Implications of climate change impacts for the Brazilian energy mix

Implicações dos impactos das mudanças climáticas na matriz elétrica brasileira

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ABSTRACT
Hydropower generation is responsible for supplying most of the electricity in Brazil. Like other renewable sources, water is highly sensitive to meteorological variables, so that climate change may have a considerable impact on it. Therefore, this study aims at assessing climate change impacts on hydropower generation and their consequences for the Brazilian electricity system. Scenario data for specific average global warming levels of 2°C and 4°C from Eta_HadGEM2-ES and Eta_MIROC5 downscaled climate models are used. Outcomes indicate that the electricity system's adaptive capacity to lower hydropower generation includes a growing share of other renewable and natural gas fired thermoelectric generation, increasing the system's marginal cost to meet projected demand in 2030. Greenhouse gas emissions are projected to increase in a 2°C scenario, but to decrease in scenarios in which warming reaches 4°C.

Keywords: Climate Change Impact. Adaptation. Hydropower generation. Hydropower generation system. Brazil.

RESUMO
A geração hidrelétrica é responsável por ofertar a maior parte da eletricidade no Brasil. Tal como outras renováveis, a fonte hídrica tem alta sensibilidade a variáveis meteorológicas, de maneira que mudanças climáticas podem impactá-la consideravelmente. Portanto, este estudo pretende analisar impactos das mudanças climáticas na geração hidrelétrica e suas consequências para o sistema elétrico brasileiro. São utilizados dados de cenários de níveis específicos de aquecimento médio global de 2°C e 4°C, provenientes dos modelos climáticos regionalizados Eta_HadGEM2-ES e Eta_MIROC5. Os resultados indicam que a adaptação do sistema elétrico ante a redução da disponibilidade hídrica inclui maior penetração de outras fontes renováveis e termelétricas a gás natural, gerando um aumento no custo marginal do sistema para atendimento da demanda em 2030. Quanto às emissões de gases de efeito estufa, projeta-se um aumento nos cenários de níveis de aquecimento de 2°C, mas uma redução nos cenários em que o aquecimento atinge 4°C.

Palavras-chave: Mudanças climáticas. Impacto. Adaptação. Geração hidrelétrica. Sistema de geração elétrica. Brasil.

1 INTRODUCTION

The Brazilian energy mix is mostly renewable, with most of the electric power generated in the country coming from hydropower plants (HPPs). Power from wind and biomass energy have also been increasing, contributing to keep the energy mix mostly renewable (MEM/EPE, 2017). In 2019, renewable energy sources accounted for 83% of domestic electricity supply (EPE, 2020). Therefore, Brazil's power generation and transmission system may be defined as a large hydro-thermal-wind system, with predominance of HPPs. Power transmission is carried out by the Brazilian Interconnected System (SIN in the Portuguese acronym), a grid consisting of four subsystems: South, Southeast/Center-West, Northeast and most of the Northern region. Interconnection of power systems through the transmission grid enables energy transfer between subsystems, allowing for synergistic gains and exploring the diversity of the Brazilian river basins' hydrological regimes (ONS, 2018).

Renewable energy sources are directly impacted by climate variables. This makes its supply more vulnerable to climate change than that of fossil resources (LUCENA *et al*., 2009, SCHAEFFER *et al*., 2012). Hydropower power, in particular, is impacted by changes in precipitation patterns and air temperature, which affect evapotranspiration processes in river basins, runoff, sediment transport and evaporation of reservoirs (DE SOUZA DIAS *et al.*, 2018). This can potentially reduce the inflow to run-of-river plants, thus inducing a decrease in their active volume and, consequently, stored energy. In addition, hydropower generation is vulnerable to extreme events, such as long droughts, and this represents a considerable risk to the country's energy security (LUCENA *et al*., 2009; SCHAEFFER *et al*., 2010 and 2015).

Schaeffer *et al*. (2010) and Lucena *et al*. (2009) projected a decrease in power generation as a consequence of lower flow inputs into basins at the regional level, mainly in the Northern and Northeastern regions. Lucena *et al*. (2009) estimated that firm energy would drop by around 3% in the assessed scenarios, albeit with significant regional impacts, while Schaeffer *et al*. (2010) calculated that firm energy could suffer a 30% drop. De Queiroz *et al.* (2019) pointed to an increase in firm energy in plants located in Southern region, but a reduction in most plants in other subsystems, showing projections of a significant drop in firm energy with the start of operations planned by 2030 in almost all simulated periods.

At a regional scope, De Jong *et al*. (2018) projected an up to 35% drop in HPP generation in the São Francisco basin. Arias *et al*. (2020) assessed climate change effects in the network of existing and planned reservoirs in the Tapajós River basin, which together make up about 50% of the potential for hydropower expansion inventoried in Brazil. Outcomes indicate a possible increase in disparities between seasonal electricity supply and peak demand, which may decrease hydropower generation during the dry season by 5.4% and 7.4%.

In addition to a quantitative impact on generation and an increased risk of energy supply deficit, changes in the use of renewable resources caused by climate change might impact the description of the energy mix, thus leading to a different energy balance than previously projected (DE QUEIROZ *et al*., 2016). In the SIN, the diversity of the energy mix makes it possible to offset climate impacts in power generation among the different energy sources, for example, between renewable and thermoelectric plants using fossil fuels and even among renewable sources. It provides the electrical system with an intrinsic adaptive capacity, so-called Adaptive Capacity (BRASIL, 2016).

HPP capacity to deal with changes in flow variations or changes in seasonal rainfall is associated with the water storage capacity in their reservoirs (SCHAEFFER *et al*., 2012). The greater the water storage volume, the more apt the system is to deal with climate variability (VICUNA *et al.,* 2007). However, given the increasing environmental restrictions for the construction of plants with large reservoirs, it is expected that future use of the Brazilian remaining hydropower potential is increasingly based on run-of-river plants, with small reservoirs. Therefore, the system's ability to offset climate variations by increasing storage might drop, making it more vulnerable to climate change.

Another determining element for Adaptive Capacity is complementarity between energy resources integrated in the SIN. The SIN must meet the expected load at the lowest cost, in other words, minimizing the use of thermal generation, avoiding curtailment and equalizing, to the extent possible, the marginal operating costs among interconnected regions (TOLMASQUIM, 2016).

