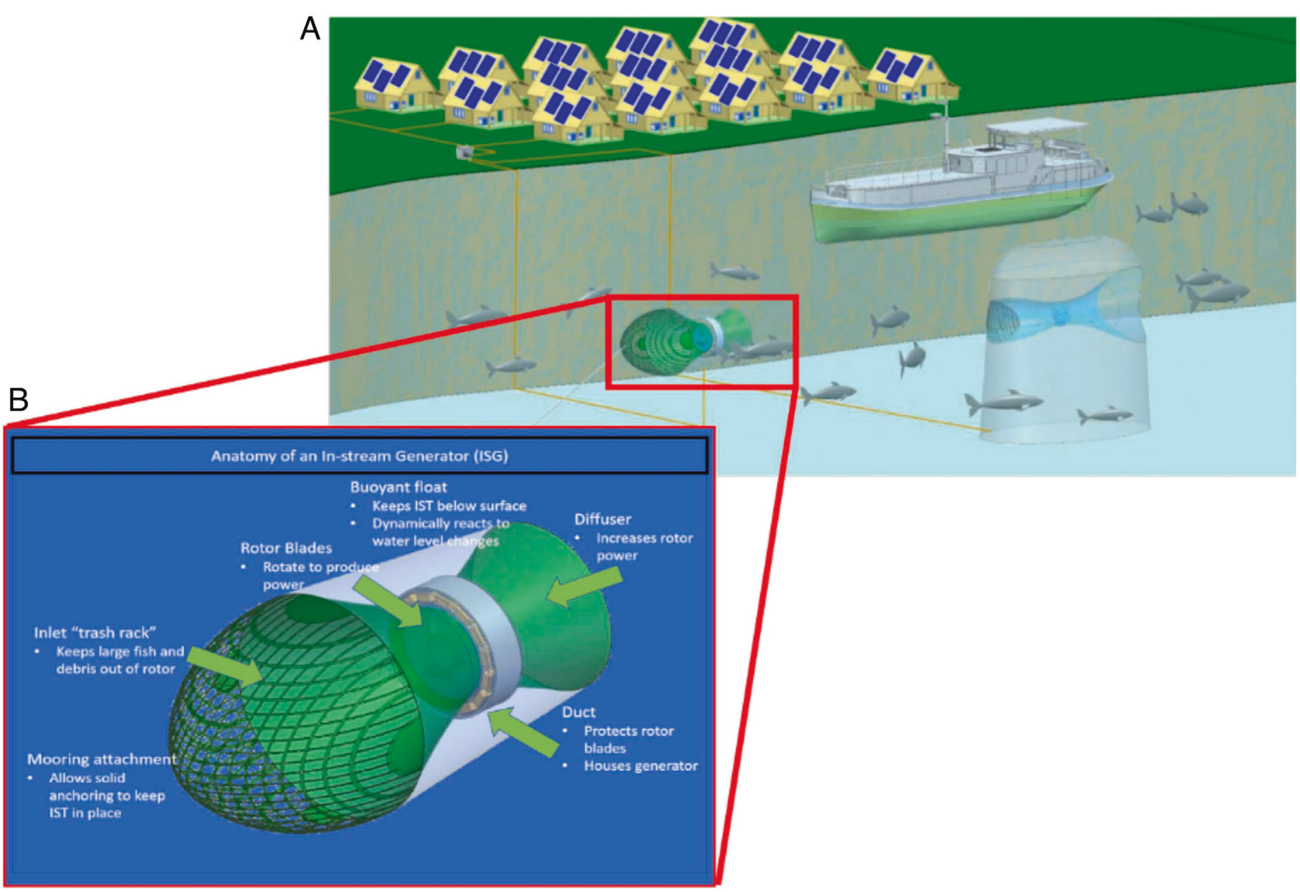

Fig. 2. An in-stream generator is shown *A*) as a hybrid PV-ISG system with multiple mooring configuration possibilities and *B*) a component-level view.

fish to bypass the rotor completely or pass through without harm (63). Fish can migrate downstream and upstream around, and through, an in-stream generator. Moreover, opposite to a conventional hydropower dam where the flow converges and accelerates into the generator (penstock), the flow approaching an in-stream generator decelerates and the majority bypasses it, conveniently guiding fish, and sediments, around the installation. In addition, the little-to-no blockage, depending on how many generators will be installed to meet energy demand, allows continued navigation of vessels, which is crucial for the economic and social activities in regions where transportation is mostly done by river.

