Why *not* continue building hydroelectric dams in the Brazilian Amazon? Contributions to a renewable and effectively sustainable electricity matrix

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ABSTRACT

The generation of electricity through large hydroelectric projects is often regarded as a renewable source; however, its sustainability is questionable. In the Amazon, these projects pose severe threats to the ways of life of indigenous and traditional communities, as well as causing significant damage to the region's fauna and flora. Paradoxically, while local populations lack access to electricity, the eletricity production in the Amazon is primarily directed to other regions of Brazil. This article proposes a critical analysis of the construction of hydroelectric projects in the Brazilian Amazon, starting from the fundamental question: **Why *not* continue building large hydroelectric projects in the Brazilian Amazon?** Based on this, we detail the ideal scenario – that being unattainable - in which such a possibility would exist. The elements of this scenario would include: (1) Ensuring zero deforestation, (2) Providing effective compensation to directly or indirectly impacted human populations, (3) Conducting ecological restoration, (4) Considering future climate scenarios, (5) Maintaining the natural flood pulse of the river (flow regime), (6) Ensuring the autonomy of the directly or indirectly affected population to decide on the construction of a hydroelectric project, and (7) Preserving the degree of endemism of the local fauna and flora. However, an analysis of ongoing, under-construction or planned projects reveals these criteria are not fully respected and cannot be fulfilled. This renders the construction of hydroelectric projects in the Brazilian Amazon unviable. To ensure access to electricity in isolated areas of the Amazon, we recommend directing investments towards more sustainable energy sources characterized by lower social and environmental impacts through small-scale production.

Keywords: Amazon, clean energy, energy policy, social justice, environmental impacts.

Introduction

The increasing expansion of hydroelectric dams represents one of the main threats to biodiversity and the livelihoods of populations in the Amazon region, whether in urban or rural areas (Couto *et al.* 2021). The global expansion of hydroelectric projects is often seen as an alternative to fossil fuels (Almeida *et al.* 2022) and as a renewable energy source, which is supposed to contribute to tackling climate change (Fearnside 2019a). This expansion occurs mainly in countries with emerging economies, and the justification is the energy demand to guarantee their economic and social development (Zarfl *et al.* 2015). In South America, the enormous hydropower potential of the world's largest rainforest makes the Amazon basin a theoretically ideal stage for expanding new hydropower (Almeida *et al.* 2019). Although exact numbers vary (Fearnside 2019b), at least 158 dams with individual installed capacities greater than 1 MW are operating and/or under construction in the five nations that make up about 90% of the Amazon basin, and another 351 new dams are in the feasibility study phase (Flecker *et al.* 2022, see Figure 1).

The construction of large hydroelectric dams in the Brazilian Amazon has significance for transnational politics in South America, as large areas are impacted, not limited to Brazil alone, but also affecting neighboring countries (Fearnside 2019a). Governments worldwide are making decarbonization pledges, with ambitious goals for emissions reductions and carbon capture (Mountford *et al.* 2021). In this scenario, Brazil claims to have a "clean" electricity matrix as it produces about 62% of its electricity from hydropower (ANEEL 2023). This discourse fuels the belief that hydroelectric dams are the best renewable source solution, concealing the seriousness of the negative socio-environmental impacts caused by hydroelectric mega-projects (Fearnside 2013, 2017). In the Brazilian Amazon, large projects such as the Santo Antônio and Jirau dams in Rondônia and Belo Monte in Pará are emblematic examples of the significant social and environmental damage caused in the Madeira and Xingu River basins, respectively (Couto *et al.* 2021).

The impacts of hydroelectric dams on the fauna and flora's biodiversity and local populations are underestimated in the Environmental Impact Assessments (EIA) carried out in the licensing process (Fearnside 2019c). During construction, traditional peoples are displaced, local populations are destabilized, and forests are removed or flooded alive to form reservoirs, harming aquatic fauna, due to increased decomposition, methane release, and reduced oxygen and food availability (Souza Jr *et al.* 2019). For years after the installation of the hydroelectric plants, the impacts continue to occur and expand, causing deforestation in the surroundings, massive mortality of flooded forests downstream (caused by disturbances in the hydrological cycle), and consequently, increases in greenhouse gas emissions. In addition, it results in health problems for riverine people living along the large rivers, leading to resource shortages (Fearnside 2014, Lees *et al.* 2016, Resende *et al.* 2019, Schöngart *et al.* 2021, Silvano *et al.* 2005).