Adaptive capacity may be achieved both from the geographic perspective and the different sources of energy available. From the geographic perspective, the SIN's operational management is influenced by the rainfall regime in the different hydrographic regions. Because these regions have different wet and dry periods, they complement each other, as the energy generated in a water-abundant region may be redirected to drier regions at a given period. This, besides increasing energy security, decreases the system's operating cost.

From the perspective of managing different energy sources in the SIN, in recent years there has been a solid growth in the number of wind farms, mainly in the Northeastern and Southern regions. Thermal power plants (TPPs), usually located near the load centers, play a strategic role as they contribute to the SIN's safety, being dispatched according to the current hydrological conditions, allowing for stored water stocks to be managed in HPPs reservoirs, thus ensuring future supply (ONS, 2018, TOLMASQUIM, 2016). However, TPP dispatch increases generation costs due to fuel prices, such natural gas and coal (EPE, 2017, 2018, 2019). In addition, fossil-based TPPs increase the Brazilian energy system's greenhouse gas emissions (GHG) (EPE, 2017, 2018, 2019 e LUCENA et al., 2018).

Coal or nuclear-fired TPPs meet the base load, that is, their supply is relatively constant throughout the day all year round. Coal-fired plants have a low variable cost; however, GHG emissions are very high. On the other hand, nuclear power plants do not directly emit GHG, but the investment is very high. Diesel and fuel oil-fired TPPs meet peak load, sporadic operations to balance the system and/or isolated systems. These power plants have very high investment cost, variable costs and emissions. Combined-cycle natural-gas-fired power plants are mostly used to meet base load, while flexible open cycle plants for meeting peak load. Natural-gas-fired power plants have varying costs and average levels of emissions when compared to other fossil-fuel-fired technologies.

Lucena *et al*. (2018) assessed the electricity sector's adaptation strategies to climate change impacts in hydropower generation. The impacts were projected by the *Global Water Availability Model* (GWAM), using the results of 16 climate models under two different radiative forcing scenarios. Outcomes indicate that climate change impacts may be offset by a broad range of alternative electricity generation sources depending on the level of mitigation effort. Mitigation efforts could result in a more diversified, less carbon-intensive mix of technology options for adaptation. Moreover, climate change impacts would lead to even higher emissions in the absence of mitigation policies. On the other hand, strategies towards lower emissions are still adopted under climate impact scenarios, which shows their strength against adaptation challenges. Thus, when considering the investment costs to adapt to climate change impacts, in some cases, mitigation might lead to a lower level of total investment.

Usually, the methodological approach to climate change impact and adaptation studies is based on scenario-specific model results for future emissions and radiative forcing. Despite the scientific validity of such approach, there is a need for more direct information on the effects at specific levels of global temperature increase, mainly for the formulation of public policies (ARNELL *et al*., 2019). Moreover, it is relevant for policy makers the use of models that are adopted by governmental energy planning bodies. This ensures that the deviations from official plans are associated with changes in climate variables, rather than with differing methods and modeling assumptions.

Therefore, this study aims at assessing climate change impacts on hydropower generation and their consequences for the Brazilian power system. To this end, hydropower generation resulting from changes in water supply in Brazil are assessed under specific warming level (SWL) scenarios by the Investment Decision Model (henceforth referred to as MDI, as in the Portuguese acronym). MDI is a power sector expansion model used in the Ten-Year Energy Plan by the Energy Research Company (EPE, in the Portuguese acronym). An assessment and discussion of the Brazilian electricity system's adaptive capacity is made, taking into consideration the system's marginal costs to meet the demand under climate change scenarios and the variation in greenhouse gas emissions.

2 METHODOLOGY

The indication of alteration in hydropower supply starts from the evaluation of runoff variation under *specific warming levels* scenarios (SWLs) of 2°C (SWL2) and 4°C (SWL4) in relation to historic simulated values, projected from the results of the Eta-HadGEM2-ES and Eta-MIROC5 downscaled climate models. This runoff variation is then used to estimate the impact on affluent natural energy (henceforth referred to as ENA, as in the Portuguese acronym) and the respective consequences on an energy mix projected for 2030. Both processes are carried out by MDI. Therefore, it is possible to assess climate impacts on ENA, installed capacity and electricity generation, as well as on marginal costs and GHG emissions for the proposed scenarios. Results are assessed against the Baseline Scenario (not affected by climate change). Figure 1 presents a simplified flowchart of the proposed methodology.

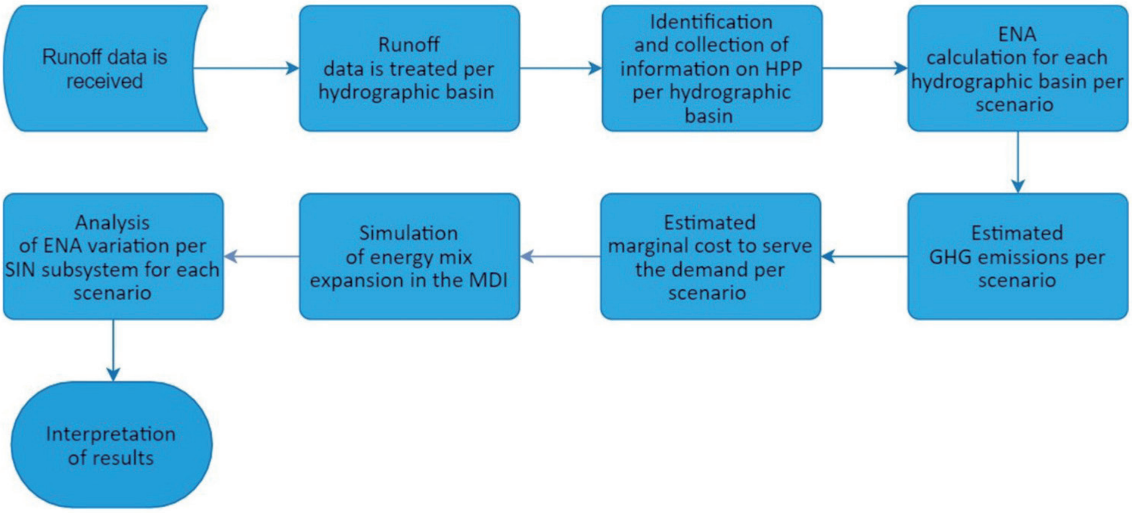

Figure 1 | Methodology flowchart for the assessment of climate change impacts on hydropower supply and energy mix

Source: Own elaboration.