Our team has worked on off-grid solutions and calculated the required initial financial investments and compared costs. As a relevant example, we found that for a local off-grid community, over a possible lifetime of 30 y, the suggested solution yields a cost per kW of approximately one-tenth that of a similarly sized diesel generator, contingent on the river flow velocity. This result is important for communities who are poor and for whom any alternative must be a significant cost improvement. This is consistent with the literature from the diffusion of innovations, participatory research, human-centered design approach, and Farmer First, in which solutions must be significant improvements over the existing systems for them to be accepted by users.

To maintain low system costs, a smart load management system is being implemented. The smart load management system reduces the load at night by utilizing a timer for the refrigerator, for example, that turns it on only at night when most other energy is off, to avoid overloading the system. The off-grid load curve was generated with typical devices utilized by local households (refrigerator, freezer, fan, lights, TV), as shown in Fig. 3 for the base case. All the above engineering work offers a starting point to test the value of this technology through our Convergence Framework, i.e., one that takes the design and estimated calculations made to engage local communities in the process of collaborative codesign and coproduction of technology and creating a governance system to ensure its sustainability. This is not a one-size-fits-all solution but the starting point for a conversation with communities within which they ask questions about the hybrid system, such as whether the energy output will be sufficient, what sorts of adaptations of daily behavior would enhance the value they gain from the available energy, and what decisions they are willing to make to match energy output with their envisioned uses.

Fostering North–South Collaboration to Advance Local Development. As we began our interactions and collaboration with the community, an important concern was ensuring that the communities could repair and maintain the technology for the long term. Our research team explored multiple avenues for manufacturing the technology. Producing the technology in São Paulo, while easier in theory than importing it from overseas, would entail moving a heavy piece of technology across thousands of miles and over roads that are not always ideal or may not even exist. A best-case scenario, given our interest in codesigning the energy system with communities and adapting to their needs, was to find local capability to produce the generator in the Amazon region—preferably close to the communities, since the Amazon is of continental proportions and distances can pose a significant barrier to availability. Hiring a local manufacturer also might reduce logistical costs and improve the economy for the region by offering training to local community members in how to maintain the generators and PVs so that it can operate sustainably.

We were fortunate to identify two separate research groups with this capability, one in the Madeira Basin, and another one

