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Designing a Brazilian energy system model for studying energy planning at high spatial and temporal resolution

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ABSTRACT

Hydropower has historically dominated Brazil's power system, leaving the country's energy supply vulnerable to extreme hydrological variations. Brazil will embrace an energy system that integrates more solar and wind resources to diversify its energy mix and further mitigate carbon emissions.

To explore this, we present PyPSA-Brazil, a novel model based on publicly accessible data and the PyPSA modelling framework. The modelling of the cost-optimal system incorporates a simplified grid with one node per federal state to optimize the operation and expansion of generation, storage, and transmission for all hours of the year. To demonstrate PyPSA-Brazil, a case study that depicts the limits on transmission grid expansion is exemplarily evaluated. Expanding today's lines by 175% could help Brazil to achieve a zero-emissions energy system, but this may require additional flexible capacity beyond the existing and planned hydro and biomass power plants. Further investment is particularly needed to expand the transmission between the new renewable energy production centres in the north-east and south of Brazil and the consumption hotspots in the south-east.

Keywords: Brazil, power system, large-scale renewable power integration, transmission network, open source

NONMENCLATURE

iNDC	Intended Nationally Determined
	Contribution
PyPSA	Python for Power System Analysis
PV	solar photovoltaic
ONS	National System Operator
AC	alternating current
HVDC	high-voltage direct current

1. INTRODUCTION

Despite the fact that Brazil is among the world leaders in the use of renewable energy (BP 2020), most of its renewable energy originates from hydropower. However, new construction or expansion of large-scale facilities is difficult since the most untapped hydropower potential is in the Amazon region, where exploitation has proved challenging due to the sensitivity of social and environmental outcomes (Soito and Vasconcelos Freitas 2011). With the rapid growth in power consumption, concerns about the security of electricity supply in Brazil have been further intensified (MME/EPE 2020). As wind and solar are the renewable energy sources with the greatest potential for expansion, a paradigm shift is taking place in the Brazilian energy sector to complete the Intended Nationally Determined Contribution (iNDC) target pledged in (Brazil 2015). Thus, the future Brazilian energy system should be able to regulate the extreme peaks and valleys associated with electricity generation from wind and solar resources, and use technologies alternative to hydropower, e.g., enhanced power transmission, battery storage, or backup generators. In order to avoid a sharp increase in electricity prices, new transmission lines and storage have to be carefully planned. For this purpose, a model with sufficiently detailed resolution is necessary (Pfenninger et al. 2018).

On a temporal scale, several studies, such as (Dranka and Ferreira 2018), (Gils et al. 2017) and (Barbosa et al. 2016), have begun to investigate both short-term and long-term energy planning in Brazil on an hourly basis. At the spatial scale, these studies examined only the predefined transmission between regions. Therefore, the benefits of interstate cooperation and the bottlenecks in the interstate grid cannot be analysed.

To effectively address energy planning studies for Brazil, novel requirements have been placed on the

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models. For instance, open source models have become increasingly popular as they ensure a high degree of transparency. (Prina et al. 2020) suggested that such models should be readily integrated with other sectors and easily extended to energy carriers other than electricity. None of the prior studies have kept up with this ongoing trend in the choice of modelling framework, whether it is EnergyPLAN (Dranka and Ferreira 2018), REMix (Gils et al. 2017), or the 100% renewable energy power system (Barbosa et al. 2016). PyPSA (Brown et al. 2018) is a well-established modelling framework that has been used to analyse various scenarios in Europe (Hörsch et al. 2018), South Africa (Hörsch and Calitz 2017), and China (Liu et al. 2019). This work therefore extends the modelling framework to Brazil.

To exemplify the model, we perform a scenario analysis focusing on the transmission line extension under an ambitious CO2 reduction target. Similar to the work done for Europe (Schlachtberger et al. 2017), a joint optimization of generation and transmission is conducted, experimentally restricting the expansion of transmission capacity from the current value to infinity.

2. MODEL AND DATA

In this case study, the Brazilian power system in 2050 is deployed using the PyPSA framework, which optimizes short-term dispatch and long-term investments with a linear optimization approach. Intermediate steps of accumulation from today to 2050 are not analysed. A partial greenfield approach is chosen, whereby the auctioned (operating, constructing or not yet started up) hydro and biomass power plants, as well as the current grid topology are considered.

2.1 Optimization problem

The model runs at an hourly resolution for a full year. The power system in 2020 is regarded as the starting point for optimization. All inputs hence pertain to this year, except for the power feed-in profiles for renewable energy, empirically based on meteorological data of 2005. The model consists of 27 nodes, representing the 26 federal states and the federal district of Brasília. These nodes are connected according to today's grid topology.

The objective is to minimise system costs, including the annualised capital costs of expanding generation, transmission and storage capacities, and the operational costs of dispatch (Brown et al. 2018). In modelling the physical process, linear eligibility is assumed.