Runoff variation, modeled by RIBEIRO *et al*., 2016, was projected for 23 basins (Annex I) on a daily time scale. The Eta-HadGEM2-ES and the Eta-MIROC5 models have two important databases, one with a simulation of historic runoff information and the other with projections for each warming level.

Both information are reviewed and verified by observing the alignment of the seasonality trend of the simulated runoff for each simulated historic period (*simulated h.*) of each climate model. After verifying that both climate models present similar seasonal behavior for each hydrographic basin, monthly averages and annual averages for each scenario were calculated. The monthly averages calculated for each hydrographic basin are used to calculate the relative variation of each warming level in relation to the simulated historic period, as per equation (1), below:

$$(Relative\ variation\ factor = \frac{Q_{scenario\ SWL\ x} - Q_{simulated\ h\ x}}{Q_{simulated\ h.\ x}} \quad (1)$$

Where:

$Q_{scenario\ SWL\ x}$ = Average runoff from hydrographic basin *x* from a given warming level scenario - SWL

$Q_{simulated\ h.\ x}$ = Average runoff from hydrographic basin *x* simulated historic period

For runoff data to be translated into ENA, first operational and under construction HPPs (with installed power greater than 30 MW) must be located geographically (Annex I). This is made from a snapshot of hydrographic basin/SIN subsystem, through a geoprocessing software. This allows for (i) an assessment of HPP location by each basin/SIN, (ii) identification of the most relevant basins in terms of installed capacity and (iii) the use of an “adjustment factor”, which allows incorporating runoff projections into the historic inflow time series for each HPP in the SIN.

Hence, the observed historic data for inflow to each HPP is identified (*observed h.*). This factor is a monthly percentage value between the *observed.h* and the other scenarios obtained by projected runoff data for each SWL scenario. Thus, the inflow to each HPP is considered to vary according to the projected flow data for the hydrographic basin to which it belongs for a given month, as per equation (2).

$$Q_{usina\ y,i} = \frac{Q_{SWL,i,y}}{\overline{Q}_{h.simulado,i}}\ x\ \overline{Q}_{h.observado\ ,i} \qquad (2)$$

Where:

$Q_{power\ plant\ y,i}$ = HPP natural inflow at year *y*, month *i* (m^3/s)

$\overline{Q}_{SWL,i,y}$ = Average basin runoff *x* month *i* in SWL2 and SWL4 scenarios (m^3/s)

$\overline{Q}_{SWL,i,y}$ = Average basin runoff *x* month *i* in SWL2 and SWL4 scenarios (m^3/s)

$\overline{Q}_{observed\ h.,i}$ = Observed historic inflow of each HPP (m^3/s)

Inflow series for projected SWL scenarios are used as MDI inputs. MDI is an optimization model proposed by Gandelman (2015) and used in the Ten-Year Energy Plan by the Energy Research Company (EPE, 2017a and EPE, 2017b to 2019), to determine the expansion of the Brazilian electricity system. It considers a portfolio of sources and generation projects, with their fixed and variable costs, as well as their monthly generation expectation and contribution for peak demand. It uses a number of hydrological series to find an expansion portfolio that is optimal in the stochastic sense.

MDI calculates hydropower generation variation in the SIN, represented by ENA (MWmed), according to the climate change impacts projected in the different scenarios. ENA is the energy generated from the sum of the natural inflow (minus curtailment) to each plant times their average productivity. Thus, it represents the power that can be generated by an HPP. ENA variation leads to changes in the installed capacity in the expansion of power supply. Based on these changes, it is possible to assess how climate change impacts on hydropower generation can affect the energy mix expansion, the variation in the system's marginal cost and the variations in GHG emissions for each scenario.

The Baseline Scenario expansion plan considers the cost, the location of power plans per subsystem, seasonal generation, reliability of each energy source and the investments costs for new generation plants per type of technology (GANDELMAN, 2015 e EPE, 2017b). The expansion cost is composed by the investment cost plus operation and maintenance costs (Table 1).

Levelized costs of energy (LCOE), which provide a normalization between fixed and variable energy generation costs, are also presented. Wind and solar sources have particularly competitive LCOE and wide supply availability, but their intermittence prevents MDI from seeking an expansion based only on these sources, due to a restriction that guarantees meeting peak demand (energy security restriction).

Table 1 | Technical and economic parameters considered for the expansion of the electricity complex

	Investment cost US$/kW	Variable cost (US$/MWh)	Fixed cost O&M(US$/kW/year)	LCOE (US$/MWh)	Average capacity factor (annual)	Emission factor (tCO2eq/MWh)
HYDROPOWER PLANT	1143 to 6811		66 to 141	68.49	0.25 to 0.89	
NATURAL GAS – OPEN CYCLE	700.00	95.43	41.43	193.54	dispatchable*	0.2125
NATURAL GAS – COMBINED CYCLE	1,000.00	137.17	32.22	147.86	dispatchable*	0.2125
COAL	2,761.75	30.69	107.40	103.14	dispatchable*	0.3529
NUCLEAR	5,000.00	7.85	98.20	65.69	dispatchable*	
BIOMASS	1,227.45		39.89	35.19	0.33	
ON-SHORE WINDFARM	1,626.37		42.96	35.44	0.40	
SOLAR - PV	1,300.00		30.69	43.73	0.5	
DIESEL OIL**						0.2915

Note: Costs in dollar, 1 U$ = BRL 3.26

* Will depend on the hydrological scenario

** The model does not consider it as an expansion alternative

Source: Own elaboration based on EPE data (2017b) and KREY et al (2014) and SIMS et al (2007).

Electricity demand is the average of electrical loads requested for the electric power system by the consuming systems. Thus, the optimal solution for each scenario must meet a 92.194 MWmed demand in 2029. The assumptions and restrictions adopted by the modeling exercise are: (i) Sugarcane biomass expansion is limited to a maximum of 500 MW/year from 2021, forest biomass expansion is limited to 100 MW/year from 2023 due to limitations of raw material supply, and limitations to the expansion of the agricultural frontier; (ii) there is no restriction on the expansion of wind and solar plants, as occurs in the Ten-Year Energy Expansion Plan 2026 (EPE, 2017); (iii) peak demand load is restricted by capacity credits (intermittent sources have lower contribution, and must be offset by other sources, such as TPPs, to keep the system secure); (iv) the power contribution of HPPs is estimated from ENA calculated herein; (v) new coal-fired TPPs can only be installed from 2029 onwards, as per (EPE, 2017) – the government underlines the outcomes of this source, such as job generation and energy security, in order to justify supply (EPE, 2019), therefore, this assumption was kept so that the results are directly comparable; (vi) Indication of a uniform expansion (whose amount was optimized by MDI) of wind supply between the Northeastern and Southern regions as of 2021, with 80% 80% allocated in the Northeast and 20% in the South, as proposed by (EPE, 2017).