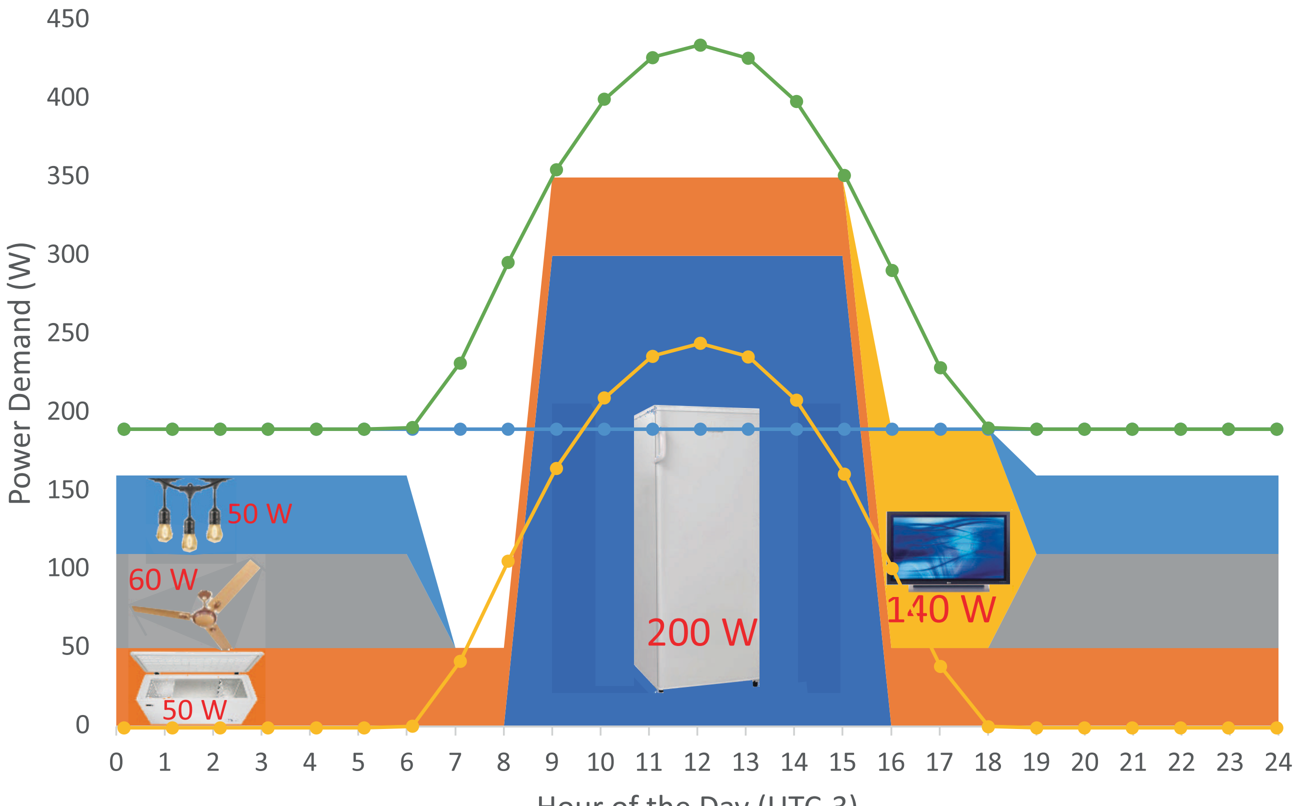

Fig. 3. Visualization of load curve by devices, with in-stream hydro and augmented PV.

in the Tapajós Basin. The former is associated with the Federal University of Rondônia (UNIR) in Porto Velho and its department of mechanical engineering, while the latter is associated with the Federal University of the West of Pará (UFOPA) in Santarém and its Institute for Renewable Energy. We have discussed our proposed solution with both groups and have become familiar with their own efforts to develop hydrokinetic energy for the benefit of isolated communities. The challenges are many, as they were generous to point out: any turbine would require cleaning and maintenance with much greater frequency than we imagined; long distances over poor roads and limited access by boat makes carrying a generator and numerous solar panels to their destination difficult; the generator has to cope with sticky sediments and animals, such as snakes, that can get caught in the blades, requiring that the generator be taken out of the river and put back with some frequency; and somebody needs to be on site to address such problems immediately as the community will come to rely on this energy source. Thus, alongside our effort to codesign with the community, we undertook codesign activities with the engineering partners in the region to arrive at a generator that could be produced locally to facilitate its transport, installation, and functioning. A major component was to develop a training program for community members interested in knowing the basics of how to service and maintain the two technologies (in-stream generators and PVs).

The in-stream technologies of these two Brazilian university teams are similar in the fact that they have rotating blades that allow for energy extraction, they both utilize ducts around the rotating section of the device, and both technologies could be scaled to fit the needs of the communities and could be coupled with PVs to complement the produced electricity. The devices have differing merits that could favor various deployment environments, in terms of available riverine area available, the amount of sediment and debris in the river, and the ability to moor the device in the river or on the nearby shore.

The technology developed at UNIR, tested in the sediment-rich riverine environment of the Madeira River, has a relatively compact and modular design, which makes it easy to transport which can reduce logistical costs. The device can be moored to the riverbed directly, with the housing designed to accelerate the river flow to increase the power extracted by the device. This mounting configuration could be beneficial for areas where there is a high seasonal change in water level and an easily wearable shoreline that could be difficult to mount as an anchoring system. However, the engineering had not yet been able to deal with the sticky nature of sediment in the Madeira and was at the time of our discussions with them not ready for community implementation. It remains experimental and solutions will need to be found to deal with the stickiness problem. We plan to stay in touch so that we can help communities in that region where we have already done significant field work in the past and which have shown interest in getting renewable energy.

A second technology, designed by van Els (64, 65) from the University of Brasilia, can be built locally in Santarém, and is different because it relies on support by either a retractable arm mounted on the shore or by a floating frame moored to the riverbed. The device is in an axial configuration (the axis of rotation is parallel to the flow direction), which is generally shown to produce more power over a wider operating range than crossflow counterparts (66), such as the UNIR design, where the rotor axis is perpendicular to the flow direction. The retractable arm is a convenient design for the local community members, in that it allows for easy maintenance, especially for routine maintenance that needs to be performed often. However, it requires a strong shore area to mount it to, to avoid breaking the device during a flood event, when the river may overflow its banks. This past problem with maintenance led to conversations with a local machine shop that came up with a second design using a floating frame, with a built-in mechanism, that allows users to pull up the generator for easy clean up, simplifying one of the great challenges to maintenance of the technology given the high organic matter content that the river carries routinely. This is another example of how this interweaving of social science, community experiences, and engineering design leads to novel solutions to address the energy problem at hand. The generator design differs a good bit from the original idealized design in Fig. 2 and is an example of the flexibility required to adjust to local maintenance realities. This technology has been presented to the community and a course in August 2022 prepared them for the installation and maintenance tasks involved. An additional training course and the installation will take place in late November 2022. It will carefully document in video the entire process to have a permanent record of the community interactions with the technology and our team. It can also serve to prepare the next communities, so they can consider whether this is what they want or whether they wish to consider some other redesign that better addresses their needs.

