World Development 178 (2024) 106570

Contents lists available at ScienceDirect

World Development

journal homepage: www.elsevier.com/locate/worlddev

Regular Research Article

Spatial injustice to energy access in the shadow of hydropower in Brazil

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ARTICLE INFO

Keywords:
Spatial justice
Energy justice
Energy access
Hydroelectric dams
Brazil

ABSTRACT

Hydroelectric dams generate adverse social and ecological consequences for communities in their vicinity, particularly those situated in rural areas, far from urban centers, and lacking significant political and economic influence. There is relatively little research on how hydroelectric projects change local energy services. In this study, we investigate whether Jirau and Santo Antônio—two dams in the Brazilian Amazon—have impacted energy sources, access, and electricity prices for households in communities near the construction sites using survey data and geospatial analysis. We evaluate these changes' spatial and political determinants. Our findings reveal that certain households still rely on diesel generators for their electricity. Furthermore, we find that communities experienced spatial injustices in energy access. Spatial and political factors explain differences in energy sources and access between households. Households adversely affected by construction, particularly those in distant upstream and downstream communities, those who were not resettled, and those who did not engage directly in negotiations with dam builders, were less likely to experience improvements in energy access and sources. Most of these households perceived that their energy prices increased after the construction. Our study implies that hydroelectric dams do not consistently improve energy access in nearby communities and, in fact, contribute to the persistence of spatial injustices.

1. Introduction

Energy security is critical for improving human health, nutrition, education, and entrepreneurship (Echeverry et al., 2017; Grogan, 2016; Rao et al., 2019; Vernet et al., 2019). However, around 13 % of the global population lacked energy access in 2018 (World Bank, 2018). This problem is most prevalent among populations living in rural areas of low and middle-income countries since they represent 80 % of those without electricity (World Bank, 2018). Dam builders and governments often promote hydropower as a clean and affordable solution to reduce energy insecurity without depending on fossil fuels. However, not all communities near dams receive improved energy services, affordable energy, or related benefits (Siciliano and Urban, 2017). Rural, low-income, and indigenous populations, despite their proximity to the plants, are usually left without energy access from dams built (some examples are: Aeria, 2016; Fearnside, 1999; Siciliano and Urban, 2017) and facing negative impacts on their social-ecological systems and livelihoods (Castro-Diaz et al., 2023).

Large-scale hydroelectric dams impose negative social-ecological impacts that outweight their benefits (Moran et al., 2018). These dams disrupt river morphology, contribute to significant fish mortality, escalate deforestation, and release greenhouse gas emissions (Almeida et al., 2019; Arantes et al., 2019; Arantes et al., 2023; Bertassoli Jr. et al., 2021; de Araújo et al., 2019; Fearnside, 2016; Oliveira et al., 2021; Santos et al., 2020). Additionally, hydroelectric dams adversely affect the livelihoods of nearby populations (Fan et al., 2022; Mayer, Lopez, and Moran, 2022). Over the latter half of the twentieth century, large dams have displaced more than 80 million people globally (WCD, 2000), and approximately 20 million since 2011 (Cernea and Maldonado, 2018). However, compensation schemes fail to adequately address the losses experienced by displaced and other affected populations (Adams, 1985; Mayer, Lopez, Leturcq et al., 2022). While one might anticipate that dams would enhance energy services for host communities, the reality is quite different. Energy benefits tend to accrue to urban centers and

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https://doi.org/10.1016/j.worlddev.2024.106570
Accepted 9 February 2024
Available online 4 March 2024

industries, leaving communities near dams with costly and polluting diesel generators (Aeria, 2016; Dao, 2010; Fearnside, 1999; Green and Baird, 2016; Judge, 1997; Okuku et al., 2016; Siciliano et al., 2018; Thomas et al., 2021; Yoshida et al., 2013).

Although research implies that dams do not improve energy services for nearby communities, few studies have evaluated differences between households in those communities, and the determinants of those differences. Also, much of this literature concentrates on socio-economic differences in accessing energy but does not fully account for spatial factors across communities or in terms of spatial relationships to dams. Recent literature suggests that geographic location has a central role in generating energy injustices (Bouzarovski and Simcock, 2017; Meng, 2018; Reames, 2016; Sovacool and Furszyfer Del Rio, 2022; Yenneti et al., 2016). The aspects of geographical location can be a combination of ecological and socio-political-technological factors. For instance, Bouzarovski and Simcock (2017) explain how spatial variation in weather patterns, housing stock, and access to energy technologies can create energy insecurity.

In the case of hydroelectric dams, the spatial difference between upstream and downstream communities is critical (Adams, 1985; Baird et al., 2021; Castro-Diaz et al., 2018; Owusu et al., 2019; Richter et al., 2010). Dams negatively affect downstream communities, but, contrary to upstream communities that will be resettled, they are often entirely neglected from consultation, resettlement, and compensation schemes (Baird et al., 2021; Castro-Diaz et al., 2018; Mayer, García et al., 2022; Richter et al., 2010). Nonetheless, this literature does not assess differences in energy access between upstream and downstream communities.

In this study, we inquire if households within communities surrounding dams report better or worse energy access after construction and evaluate the spatial factors explaining those changes. We draw on the concept of spatial justice in the energy context. We understand spatial injustice as the unequal geographical distribution of resources and negative consequences generated by the energy system (Sbicca et al., 2021; Yenneti et al., 2016). We focus on the differences between households in upstream and downstream communities and between those in riverine and inland communities. It is crucial to highlight that dam-related injustices do not necessarily occur because the communities disrupted by their construction do not benefit from the electricity generated by the dams. Rather, injustices arise when these surrounding communities are not granted improved energy services following the disruption of their livelihoods caused by hydro dam construction. In addition, our study focuses on the injustices against human communities, but we acknowledge that a comprehensive justice perspective includes multi-species approach since, as aforementioned, this hydropower affects human as well as non-humans (e.g., forest, river, fish, among others) (Araujo, 2024; Celermajer et al., 2020; Wintera and Schlosberg, 2023).

We use data from households in communities surrounding the Jirau and Santo Antônio dams in the Madeira River in the Brazilian Amazon. The Amazon has numerous dams, in part, because Brazil has relied upon hydropower to provide "clean," affordable, and reliable energy sources to facilitate economic development (Atkins, 2017, 2018). Jirau and Santo Antônio are pertinent for exploring the spatial factors associated with changes in energy access. These dams caused social-ecological impacts on both downstream and upstream communities (Baird et al., 2021; Mayer et al., 2021; Santos et al., 2020). Nevertheless, the Environmental Impact Assessments (EIAs) for Santo Antônio and Jirau in the Madeira River established that the downstream affected area was 12 km from the construction site of Santo Antônio, preventing further downstream communities from being compensated or resettled (Baird et al., 2021; Furnas et al., 2004). The upstream affected area was up to the Bolivia border, although the community Abunã, which is in that area was not recognized as impacted (Furnas et al., 2004). Most of the research on the spatial aspects of energy injustice has been conducted in the Global North (Lacey-Barnacle et al., 2020; Perez-Sindin et al., 2022; Yenneti et al., 2016). We extend this work by situating our study in the Global South.

This study also contributes to the global debate on whether hydroelectric dams should be constructed. Currently, there is a surge in the construction boom of large hydro dams in some of the most biodiverse basins in the Global South, such as the Amazon, Congo, and Mekong, while certain countries in the Global North are decommissioning their aging dams (Moran et al., 2018). In its 2050 Energy Plan, Brazil outlines the construction of multiple hydroelectric dams in the Amazon, driven by the region's significant hydropower potential (Ministério de Minas e Energia, 2020). The most recent Decennial Energy Expansion Plan published in December 2022 emphasizes the necessity of modernizing the existing hydroelectric plants in the country as part of a substantial expansion of this energy source. This expansion aligns with adjustments required to address challenges posed by climate change (Ministério de Minas e Energia, 2022). In this context, we provide recommendations to improve energy access in communities surrounding and impacted by the sitting of new or recently built dams.

2. Hydropower impacts and spatial justice in energy systems

2.1. Hydropower social-ecological impacts

The ecological effects of hydropower dams include: the decline of fish stocks, loss of sediment movement downstream from dams resulting in fewer nutrients for all riverine ecosystem functions, an increase in turbidity and reduced light penetration affecting plant species, the transformation in the annual cycles of river ebb-and-flow that affects fish migrations and terrestrial vegetation on riverbanks; and an increase in deforestation (Arantes et al., 2019; Doria,et al., 2018; Nickerson et al., 2022; Oliveira et al., 2021; Ziv et al., 2012). Negative social impacts include forced displacement of communities living near the area of construction, disruption of people's livelihoods, such as loss of social networks, and physical capital (houses and land), and disarranging of fisheries and their activities (Aiken and Leigh, 2015; Castro-Diaz et al., 2023; Kirchherr et al., 2016; Mayer et al., 2021; Mayer, Lopez, Leturcq et al., 2022; Santos et al., 2020).