Finally, greenhouse gas emission was represented by accounting for equivalent carbon dioxide ($CO2_{eq}$). The IPCC provides the guidelines for measuring GHG inventories per sector (IPCC, 2006 e 2019). For the energy sector, IPCC (2006) determines emission factors for each fuel in kg GEE/TJ based on Lower Heating Value (LHV). In order to determine the energy sector's emission factors, it is necessary to have information on the quantity of fuel consumed by each generation unit (MWh, for example), per technology. The quantity of fuel must be converted from its original units into energy units. For this conversion, LHV is used, as this parameter corresponds to the heat exchange processes that effectively occur during combustion, since, in practice, the processes are carried out at constant pressure and water is released as vapor (LICKS and PIRES, 2010). Emission factors for fossil fuel energy sources, in tCO2eq/MWh, are obtained from IPCC reports (KREY et al., 2014 and SIMS et al., 2007). The reports gather emission factors from a number of studies, per energy generation technology. Thus, the figures chosen herein are reference figures, aiming at assessing response variation of the MDI expansion model against climate impacts on hydropower generation and the Brazilian energy mix.

3. RESULTS

3.1 RUNOFF

After assessing runoff seasonality, simulated in baseline scenarios for each basin, it was determined that Eta-HadGEM2-ES and Eta-MIROC5 climate models have an analogous monthly seasonality. However, all in all, Eta-HadGEM2-ES presents greater runoff reduction values than those obtained by Eta-MIROC5, mainly in the Southern and Southeastern regions, where the results vary above 20% between the two models.

SWL2 scenarios show an upward trend in runoff in the Southern region, except for the South Atlantic and Uruguay basins. For the other basins assessed, climate models show negative results. Basins in the Northern and Northeastern regions show greater runoff decrease, such as the ones in the Tocantins, Araguaia, Parnaíba, São Francisco, East Atlantic and Doce Rivers, which together account for 28% of the country's total HPP installed capacity.

In the Southeastern region, Paraná is SIN's most important basin, both in terms of installed capacity (35.4% of the country's total hydropower installed capacity), as in terms of energy demand, as it encompasses Brazil's most populated areas. Hence, reduction of water availability in this region, in addition to undermining hydropower generation can also increase conflicts caused by the different uses of water in the basin. In this basin, the Eta-HadGEM2-ES SWL2 scenario indicates a runoff reduction between 20% and 40%. On the other hand, the Eta-MIROC5 SWL2 scenario shows a small runoff increment (by 20%).

However, for this warming level, due to seasonal complementary characteristics between the Southern and Southeastern/Center West and Northern regions, it is likely that a reduction in runoff in the Northern and Northeastern regions are offset by an increase in the Southern region.

In the SWL4 scenarios, runoff results presented more critical reductions than those in SWL2 scenarios in both climate models for all basins assessed, except for South Atlantic and Uruguay basin, where even higher runoff values were obtained compared to SWL2 scenarios. The Paraná basin also shows the same increase pattern as that of the Eta-MIROC5 SWL2 scenario. However, although there is still the seasonal runoff complementarity among the country's regions, the presence of more extreme values indicates longer periods of lower runoff, which can compromise reservoir energy storage capacity.

3.2 AFFLUENT NATURAL ENERGY (ENA)

The Baseline Scenario shows that the largest contribution to total ENA (43%) is in the Southeast/Center-West (SE/CO) subsystem, followed by the Southern (S) subsystem with 28%, Northern (N) subsystem with 17% and Northeastern (NE) subsystem with 12%. SIN analyses show that the ENA for each SWL scenario, when compared to the baseline scenario, indicates a possible decrease in hydropower generation for all warming scenarios, with the Eta-HadGEM2-ES model showing the greatest impacts, with a reduction ranging from 27% to 41%. The Eta-MIROC5 model shows reductions in hydropower generation between 6% and 10%. This result indicates that in both climate models all warming levels would force the SIN to adapt expanding and changing the energy mix.

A detailed analysis by warming level scenario shows the distribution of impacts in ENA per subsystem for each downscaled model. Results are shown in Figure 2. The Eta-HadGEM2-ES model shows that the NE subsystem is the one with the greatest ENA reduction: 42% (SWL2) and 56% (SWL4). On the other hand, the S subsystem is the one with the lower reduction potential, with variations of -16% (SWL2) and -25% (SWL4).

In the Eta-MIROC5 model, the two warming levels show the S subsystem with an ENA increase of 13% (SWL2) and 23% (SWL4). This is justified because in this region are the river basins with positive impacts due to the increase in runoff as the warming level increases. On the other hand, the N, NE and SE/CO subsystems indicate an ENA reduction by 40% e 2,5% respectively, for the SWL4 scenario.

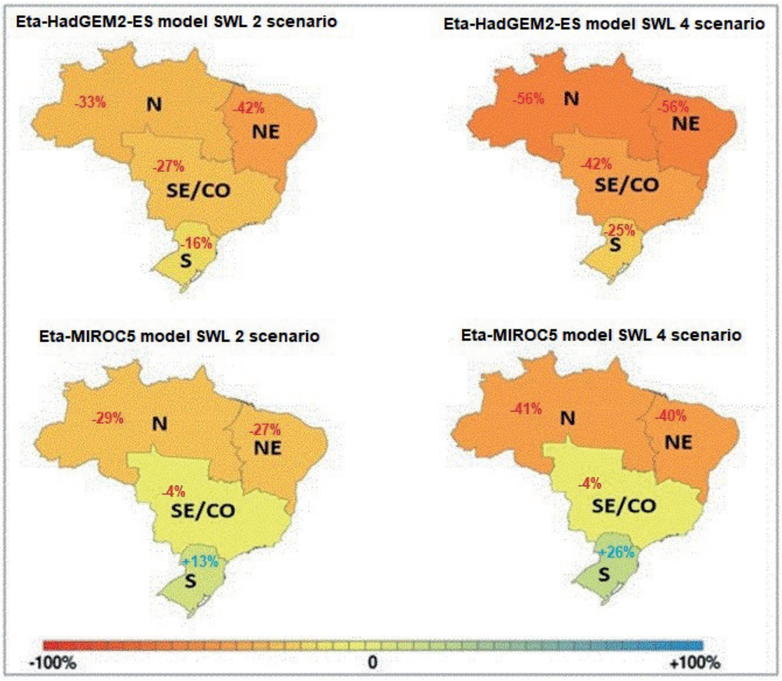

Figure 2 | Variation of ENA of each warming scenario relative to the Base Scenario.