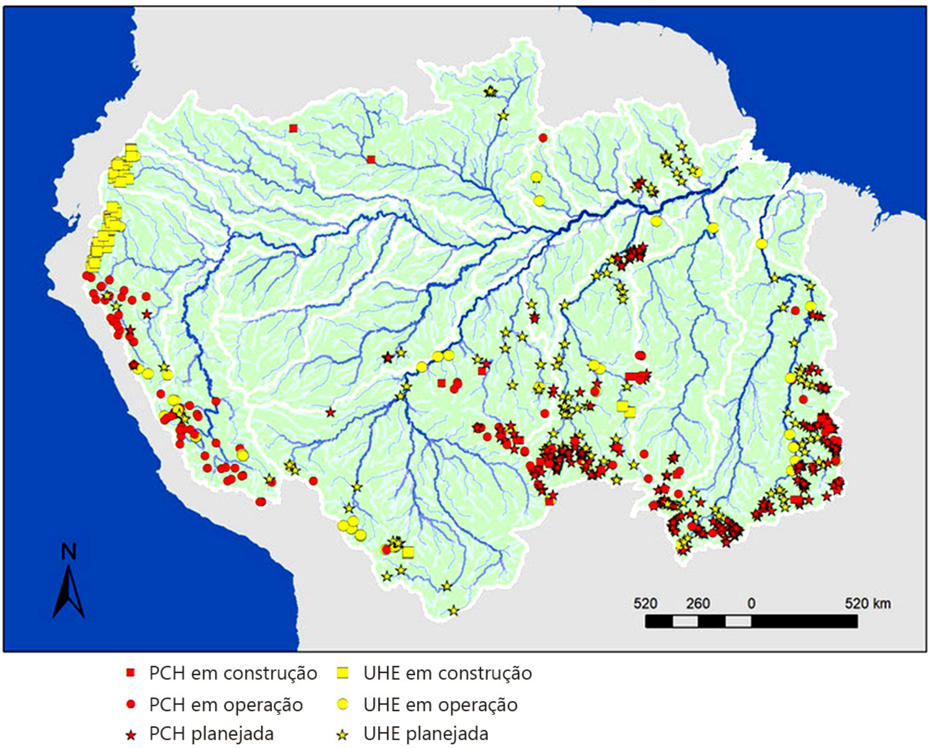

Figure 1 Illustrative map indicating hydroelectric enterprises in the Amazon Basin. Prepared by Thiago Couto. Available at: https://amazoniacienciaciudadana.org/pt/impactos-pequenas-hidreletricas/

Hydropower produced by the standard method in Brazil may be renewable, but it is far from sustainable. In order to produce energy through conventional hydroelectric plants, it is necessary to convert the mechanical energy generated by the passage of water through the turbines into electrical energy, and there must be a difference in the water level to activate the movement of the turbines (Bagher *et al.* 2015). Less impactful models, such as the “run-of-river” type installed in the Santo Antônio and Jirau hydroelectric plants and in Belo Monte, use the river current to generate energy, but precisely because they do not have large reservoirs, their electricity production is reduced during periods with low rainfall (Roberts 1995), which in parts of the Amazon can last up to seven months per year (Carvalho *et al.* 2021, Sombroek 2001). Another relevant point is that a significant part of the production of large hydroelectric plants in the Amazon is directed to other regions

The energy produced in the Amazon, and exported to other regions of the country, carries high economic, social, and environmental costs that are shifted onto the local populations, fauna, and flora (Randell & Klein 2021). At the same time, a recent survey found that Amazon has more than 990,000 people without access to electricity, with Pará being the state with the highest number of people without access to electrical energy (more than 409,000 residents) and Acre the one with the highest proportion of victims of electrical exclusion, affecting around 10% of its population (IEMA 2020). These excluded people lack the energy to carry out their daily activities, such as freezing fish or fruit pulp for their consumption or sale, studying, and accessing information via TV and/or the internet.

This white paper, produced by the working group "Free Waters" of the São Paulo School of Advanced Science Sustainable and Inclusive AMAZON (São Pedro-SP, Brazil – November 21 to December 5, 2022), analyzes the impacts of hydroelectric projects in the Amazon and elaborates an ideal scenario, never fulfilled and impossible to be achieved, for the construction of new projects, showing, in practice, why hydroelectric plants should not be built in the Brazilian Amazon. The white paper is complemented by a communication piece addressed to the Brazilian population, with crucial data and information regarding the impacts and costs involved in maintaining and constructing new large hydroelectric plants in the Brazilian Amazon.

Economic, ecological, and social impacts of large hydropower plants in the Brazilian Amazon

Hydropower is currently considered the largest source of renewable energy worldwide, playing an important role in clean, low-carbon development (Li & He 2022) and propelling development in the economy of the global power industry (Edwards 2005). This statement, however, does not comprise the whole truth since hydropower plants emit large amounts of carbon (Bertassoli Jr *et al.* 2021, Fearnside 2009), and the efficiency of energy production can be relatively low, as in the case of the Balbina hydropower plant (Fearnside 1995). Building a hydropower plant is expensive, and most developments take longer than expected. In addition, hydropower causes unquestionable negative environmental and social impacts, especially in the Amazon, given its richness and plurality of fauna, flora, and socio-cultural characteristics (Moran *et al.* 2018). This section will present the main economic, ecological, and social impacts of large hydroelectric dams in the Brazilian Amazon.