Both upstream and downstream communities suffer negative social-ecological consequences, but the latter communities are often overlooked by dam authorities in compensation and resettlement schemes (Baird et al., 2021; Castro-Diaz et al., 2018; Hallwas et al., 2013; Owusu et al., 2016, 2019; Richter et al., 2010; Runde et al., 2020). Richter et al. (2010) calculate that around 472 million people worldwide living in downstream communities were potentially impacted by about 7,000 large dams built up to 2010. In Brazil, this number was between 1 and 2 million people in the same period (Richter et al., 2010). Baird et al. (2021) suggest that downstream communities suffered from water quality and other problems from changes in the river's hydrology, which in turn had social consequences due to the impact on fish, and human water consumption after dams' construction in Canada, the Mekong in Asia, and Brazil. Yet, these downstream communities were neglected from compensation and resettlement, due to their long distance from the dam, political boundaries, and difficulties in identifying ecological changes (Baird et al., 2021).

Large hydropower projects do not typically improve energy access of communities surrounding the construction sites (Aeria, 2016; Dao, 2010; Fearnside, 1999; Green and Baird, 2016; Judge, 1997; Okuku et al., 2016; Randell and Klein, 2021; Yoshida et al., 2013). Instead, communities near dams tend to rely on costly and polluting diesel generators (Aeria, 2016; Fearnside, 1999; Siciliano and Urban, 2017).

2.2. Energy and spatial justice

Energy justice encompasses a research agenda spanning multiple disciplines, addressing issues of (in)justices in the production, consumption, and distribution of electricity (Heffron and McCauley, 2017; Jenkins et al., 2016). *Distributional* justice specifically concerns the social distribution of burdens and benefits related to energy production and consumption (Heffron and McCauley, 2017). A scenario may be deemed distributionally unjust if communities bearing the social-ecological costs of energy production do not simultaneously receive benefits that adequately offset these costs. Scholars have recently emphasized that this injustice is intricately liked to an uneven geographical distribution (Bouzarovski and Simcock, 2017; Meng, 2018; Reames, 2016; Sovacool and Furszyfer Del Rio, 2022; Yenneti et al., 2016). Bouzarovski and Simcock (2017) "start from the premise that geographic disparities in the risk and incidence of domestic energy deprivation are a key component of energy justice" (640). Bouzarovski and Simcock (2017) argue that most of the literature has analyzed inequalities across distributional justice between groups of people, mainly in terms of their socioeconomic status, with little attention to spatial (in) justice. Spatial injustice refers to "the geographical dimensions of inequality and inequity" (Bouzarovski and Simcock, 2017:640). In other words, the inequitable spatial distribution of resources, benefits, and burdens related to energy production, distribution, and consumption across spaces (Sbicca et al., 2021; Yenneti et al., 2016). This concept is rooted in urban geography, especially in Soja's (2010) seminal contributions. For this author, a spatial analysis allows a theoretical and practical framework to understand energy justice. Energy geographies "emphasise the critical role of space and spatial analyses in energy and environmental justice" (Lacey-Barnacle et al., 2020:130). The literature on spatial justice reminds us that space can generate social, economic, and ecological exploitation and discrimination and those social, economic, and ecological factors can create spatial injustices (Bouzarovski and Simcock, 2017; Soja, 2010).

Bouzarovski and Simcock (2017) propose four concepts to explain how spatial injustices happen due to ecological and/or social-political reasons. In this study, we use three of the four concepts.[1] *Landscape and material deprivation* refers to the unequal distribution of energy poverty across space or geography due to ecological or material reasons (Bouzarovski and Simcock, 2017). Scholars have found differences in energy access based on place of living according to ecological conditions (e.g., altitude, weather, and rural vs. urban conditions) or to other material deprivations (e.g., houses that are less energy-efficient and need more energy in cold places) (Bouzarovski and Simcock, 2017). G*eographic underpinnings of energy affordability* refers to the relationship between energy prices, energy availability, access to energy technologies, and socioeconomic status across spaces (Bouzarovski and Simcock, 2017). *Spaces of misrecognition* occur because some populations are not recognized for the benefits of the energy system, due to their culture, identity, or politics. This lack of recognition is associated with geography. Bouzarovski and Simcock (2017) provide the example of the U.S., a nation with high levels of energy consumption but poverty is spatially concentrated. The energy needs of those living in areas with spatially concentrated poverty are seldom recognized.

3. Methods

3.1. Research questions and hypotheses

Research question 1: do people near the hydropower dams report that their energy access improved after construction? Our hypothesis is that these communities report that after Jirau and Santo Antônio dam, their energy sources, energy access, and prices stayed the same or got worse. This hypothesis tests a distributional injustice in energy access.

Research question 2: what spatial dimensions explain the changes in electrical energy sources, access, and prices in households surrounding the hydroelectric dams after the sitting? Our first hypothesis for this question is that households in upstream and reservoir communities improved their energy access compared to households downstream since usually the latter communities are not recognized by dam authorities as affected. Since our case study is based on a hydroelectric complex of two dams, we test whether households are upstream of both dams, near the reservoir (or between the dams), or downstream. In the rest of the paper, we refer to these categories as households in upstream, reservoir, or downstream communities. This hypothesis tests spatial injustice due to socio-political reasons. The second hypothesis for this question is that we expect people living inland to experience a greater improvement in their energy access than riverine households. Inland communities are more likely to be linked to the electricity grid because they are reached by roads and the electricity transmission lines follow the roads. Meanwhile, riverine communities live in the forest and it is difficult to open the forest to install the transmission lines and maintain these. This hypothesis tests spatial injustice due to ecological reasons.

Research question 3: what political dimensions explain changes in energy sources, access, and prices? Our hypothesis for this question is that households resettled, compensated, and that negotiated directly with dam builders are more likely to report that their energy access improved compared to those that did not get compensation, were resettled, or did not negotiate. Thus, in this last question, we evaluate the effect of three political variables: households' participation in negotiation with dam builders, being resettled, and being compensated by the dam authorities.

3.2. The study area context

While Brazil is acvitely working on diversifying its energy production, it remains heavily reliant on hydropower (Brazil, 2022). By 2020, 63.8 % of the country's energy was from hydropower. Meanwhile, only 26.6 % of the world's energy came from hydropower in that same year (Schutze et al., 2022). The Amazon has the greatest remaining potential for hydropower development and is the country's most recent frontier in large, medium and, small dam construction (Moretto et al., 2012). Yet, many communities remain without access to electricity despite its closeness to energy infrastructure that powers distant regions of the country. The off-grid communities in the Amazon, estimated to be nearly 1 million people (IEMA, 2020), usually rely on diesel or gasoline generators, whenever they can afford the fuel. This technology is expensive to buy and maintain given the distance of these communities from the urban centers, making it hardly accessible to impoverished isolated communities. Besides, diesel generators also pollute the environment (Sánchez et al., 2015). The scarce access to electricity restrains access to health, education, sanitation, and other basic services associated with social development (Van Els et al., 2012). People living in energy production sites still lacked energy access. The Brazilian States in the Amazon produce 25.7 % of the country's electricity by 2020, but 14 % of their inhabitants lacked energy (Schutze et al., 2022).

Santo Antônio and Jirau dams were built within 120 km of each other, and the construction started in 2008. The Santo Antônio dam is close to the capital of Rondônia state, Porto Velho (400,000 inhabitants approx.), and its installed capacity is 3,750 MW. Jirau is located upstream of the Santo Antônio dam, and it has an installed capacity of 3,568 MW. Our study was carried out on eight communities along the Madeira basin near the two dams. We included communities located from approximately 4 Km to 147 Km from the nearest dam. All of them are within Porto Velho municipality, which comprises the areas that were considered directly or indirectly influenced by the dams' construction (LEME, 2005). They are riverine or inland communities; upstream, near the reservoir, or downstream; and previously existed or were formed by resettled populations due to displacement by the construction. Fig. 1 shows a map of the communities in the study.

[1] The concept that we do not include is *vulnerability*. This concept focuses on populations with more energy needs due to different conditions (e.g., people with illnesses need more energy due to technological equipment to deal with their infirmities). We do not include it because is not part of our research objectives.