With regard to the PVs, we have learned a great deal from the experience of NGOs, like Saúde e Alegria and World Wildlife Fund, who have a long history of community engagement in the Tapajós river, and who have been working with both indigenous and nonindigenous communities to install solar panels to meet community needs. Local reality also changed the plans for battery deployment. Instead of the lithium ion batteries that were technically the best to install, local economic reality led to changes in plans that favored the use of acid lead batteries which are more affordable and easier to replace as needed than still difficult to obtain and costly lithium ion batteries. Those previous experiences are crucial in our ongoing community engagement, and they have generously shared their system specifications and problems they faced. The first community that has agreed to the installation has indicated that they prefer to have the energy directed at community needs rather than individual households, and that is what we plan to do in the first installation. Community buildings such as schools, churches, and a central place for people to charge their phones and other devices and run their router for internet access were selected by this first community as priorities. These solar panels will be coupled to the transmission line bringing the power from the in-stream generator to offer the advantages of the hybrid system. To make the energy transition less challenging, the community decided to keep the diesel generator as a backup when repairs or other maintenance reduces available energy. They were glad to know that they will have a backup system if they need one. This addresses what seems to be a problem for low-income populations as they consider an energy transition. In the national representative survey that our team designed, we discovered that as an individual respondent's income declined, they were less favorable to renewable energy, since they were less familiar with it and unfamiliar with its reliability. The assumption that people will embrace renewables across social classes needs further examination and some additional efforts may be needed to ensure that the population is confident of its low cost and reliability.

An important consideration has been how to structure the training program for local people to learn how the technologies work and how to install and maintain them. Together with the communities, the training program brought a minimum of three members from each community, chosen by the residents and including all genders, to take part in the training. The training course covered both solar technology principles and applications and engaged the trainees in the installation and maintenance of the technology. This helps not only to maintain the technology in each community but also to create local industry opportunities and lead to employment of the trainees to support the solar and generator technologies in the region, thereby encouraging education and job opportunities for future students and electricians in the area. Without addressing the challenge of training students to maintain the energy technology, the efforts to provide energy will be for naught. During the technical course, we facilitated the discussion of cocreation of the governance of the energy system that had been started during the visioning workshops.

Critical to this conversation with communities and local universities was to think of ways to use the energy produced beyond the basic needs of the community. Electricity opens opportunities for industrial and educational development. Many of these communities are poor because they have been isolated and without power. The availability of energy will open opportunities for entrepreneurship and welfare enhancement that is often latent in these communities. Processes that have been slow and tedious can be mechanized by energy, such as producing manioc flour, processing fruit concentrates, bottling the concentrate for export to other communities, processing agricultural products to generate more income for members of the community, and promoting community cohesion and social development and other goals through engagement not only with the energy technology but also across the full array of community-based initiatives. This issue was also addressed during the training course. Many ideas were suggested by community members on what might be strategies that could result in income to support community energy, such as an ice-maker (which now requires a long 15-h trip into the nearest town each time ice is needed for fishermen to keep their catch or for community social gatherings). Part of the polycentric governance for the communities advocated in the project is a constant reassessment of how the energy is used and how to allocate the energy as economic activities shift over time (67, 68). This is inevitable and has been a part of the community engagement from the start and central to how an inclusive engineering contributes to society.

Discussion

In the above sections, we have shown how we moved beyond the preliminary design and financial estimates of in-stream turbines and associated PV hybrid systems developed during an earlier research effort by our team, to their practical implementation in the current research, through a Convergence Framework that includes community engagement. We are cocreating site-specific system solutions to achieve acceptability and adoption with the first community having installation of its energy system scheduled for November 2022. To get to this point, we engaged in several preparatory activities and field trips to three communities in the Tapajós Basin. We have carried out a content analysis of news published by Brazilian media to understand what messages and discourses may have shaped the views of the communities we are studying. Then, in a series of field trips, we confirmed the persistence of those discourses in the views of the communities' members.