Economic impacts

The actual costs of hydropower construction are difficult to measure due to the particularity of the installation region's geology, hydrology, and associated ecosystems and social factors. However, it is given that large hydropower developments usually exceed the estimated economic costs (Ansar *et al.* 2014, Sovacool *et al.* 2014). A global hydropower construction report analyzed 245 large dams from 1934 to 2007 in 65 countries, showing that one in 10 dams cost more than three times the amount initially estimated (Ansar *et al.* 2014).

The cost of building large hydroelectric dams tends to be very high, limiting the positive return on investment, even without considering the project's socio-environmental impacts (Scudder 2006, Sovacool *et al.* 2014). For example, the Belo Monte hydroelectric plant had an initial budget of 19 million reais (Machado *et al.* 2011), however, by the year 2019, its cost had already risen 42 billion reais, with the activation of the 14th turbine of the Main Powerhouse. Belo Monte became the largest hydroelectric plant in Brazil, providing a capacity of 8,788.5 MW and becoming the largest investment project of the Brazilian government in the last two decades (Agência Brasil 2019). Due to the fluctuations in the level of the Xingu River and the installed "run-of-river" system, the capacity factor (physical guarantee or guaranteed capacity) is around 43% of the installed capacity for energy production (Almeida Prado *et al.* 2016). Therefore, the actual average production is 4,571 MW and not 11,223.1 MW (Norte Energia 2021, 2022). Only in 2019, four years after the start of Belo Monte's operation, the hydroelectric started operating with all turbines, having produced an average of 3,445.8 MW in 2020 and 2021, which corresponds to about 75% of the guaranteed capacity (Norte Energia 2021, 2022). Because of the Xingu River's seasonality, production is considerably reduced in the drier months, with Belo Monte producing an average of 431 MW in September 2021, less than 11% of the guaranteed capacity (Norte Energia 2022).

Arguments in favor of building hydroelectric dams are usually based on the country's growing demand for electricity. The national electricity demand is projected to grow by 2.2% per year until 2050 (PNE 2050). However, given the country's current economic situation, this estimate is overestimated and does not align with the projected growth. Current energy demand can be met with 48% of energy production capacity (Tolmasquim *et al.* 2021). Thus, constructing new hydroelectric plants in the Amazon with the primary justification of energy demand is misguided. The construction of hydroelectric dams and their economic viability need to be reassessed, especially considering their negative socio-environmental impacts..

Ecological impacts

Disruption of the natural flow of rivers impairs hydrological connectivity (Vannote *et al.* 1980), changing the dynamics and composition of aquatic and terrestrial communities at both local and regional levels (Fearnside 2013). In addition, this interruption of rivers results in changes in the physical, chemical, and biological characteristics of the aquatic environment and ecosystems at the terrestrial-aquatic interface in areas adjacent to hydropower plants (Fearnside 2019a). River impoundment affects environmental conditions upstream (i.e., new habitat within the reservoir) and downstream (i.e., altered water flow regime) of the dam, fragmenting longitudinal and lateral flood connectivity (Arantes *et al.* 2019). Altered hydrodynamics occur along with changes in the water chemistry of impoundment lakes, with excess river sedimentation that not only impacts hydropower production - due to loss of reservoir storage and/or damage to mechanical components of the facility - but also the environment (Fearnside 2013). Increased sedimentation upstream of hydropower dams leads to environmental effects that can persist for decades (Junk & Mello 1990). Sedimentation can culminate in turbid waters with reduced water transparency, decreasing plant productivity and negatively impacting fish and bird species (Melo *et al.* 2021).

In addition to changes in the chemical, hydrological and nutritional balance in the aquatic system and terrestrial-aquatic interface, the installation of hydroelectric plants generates Greenhouse Gas (GHG) emissions. GHGs are produced during the construction and operation of hydropower plants (Fearnside 2015). These emissions vary significantly depending on the size of the reservoir and the nature of the land flooded. Flooding causes increased vegetation decomposition and release of carbon dioxide and methane. The precise number of emissions is highly dependent on site-specific characteristics. However, GHG emissions from the water surfaces of the world's reservoirs are estimated to be 0.8 (0.5-1.2) Pg CO_2 equivalent per year, with methane (CH_4) accounting for the majority of this emission (Deemer *et al.* 2016).

Hydroelectric dams are also responsible for changes in the phenology and life cycle of tree species in flooded forests, causing massive mortality or relocation of communities downstream of the dam (Resende *et al.* 2019, 2020, Schöngart *et al.* 2021). This impact is caused by the irregular flow of water that eliminates predictability and changes the amplitude of the overflow effect of the river to the banks (flood pulse), leaving vegetation exposed to a new water condition. In addition, local populations of aquatic and terrestrial animals along the river may suffer from a reduced quality of available habitats, leading to the extinction of endemic species and changes in fauna composition (Fearnside *et al.* 2021).