Source: own elaboration

3.3 INSTALLED CAPACITY

Total capacity is projected to reach 224 GW in 2030 in the Base Scenario. Additional capacity reaches 94 GW, of which about 30% comes from wind power, 17.7% from coal, 17.3% from natural gas, 12.6% from biomass, 12% from hydropower and 10.7% from solar energy.

MDI results for installed capacity expansion consider the assumptions described in Section 2 for the baseline scenario and scenarios with climate impacts. The climate scenarios simulation in MDI shows that the HPPs share in the sector's expansion decreases significantly when compared to the Baseline Scenario in 2030 (Figure 3).

In the most impacted scenario, Eta-HadGEM2-ES SWL4, HPP contribution is only 1.3% of the projected additional capacity in the Baseline Scenario in 2030. The Eta-HadGEM2-ES SWL2 scenario expands the hydropower sector only by an additional 2.4% than projected in the Baseline Scenario. In the case of

Eta-MIROC5 SWL4 and Eta-MIROC5 SWL2 scenarios, the impact of climate change would mean that the hydropower sector can only expand 12.2% of the expected capacity in the Baseline Scenario in 2030.

The fall in the hydropower sector's installed capacity means that the expansion of the electric system has a different mix than the one presented in the Baseline Scenario. According to the Eta-HadGEM2-ES model, solar energy share in the expansion reached 31% and 34.9%, while wind power share reached 42.1% and 41.9% for warming levels at 2°C and 4°C, respectively. In addition, natural-gas-fired TPPs have increased their share by 9.7% and 11.4% in the SWL2 and SWL4 scenarios, probably due to a drop in biomass share (from 7.2% to 4.6%) together with lower ENA values. Coal-fired HPPs have the same expansion schedule as projected in the Baseline Scenario.

In the Eta-MIROC5 model, wind power was also the renewable source with the highest additional installed capacity at both warming levels (33.2% and 42% for SWL2 and SWL4). For its part, solar energy's share dropped by just over half, from 22.1% to 10.5% in the SWL2 and SWL4 scenarios, which was offset by the increase in coal-fired plants, which rose from 4.6 % to 14.1% of the total capacity to be contracted. Biomass share varied on average 1.5% in relation to the Baseline Scenario, largely due to the restriction in relation to agricultural frontier expansion for sugarcane biomass.

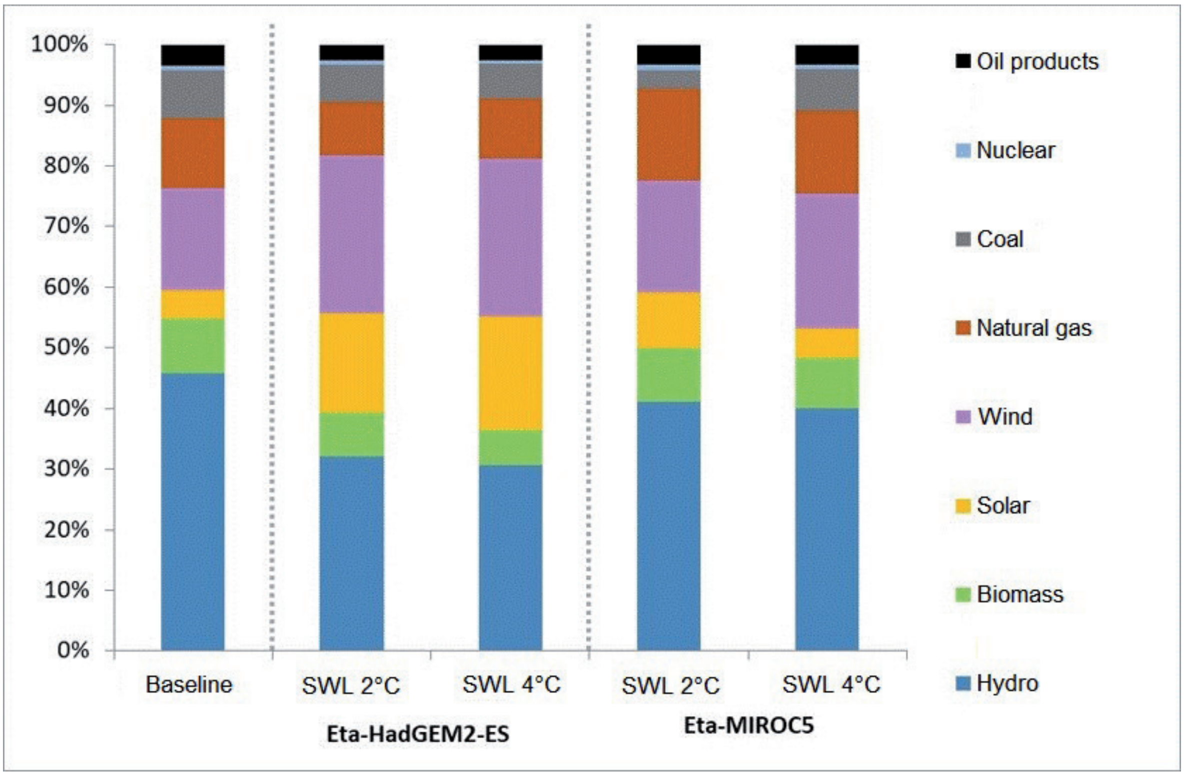

Figure 3 | Energy mix expansion in 2030. Baseline Scenario and specific warming levels (SWL) at 2°C and 4°C, Eta-HadGEM2-ES and Eta-MIROC5 climate models.

Source: Own elaboration.

3.4 ELETRICITY GENERATION

The generation profile in 2030 alters significantly among the proposed scenarios. This difference is due to the electric system projected by MDI for each scenario. Scenarios with climate impacts present a greater insertion of intermittent renewable sources (on-shore wind and photovoltaic solar energies), which leads the system to have greater supply than demand in some months of 2030, raising the average annual generation in MWmed (Figure 4).

