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The Electric Matrix of the State of São Paulo Toward the Just Energy Transition: Comparative Analysis of Strategies Based on the Experience of the 2014–2015 and 2021 Water Crises

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Abstract

This paper analyses the evolution of the electric matrix of the Brazilian state of São Paulo between 2012 and 2022, assessing the impacts on the electric system of two major water crisis events that occurred in 2014–2015 and 2021. We conducted our analysis through the lens of just energy transition, which is here understood as an approach that encompasses elements from environmental, climatic, and energy justice in the study of energy planning and policies. In this sense, in this paper we focus on elements of distributive energy justice. We find that the electric matrix of the state had a slight but still insufficient diversification, remaining tied to a dependence on hydraulic and fossil fuel generation and highly vulnerable to water crisis events. In addition, we show how both water-crisis events significantly influenced electric generation in the state, leading to increases in costs and tariffs, which are implied in issues of distributive justice. From these results we conclude that, through the perspective of just energy transition, the energy planning of the state lacked a clear path to decarbonization and diversification, perpetuating a weakness that produces issues of energy justice in crisis scenarios.

Keywords: just energy transition, energy justice, environmental justice, energy planning, electric system planning, water crisis

1. Introduction

Challenges to sustainability in Brazil's energy system are quite different from those observed in other countries. It ranks first in the world in total renewable water resources (FAO, 2023) at around 8.6 trillion cubic meters available per year, almost twice that of the second place country (Russia with 4.5 trillion) and representing about 15.7% of the global total. This wealth also turns Brazil into one of the top countries in hydroelectric potential, estimated at 172 GW, of which about 60% is already being used (EPE, 2018). Consequently, the inclusion of renewable sources in the Brazilian energy matrix is significant, especially in comparison with other major economies (E+, 2020). In 2021, renewables represented 46% of Brazil's primary energy consumption, a share far superior to the observed consumption for the OECD countries of 15% (BP, 2023). This is reflected in the profile of the country's greenhouse gas (GHG) emissions, in which energy-related emissions are not predominant and mostly come from the transport sector (MCTI, 2023). Thus, Brazil's energy transition strategies must consider these fundamental differences and the contradictions and limits present in the current system configuration. With the goal of decarbonizing the generation of electricity already fulfilled to a large extent and with the fast growth of solar and wind participation on a predominantly hydropowered matrix, there is still work to be done in assuring the diversification of sources and the security of the system (E+, 2020). In addition, social issues must be addressed when considering a genuinely sustainable vision for the energy system, and Brazil still is far behind in this respect.. With Brazil's history of silencing and violating rights in high-impact energy projects, environmental justice must be a major concern in shifting the country toward a just energy transition.

1.1 Just Energy Transition: Energy Transition and Energy Justice

Just energy transition is a research agenda that seeks to integrate environmental, energy, and climate justice concerns into the energy transition toward low-carbon sources (McCauley & Heffron, 2018). Discussions on energy transition arise as a response to the challenges posed by global climate change, proposing an entire shift from fossil fuels toward renewables in a large-scale process, which implies profound technical and social changes in our current system (Wang & Lo, 2021). The energy transition can be seen as one of the multiple necessary socioecological transitions toward sustainability, but one so fundamental as to affect society in its modes of living, economics, and politics as much as it reshapes the whole energy-system infrastructure (García-García et al., 2020). Fossil fuels occupy a large share of the global energy matrix (BP, 2023), and phasing them out requires immense investments in new projects for the system's capacity to meet energy demands. Some conceptions of energy transition end up emphasizing the technological aspects of shifting toward energy sources, but it is generally understood that these transition effects are beyond its tangible elements, reconfiguring agents' relations and the system's very foundations (García-García et al., 2020).

Energy justice emerges from the field of environmental justice, which is focused on questions regarding the unequal distribution of environmental resources and affects society as much as the power relations on which such inequalities are based. With this in mind, Sovacool defined energy justice as "a global energy system that fairly disseminates both the benefits and costs of energy services and one that has representative and impartial energy decision-making" (Sovacool & Dworkin, 2015). This definition highlights the two main dimensions usually considered when addressing energy justice: distributional and procedural justice. Distributional justice refers to equity in the partition of material outcomes. In contrast, procedural justice is focused on assuring effective participation from interested parties in decision-making, broad access to environmental information, and due legal process in case of violation of rights. Some authors include even more dimensions in the concept, such as recognition justice (García-García et al., 2020; Jenkins et al., 2015). Recognition problems concern the failure to acknowledge differences in perspectives and experiences of the parties involved, which could lead to cultural and political domination.