For fish, the abrupt shift from lotic (river) to lentic (lake) environments with the construction of hydropower reservoirs results in adverse effects on abundance and taxonomic and functional richness (Keppeler *et al.* 2022). Hydropower construction raises the risk of extinction of endemic species that depend on maintaining local hydrological dynamics (Fitzgerald *et al.* 2018, Latrubesse *et al.* 2020, Zuanon *et al.* 2020). For example, long-migrating fish species are severely affected after the construction of hydroelectric dams, given the need for connectivity along the river to complete their life cycle, with the impoundment being a barrier that interrupts reproductive migrations (Duponchelle *et al.* 2021). Because of these processes, fish production tends to be drastically reduced after the construction of hydroelectric dams, especially of migratory species of high commercial value, which leads to a reduction in fishing income (Arantes *et al.* 2022, Lima *et al.* 2020). The impacts on fishing, therefore, also lead to harmful consequences for social dynamics, which are addressed below.

Social impacts

A series of cases analyzed by researchers, traditional peoples, and civil society organizations illustrate the severe impacts on the livelihoods of populations in regions flooded or downstream of hydroelectric dams in the Amazon region. Even if we consider only the Tucuruí, Balbina, and Belo Monte hydroelectric dams, there are notable examples of forced removal or compulsory displacement of populations, including indigenous peoples who had territories flooded or indirectly impacted by the reservoirs, in addition to severe health impacts, whether due to mosquito proliferation or mercury methylation, loss of food security and sovereignty or increased indicators of suicide and violence, especially against women (Barroso 2019, Brum & Glock 2020, Fearnside 2019a).

A series of irregularities in the licensing processes are associated with the social impacts of hydroelectric dams and the decision-making process that precedes them (Fearnside 2019c). The case of Belo Monte is again emblematic: In 2022, the Federal Supreme Court finally recognized that there was no widespread public consultation, with the necessary clarification of potential socio-environmental impacts - many of them severe and difficult to reverse - nor the necessary debate with society, as provided for in the Brazilian Constitution of 1988 and ILO Convention No. 169, to which Brazil is a signatory. In short, it is concluded that projects such as the Belo Monte hydroelectric dam are direct causes of ecocide and ethnocide (Observatório da Volta Grande do Xingu 2023).

The construction of hydroelectric power plants generates direct impacts on the quality of life of riverine populations, including health problems stemming from feelings of frustration, fear, and helplessness among those affected (Fearnside 2017, 2019a). Therefore, it is necessary to broaden health discourse and create room for interventions to be structured in order to consider those affected by hydroelectric power plants as empowered political subjects (Giongo *et al.* 2015). There is a need to incorporate and identify, within studies of impacts associated with the construction of hydroelectric power plants, the impacts on the quality of life of the affected populations (Grisotti 2016). Few research and evaluation programs longitudinally track the pre and post-installation processes of hydroelectric power plants., and there are few studies assessing health status beyond purely medical aspects, which is aggravated by the lack of official health data on affected populations (Grisotti 2016). Studies that consider assessing the impacts of hydroelectric projects on the population’s health are fundamental, as they assist in decision-making regarding project proposals that integrate health promotion and prevention of health issues. Such studies can also contribute to the development of programs and public policies focused on the health of the affected population, based on integrated models that encompass economic, political, social, and environmental aspects (Okochi & Marques 2019).

Current government guidelines and growth trends in the electricity sector

According to the National Energy Plan for 2050 (PNE-2050, 2020), Brazil bases its energy production expansion planning on four fundamental pillars: energy security, adequate return on investment, availability of access to the population, and socio-environmental criteria. Although the fourth pillar, related to socio-environmental criteria, is mentioned, its approach in the plan must include further analysis.

One of the goals set in the PNE is Brazil's transition from an energy-importing country to an energy-exporting country. However, this goal raises concerns as it may exacerbate existing disparities in access to clean energy rather than focusing on ensuring such access for isolated communities. This transition would mean a reallocation of energy produced in one location to be transferred to other countries, potentially widening energy injustice.

The plan also foresees an increase in energy efficiency, with a growing interest in the electrification of the energy matrix. In addition to electrification, the PNE establishes guidelines for decarbonization and the pursuit of low-carbon energy sources. In Brazil, there is an adherence to the global trend of adopting more sustainable renewable energy sources, driven by the decline in costs of solar and wind energy generation technologies.

However, contrary to this discourse, the plan also foresees the expansion of the hydropower sector in Brazil (PNE-2050, 2020). More than 100% increase in hydropower production is planned through the modernization and repowering of old plants and the construction of already inventoried plants. This expansion comes amid a worrying 77% overlap of inventoried hydroelectric plants with protected areas in the Amazon. The Bem Querer, Castanheira, and Tabajara power plant projects are already underway (PNE-2050, 2020), which are part of these expansion plans in the Amazon region.

Hydropower construction: an ideal scenario never fulfilled

In order to highlight why we should not continue to build hydroelectric plants in the Brazilian Amazon, we have drawn up a summary of our proposal, presented in Figure 2. These guidelines or limiting criteria show the non-viability of building new hydroelectric projects. As previously pointed out, if these criteria are never respected in practice, it is not possible to continue building new hydroelectric plants in the Brazilian Amazon. In addition, the modernization and review of projects already in operation should follow these same criteria as far as possible. Next, we suggest some alternatives for electricity generation in Brazil, especially in the Amazon.