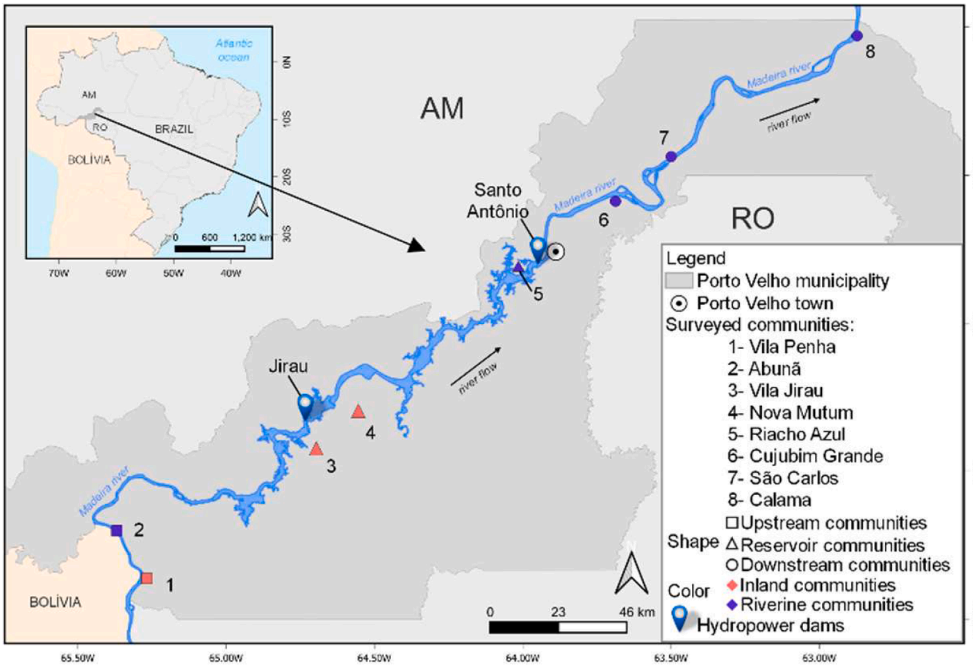

Fig. 1. Map 1. Study site: Porto Velho municipality and communities impacted by Santo Antônio and Jirau hydropower dams' construction. Note: AM: Amazonas state, RO: Rondônia state.

3.3. Survey data collection

To develop our sampling frame, we used satellite imagery to identify potentially eligible structures (i.e., homes) in each community. Next, team members visited to confirm that the identified structures were homes, not businesses, churches, schools, or other ineligible structures. The households of dam operators were excluded from our sample since they are not a local resident population. The eligible structures were then assigned numbers, and we sampled homes proportional to the population size in each community. The fieldwork period ran between August 2019 and March 2020. Six hundred and seventy-three people completed the survey with a 3.04 % margin of error and 95 % confidence level.

3.4. Dependent and independent variables

Our dependent variables are derived from survey questions that measured: self-reported electricity source, perception of changes in electricity access, and perception of changes in electricity prices. The independent variables of spatial justice were measured by identifying if the households are in an upstream, reservoir, or downstream community; and if they are in an inland vs. riverine community. The former indicator captures the political dimensions of spatial injustice, as downstream communities are rarely included in the political processes that redress the damage created by hydropower projects. The second indicator, inland vs. proximate to the river, operationalizes the ecological dimensions of spatial injustice described above as communities close to the river typically experience less access to the transmission line since it is very difficult to maintain the transmission line due to vegetation encroachment. For political factors we measure whether the household had to move due to the dam building; whether the household received any compensation; and if the household negotiated with dam authorities.

3.5. Data analysis strategy

We employ two strategies to investigate the relationship between spatial and political factors and changes in energy access. Initially, we provide descriptive statistics presented on maps, offering insights into the alterations in energy sources, access, and prices. Descriptive maps elucidate the spatial patterns or geographical distributions associated with each of the dependent variables. These statistics visually portray distintions among respondents based on their residential locations. Maps play a crucial role in comprehending spatial justice issues and identifying target populations for policy recommendations (Reames, 2016; Sbicca et al., 2021). We used geoprocessing tools of QGIS software version 3.14, an open-source Geographic Information System (GIS) licensed under the GNU General Public License, to produce the maps and represent selected variables spatially.

We present, as the second analytical strategy, four statistical models to understand if those spatial differences and other political factors are statistically related to differences between households in energy access, and prices. The first two models (Models 1 and 2 in Table 2) predict changes in energy access. This variable is scored on a categorical ordinal scale (improved, stayed the same, decreased). Ordered Logit is usually the statistical model to regress independent variables on this type of dependent variables if the parallel lines assumption is not violated. We conducted a Brant test, which indicated that the parallel lines assumption was violated by a few variables (e.g., resettled). Thus, we rely upon the partial proportional odds model (PPO). The PPO is a compromise between the multinomial logistic regression model and the ordinal logistic regression model (Williams, 2016).[2] We ran two PPO models. The first tested the effect of living in an upstream, reservoir, or downstream community on the probability of improved energy access after dam construction. The second model assessed the effect of living in an inland or riverine community. As we show in the results section below, it seems

[2] This model relaxes the proportional odds assumption for variables that are found to violate the assumption. In effect, this means that those variables have a different coefficient (and standard errors and p-values) for each category of the outcome variable. But, for the variables that do not violate the assumption, the effect is constrained to be equivalent across categories of the outcome. In this way, the partial proportional odds model is much more parsimonious than the multinomial logit model but also can reveal important nuances about the effects of predictors that are masked in the ordinal logistic regression model.

that the association between energy access and the variable of inland vs. riverine communities is highly affected by the community Nova Mutum. Thus, we ran two additional models. One regresses Nova Mutum to changes in energy access (Model 2b in Table 2), and the other regresses the variable of inland vs. riverine community without Nova Mutum (Model 2c in Table 2). Our spatial indicators, "upstream, reservoir, or downstream community," and inland vs. riverine community, are collinear with each other; hence we estimate separate models.[3]

The last two models predict the changes in energy prices (Models 3 and 4 in Table 2). This variable is categorical and highly skewed since most of the respondents (84.0 %) indicating an increase in prices post-construction. For the purposes of regression analysis, we re-coded this variable such that "decreased" or "stayed the same" were scored as a zero, and "increased" was scored as a one. We used a variation of logistic regression that is robust to data sparsity—this method is typically called the "Firth logistic regression" (Firthlogit) and has been found to produce less biased estimates when the distribution of a binary outcome is skewed (Firth, 1993; Heinze and Schemper, 2002; Rainey and McCaskey, 2021). For changes in energy prices, we estimated two Firthlogit models. The first regresses living in an upstream, reservoir, or downstream community, while the second inland or riverine community. Likewise, in the previous case, we ran two models due to multicollinearity.

To compare the models, we employed the Bayesian Information Criterion (BIC) (Raftery, 1995), and Akaike Information Criterion (AIC) tests. When comparing the BIC and AIC scores between models, the one with less score is judged a better fit (Raftery, 1995). Analyzing our indicator for energy source (diesel or transmission line) ran into some unforeseen challenges—nearly all the respondents with access to a transmission line were located upstream from the dams. This degree of data separation renders any estimates derived from regression models questionable. Accordingly, we use bivariate correlations and chi-squared tests to understand the relationships between our independent variables and energy source. For all the statistical analyses we utilized Stata16.1, and for a more intuitive interpretation of the results of the four models, we display Average Marginal Effects (AMEs).

4. Results

4.1. Description of changes in energy access

In this section, we address Research Question 1: do people near the hydro plants report that their energy access improved after construction? Descriptive statistics reveal that those living in proximity to the construction site reported a decline or no change in their energy access subsequent to the completion of the dams (Table 1). We identify that almost all households (99.26 %) stated that they had electricity after construction. Sixty-four percent of households were tied to the transmission lines, while 36 % relied on diesel generators. According to our observations in the field, these diesel generators are typically large central generators providing energy for all the households in a community. Concerning changes in energy access, 18.1 % said energy access got worse, 52.6 % that it stayed the same, and 29.3 % that energy access improved. Eighty-four percent reported that energy prices increased and 16 % reported that prices decreased or stayed the same.[4]

Table 1
Descriptive Statistics of Dependent, Independent, and Control Variables. Standard Deviations for Numerical Variables are in Parentheses.

Variable	Percentages/Mean	
Dependent variables	Does the electricity to your house come from a diesel generator or a transmission line?	
	Diesel	36.2 %
	Transmission line	63.8 %
	Has the ability to access electricity for your household remained the same, gotten worse, or improved (due to the building of the dam(s))?	
	Got worse	18.6 %
	Stayed the same	52.2 %
	Improved	29.2 %
	Has the price of electricity for your household stayed the same, decreased, or increased (due to the building of the dam(s))?[Increased Energy Prices?]	
	Increased [Yes]	84.3 %
	Decreased or stayed the same [No]	15.%7
Independent variables	Location	
	Riverine community	73.8 %
	Inland community	26.2 %
	Type of Community	
	Downstream	50.9 %
	Reservoir	29.5 %
	Upstream	19.6 %
	Did you and your household move from one community to another community as a result of the dam construction?	
	No	77.9 %
	Yes	22.1 %
	Did you or anyone in your household receive any type of compensation/mitigation because of the dam? (before, during, or after dam construction).	
	No	85.4 %
	Yes	14.6 %
	Does someone in the household has to participate in negotiations (before, during, and after dam construction)? / Did a leader or leaders of your community participate in any negotiations before/during/after the construction of the dam on your behalf and/or on behalf of your community?	
	No negotiation	70.0 %
	The household negotiated directly	8.7 %
	A leader negotiated for the household	14.6 %
	The household and a leader negotiated	6.7 %
Control variables	Respondent sex	
	Male	48.3 %
	Female	51.7 %
	Respondent age	48 (15.2)
	Respondent schooling	
	No formal education	11.8 %
	Primary	54.0 %
	Secondary	26.2 %
	Technical /vocational	8.0 %
	Respondent's occupation is fishing or farming	
	No	68.4 %
	Yes	31.6 %

[3] Collinearity is when at least two of the independent variables are highly correlated, thus, one variable can be predicted by the other. This problem can impact the coefficients, standard errors, and the interpretation of results. For high collinearity, we used the Variance Inflation Factor (VIF) test. A score higher than 2.5, is considered problematic (Johnston et al., 2018).