Adaptation of the SIN to climate impact on hydropower generation means replacing energy loss with other technologies to meet the demand. MDI seeks the optimal solution to adapt to hydropower reduction considering the subsystem where the reduction occurred, the limits and transmission costs (operation and expansion) and the location of energy availability.

The Eta-HadGEM2-ES SWL4 scenario is the impacted the most in term of hydropower supply, having the greatest negative impact on the SE/CO subsystem, which concentrates the largest amount of ENA. SIN adapts by seeking the lower costs, mainly in *on-shore* wind and photovoltaic solar energies. Thermoelectric generation based on natural-gas and biomass dropped by 17% and 2% in relation to what was projected for 2030, respectively. coal-fired TPPs, in turn, have a small growth of 1%.

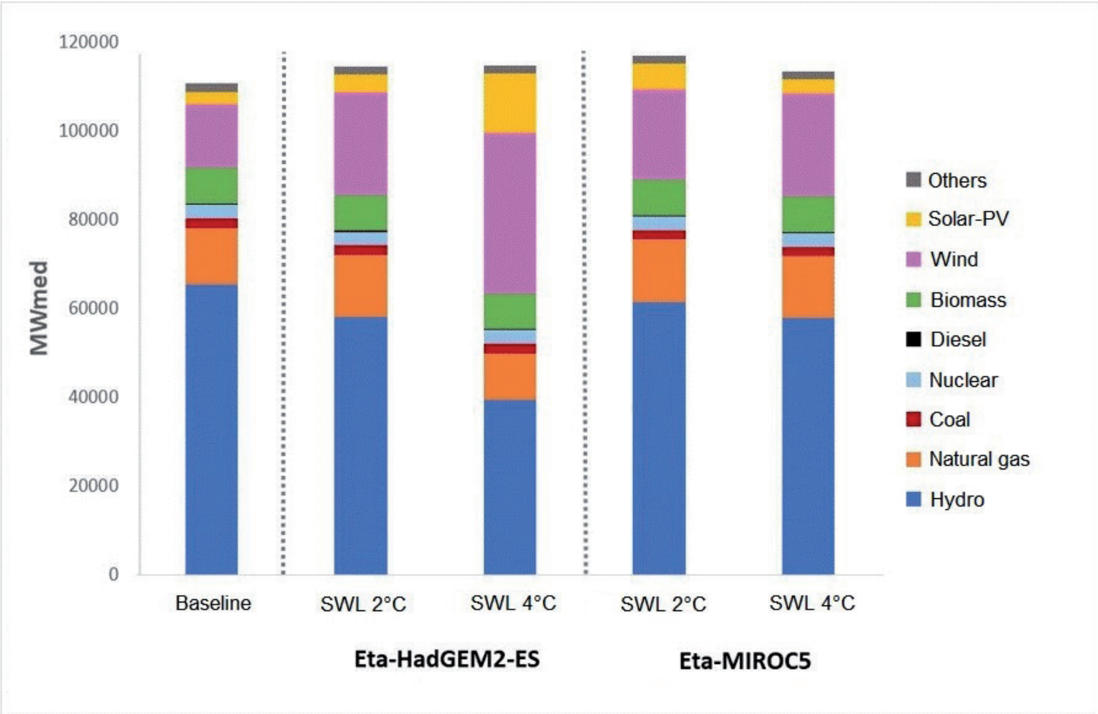

Figure 4 | Electricity generation for Baseline Scenario and specific warming levels (SWL) at 2°C and 4°C, Eta-HadGEM2-ES and Eta-MIROC5 climate models.

Source: Own elaboration.

The Eta-MIROC5 SWL4 scenarios is the second most affected in terms of hydropower generation, followed by Eta-HadGEM2-ES SWL2 and Eta-MIROC5 SWL2. In the four scenarios presenting climate impacts, MDI opts for a larger wind and solar generation, as well as a lower proportion of natural gas generation. In these scenarios, there is a slight drop in coal-fired generation and no variation in biomass, nuclear and diesel-fired TPPs.

3.5 MARGINAL COST OF ENERGY AND GREENHOUSE GAS EMISSIONS

Figure 5 shows the marginal expansion cost and the relative increase in CO_2 emissions for each scenario. The marginal cost of expansion, in R$/MWh, shows the cost of meeting additional energy demand. This cost increases rapidly with increased demand. Somehow, a drop in hydropower generation in climate change scenarios is perceived by the MDI as similar to an increase in net demand, since this energy will have to be supplied by the expansion of the generating system.

The marginal cost of expansion considers expansion and operation costs. The higher the system's net demand, the higher this cost tends to be. Among the different scenarios tested, cost for each power generation source is the same, with ENA being different. Therefore, marginal costs are directly linked to this reduction, since the model needs to invest in new power plants to offset energy loss, in addition to increase operation of the thermoelectric system.

Thus, in SWL4 scenarios, where ENA showed greater reductions, costs are higher. In addition, the greater share of renewable sources in the Eta-HadGEM2-ES SWL4 scenario is due to the high marginal cost, mainly that of solar energy. Therefore, a higher marginal cost indicates a decrease in cheaper generation alternatives, making more expensive sources and generation projects possible.