2.2 Generation

The dispatch of thermal power plants is assumed in this case study to operate at a high degree of flexibility, i.e., no ramp-up, ramp-down, start-up or shut-down costs. The output of wind and solar generators is further constrained by the renewable resources, which are dependent on local weather conditions. The maximum electricity that can be produced per hour is a product of the geographic maximum installable capacity and the time series of unit capacity, as provided by EnDAT (Scholz 2012), a global resource assessment tool, with 2005 MERRA-2' historical weather reanalysis data. In Brazil, solar potential is fairly evenly distributed across the country, with PV generation being quite stable and less volatile. In contrast, the best wind energy potential is concentrated in the northeast and south of the country.

By 2020, Brazil has 171.2 GW of installed capacity, including 9.2 GW of oil thermal, 3.6 GW of coal thermal, 14.0 GW of natural gas thermal, 1.99 GW of nuclear, 15.3 GW of biomass thermal, 15.5 GW of onshore wind, 2.5 GW of PV, as well as 103.0 GW of large, 5.3 GW of small and 0.8 GW of mini hydropower (ANEEL 2021). In the 100% carbon reduction scenario introduced below, onshore wind and PV plants are assumed to be fully deployed by 2050, while for biomass thermal plant expansion, today's installed capacity is presumed to be the lower bound and auction capacity the upper bound.

2.3 Load time series

Electricity load patterns for the 26 federal states and Brasília are derived from the official statistics published by the National System Operator (ONS) (ONS 2021b). The hourly load profile is given for the four regions defined by the National Interconnected System (SIN), and in this study is spatially dispersed for each state in proportion to the annual consumption released by (EPE 2021).

The projection for electricity consumption is taken from the "Expansion Challenge" scenario announced in (MME/EPE 2020), which predicted an annual demand of 2100 TWh in 2050, roughly a fourfold rise compared to 2020, as shown in Fig. 1. The load centres are mainly located along the coast and in the south-centre part, e.g., São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ).

2.4 Grid topology

The Brazilian grid is split into four regional grids, each spanning several federal states, shown in Fig. 1. Suppose that the 27 nodes lie at their geometric centres and are connected by the transmission lines given in (EPE 2020b).



Fig. 1. Network model of the future Brazilian grid, based on the current grid topology connecting the states. Line width refers to the line volume. Different sizes of circles indicate the annual electricity demand in 2050 for each state, based on (ONS 2021b) and (EPE 2021). The abbreviations stand for the name of the federal states. The four regions defined by SIN are marked in different shades of blue.

The node-to-node power flow is emulated using a transport modelling approach, which omits the effect of power parameters on the power flow (Cao et al. 2021). Following (Oeding and Oswald 2011), the transmission capacity of each alternating current (AC) line is calculated assuming a line type of 490-AL1/64-ST1A 380.0. The length is decided by (EPE 2020b). There are eight highvoltage direct current (HVDC) lines in Brazil: four 600 kV lines connect SP to Paraná (PR), two 600 kV lines connect SP to Rondônia (RO), and two 800 kV lines connect Pará (PA) to RJ and MG. For obtaining the parameters of links among the nodes, the transmission capacity of individual lines is added up, while the efficiency and length are averaged for those lines with the same start and end nodes. During optimization, the transmission capacity can be expanded, but is limited by the total allowed line volume in the scenario analysis, which is a multiplication of transmission capacity and line length.

2.5 Storage

Hydropower plants are modelled as reservoirs in the absence of sufficient details of spatial resolution (ONS 2021a), whereby the reservoir can only be discharged at full rated power for a fixed duration, assumed to be 18 hours based on (ONS 2021d). Because of the seasonal pattern of generation and annual cyclicality of demand, a cyclical charge state is postulated. Unlike (Fichter et al. 2017) and (MME/EPE 2020) that used monthly average inflows over 80 years of history, PyPSA-Brazil applies the inflows in 2020 at the daily and regional level (ONS 2000-2020). By hypothesizing a linear correlation between the inflow and each state's installed hydroelectric capacity, the regional inflows are allocated to the state level and finally averaged to each hour of the day. Despite the great potential claimed by (Pereira et al. 2012), the National Ten-Year Expansion Plan discourages the scale-up of hydropower by restraining auctions (MME/EPE 2020). As a result, the capacity cap is set at 111.3 GW and allowed to expand by only 5 GW (ANEEL 2021).

Another type of energy storage is also considered at each node, a lithium-ion battery with a 6-hour duration (Schlachtberger et al. 2017) and no expansion limit.

2.6 Carbon emission and cost assumptions

The total GHG emissions of the power system in 2020 are 49 MtCO2e (EPE 2021). In the case study, scenarios of 100% carbon reduction are discussed from a system cost perspective, which are affected by the changes in the allowed expansion of interstate transmission.