"Just transition" appeared as a concept in the trade union movement as a way to mobilize the demand for the maintenance of employment in the face of the discontinuation of fossil fuels. It was used as a call for quality "green jobs" during the energy transition, bringing a social issue into the transition challenges (McCauley & Heffron, 2018). It has since evolved into a wider concept integrating the issues sought by environmental and energy justice in the transition agenda (García-García et al., 2020). Sovacool's framework of the principles of energy justice as a reference in decision-making can be quite elucidating of how a fair energy transition could be addressed. In such context, eight principles were determined: availability, the capacity of guaranteeing energy resources; affordability, stability and equity in prices so that access is granted; due process, ensuring participation and access to justice; good governance, access to information and prevention of corruption; sustainability, prevention of depletion of natural resources; intragenerational and intergenerational equity, distributive justice within a generation and between multiple generations; and responsibility, the shared duty and the differences in roles of the different nations in ensuring environmental and energy justice (Sovacool & Dworkin, 2015).

1.2 Water Crisis in 2014–2015 and 2021

The water crisis of 2014–2015, which struck most severely in Brazil's southeast, exposed many weaknesses in the energy and water systems of the country's richest and most populated regions, showing how such abundance can be misleading if the management is poorly conducted (Neto, 2016). In the state of São Paulo, the prolonged drought that led to lower precipitation in crucial months had severe impacts in both water supply and electricity generation. The Cantareira System, the largest water supply system in the state, responsible for ensuring water access to more than eight million people in the São Paulo metropolitan region, was highly affected, leading to an "unofficial rationing" through reduction of water pressure in specific regions, mostly low income and peripheral. Many of the state's hydroelectric reservoirs saw large volume reductions, leading to lower electricity generation and an increase in the more expensive and carbon-intensive gas-thermoelectric generation to cover the shortages (Fracanlanza & Freire, 2016). Conflicts among multiple water uses were also observed, as the hydroelectric reservoirs in the state sustain multiple activities in its subjacencies.

The precipitation regime in Brazil's southeast is well-defined, seeing higher rainfall in the summer months, with typical tropical downpours, while in the winter months the lowest precipitation rates are registered. The water crisis of 2014–2015, which affected not only São Paulo but also many other parts of the southeast region, had an extended drought in the summer months as its climatic background (Marengo & Alves, 2016).

Multiple mechanisms influence weather formation in the southeast. One of the most important sources of moisture coming to the region is the evapotranspiration from the Amazon rainforest, which is transported by a low-level jet mechanism and, as it converges with the cold air masses, creates the summer rainfall. An abnormal high-pressure area that persisted during these months beginning in December of 2013 was found to be responsible for disrupting this mechanism, and in turn, precipitation in the summer months was significantly lower.

However, the causes of the water crisis in São Paulo go way beyond its climatic conditions. Such events are predictable with relative security using state-of-the-art climatic modelling. Therefore, the actual cause of the water crisis was attributed to the lack of planning to increase the system's resilience to such events and the mismanagement of water resources during the drought (Neto, 2016). Climatic analysis research tried to verify a connection between the drought and deforestation in the Amazon but was found to lack evidence to establish such a relation, and the cause of the drought was attributed to natural climatic conditions (Alverenga Cumplido et al., 2023). Still, it was highlighted that the events observed are similar to the climate change impacts predicted by the Intergovernmental Panel on Climate Change (IPCC). Thus, such circumstances are virtually certain to occur again in the long run, and therefore the energy transition needs to evaluate its effects and make effective planning considering these experiences.

The 2021 drought in Brazil that was labelled "the worst in 91 years" by the Energy and Mines Ministry also had immense impact on the electric system. The anomaly observed in precipitation and temperature was higher in that year than in 2014, as shown by a climatic analysis study (Alverenga Cumplido et al., 2023). This effect still has not had its physical causes as thoroughly analyzed as the 2014–2015 event, and the literature is fairly scarce in comparison. The crisis severely affected the Paraná and Paranapanema Rivers, dropping their levels to historic lows. Both rivers have several dams and reservoirs, which are crucial for the electric system not only of the southwest region but also of the whole country. In comparison, the crisis in 2021 did not have as large an impact on water supply as did the 2014–2015 crisis.

The electric matrix of São Paulo state changed significantly from 2014, witnessing a rapid advance in solar PV and sugarcane biomass generation (ONS, 2023). This may be the beginning of an important shift for the electricity supply in the state, which is characterized by the already cited dependency on hydropowered generation and on electricity generated outside the state (also mostly hydraulic) (Brazil, 2016). Brazil has a National Interconnected System , a nation-wide mechanism for coordinating electricity generation and transmission throughout the country that can guarantee supply in crisis scenarios with electricity produced in other regions. Nevertheless, both water crisis events showed that the electric system still carries many vulnerabilities.