[4] Only 27% of the households reported their community received any infrastructure (including electricity) as compensation. This 27% includes households that were only compensated or resettled. Of that, 27%, only 9 respondents living in Nova Mutum, a community that was designated to take in resettlers, said that their community received electricity from dam builders. This is a community that includes houses of dam operators, who live in houses that include air conditioning and other amenities.

4.2. Spatial factors explaining energy sources, access, and prices after dams

This subsection addresses research question 2: what spatial dimensions explain the changes in energy sources, access, and prices in households surrounding the hydroelectric dams after the siting? Table 2 presents the odds ratios, standard errors, and AIC and BIC scores for all the models. The results suggest that spatial patterns partially account for differences in energy sources and access between households surrounding dams, but the evidence is not as strong as for explaining changes in prices.

4.2.1. The differences between living upstream, reservoir, or downstream: assessing political-driven spatial injustices

Fig. 2 illustrates a map with a notable distinction: only households downstream reported the use of diesel generators, whereas all households in upstream and reservoir communities relied on a transmission line as their primary electricity source. Eighty-seven percent of respondents in Calama and 100 % in São Carlos reported having electricity from diesel. Both are downstream communities that have a centralized energy system based on large generators supplied with diesel or biodiesel by the local electricity distribution company. Calama is particularly distant from both dams and spatially isolated from the other communities. Cujubim Grande is the remaining downstream community, but 100 % of the households have energy access through the transmission line. One explanation might be because Cujubim Grande is largely inhabited by dwellers resettling from the 2014 flooding that caused their previous settlement to collapse and much closer to Port Velho the capital of the Rondônia state. This pattern is confirmed in Fig. 3, which shows the difference in energy sources between downstream, upstream, and inland communities is statistically significant ($p = 0.000$).

Upstream, reservoir, or downstream status also explains reported changes in energy access after the dams were built. Fig. 4 (Map 3) shows that households in upstream communities from the dams, Vila Penha and Abunã, are more likely to report that energy access got worse or stayed the same after construction than households in other communities. These two communities are distant from the dams and located on the border between Brazil and Bolivia. Model 1 in Table 2 reports similar results, and Fig. 5 shows the corresponding AMEs. Panel 1 in Fig. 5

Table 2
Regressions Models for Energy Access Improved and Energy Prices Decreased or Stayed the Same.

Variables	*Partial Proportional Odds Logistic for Energy Access Improved*				*Partial Proportional Odds Logistic Energy Access Improved (Nova Mutum)*		*Partial Proportional Odds Logistic Energy Access Improved (Without Nova Mutum)*		*Firthlogit for Energy Prices Decreased or Stayed the Same*	
	Model 1		Model 2		Model 2b		Model 2c		Model 3	Model 4
	Got worse	Stayed the Same	Got worse	Stayed the Same	Got worse	Stayed theSame	Got worse	Stayed theSame		
Independent										
Type of community (ref = upstream)										
Reservoir	3.71***	1.99**							2.33**	
	(1.16)	(0.60)							(0.88)	
Downstream	6.76***	1.17							0.92	
	(1.80)	(0.32)							(0.31)	
Inland communities 1 = Yes			1.55**	1.55**			1.25	1.25		1.68*
			(0.32)	(0.32)			(0.30)	(0.30)		(0.45)
Nova Mutum 1 = yes					2.35***	2.35***				
					(0.75)	(0.75)				
Resettled 1 = Yes	1.06	3.48***	0.94	4.54***	0.83	3.89***	1.02	4.01***	0.77	1.03
	(0.35)	(0.99)	(0.28)	(1.21)	(0.26)	(1.09)	(0.37)	(1.29)	(0.29)	(0.35)
Compensated 1 = Yes	0.78	0.78	0.73	0.73	0.68	0.68	0.57	0.57	0.78	0.87
	(0.25)	(0.25)	(0.23)	(0.23)	(0.22)	(0.22)	(0.23)	(0.23)	(0.34)	(0.37)
Negotiation with dam builders (ref = no negotiation)										
The household negotiated directly	2.36**	2.36**	2.42**	2.42**	2.66***	2.66***	3.51***	3.51***	0.69	0.83
	(0.87)	(0.87)	(0.88)	(0.88)	(0.98)	(0.98)	(1.55)	(1.55)	(0.33)	(0.39)
A leader negotiated for the household	0.75	0.75	0.69	0.69	0.68*	0.68*	0.69	0.69	0.42**	0.41**
	(0.18)	(0.18)	(0.16)	(0.16)	(0.16)	(0.16)	(0.17)	(0.17)	(0.18)	(0.18)
The household and leader negotiated	0.83	0.83	0.84	0.84	0.89	0.89	0.86	0.86	0.70	0.84
	(0.31)	(0.31)	(0.31)	(0.31)	(0.33)	(0.33)	(0.40)	(0.40)	(0.37)	(0.43)
Control										
Female 1 = yes	0.93	0.93	0.80	0.80	0.81	0.81	0.82	0.82	1.11	1.07
	(0.16)	(0.16)	(0.13)	(0.13)	(0.13)	(0.13)	(0.14)	(0.14)	(0.26)	(0.25)
Age	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Education										
Primary	0.83	0.83	0.85	0.85	0.84	0.84	0.90	0.90	0.71	0.69
	(0.23)	(0.23)	(0.23)	(0.23)	(0.23)	(0.23)	(0.26)	(0.26)	(0.26)	(0.25)
Secondary	0.81	0.81	0.94	0.94	0.87	0.87	0.98	0.98	0.52	0.52
	(0.26)	(0.26)	(0.30)	(0.30)	(0.28)	(0.28)	(0.34)	(0.34)	(0.23)	(0.23)
Technical /vocational	0.93	0.93	1.21	1.21	1.11	1.11	1.17	1.17	0.36*	0.36*
	(0.37)	(0.37)	(0.47)	(0.47)	(0.43)	(0.43)	(0.48)	(0.48)	(0.22)	(0.22)
Occupation 1 = farming and fishing	0.87	0.87	1.12	1.12	1.10	1.10	1.21	1.21	0.85	0.81
	(0.17)	(0.17)	(0.21)	(0.21)	(0.20)	(0.20)	(0.23)	(0.23)	(0.23)	(0.21)
Observations	640		640		640		569		603	603
AIC	1171.834		1225.733		1222.965		1087.045		490.856	495.3484
BIC	1252.141		1292.655		1289.887		1152.203		552.4828	552.5734
mean VIF	1.86		1.71		1.75		1.71		1.95	1.78
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$										

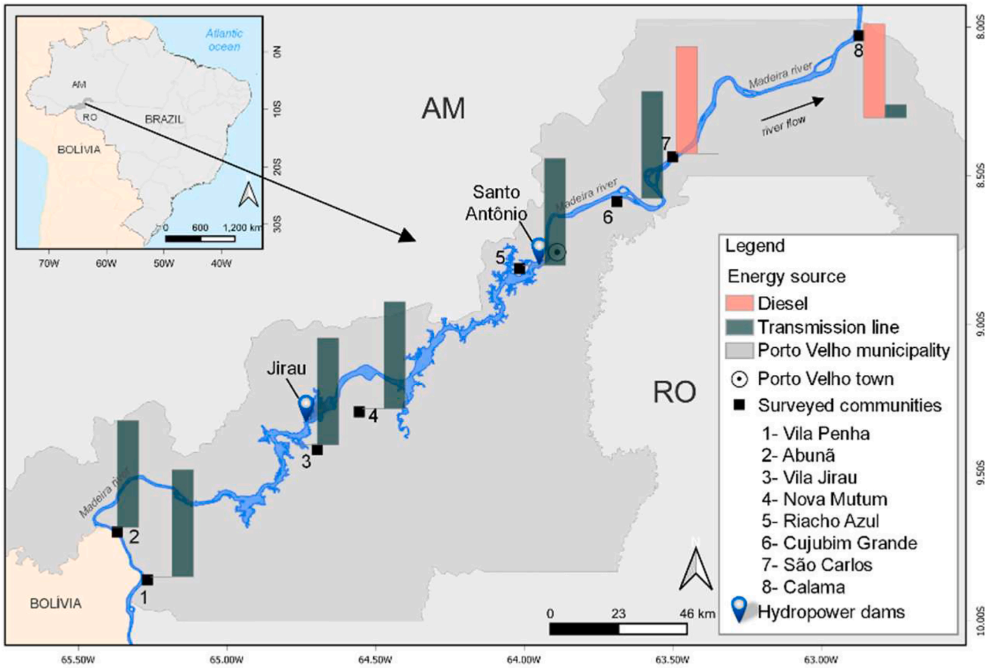

Fig. 2. Map 2. The proportion of households reporting the type of energy source after the Santo Antônio and Jirau hydropower dams' construction, by the community. The data depicted on Map 2 can be found in Table B1 within the Appendix.