Assumptions of investment, fixed operation and maintenance (FOM) cost, efficiency, lifetime and the data sources are documented in (Deng 2021). The capital cost of each technology is converted into a net present value cost, which is annualized over the economic life at a discount rate of 8% (MME/EPE 2020).

2.7 Validation

The model should be as similar as possible to the current power system. By comparing the hourly output of generation from the model with the reference (ONS 2020) for the base year 2020, the root mean square error is 9.9 GWh, while the annual generation is greater than 2100 TWh. It is evident that the model can resemble historical production patterns.

3. RESULTS AND DISCUSSION

As an exemplary result from PyPSA-Brazil, Fig. 2 shows the annual system cost breakdown for each technology in each state under different scenarios. These scenarios, illustrated by the bars with various hatches, reflect how strictly the expansion of transmission capacity is limited by a predefined factor of total allowed line volume (described in 2.4.). What stands out is that the increase in total allowed line volume has solely an impact on system costs in Alagoas (AL), Mato Grosso do Sul (MS), Rio Grande do Sul (RS), Rio Grande do Norte (RN), MG, RJ and SP. The changes in system costs stem from a diverse use of wind and solar resources, enabled by an increasing power interchange between states through the given or extended grid infrastructure.



Without expansion, i.e., at 140 TWkm, the system tends to heavily install new battery storage and makes significant use of the local solar potential, notably in MG and SP. In these states, even a slight uptick in total allowed line volume could result in immediate cost savings by importing power from other states. With grid expansion, investments into wind turbine installations take place, such as in RN, PB, and PE, which help to level out the wind fluctuations. This can be attributed to the relatively low electricity consumption in northeast Brazil, which, however, has a good quality of wind and solar energy in terms of annual power generation potential, i.e., in AL, RN, PB and PE. The export of power generated from wind and solar in these states to demand centres in the south-eastern states is a key determinant in realising a zero-emission system. If power imports from RS to southeast Brazil via PR are leveraged, a zero-emission power system is still feasible without expanding today's grid. However, transmission between Bahia (BA) and MG, MG and SP, and PR and SP may become a bottleneck.

The annual system cost is dominated by the expansion of PV generators, which contributes 37% to 39%. For an increasing total allowed line volume, the system cost drops by 3.2% compared to the case without expansion. The optimal line volume for such a zeroemission Brazilian power system is hence 246 TWkm, which corresponds to about 175% of the currently installed transmission capacity. The implementation of the grid expansion project to this extent appears to be more feasible than the nine-fold expansion identified for Europe (Schlachtberger et al. 2017), especially in the face of the social acceptance issues (Battaglini et al. 2012). The average marginal cost obtained from the model is 52 R\$/MWh, compared to 161 R\$/MWh in 2020 (ONS 2021c), revealing that developing such a zero-emission system is beneficial. Moreover, this value is about 25% lower than the one observed for the European, Middle Eastern, and North African system, which exhibited an optimal line volume of 375 TWkm (Bussar et al. 2014).

New PV facilities are mainly installed in AL and RJ, where considerable capacity factors can be achieved. This indicates the added value of investing in flexibility to exploit the enormous solar energy potential locally.

In all scenarios, significant new battery storage is required, representing about 17-18% of the total system cost. In particular, taking advantage of the high capacity factors for PV in AL, MS, RJ, RN, and RS causes the need for such flexibility. The share of hydropower in the energy mix remains below 20%.

4. CONCLUSIONS

We present a new Brazilian energy system model, PyPSA-Brazil, characterized by the fact that the modelling framework is open source and uses publicly available datasets. For example, it can be used to explore the impact of different levels of interstate transmission and storage expansion on system costs. To demonstrate the model, the Brazilian power system with 100% carbon reduction is explored in the case study. A zero-emission power system in Brazil is achievable by expanding the current line capacity to an economically optimal size of 175%. Our results indicate that expanding the power transmission capacities between the renewable producer hubs in north-eastern states (i.e., RN, PA, PE, AL) and the demand centres (i.e., MG and SP) is highly beneficial for implementing a zero-emission system in Brazil. These measures will not significantly increase the

annual system cost and can be effectively realised by new HVDC lines. However, this requires a substantial installation of new short-term storage, particularly in the federal states of AL, RJ, RN, and RS, if additional flexibility beyond the auctioned hydro and biomass power plants is not possible. In this way, the share of hydropower in the energy mix can be reduced to less than 20%, which is in line with the national energy strategy.

As a next step, PyPSA-Brazil will be extended to other energy sectors. This is an evident choice for Brazil, as it includes more of Brazil's emissions and brings more flexibility, especially the transportation sector, which makes up the most share in final energy consumption and is the largest emitter of carbon (EPE 2020a).

PyPSA-Brazil is compatible with PyPSA version 0.17.0 (PyPSA 2020) and the Brazilian public datasets reported in this paper, as the initial version of PyPSA-Brazil does not involve any extensions to the PyPSA framework.

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