From initial contact to explore their interest in working with us, to later trips where we started our engagement with the three communities, we began to lay out the options for a hybrid energy system that might address the needs of these communities that until now had only a few hours of energy produced by diesel generators. Through household in-person surveys, community meetings, and visioning workshops, we gained further insight into what the needs, values, and capabilities of the community were and began a process of codesign of the energy system wherein the community could express their preferences for how to deliver the energy to whom and how to maintain and repair the system. The first installation scheduled for late November 2022 represents the implementation of their vision, which will be done partnering with a local university engineering group working with community members trained during the training course in August 2022 on the installation and maintenance of the technologies. We will then evaluate, together with community members, how well these systems perform on site and modify them accordingly before going to a second and then a third community. With communities, we will identify problems, examine how solutions can be improved, and determine how these off-grid solutions might scale up to achieve wide social acceptability to other communities in other regions. This is a consummate example of convergence research introducing collaboration among communities, engineers, social scientists, communication scholars, and other stakeholders—a rather rare and innovative interaction to address an urgent global problem such as providing affordable and sustainable energy solutions to communities not reached by national energy grids.

The lessons gained in the past 2 y confirm the findings of earlier efforts by other research groups doing collaborative and transdisciplinary research. Among these findings are that it is important to gain the trust of the communities and engage them in all steps of the process. Further, that the technology must bring about a significant improvement over whatever technology they currently have and be more affordable and just. Finally, that the design of the system and its governance must be emergent from the community social dynamics and not be simply brought from the outside. Combining technical training with discussions of governance has been a useful strategy that resulted in greater confidence by community members in appropriating the system as their own.

Our convergence approach is different from legacy approaches because it integrates engineering with the social sciences in a way that transforms how engineers and social scientists build their knowledge. It is not simply a matter of engineers behaving ethically (e.g., humanistic engineering), or of engineers being conscious of their social responsibility (e.g., Engineers Without Borders). We have developed a form of transdisciplinary engineering, inclusive engineering, in which complex global-to-local problems are tackled by different areas of knowledge, with social science playing a crucial part by introducing how local knowledge can inform engineering. There is an impressive amount of literature on sustainability from a variety of academic fields (e.g., social sciences, natural sciences, engineering). However, it is a mostly disconnected knowledge base. Inclusive Engineering (which we see as inherently connected to and informed by social science) connects the role of local knowledge, needs and wants, as inherent in the way the engineering/social science work is conducted—balancing these various considerations through community engagement. Just as Traditional Ecological Knowledge (TEK) has transformed current biodiversity research, inclusive engineering seeks to integrate the local knowledge needed to have engineering adapted to local social reality. The discussion, for example, of how one might simplify the cleaning of the generator led to a change in the design of the generator to make this much easier than the original generator had had in previous iterations, which also led to abandoning the swing arm that moved the turbine in and out of the water, and choosing instead a floating structure where it was easier to clean the turbine and lessened the risk of the river bank eroding and leading to the collapse of the turbine into the river. The community, the engineers, and the social scientists in our group found this solution to be superior to what any one of these groups could have come up on their own. The convergence approach is a way to have discovery and innovation through this intense interaction of communities with the scientists driven by the engagement of all participants in solving a salient problem.

Conclusions

In this paper, we propose a Convergence Framework coming from an on-going original research project funded by the NSF and the Mott foundation, where disciplines merge as they address problems faced by underserved communities. Our Framework was developed in the context of addressing a significant challenge faced by millions of people globally: delivering energy solutions to communities in isolated and off-grid regions, unreachable to date by national energy systems. Our Framework can be scaled up to other contexts to address how to improve their well-being, their education, and their economic activities and to find sustainable futures with an energy system that is just, democratic, and equitable. In short, the solution highlights and utilizes the massive talent found within these millions of people left behind by legacy systems.

We applied our Convergence Framework in off-grid communities in the Brazilian Amazon. In this region, enormous distances, low population density, highly fluctuating river levels and speeds, and precarious road and river infrastructure add to the difficulty in reaching these communities. Part of the problem lies in the traditional neglect of these isolated populations and their lack of political clout. Another revolves around the building of large-scale hydropower engineering projects along Amazonian rivers that were carried out without participation from local populations, to produce energy that goes to distant cities and industries and leaves the region and its inhabitants with all the negative impacts of the projects and none of the energy they need (19, 33, 69–71). There has been a lack of political will to push the energy sector to deliver 24-h electricity to these communities, thereby depriving them from achieving their potential. Instead, they have felt the full socioeconomic and environmental negative impacts of hydropower projects without gaining access to electricity and associated development benefits that could have been generated which have made them economically marginalized, afraid of energy development, and being forced to navigate persistent energy injustice.