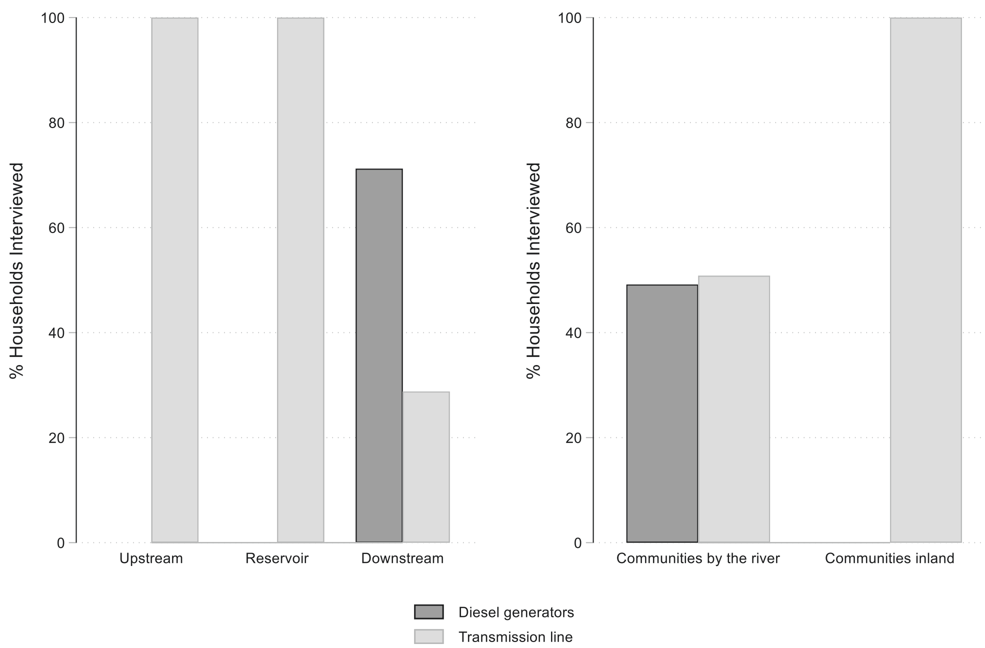

Fig. 3. Energy Source by the Type of Community after Dams Construction.

indicates that living in an upstream community was associated with a 0.43 increase in the probability of stating that energy access "got worse," while living in a reservoir and downstream community is only associated with a 0.17 and 0.10 increase, respectively. On the contrary, downstream status is associated with a 0.63 increase in the probability of stating that energy access "stayed the same," while upstream with 0.33 and reservoir with 0.46 (Panel 2 in Fig. 5). Yet the AMEs for "improved" (Panel 3 in Fig. 5) are generally more similar than the other categories.

Nonetheless, our results suggest that community location (upstream, reservoir, or downstream) does not explain households reporting changes in energy prices. Fig. 6 (Map 4) illustrates how most of the households in all communities reported that energy prices increased. Likewise, both Models 3 and 4 (Table 2 and Fig. 7) present no statistically significant difference between households when considering this variable.

4.2.2. The differences between living in inland or riverine communities: assessing ecological-driven spatial injustices

Maps 2, 3, and 4 do not show clear patterns of differentiation in terms of energy sources, access, and prices between households in riverine and inland communities. This ambiguity is also seen in the

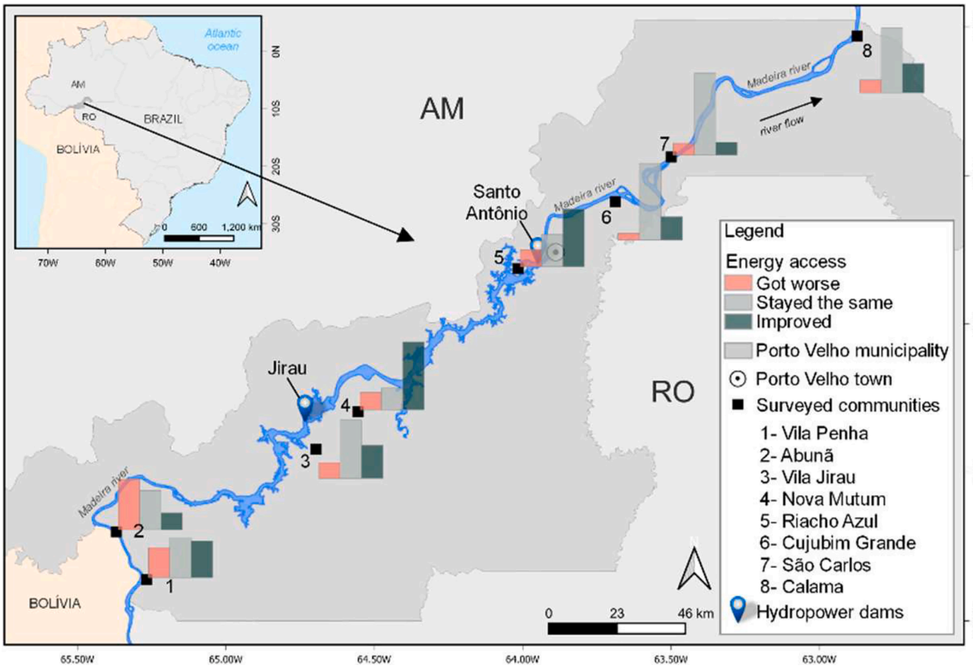

Fig. 4. Map 3. The proportion of households reporting changes in energy access after Santo Antônio and Jirau hydropower dams' construction, by the community. The data depicted on Map 3 can be found in Table B1 within the Appendix.

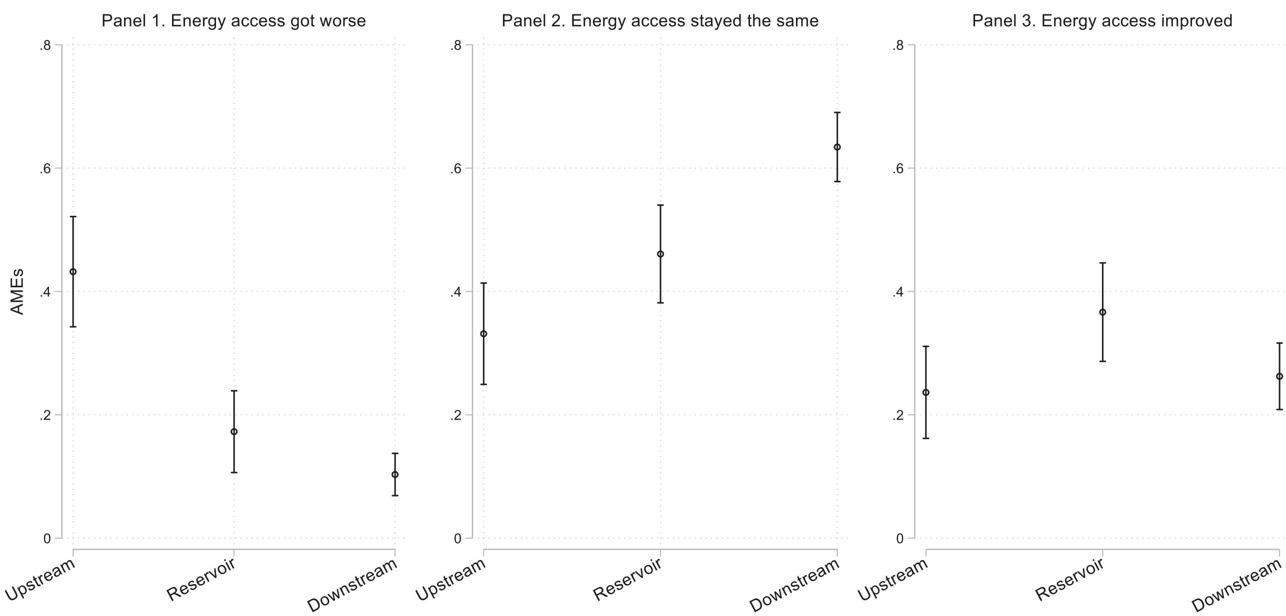

Fig. 5. AMEs for Households Reporting Changes in Energy Access According to the Community (Upstream, Reservoir, and Downstream) in which Households are Located.

descriptive statistics for energy sources and Models 2 and 4 for energy access and prices, respectively. Fig. 3 shows that all households in inland communities have transmission lines. Meanwhile, some households in riverine communities have diesel generators and other transmission lines. It is not clear the reason for this phenomenon.

Model 2 drops the variable for upstream, reservoir, and downstream locations and replaces it with the variable for inland vs. riverine locations to explain changes in energy access. There is a statistically significant association between households living inland vs. by the river, and changes in energy access (Table 2). Fig. 8 reports the AMEs for the variable inland vs. riverine. Panel 1 in Fig. 8 implies that riverine communities were slightly more likely to state that energy access had "gotten worse" (0.20 probability) than households in riverine communities (0.14 probability). Yet inland communities were incrementally more likely to state that energy access had "improved" (0.35 probability) than households in riverine communities (0.27 probability).