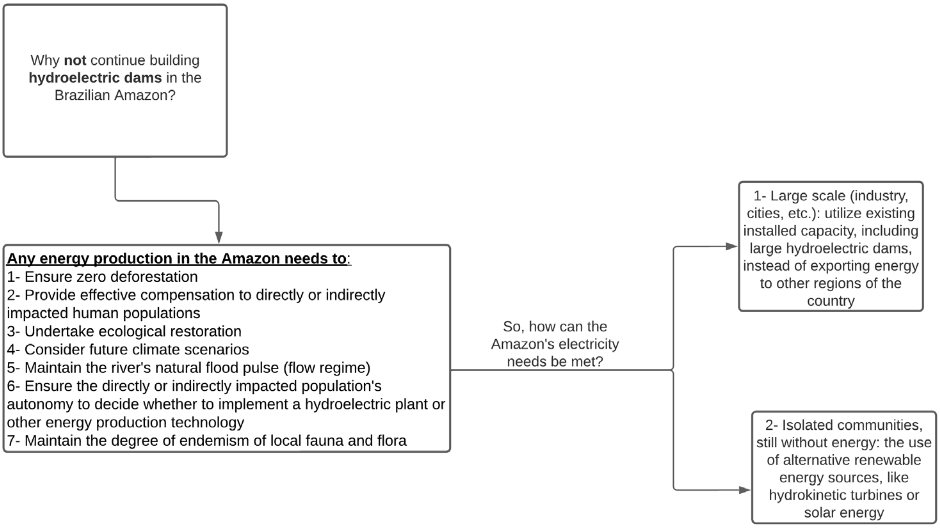

Figure 2 Why does it not make sense to continue building large hydroelectric dams in the Brazilian Amazon? Justifications and proposed intervention.

Ensure zero deforestation

Every enterprise brings environmental impacts (Barbosa Filho *et al.* 2015). Although several studies show a clear association between the construction of hydroelectric dams and increased deforestation (Barreto *et al.* 2011; Fearnside 2014, Nickerson *et al.* 2022), strategies that seek to mitigate or compensate for the loss of vegetation cover in the vicinity of hydroelectric dams are still little explored and rarely included in the planning of new projects. With this in mind, we propose the "zero deforestation" criterion, which consists of restricting any loss of native vegetation cover near hydropower plants.

As a strategy, hydroelectric projects should prioritize the creation of conservation units and indigenous lands to minimize predatory occupation around reservoirs (Silva Júnior *et al.* 2018). This criterion aligns with resolutions 10/1987 and 02/1996 of the Brazilian Environmental Council (CONAMA), which establish that licensing large environmental impact projects requires implementing a protected area in the public domain. In addition, it is essential to discourage occupation through settlements and the opening of roads, as these variables are key to increasing deforestation rates through, for example, the conversion of forests into plantation areas and cattle ranching (Fearnside 2005).

It is also suggested the establishment of methodologies for monitoring compliance with this criterion in projects already in operation. A possible methodology could be based on the definition of a radius of the impact of a hydropower plant (e.g., 120 km radius, see Resende *et al.* 2019) and the establishment of a reference forest cover (e.g., MapBiomas), based on the year in which the construction of a hydropower project is approved. In addition, a time horizon for annual monitoring should be established. In this case, an example would be: within the vicinity of a project (120 km radius), there are 30,000 km² of forest cover in the year 1989 (when construction begins); therefore, over the next 30 years, this cover should remain stable or increase, with the replacement of mature forests by young forests being unacceptable. Monitoring should be done by a reputable organization (e.g., MapBiomas).

Provide effective compensation to directly or indirectly impacted human populations

The removal of local populations occurs to make room for the construction of hydroelectric dams, either for the powerhouse (where power generation takes place), for the construction of water containment dikes or even due to the rise in the level of the river upstream, directly affecting riverside populations and urban areas on the banks of the rivers (Mayer *et al.* 2021). Population displacement is associated with significant social impacts produced by hydroelectric dams in the Amazon. This happens because the removal of populations from their original location results in these populations losing neighborhood relationships, connections with family members, and even their sources of subsistence (Mayer *et al.* 2022). Such problems are familiar and specific to the construction of hydroelectric dams in the Amazon. Studies around the world have already shown that population displacement is harmful to local populations, being associated with the loss of social capital in China (Tilt & Gerkey 2016), loss of agricultural land and livestock in northern Iran (Tajziehchi *et al.* 2013), impoverishment of the population in India (Cernea 2004) and growth of social inequalities in Vietnam (Huu 2015). It is important to note that these processes take place in developing countries, as it is in these regions that the expansion of hydroelectric construction is occurring, while developed countries have invested in harnessing their hydroelectric potential in the past and are now turning to alternative energy sources, potentially less harmful to the environment and the population (Moran *et al.* 2018).