By centering on the needs and characteristics of off-grid communities, our Framework recognizes that collaborative efforts are essential to address energy injustices and ensure sustainable delivery of energy solutions. Hence, our Framework stresses the necessity of collaboration across disciplines together with communities resulting in the emergence of unique knowledge that shapes both theory and practice. This is done by operationalizing transdisciplinarity through the development of a shared language and a deeply integrated approach among communication scholars and practitioners, social and natural scientists, and engineers, with a profound commitment to integrate community needs and desires from the beginning in the energy system. The Framework presents a set of steps on how this can be achieved, and it gives priority to capacity building of a generation of researchers that recognize the centrality of community engagement, social equity, energy justice, and community-based governance. In doing so, the Framework contributes to addressing specific needs of off-grid communities, while still developing rigorous knowledge that can be applicable to a wide array of other sustainability challenges. Finally, collaboration and partnerships between researchers based in the Global North and the Global South are key to produce scalable outcomes on a range of challenges faced by populations across the globe. The Framework proposes that science is better at delivering solutions when it is coproduced. We bring together academic knowledge and the human ingenuity embedded in communities to solve problems in a way that is more environmentally, socially, and economically acceptable, just, and equitable—i.e., a system that is truly sustainable. We believe this Convergence Framework can be employed successfully to solve urgent problems that legacy approaches failed to adequately address. The future of science, and democracy, is at stake in how well we work together to meet these challenges.

Data, Materials, and Software Availability. All study data are included in the main text.

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1. International Energy Agency (IEA), "Tracking SDG7. The energy progress report" (IEA, 2018).
2. J. Aguirre, The impact of rural electrification on education: A case study from peru. *Lahore. J. Econ.* **22**, 91–108 (2017).
3. A. Dijk, J. Clancy, Impacts of electricity access to rural enterprises in Bolivia, Tanzania and Vietnam. *Energy Sustain. Dev.* **14**, 14–21 (2010).
4. T. Dinkelman, The effects of rural electrification on employment: New evidence from South Africa. *Am. Econ. Rev.* **101(7)**, 3078–3108 (2011).
5. W. R. Catton, *Overshoot: The Ecological Basis of Revolutionary Change* (University of Illinois Press, 1980).
6. K. C. Seto *et al.*, Carbon lock-in: Types, causes, and policy implications. *Annu. Rev. Environ. Resour.* **41**, 425–452 (2016).
7. F. W. Geels, Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. *Theory Cult. Soc.* **31**, 21–40 (2014).
8. J. Baxter *et al.*, Scale, history and justice in community wind energy: An empirical review. *Energy Res. Soc. Sci.* **68**, 101532 (2020).
9. H. Kunreuther, P. Slovic, D. MacGregor, Risk perception and trust: Challenges for facility siting. *Risk* **7**, 5 (1996).