Nevertheless, caution should be exercised in interpreting the aforementioned results regarding the regression of residing inland or by the river on changes in energy access. The differences between inland and riverine communities are not statistically strong and standard errors are high (Table 2). One potential explanation is that one of the inland communities is Nova Mutum, which was one of the communities resettled and compensated by dam builders, including electricity as compensation, and where many dam operators reside (although they

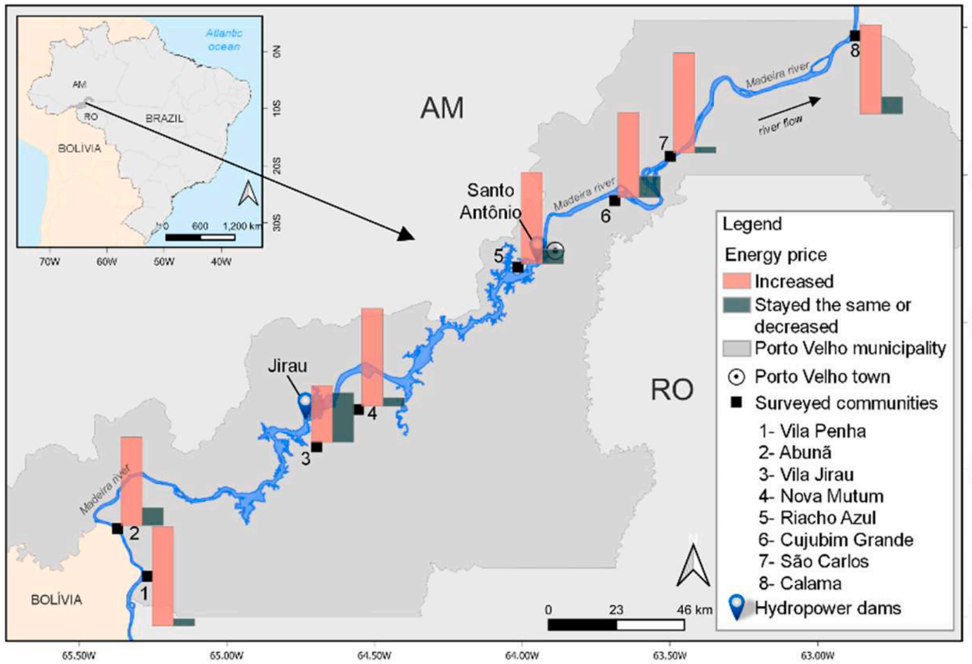

Fig. 6. Map 4. The proportion of households reporting changes in energy prices after the Santo Antônio and Jirau hydropower dams' construction, by the community. The data depicted on Map 4 can be found in Table B1 within the Appendix.

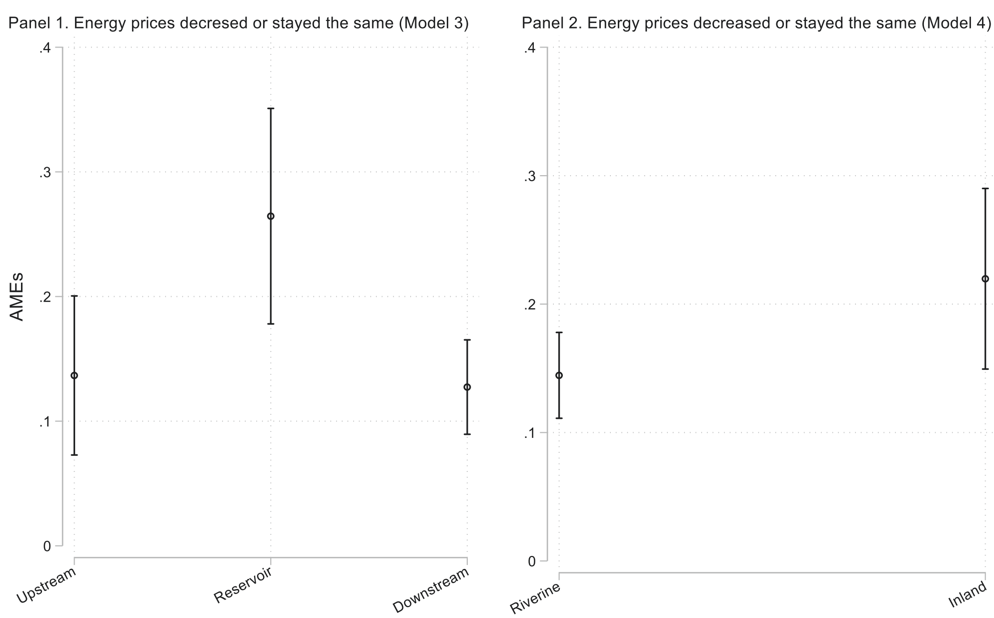

Fig. 7. AMEs for Households Reporting Energy Prices Decreased or Stayed the Same According to the Community in which Households are Located.

were not included in our sample). We estimated a PPO model that uses energy access as the dependent variable and a binary indicator for Nova Mutum as the independent (0 = all other, 1 = Nova Mutum) (Model 2b in Table 2). Model 2b in Table 2 shows that this binary variable has a statistically significant association with improved energy access. Thus, the effect of inland vs. riverine is somewhat driven by a single community. To confirm this, we ran a PPO model with the inland vs, riverine community variable excluding the observations from Nova Mutum (Model 2c in Table 2). Model 2c shows that without Nova Mutum, the variable inland vs. riverine is not statistically significant to explain changes in energy access.

Model 4 reports that households in inland communities have a 0.22 probability to say that energy prices decreased or stayed the same, while riverine households have a 0.14 probability (Table 2 and Panel 2 in Fig. 7). However, these results should also be taken with caution since the differences in the probabilities between households across the different communities are low, and the confidence intervals are wide (Panel 2 in Fig. 7).

The ambiguity of the results for the variable of inland vs. riverine community is shown when comparing the models regressing this variable (Models 2 and 4), and the models regressing upstream, reservoir, and downstream communities (Models 1 and 3). The AIC and BIC statistics imply that Model 1 fits the data better than Model 2, suggesting that downstream, upstream, and reservoir status better explain perceptions of changes in energy access. The same can be said for energy prices—Model 3 has lower AIC and BIC scores compared to Model 4

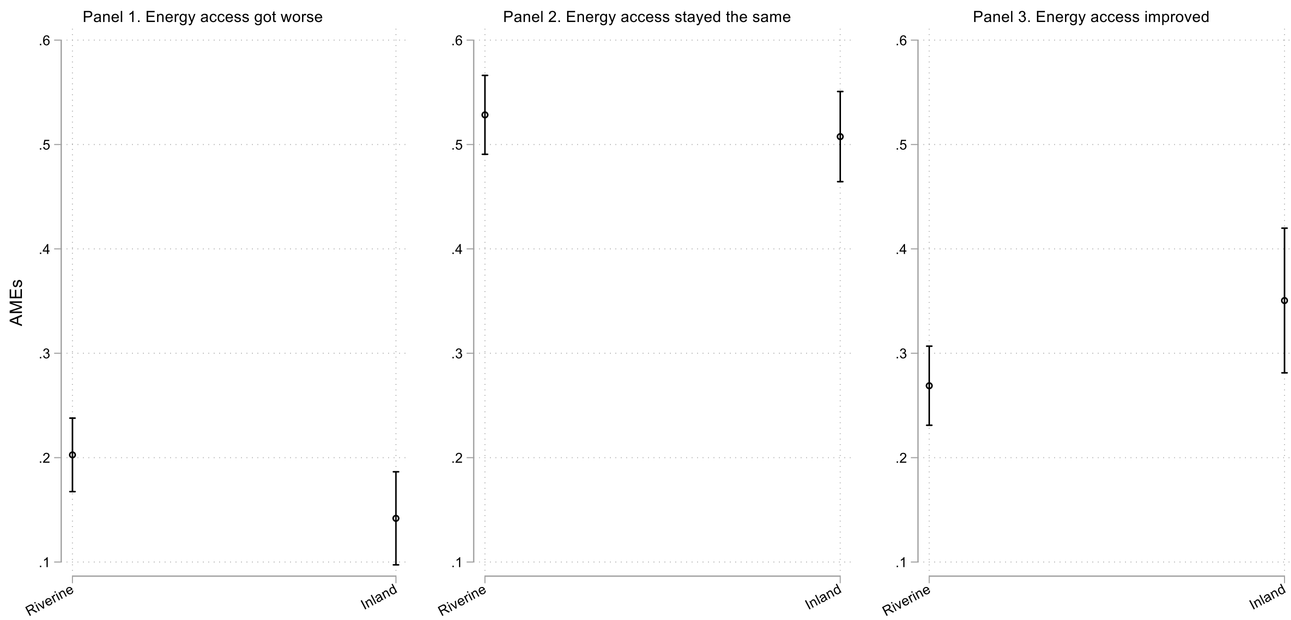

Fig. 8. AMEs for Households Reporting Changes in Energy Access According to the Community (Inland vs. Riverine) in which Households are Located.

(Table 2), suggesting that downstream, upstream, and reservoir status accounts for perceptions in energy prices better than inland vs. riverine.