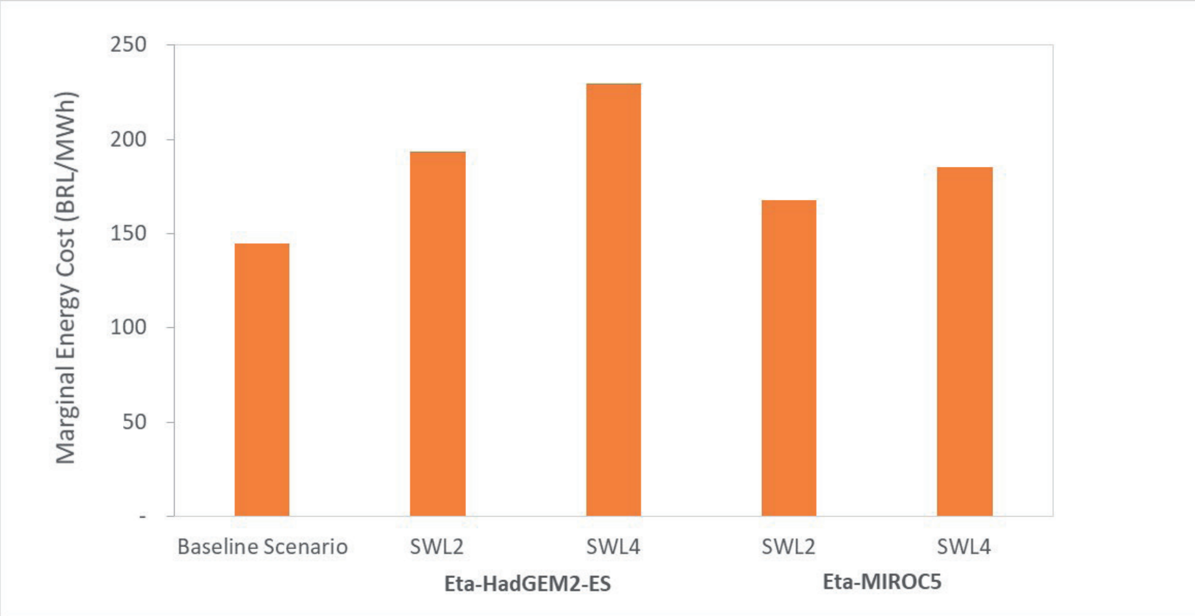

Figure 5 | Energy mix marginal cost per scenario for Eta-HadGEM2-ES and Eta-MIROC5 climate models

Source: Own elaboration.

In relation to GHG emissions, the significant input of intermittent renewable energy, in order to offset hydropower loss, leads to a reduction in emissions in the most impacted scenarios, namely Eta-MIROC5 SWL4 and Eta-HadGEM2-ES SWL4, the latter showing a much more significant reduction in GHG emissions (-12%). In the SWL2 climate scenarios, despite showing other renewable sources replacing hydropower, estimated emissions are higher than in the Baseline Scenario, due to a greater proportion of TPPs dispatch and natural gas. Table 2 shows the percentage variation of GHG emissions in comparison to the Baseline Scenario in 2030.

Table 2 - Relative variation of GHG emissions from the expansion of the energy mix for SWL2 and SWL4 warming levels for Eta-HadGEM2-ES and Eta-MIROC5 climate models.

	Eta-HadGEM2-ES		*Eta-MIROC5*	
	SWL2	*SWL4*	*SWL2*	*SWL4*
GHG EMISSIONS VARIATION (%)	6.46	-12.36	4.52	-0.93

Source: Own elaboration.

4 DISCUSSION

Studies usually assess climate impacts and vulnerability of energy sources individually (e.g. the potential of hydropower, wind and solar energies) (MCTI, 2016 e RUFATTO-FERREIRA et al., 2016). The originality of this study involves an analysis of the impact on the energy mix, in the face of climate change scenarios, not only in the potential, but also in the hydropower generation, through the MDI model, used in the official Brazilian planning. Moreover, the ENA modeling considers the location of power plants per SIN subsystems, which represents an improvement in projections per basins. In addition, this study assesses downscaled climate model scenarios, whose spatial resolution encompasses a greater degree of detail of the climate variables analyzed. Results combined with information on the variation of marginal costs to meet total demand and GHG emissions from the electricity system provide new data for a better analysis of the sector's future planning, considering its vulnerability against climate changes, which is increasingly evident in the country.

The climate scenarios used consider 2°C and 4°C increase in global average temperature. The Eta-HadGEM2-ES downscaled climate model shows a greater negative impact than the Eta-MIROC5 model on hydrographic basins runoff and, as a consequence, a greater impact on Brazilian ENA and hydropower generation. Even though the degree of impact varies across climate models and scenarios, the results are consistent in identifying that the SE/CO subsystem would experience a reduction in the ENA potential. This is the most relevant subsystem, as it has the largest reservoir storage capacity and the country's largest demand. On the other hand, the SE/CO subsystem imports energy from other subsystems, mainly the S subsystem, whose impact is slightly negative at Eta-HadGEM2-ES and positive at Eta-MIROC5).

SIN's adaptive capacity may offset part of the negative impacts in the system's generation. A drop in hydropower generation is offset mainly by natural gas, wind and solar power. Results of both the base scenario and climate impact consider expansion with assumptions that seek to contribute to the reduction of GHG emissions, as explained in Section 2. This is an indication that mitigation strategies to reduce emissions are robust against climate change impact shocks, thus contributing to the sector's adaptation challenges. These results are coherent with those by LUCENA et. al. (2018).

The greater TPP dispatch in the face of climate change implies an increase in the marginal cost to meet the net demand for electricity. Using TPPs is necessary to offset an increased insertion of intermittent renewable sources, which need an associated supply guarantee (meeting the maximum energy demand). For this purpose, open-cycle natural-gas-fired TPPs are added to the system, as their technical and economic characteristics provide them with the operational flexibility capable of offsetting the intermittence of renewable sources. Another aspect is the seasonal increase in electricity demand, which is no longer met due to the loss in hydropower generation. This seasonal generation, especially during dryer months, is well modulated by the expansion of flexible thermal systems, that is, those whose operator can choose to dispatch or not. These power plants, which are expected to generate energy not only to cope with intermittence, are combined-cycle natural-gas-fired TPPs, which have a higher fixed cost, but have a lower variable cost when compared to open-cycle TPPs, leading to a thermal alternative with lower cost per MW/h.

Variations in GHG emission in the climate scenarios compared to the Baseline Scenarios for 2030 are coherent with the generation mix shown in Figure 4. The electric system's adaptive capacity seeks an optimum generation cost, taking into account the choice of technologies that contribute to GHG mitigation.

In an intermediate climate change scenario (SWL2), the electrical system still considers a greater share of natural-gas-fired TPPs in the expansion, in comparison to renewable energy sources, mainly to offset the reductions in hydropower generation and, therefore, the increase in GHG emissions in SWL2 scenarios. On the other hand, in a more severe scenario (SWL4), emissions might drop by 12% due to a greater share of renewable sources in the energy mix. It should be noted that GHG emissions in the Eta-HadGEM2-ES SWL2 scenario are higher than in the Eta-MIROC-5 SWL2. Even though the impact on hydropower generation is greater in the first scenario, the MDI opts for a greater share of open-cycle natural-gas-fired TPPs, whose emission factor is higher than combined-cycle TPPs.

5 FINAL CONSIDERATIONS

An power system planning aims at identifying and meeting projected future energy needs. These Plans support decision-making in expansion projections. For that purpose, it is necessary to conduct studies on future climate scenarios, whose results may be considered in management instruments, as is the case of the Ten-Year Energy Plan.