10. S. Hilgartner, R. C. Bell, R. O'Conner, *Nukespeak: The Selling of Nuclear Technology in America* (Penguin, 1983).
11. D. Goulet, Global governance, dam conflicts, and participation. *Hum. Rights. Q.* **27**, 881–907 (2005).
12. B. Tilt, D. Gerkey, Dams and population displacement on China's upper Mekong river: Implications for social capital and social–ecological resilience. *Glob. Environ. Change* **36**, 153–162 (2016).
13. E. A. Rosa *et al.*, Nuclear waste: Knowledge waste? *Science* **329**, 762–762 (2010).
14. G. Jacob, *Site Unseen: The Politics of Siting Nuclear Waste Repositories* (University of Pittsburgh Press, 1990).
15. R. Prăvălie, G. Bandoc, Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications. *J. Environ. Manage* **209**, 81–92 (2018).
16. T. Scudder, *The Future of Large Dams* (Routledge, 2012).
17. A. Mayer, L. Castro-Diaz, M. C. Lopez, G. Leturcq, E. F. Moran, Is hydropower worth it? Exploring Amazonian resettlement, human development and environmental costs with the Belo Monte project in Brazil. *Energy Res. Soc. Sci.* **78**, 102129 (2021).
18. E. F. Moran, M. C. Lopez, N. Moore, N. Muller, D. Hyndman, Sustainable hydropower in the 21st century. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 47 (2018).
19. C. C. Arantes, D. B. Fitzgerald, D. J. Hoeinghaus, K. O. Winemiller, Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. *Curr. Opin. Environ. Sustain.* **37**, 28–40 (2019).
20. C. R. C. Doria *et al.*, Understanding impacts of dams on the small-scale fisheries of the Madeira River through the lens of the Fisheries Performance Indicators. *Mar. Policy* **125**, 104261 (2021).
21. P. M. Fearnside, Social impacts of Brazil's Tucuruí dam. *Environ. Manage* **24**, 483–495 (1999).
22. P. M. Fearnside, Impacts of Brazil's Madeira River dams: Unlearned lessons for hydroelectric development in Amazonia. *Environ. Sci. Policy* **38**, 164–172 (2014).
23. G. Siciliano, F. Urban, Equity-based natural resource allocation for infrastructure development: Evidence from large hydropower dams in Africa and Asia. *Ecol. Econ.* **134**, 130–139 (2017).
24. M. A. Garcia, L. Castro-Diaz, S. Villamayor-Tomas, M. C. Lopez, Are large-scale hydroelectric dams inherently undemocratic? *Glob. Environ. Change* **71**, 102395 (2021).
25. A. Mayer, M. A. Garcia, L. Castro-Diaz, M. C. Lopez, E. F. Moran, Pretend participation: Procedural injustices in the Madeira hydroelectric complex. *Glob. Environ. Change* **75**, 102524 (2022).
26. S. Sorby, N. Fortenberry, G. Bertoline, Stuck in 1955, Engineering education needs a Revolution. *Issues Sci. Technol.* **13** (2021).
27. H. Ahlborg, I. Ruiz-Mercado, S. Molander, O. Masera, Bringing technology into social-ecological systems research—motivations for a socio-technical-ecological systems approach. *Sustainability* **11**, 1–23 (2019).
28. B. K. Sovacool, Deploying off-grid technology to eradicate energy poverty. *Science* **338**, 47–48 (2012).
29. K. Jenkins, D. McCauley, R. Heffron, H. Stephan, R. Rehner, Energy justice: A conceptual review. *Energy Res. Soc. Sci.* **11**, 174–182 (2016).
30. D. McCauley, R. Heffron, H. Stephan, K. Jenkins, Advancing energy justice: The triumvirate of tenets and systems thinking. *Int. Energy Law. Rev.* **32**, 107–116 (2013).
31. G. Siciliano, D. Del Bene, A. Scheidel, J. Liu, F. Urban, Environmental justice and Chinese dam-building in the global South. *Curr. Opin. Environ. Sustain.* **37**, 20–27 (2019).
32. D. Del Bene, A. Scheidel, L. Temper, More dams, more violence? A global analysis on resistances and repression around conflictive dams through co-produced knowledge. *Sustain. Sci.* **13**, 617–633 (2018).
33. A. Mayer, M. C. Lopez, E. F. Moran, Uncompensated losses and damaged livelihoods: Restorative and distributional injustices in Brazilian hydropower. *Energy Policy* **167**, 113048 (2022).
34. Instituto de Energia e Meio Ambiente (IEMA), Amazônia legal: Quem está sem energia elétrica. http://energiaeambiente.org.br/produto/exclusao-eletrica-na-amazonia-legal-quem-ainda-esta-sem-acesso-a-energia-eletrica. Accessed 26 April 2022.
35. A. S. Sánchez, E. A. Torres, R. D. A. Kalid, Renewable energy generation for the rural electrification of isolated communities in the Amazon Region. *Renew Sustain. Energy Rev.* **49**, 278–290 (2015).
36. A. L. Schmid, C. A. A. Hoffmann, Replacing diesel by solar in the Amazon: short-term economic feasibility of PV-diesel hybrid systems. *Energy Policy* **32**, 881–898 (2004).
37. S. Sulaeman, E. Brown, R. Quispe-Abad, N. Müller, Floating PV system as an alternative pathway to the Amazon dam underproduction. *Renew Sustain. Energy Rev.* **135**, 110082 (2021).
38. S. Chaudhari *et al.*, In-stream turbines for rethinking hydropower development in the Amazon Basin. *Nat. Sustain.* **4**, 680–687 (2021).
39. E. Brown *et al.*, Feasibility of hybrid in-stream generator-photovoltaics systems for Amazonian off-grid communities. *PNAS Nexus* **1**, 1–9 (2022a).