4.3. Political factors explaining energy sources, access, and prices after dams

In this subsection, we address research question 3 by examiting the political factors linked to individuals reporting energy sources, improvement in energy access, and price changes following the establishment of the Jirau and Santo Antônio hydro dams. We assess three interrelated political phenomena: being resettled, compensated, or included in negotiations with dams authorities.

According to statistics from our survey, Calama and São Carlos, communities in which most of the households depended on diesel generations, were not compensated, and most did not participate in negotiations with dam authorities (See Table A1 in Appendix). Besides, households in these communities were not resettled, but their physical and social capital were impacted[5]–though dam authorities insisted that they were not negatively affected (See Table A1 in Appendix).

We also found political factors associated with reporting changes in energy access. According to Models 1 and 2, resettlement increases the odds of "improved" energy access (Table 2). The AMEs from the data of Table 2 report that households that were resettled have a probability of 0.50 to say that energy access improved, and those not resettled 0.23. In contrast, households not resettled have a 0.58 probability saying that energy access stayed the same, while those resettled only 0.32. No differences were found for energy access to get worse. Likewise, according to Fig. 9, respondents who negotiated directly with the dam builders were more likely to report that energy access had gotten better (0.46 probability in Model 1 and 0.47 in Model 2), whereas those that did not negotiate or relied upon a leader were more likely to state that energy access had stayed the same or gotten worse. Regarding the political factors explaining changes in energy prices, both Models 3 and 4, indicate that households that negotiate with dam builders through a community leader are less prone to say that energy prices decreased or stayed the same (0.9 probability) than households that did not negotiate or negotiate directly with dam builders (0.8) (Fig. 10). In any of the four models, being compensated explains energy access getting worse.

5. Discussion

We discovered that residents in communities surrounding hydroelectric dams reported no enhacements in energy prices, energy services, or access to energy post-construction, mirroring findings observed in studies on other hydroelectric dams (Aeria, 2016; Dao, 2010; Fearnside, 1999; Green and Baird, 2016; Judge, 1997; Okuku et al., 2016; Randell and Klein, 2021; Siciliano et al., 2018; Yoshida et al., 2013). Our contribution to the literature showed that some households benefit less than others, and that geography plays an important role in explaining those differences. In our case study, this distributional injustice in energy access was explained by a spatial energy injustice associated with political factors.

Households in the reservoir communities, which include resettled communities, report more benefits in energy access. They perceived that their electricity access improved, and they relied on the transmission line. It is important to note that resettled communities also suffer from environmental injustices due to dam construction, such as forced displacement and livelihoods disruption (Castro-Diaz et al., 2023). Meanwhile, households in downstream and upstream communities, which are further from the dams, are the ones reporting fewer benefits or that energy access did not change. For these households, staying the same is not an ideal situation. Those upstream and distant from the dam report that their energy access got worse, but they have access to the transmission line. According to field observations, energy access got worse largely because prices increased and the service was not always reliable. Though downstream communities are affected, dam builders usually do not recognize them as impacted and do not compensate them (Baird et al., 2021; Castro-Diaz et al., 2018; Hallwas et al., 2013; Owusu et al., 2016, 2019; Richter et al., 2010; Runde et al., 2020). Typically, only upstream communities that will be displaced are included in compensation programs, so it is not surprising that we find that upstream communities far away from the dams also experienced a loss of energy access, and that they were not compensated. In fact, upstream communities, further from the dams and on the border with Bolivia, are the ones that suffered the most in terms of energy access. This result confirms the idea that most distant communities to dams are less likely

[5] Inhabitants say that after construction, the value of their houses decreased (in Calama, 36.9% of interviewed, and 68.9% in São Carlos), as well as the frequency they met with friends and family (in Calama, 74.7 % of interviewed, and 40.4% in Sao Carlos).

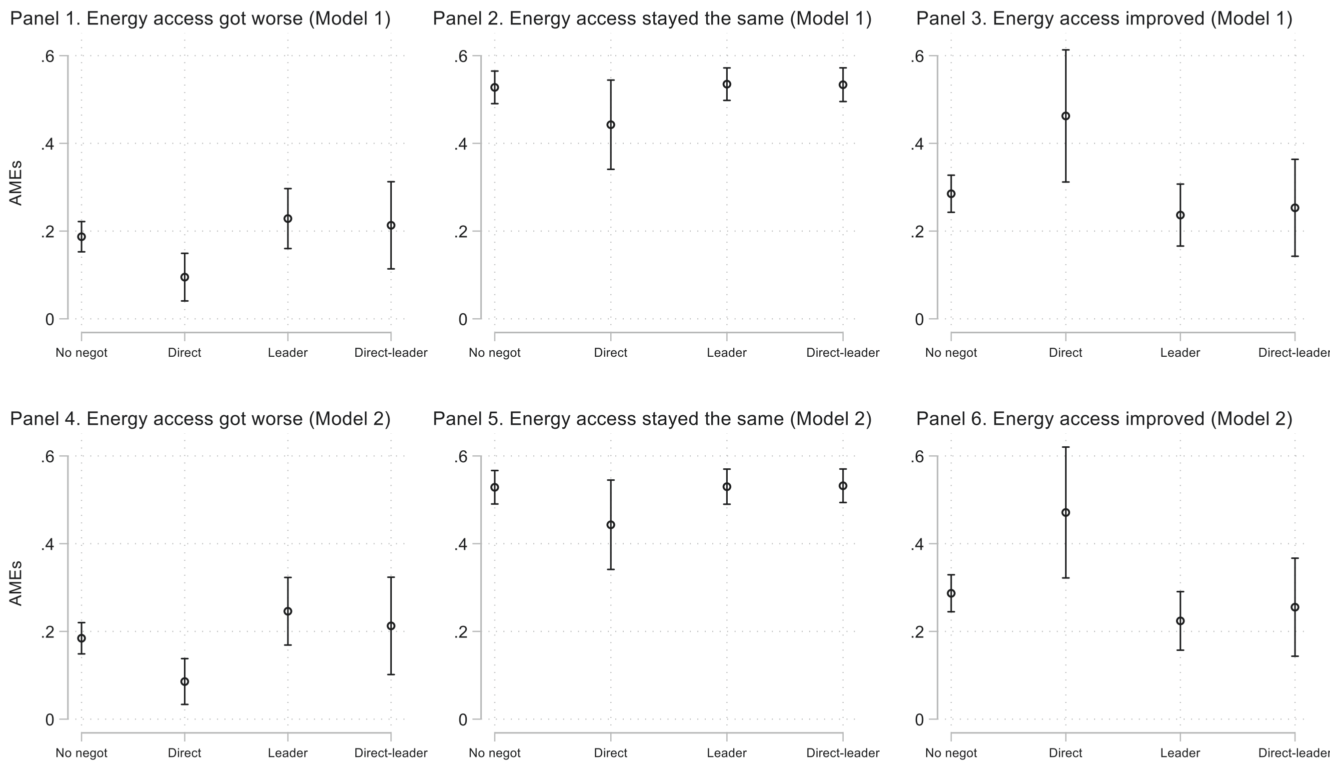

Fig. 9. AMEs for Households Reporting Changes in Energy Access by the Type of Negotiation with Dam Authorities.

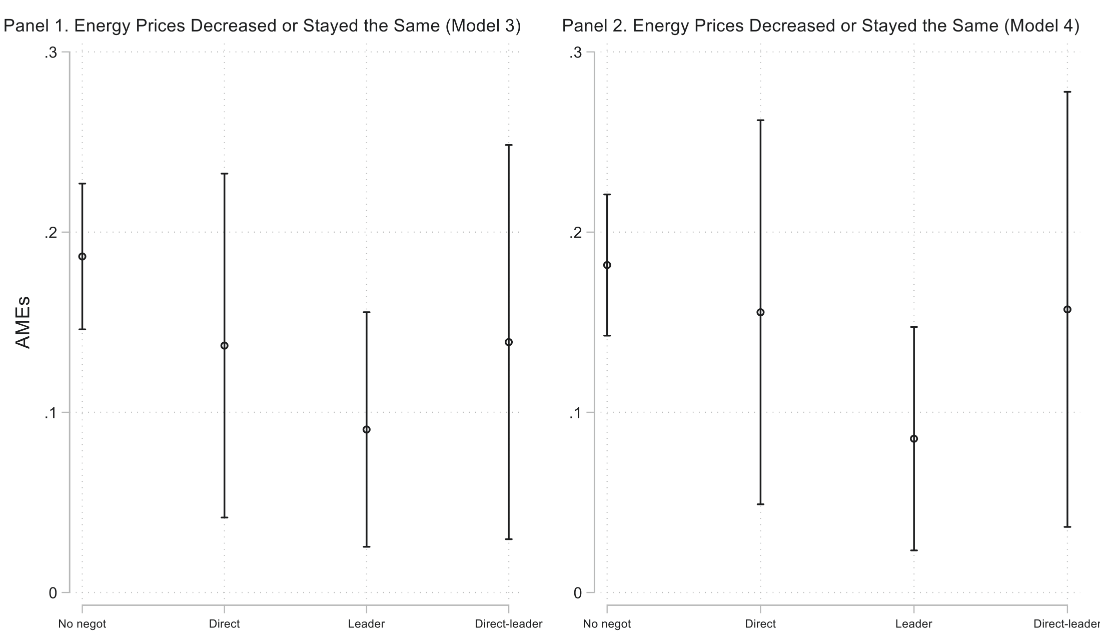

Fig. 10. AMEs for Households Reporting Changes in Energy Prices by the Type of Negotiation with Dam Authorities.

to receive the benefits, even though they are impacted (Baird et al., 2021; Santos et al., 2020), whether downstream or upstream. More research should be done to assess how far from the dams communities perceive these impacts.