In an ideal scenario, no infrastructure project in the Amazon could carry out compulsory population displacement. In this way, the main cause of the social impacts of hydroelectric dams in the Amazon would be extirpated. This scenario, however, does not find a basis in reality. Thus, the minimum to be guaranteed is that the local populations must consent, for the most part, to the construction of the enterprise, through effectively participatory and democratic processes and that they must be brought greater social and economic benefits than harm. Thus, local populations must be duly compensated for the impacts generated by the construction of hydroelectric plants, and such compensation must occur before the installation and effective operation starts, which was not the case, for example, of Belo Monte (Gauthier & Moran 2018).

However, there are rare studies that show some success in the process of providing compensation to local populations impacted by hydropower construction (Randell 2016). Compensation programs are often unavailable to all impacted population groups, especially downstream of dam construction (Castro--Diaz *et al.* 2018, Richter *et al.* 2010, Zhouri & Oliveira 2007). In addition, some losses resulting from hydropower construction are difficult to quantify, such as social capital, emotional ties to the site, and cultural heritage, so these are rarely included in compensation programs (Green & Baird 2016, Vanclay 2017).

As long as compensations are *pro forma,* in order to secure the installation license from the Brazilian Institute for the Environment and Natural Resources (IBAMA) and subsequently renew the operating licenses of hydropower plants, such programs will remain ineffective in terms of ensuring real and permanent improvement of life for impacted populations.

Undertake ecological restoration

Forest restoration has been promoted as the most effective solution for climate change mitigation due to the rapid storage of carbon in biomass at lower costs than available technological alternatives (Bastin *et al.* 2019, Griscom *et al.* 2017, Lewis *et al.* 2019). Restoration programs with bold goals have been established in Brazil and worldwide, in line with the decade of restoration proposed by the United Nations. The maintenance of several ecosystem services essential to the well-being of the population, such as the protection of springs and the production of forest goods, is of profound social and economic interest, and restoration is one of the main solutions for obtaining these services (Brancalion *et al.* 2019). Scaling up forest restoration brings immediate scientific and technological challenges since it has been developed as a local-scale activity, mostly planned, implemented, and monitored at the plot level (Holl 2017).

In addition to ensuring zero deforestation, hydropower projects should commit to restoring areas under their region of influence (e.g., 120 km radius), including areas that were converted before or during the project's period of operation. A maximum acceptable percentage of the area that can be restored should be established in advance. For example, every time there is an area larger than the value established by law for an alternative use area (e.g., 20% for the Amazon, since 80% must constitute the Legal Reserve and Permanent Preservation Areas in forest areas in the Legal Amazon), except in urban areas, within the radius of influence of the hydroelectric plant, ecological restoration of the original ecosystems must be carried out.

Considering future climate scenarios

Historically, most hydropower risk assessments have assumed a steady state in the variability of climate phenomena, including the frequency and magnitude of extreme events (Fluixá-Sanmartín *et al.* 2018). However, studies of hydroclimatic scenarios have been conducted, identifying the effects of hydrological changes, global warming, and deforestation on changes from mesoscale (respectively, Sorribas *et al.* 2016, Commar *et al.* 2023) to macro-scale (Arnell & Gosling 2016) and their impacts on hydropower operation (e.g., Kahaduwa & Rajapakse 2022, Men *et al.* 2019). This has raised concerns about water availability, and many investigations focus on future changes in the hydrological cycle. Such studies point to warmer and drier climate conditions, with prolonged droughts and a reduction in the amount and intensity of precipitation in several areas of the planet, including the Amazon basin (IPCC 2021).

For the Amazon, changes in rainfall distribution patterns and the intensification of seasonality are already being identified (Gloor *et al.* 2013). Such changes are pointed out in future projections, where a warmer and drier dry season and a cooler and wetter rainy season are observed in different portions of the Amazon (Baker *et al.* 2021, Duffy *et al.* 2015). One of the main consequences of climate change will be the loss of flood pulse predictability, making the variation of low and high waters increasingly imponderable (Sorribas *et al.* 2016).

Therefore, stationary climate baseline assumptions are no longer appropriate for long-term dam safety management (Kahaduwa & Rajapakse 2022). Consequently, hydropower developments must consider extreme climate scenarios and be designed for adaptation and decision support under a more resilient approach, thus avoiding large hydropower plants' failure in terms of power generation, with serious economic, environmental, and social consequences. Based on scientific studies, hydroelectric projects' climate variables that influence or can be influenced locally should be surveyed. Time horizons like those provided by future climate models should be considered.

Maintain the river's natural flood pulse (flow regime)

The combination of various factors, such as seasonal precipitation and the vast extents of different watersheds, causes the accumulation of water to be concentrated in one or more times of the year, thus characterizing the 'Flood Pulse' (Junk *et al.* 1989). In the large rivers of Central Amazonia, for example, the annual difference in level can be more than 10 meters. In large free-flowing rivers, this phenomenon is generally annual and predictable (Junk *et al.* 2011, Grill *et al.* 2019).