40. Energy Information Administration (EIA), Beyond natural gas and electricity: More than 10% of US homes use heating oil or propane. https://www.eia.gov/todayinenergy/detail.php?id=4070#. Accessed 20 September 2022.
41. Energy Information Administration (EIA), 2015 residential energy consumption survey data. https://www.eia.gov/consumption/residential/data/2015/. Accessed 20 September 2022.
42. R. Pirog, "Winter fuels outlook, 2017–2018" (Tech. Rep. 45052, Washington, DC, 2017).
43. L. Ross, A. Drebohl, B. Stickles, "The high cost of energy in rural America" (American Council for an energy efficient economy, 2018).
44. D. J. Bednar, T. G. Reames, G. A. Keoleian. The Intersection of energy and justice: modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy and Buildings* **143**, 25–34 (2017).
45. E. M. Rogers, *Diffusion of Innovations* (New York: Free Press, 2003).
46. R. R. Rice, *Diffusion of innovations* (Oxford Bibliographies, 2016).
47. S. R. Arnstein, A ladder of citizen participation. *J. Am. Plann. Assoc.* **35**, 216–224 (1969).
48. N. Kabeer, Resources, agency, achievements: Reflections on the measurement of women's empowerment. *Dev. Change* **30**, 435–464 (1999).
49. R. Chambers, The origins and practice of participatory rural appraisal. *World Dev.* **22**, 953–969 (1994).
50. L. M. Vaughn, F. Jacquez, Participatory research methods–Choice points in the research process. *J. Particip. Res. Met.* **1**, 1–13 (2020).
51. F. Baum, C. MacDougall, D. Smith, Participatory action research. *J. Epidemiol. Community Health* **60**, 854–857 (2006).
52. S. Wyche, J. Olson, M. N. Karanu, Redesigning agricultural hand tools in Western Kenya: Considering human-centered design in ICTD. *Info. Tech. Inter. Dev.* **15**, 97–112 (2019).
53. E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge University Press, 1990).
54. M. Cox, G. Arnold, S. V. Tomás, A review of design principles for community-based natural resource management. *Ecol. Soc.* **15**, 4 (2010).
55. F. Fleischman *et al.*, Governing large-scale social-ecological systems: Lessons from five cases. *Int. J. Commons.* **8**, 2 (2014).
56. M. Brasler, "Interdisciplinary problem-based learning—A student-centered pedagogy to teach social sustainable development in higher education" in *Teaching Education for Sustainable Development at University Level*, W. Leal Filho, P. Pace, Eds. (Springer, 2016), pp. 245–257.
57. A. Wiek, D. Iwaniec, Quality criteria for visions and visioning in sustainability science. *Sustain. Sci.* **9**, 497–512 (2014).
58. C. Matos, *Journalism and Political Democracy in Brazil* (Lexington Books, 2008).
59. B. Kucinkski, *A síndrome da antena parabólica: Ética no jornalismo brasileiro* (Editora Fundação Perseu Ábramo, 1998).
60. R. R. Mourão, G. Neuls, K. Ninni, Hydropower in the news: How journalists do (not) cover the environmental and socioeconomic costs of dams in Brazil. *Envirol Commun*, https://doi.org/10.1080/17524032.2022.2115095.(2022)
61. National Aeronautics and Space Administration (NASA), *The Power Project NASA*. https://power.larc.nasa.gov/. Accessed 17 January 2022.
62. E. F. Moran, M. C. Lopez, N. Moore, N. Müller, D. W. Hyndman, Sustainable hydropower in the 21st century. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11891–11898 (2018).
63. E. Brown, S. Sulaeman, R. Quispe-Abad, N. Muller, E. F. Moran, Safe Passage for Fish: The case for in-stream turbines, *Renew. Sustain. Energy Rev.*, in press.
64. R. H. van Els, J. N. de Souza Vianna, A. C. P. Brasil Jr., The Brazilian experience of rural electrification in the Amazon with decentralized generation–The need to change the paradigm from electrification to development. *Renew Sustain. Energy Rev.* **16**, 1450–1461 (2012).
65. R. H. van Els, A. C. P. Brasil Jr., The Brazilian experience with hydrokinetic turbines. *Energy Procedia.* **75**, 259–264 (2015).
66. E. L. C. Arrieta, A. R. Clemente, "Computational fluid dynamic simulation of vertical axis hydrokinetic turbines" in *Computational Fluid Dynamics Simulations*, G. Ji, J. Zhu, Eds. (IntechOpen, 2019).
67. T. Heikkila, S. Villamayor-Tomas, D. Garrick, Bringing polycentric systems into focus for environmental governance. *Environ. Policy Govern.* **28**, 207–211 (2018).
68. A. Thiel, D. E. Garrick, W. A. Blomquist, Ed., *Governing Complexity: Analyzing and Applying Polycentricity* (Cambridge University Press, 2019).
69. L. Castro-Diaz, M. C. Lopez, E. F. Moran, Gender-differentiated impacts of the Belo Monte hydroelectric dam on downstream fishers in the Brazilian Amazon. *Hum. Ecol.* **46**, 411–422 (2018).
70. A. Mayer, M. C. Lopez, G. Leturcq, E. F. Moran, Changes in social capital associated with the construction of the Belo Monte Dam: Comparing a resettled and a host community. *Hum. Organ.* **81**, 22–34 (2022).
71. C. Doria *et al.*, The invisibility of fisheries in the process of hydropower development across the Amazon. *Ambio* **47**, 453–465 (2017).