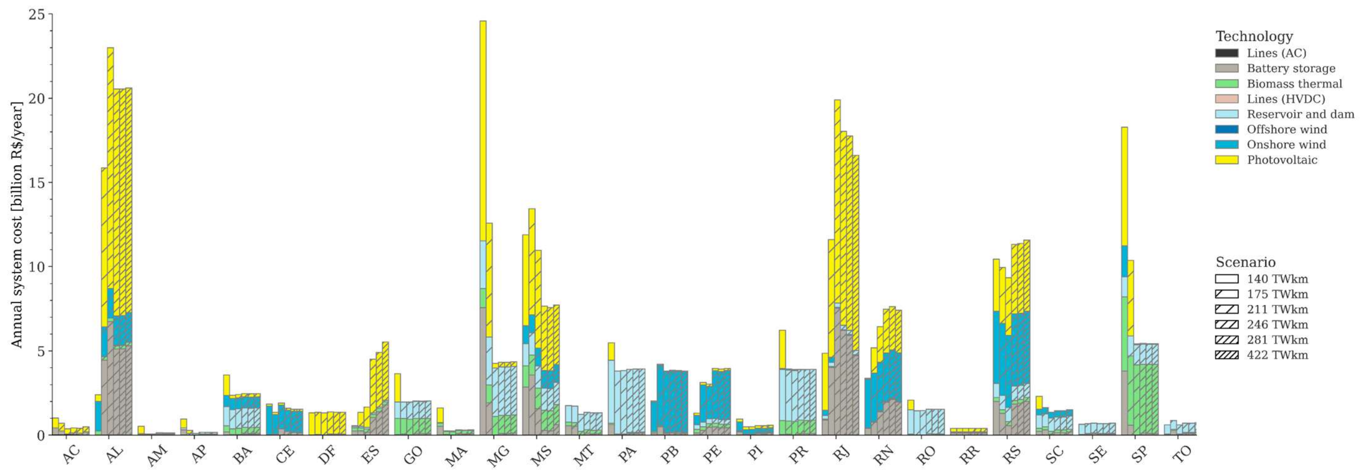

Fig. 2. Annual system cost composition for distinct total allowed line volume for a zero-emission power system in 2050. The scenario with no expansion is 140 TWkm.

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 zero-emission 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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