Changes in the natural river regime cause various direct damages to local animal and plant communities and human populations (Schöngart *et al.* 2021). Specifically, in the case of hydroelectric dams, the impoundment of rivers by power plants produces flood pulse losses and negatively affects riparian ecosystems downstream of the dam (Neves *et al.* 2019). In addition, in the operational period of dams, flooded *igapó* and *várzea* forests are strongly impacted by permanent flooding conditions at low topographic elevations. About 12% of floodplain forests are affected along a downstream river stretch of more than 125 km (Resende *et al.* 2019, Schöngart *et al.* 2021).

Thus, it is necessary to maintain the flood pulse to mitigate the impacts generated and avoid socio-environmental loss. It is possible to do so by taking into account the quantity, duration, and quality of water levels to sustain the aquatic ecosystem (Arthington *et al.* 2018). Parameters such as duration and timing of flood onset can be maintained in natural regimes without reducing energy production (Kuriqi *et al.* 2019). However, in cases comprising the detour of water from the natural channel, such as in the Volta Grande of the Xingu River, there is a need to reduce energy production due to the impacts of climate change on such hydrological parameters. Hydrological change metrics based on these parameters should assist decision-makers, ensuring the operation of the hydroelectric plant and the stability of wetland ecosystems in the Amazon basin, so fundamental for riverine and indigenous populations.

Ensure the directly or indirectly impacted population's autonomy to decide whether to implement a hydroelectric plant or other energy production technology

The decision-making process for constructing hydroelectric dams in the Brazilian Amazon faces serious problems. According to Fearnside (2019b, p. 79),

> [...] the actual decision on whether or not to build a dam is made by a few people in government long before environmental studies

> are prepared, public hearings are held, and the environmental agency analyzes the information gathered. Because they are made before information on impacts is gathered, political decisions ignore many social and environmental consequences, and the licensing process becomes a mere bureaucratic step to legalize decisions already made.

That said, the decision-making process for the construction of hydroelectric dams must be reformulated. The autonomy of the population directly or indirectly impacted by the project must be respected. At the same time, it is necessary to promote a broader debate about the socio-environmental costs of hydroelectric plants so that the population can access qualified information.

To deal with this problem, we have two proposals. The first concerns the creation of a Permanent Forum on Energy Transition, made up of representatives of civil society and the public authorities, with functions of interdepartmental debate and dissemination to non-specialist audiences regarding hydroelectric plants and, more broadly, alternative sources. This forum would align with the proposals of Ministers Anielle Franco, Marina Silva, and Sônia Guajajara (Ministries of Racial Equality, Environment and Climate Change, and Indigenous Peoples, respectively). They emphasize that issues such as inequality, hunger, climate change, and racism - part of the problems surrounding hydroelectric dams in the Amazon - require transversal treatment, uniting different portfolios of public power and civil society (Vick 2023).

The second proposition includes the importance of adopting binding legal mechanisms that guarantee the population's autonomy, directly and indirectly impacting the decision to build hydroelectric dams in the Amazon. We highlight the need to recognize and adopt community/autonomous protocols for consultation and prior, free, and informed consent. These are documents provided for by Convention 169 of the International Labour Organization (ILO) and prepared by indigenous, *quilombola*, and traditional peoples that establish the rules for the procedure of prior, free, informed, and good faith consultation, in a manner that respects cultural specificities, their legal systems, forms of social organization and collective deliberation (Observatory of Community Protocols 2023; see also Marés *et al.* 2019). In addition to adopting those that already exist, we suggest allocating public resources so that new community protocols can be created. In cases with no such protocols, we emphasize the importance of the Federal Government conducting free, prior, and informed consultation processes in effective compliance with the Federal Constitution and ILO Convention 169.

Maintain the degree of endemism of local fauna and flora

The choice of the site for the construction of hydroelectric plants is fundamental for the preservation and conservation of endemic species (flora and fauna) due to the biodiversity and peculiarities of each region (Nunes-Gutjahr & Braga 2015, Ziober & Zanirato 2014). The physical and biological changes caused by the construction and implementation of dams can cause permanent damage to habitats and biodiversity (Wu *et al.* 2019), as they put at risk of extinction endemic species whose occurrence is limited to the area of direct influence of the project. It is known that the extinction of a single species in a given location causes an imbalance in the ecosystem since the species that retain an ecological relationship with it are affected and, consequently, extinct (Choueri 2013).

Thus, it is necessary to identify areas with endemic species, conduct flora and fauna inventories and species distribution models (Park *et al.* 2003), and consult peer-reviewed scientific papers. Finally, protected areas should be created to ensure species conservation, where they occur, and to reduce biodiversity loss. Regulatory bodies should require constant monitoring and reporting on the performance of endemic species populations.