Connecting riverine communities to transmission lines is more difficult due to vegetation and lack of roads. But we found that the effect of inland vs. riverine status was inconsistent, and largely driven by a single community—Nova Mutum, where dam operators reside and a community where people were resettled.

The fact that dam authorities did not recognize distant upstream and downstream communities as impacted by the construction generates distributional injustices through *spaces of misrecognition* (Bouzarovski and Simcock, 2017). Households in these distant communities are less likely to benefit from better energy access and prices. This phenomenon is intertwined with the fact that, after dams, some of the households in nearby communities still rely on diesel generators, causing *energy deprivation* due to material aspects (Bouzarovski and Simcock, 2017). In other words, these communities are deprived of access to the energy produced by the dams in their territories, or of the benefits produced by dams. Instead, dams leave these communities with the negative externalities of the construction. Despite being within the area of influence of the dams' construction, authorities view certain communities as "not impacted." The consequence is that these communities are excluded from both the Environmental Impact Assessment (EIA) and the Social Impact Assessment (SIA), receiving fewer benefits, and creating spatial energy injustices in the region. We did not find *geographic underpinnings of energy affordability* (Bouzarovski and Simcock, 2017) between households surrounding the dams since most of them said that energy prices increased.

Political factors also play a crucial role elucidating changes in energy access around the Madeira complex. People that have been resettled might expect more significant benefits from dam builders since they were moved to host or newly resettled communities in which dam builders constructed physical infrastructure (roads, schools, etc.) that they presumably did not have in their previous communities. Households in the communities of Nova Mutum and Riacho Azul exemplify our results. These communities received most of the resettled populations, and more robust investment from dam builders – including new energy infrastructure. These households were recognized by dam authorities as impacted, given their necessity to be resettled away from the construction reservoirs and other infrastructure associated with the dams.

Also, people that negotiated directly with dam builders are more likely to say that energy access improved. Our results show how people participating in the bargaining process with authorities of energy infrastructure are not only exercising a right to negotiate on a hydroelectric plant construction that will affect their lives but also are better off after the construction, at least in terms of perceiving better energy access and prices. However, it is important to note that only certain groups, in these cases people that will be resettled or impacted according to dam authorities are invited to be part of these negotiations. This result is corroborated by other research showing that hydroelectric dams usually do not generate participatory processes of decision-making with surrounding communities (García et al., 2021; Mayer, García et al., 2022). Our results also show that households that negotiated with dam builders through community leaders report no increase in energy prices. We do not have data to explain this phenomenon. But we hypothesize that negotiation through community leaders might reflect a form of collective action that gave inhabitants more power to bargain and have success with dam authorities regarding energy prices. This study reaffirms the importance of participation by affected populations.

The spatial and political factors are intertwined. For instance, households located in the communities Nova Mutum, Riacho Azul, and Vila Penha, which are in the reservoir and near the dams, were more prone to say that energy access improved or stayed the same. Households in these communities were more likely to be compensated and resettled than the others.

6. Conclusion

This study highlights that the geographical context of people's living spaces, coupled with with the extent to which a household is recognized by authorities as impacted by the dam's construction, generates a form of injustice in the distribution of benefits, at least in energy access, from the Jirau and Santo Antônio dams. The spatial energy injustices surrounding dam construction are mostly due to political reasons. Jirau and Santo Antônio dams created distributional injustices in energy access between households living in their shadow by producing spaces of misrecognition and material energy deprivation (Bouzarovski and Simcock, 2017). This result contributes to the literature on impacts of hydroelectric dams, by showing that upstream communities can also be neglected as much as downstream communities if they are distant from the dams. Besides, it contributes to the recent literature on spatial energy injustices by providing an empirical example of hydro dams in the Global South.

Our study points to several future research needs. Ideally, researchers could track the same households over several waves of data collection before, during, and after the construction of the dams—of course, this type of data is very resource intensive to gather for an adequate sample. Future research could also evaluate changes in actual energy prices, as opposed to self-reported prices as we have measured in this work. Much of the foundational literature on spatial injustice originated in the Global North, and it may be fruitful to blend these insights with concepts from decolonial thought such as internal colonialism in Latin America (see Randell and Klein, 2021; Tornel, 2022, as examples). Also, more research needs to be done on transboundary negative impacts and benefits of dams (Llamosas and Sovacool, 2021) – in this case, would be understanding energy access in communities in Bolivia that were impacted by the Jirau and Santo Antônio dams.

We conclude that large-scale hydroelectric dams are unjust (García et al., 2021; Moran et al., 2018). In our case, we show that they create distributional injustice in energy access in their shadow. For the cases of dams that were constructed, are in construction, or are planned, we recommend that spatial injustices should be considered and addressed in a direct and conscious manner. Dam builders must find ways to improve energy access and lower energy costs for households that are impacted by dams regardless of their distance to the construction site and whether they are upstream or downstream. Authorities need to include these communities in their compensation schemes or distributions of benefits despite not being resettled. Along these lines, providing more sustainable energy solutions for off-grid communities or linking them to the transmission line is critical. An off-grid solution in the area, and in which prices are decreasing constantly, is solar energy from photovoltaic panels or instream turbines (Moran et al., 2022). Offering reliable and cheaper electricity to these communities is possible and would reduce current spatial injustices.

CRediT authorship contribution statement

María Alejandra García: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Investigation. **Adam Mayer:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation. **Igor Cavallini Johansen:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Maria Claudia Lopez:** Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing, Investigation. **Emilio F. Moran:** Funding acquisition, Project administration, Supervision, Writing – review & editing, Investigation.

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.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by NSF grants #2020790 and #1639115. Igor Cavallini-Johansen is funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo (processo n° 2020/16378-6 to ICJ). We are grateful to the eight communities who participated in the social survey and answered our many questions. We also wish to thank postdocs Juliana Laffer, Amanda Silvino, and Jynessa Dutka-Gianelli, who were in charge of the field survey; Carolina Doria, Mariluce Paes, and other faculty at the Federal University of Rondonia provided immense support to our research. None of the above should be blamed for any errors, those are entirely the responsibility of the authors. The funders had no

role in study design, data collection, and analysis, decision to publish, or preparation of the manuscript.

Appendix

Table A1
Percentage of Households According to the Community and Whether They Were Resettled, Compensated, and Negotiated with Dam Authorities.

Type of community	Community name	Resettled			Compensated			Negotiation		
		No	Yes	Total	No	Yes	Total	No	Yes	Total
Upstream	Abunã	92.9	7.1	100.0	90.8	9.2	100.0	72.5	27.5	100
	Vila Penha	90.0	10.0	100.0	93.3	6.7	100.0	80.0	20.0	100
Reservoir	Vila Jirau	75.0	25.0	100.0	83.8	16.2	100.0	72.1	27.9	100
	Nova Mutum	17.8	82.2	100.0	50.7	49.3	100.0	48.0	52.0	100
	Riacho Azul	17.7	82.4	100.0	35.3	64.7	100.0	15.7	84.3	100
Downstream	Calama	97.3	2.7	100.0	99.3	0.7	100.0	88.4	11.6	100
	Cujubim Grande	91.0	9.0	100.0	96.2	3.9	100.0	74.4	25.6	100
	São Carlos	96.3	3.7	100.0	100.0	0.0	100.0	75.7	24.3	100

Table B1
Data represented in the maps 2, 3 and 4.

Community	Map 2[1] Energy source (%)		Map 3[2] Energy access (%)			Map 4[3] Energy price (%)	
	Diesel	Transmission line	Got worse	Stayed the same	Improved	Increased	Stayed the same or decreased
Abuna	0	100	47.4	36.8	15.8	83.3	16.7
Calama	87.67	12.33	12	60.7	27.3	83.9	16.1
Cujubim Grande	0	100	6.4	71.8	21.8	80	20
Nova Mutum	0	100	16.2	20.3	63.5	92	8
Riacho Azul	0	100	16	30	54	86.3	13.7
Sao Carlos	100	0	11.1	76.9	12	94.3	5.7
Vila Jirau	0	100	14.7	54.4	30.9	53.4	46.6
Vila Penha	0	100	28.1	37.5	34.4	93.3	6.7

Notes: [1]Map 2: The proportion of households reporting the type of energy source after the Santo Antônio and Jirau hydropower dams' construction, by the community.
[2]Map 3: The proportion of households reporting changes in energy access after Santo Antônio and Jirau hydropower dams' construction, by the community.
[3]Map 4: The proportion of households reporting changes in energy prices after the Santo Antônio and Jirau hydropower dams' construction, by the community.

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