The climate scenarios used consider a 2°C and a 4°C increase in global average temperature. These scenarios are used to simulate impacts on the runoff in hydrographic basins and, consequently, on the ENA and on hydropower generation, thus changing the Brazilian electric system generation mix. These results are based on the assumption that changes in the potential and hydropower generation for SWL2 and SWL4 scenarios would already be acting on system expansion since the first year of the planning horizon (2021), although warming from 2ºC to 4ºC should be gradual over time.

Still, the results presented herein show, within a ten-year horizon, what impacts climate change may cause to the Brazilian electricity system and the potential to change the course provided for in EPE's Ten-Year Energy Plans. Climate change impacts on hydropower generation has not been explicitly considered so far in the Ten-Year Energy Expansion Plan. These impacts imply a new optimum configuration of the generating complex in order to offset hydropower generation losses, leading to very different power generation profiles.

The MDI, by abiding by the 2026 Ten-Year Energy Expansion Plan, takes into account restrictions assumptions in the expansion of coal and oil-based thermoelectric generation, leaving the model free to seek an optimal solution for the expansion of other sources, such as wind, solar, nuclear and natural gas. It is understood that part of the restrictions contributes to the energy sector's mitigation efforts to comply with the Brazilian NDC. In the scenario where the impact is greater, the modeling tends to a greater share of renewable sources. This is beneficial for GHG emissions. However, the final marginal cost to meet the demand is higher.

The modeling was performed with the 2026 Ten-Year Energy Expansion Plan economic reference data. The 2029 Ten-Year Energy Expansion Plan (EPE, 2020) indicates lower investment cost values for renewable energies, which induces the likelihood of greater expansion of these sources in future climate change impact scenarios and less GHG emissions. It is noteworthy that studies carried out for Brazil indicate the probability of climate change not impacting negatively wind power (LUCENA et al., 2010, PEREIRA et al., 2013, by JONG et al., 2019) and solar power (SIMIONI & SCHAEFFER, 2019 and SANTOS, 2020). It is suggested that, in the future, studies conduct a more integrated assessment, considering impacts on hydropower generation and also on other renewable sources vulnerable to climate change, such as wind and solar power.

Finally, this study reinforces the need for an integrated planning, in which Plans, in addition to considering GHG mitigation measures, also include likely climate-change-related impacts and vulnerabilities, thus strengthening the electricity system's resilience and adaptive capacity at the lowest possible cost.

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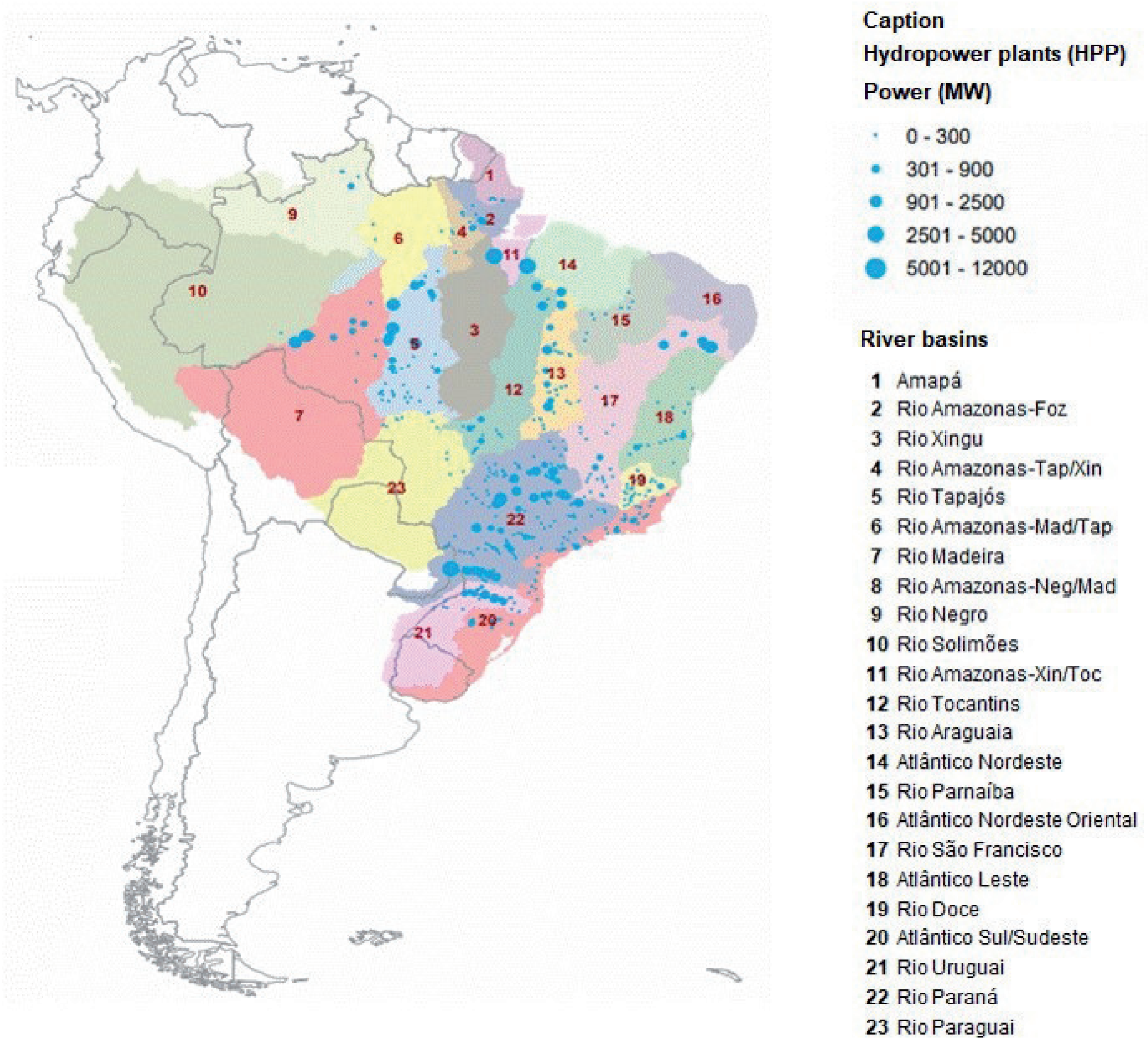
Annex

Annex I: Map of HPP and major river basins



Source: Own elaboration, based in RIBEIRO et al (2016) e (ANEEL, 2019)

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