Feasibility of the proposal: Alternatives to large dams for electricity generation in (and for) the Amazon

Considering the restrictive criteria outlined and developed in this paper, it is unlikely that new large hydroelectric dams would be built in the Amazon region. Therefore, in this section, we point out existing technological alternatives for electricity production in the Amazon, prioritizing the benefit of its residents.

First, we assume it makes no sense to maintain internal colonialism, based on which the Amazon exports most of the electricity it produces to other regions of the country (Randell & Klein 2021). Around 26% of the total national electricity is produced in the Amazon region of Brazil, mainly through hydropower; at the same time, the region consumes only 8% of the national electricity (EPE 2022, Schutze *et al.* 2022). Thus, it is assumed that the region already has enough electricity production to develop (on a sustainable basis, but we will not delve into this discussion) over the next decades for cities, large urban centers, and other areas connected to the power grid. However, about 1 million people are still without electricity in the Amazon (IEMA 2020), comprising especially isolated populations not connected to the grid, either by distance or by the environmental impact that the extension of the grid to them will bring (deforestation, for example). For such populations, technological alternatives already exist, but they lack public policies to become economically viable.

One of the most promising technologies, which has been improved for the Amazonian context, is small in-stream turbines for hydrokinetic energy generation. Such equipment, installed in rivers, enables energy production from the current itself without damaging the river flow or any deviation from its course. In addition, fishes can pass through the turbine propellers without being harmed. Finally, by not building dams, the connectivity and navigability of rivers are maintained, so crucial for connecting local populations. This technology is constantly being improved, is the focus of scientific studies, and has already been working in several places worldwide (Built *et al.* 2015, Mendes *et al.* 2020, Van Zwieten *et al.* 2015, Zhou & Deng 2017). Obviously, Amazonian rivers have specificities. Therefore, studies developed to adapt the technology to the characteristics of these rivers must be considered (Els & Junior 2015, Moran *et al.* 2022b). In this direction, a recent survey pointed out that 63% of the total energy planned to be generated by conventional hydroelectric plants in the Brazilian Amazon could be produced using turbines in the riverbed itself, using the kinetic energy of water as a source and without requiring dams (Chaudhari *et al.* 2021).

There are other promising sources for decentralized power generation in the Brazilian Amazon. Solar photovoltaics, currently the second largest energy source in Brazil (Canal Energia 2023), is also the basis of public policy in the Amazon to provide energy to isolated communities through the *Mais Luz Para a Amazônia* Program (Brazil 2022). Another potential to be explored in the Amazon, on a small scale, is the generation of energy from biomass. This source can be linked to bioeconomy activities, i.e., producing products with raw materials from the region to generate work and income for the local population from the valorization of the standing forest. The states of Amapá, Amazonas, Rondônia, and Roraima together can generate enough biogas to serve 107,000 households, which means about 429,000 people (Instituto Escolhas 2020).

Considering the diversity of potential energy sources in the Brazilian Amazon, we suggest that localized strategies for electricity production in the region be developed, based on the level of demand and, above all, the local environmental specifics that favor the use of certain technology over others. It is also worth mentioning that energy generation can be carried out in a combined way, that is, from hybrid systems, mixing different sources of production that enhance each other. As an example, a recent study pointed out the feasibility of using in-stream hydrokinetic turbines in conjunction with solar photovoltaic panels to produce electricity for isolated communities in the Brazilian Amazon, highlighting the importance of social sciences and engineering working together to develop effective and sustainable systems, appropriate to the local reality (Brown *et al.* 2022).

Conclusion

We are convinced that the restrictions proposed here can assist decision-makers in deeply reflecting on the inherent impacts of building hydroelectric dams in the Amazon and encourage them to prevent new hydroelectric developments in the region. We also hope they can use this framework to reevaluate the dams already constructed, with the aim of minimizing the damage already caused. It is likely that interested companies will argue that following the proposed restrictions is unfeasible, underscoring the impossibility of approving new construction requests. Therefore, our work points to the infeasibility of building new hydroelectric dams in the Amazon without causing harm to the environment and local communities, in line with what Fearnside *et al*. (2021) have indicated.

The increase in energy consumption and greenhouse gas emissions is often associated with the growth of wealth indicators, such as Gross Domestic Product (GDP). However, this correlation has been disassociated in many countries, including the United States and the United Kingdom. Brazil can also reduce its emissions, even with a rising GDP. To do so, it needs to reconsider the fallacy of "clean" energy produced by large hydroelectric plants since these, in addition to harmful social effects, also have evident and well-documented environmental impacts, including the growth of carbon dioxide and methane emissions. Furthermore, ideally, electricity generation should be close to the consumer market, avoiding not only energy losses and transmission expenses but primarily promoting environmental justice, as all energy generation causes externalities that should be shared, especially among those who benefit from them. Alternatives to large hydroelectric plants exist, but to become competitive, they need to be the focus of public policies centered on the well-being of the national population and the preservation of the country's environmental heritage.

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ANEXX I

Infographic aimed at the general population, containing key data and information about the impacts and costs associated with the construction and maintenance of hydroelectric dams in the Amazon.

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