Just energy transition encompasses concerns from energy justice, including distributional and procedural justice, and thus, from this perspective, it is imperative not only to guarantee the supply while transitioning to low-carbon sources, but also to assure an equitable access to energy and related natural resources while securing the environmental rights of the parties involved and promoting participation (Maguire & Shaw, 2021). In this paper we aim to evaluate whether changes in São Paulo's electric matrix in a period that included both water crises (2012–2022) responded to transition challenges and helped the state build resilience to such climatic events, as well as to assess the impacts of the water crises on the distributive justice dimensions—as envisioned by the concept of fair energy transition— of availability, affordability, and intragenerational equity.

2. Methods

In this study we assess the development of the electric matrix in the Brazilian state of São Paulo between 2012 and 2023 through the lens of fair energy transition, comparing the water crises of 2014–2015 and 2021 to evaluate the level of dependence on hydroelectric generation and fragilities associated with it. We focus on distributional justice concerns, based on three of the principles raised by Sovacool and Dworkin: availability, affordability and intragenerational equity (Sovacool & Dworkin, 2015).

To evaluate the availability of electricity in the state and the impact of both water crises on electricity generation, generation source, and the types of acting of the plants, we used public data from Brazil's National Electric Energy Agency (ANEEL), to characterize the evolution of the installed capacity of the state's matrix in the period. In comparison to the installed potential, we assessed the electricity effectively generated inside the state in that period by considering the different generation sources through data from the National Operator of the Electric System (ONS) and data from the 2022 energy balance produced by the state's government. Also, we investigated the state's hydroelectric system through the average reservoir's live storage of the state's four generation chains, which correspond to its main drainage basins: Tietê, Paraná, Paranapanema, and Grande. We calculated the effective volume available in each chain from 2012 to 2022 through a weighted mean of each reservoir's effective volume in the period, with the weights being the reservoir's energy-storage-capacity ratio in relation to the subsystem's total capacity. It is worthy of notice that we considered reservoirs outside the state in the Grande chain analysis, as these reservoirs are vital to discharge regulation in the basin and therefore cannot be left out. From this comparison we evaluated the impacts of both water crises, as well as the effects of the state's energy planning on the evolution of the electric matrix.

We evaluated affordability through analysis of the electricity tariff evolution, as well as of the marginal operating costs of electricity in the period, also using public data available from Aneel and the ONS. This makes possible a discussion of the intragenerational equity in the electric system, which puts in question who benefits from the current state of the electric system and the transition efforts in place, and who pays the price of such a state and of the vulnerability scenarios created by water stress situations, as in the two crises at issue.

3. Results

3.1 Evolution in the Electric Matrix of the State of São Paulo

Renewables already make up most of the gross domestic-energy supply in the state of São Paulo, with a participation of 58.5% in 2021 (São Paulo, 2022a). São Paulo's large sugar cane agroindustry reflects the growing participation of sugar cane products on the supply, at 32.7%, while hydraulic and electricity made up 18.7%. Still, the remaining 41.5% of fossil fuel energy, consisting primarily of petroleum and derivatives (33%), with a significant amount of gas usage (8.5%), represents a deep and structural challenge for energy transition, considering the main uses of fossil fuels in the state. The transportation sector is by far the largest consumer in São Paulo, which, like most states in Brazil, still has a large dependency on motor vehicles, relying on its fleet of more than 32 million vehicles (IBGE, 2023). The use of fossil fuels in thermoelectric power plants is only a small fraction in comparison, but these plants play a vital role in the state's electric-system stability.

Regarding the electric supply in the state, the first thing that stands out is the decrease in electricity produced inside the state, going from 86,589 GWh in 2012 to 51,788 GWh in 2021, in spite of the matrix having been expanded and diversified. This implied an increase in imports: while the gross supply remained relatively constant, the percentage of electricity produced inside the state fell from 50.6% in 2012 to 38% in 2015, the peak of the water crisis, and saw a small recovery to 43% in 2017, ultimately plunging to 30% in the 2021 water crisis (São Paulo, 2022a). Such a situation, while not necessarily implying restrictions due to an increase in demand, may create insecurity in transmission. Table 1 shows the electric matrix in the state in the years 2012 and 2023, highlighting installed capacity and the number of plants (ANEEL, 2023).

Table 1. Electric Matrix of the State of São Paulo in 2012 and 2023

Energy Source	Installed Power (MW)		Number of Plants	
	2012	2023	2012	2023
Biomass	5392	6821	187	234
Wind	0.002	0.002	1	1
Solar PV	0.016	791	3	60
Hydraulic	14831	14901	118	126
Fossil	2437	2670	514	704
Total	22661	25184	823	1125

The data show that, even though the electricity generated inside the state decreased in the period, the installed capacity had an increase of 2,523 MW (11.2%). This increase was mainly driven by biomass, which added 1,429 MW in capacity to the matrix, and also by the quick growth in solar PV, which came from virtually zero to an incipient contribution of 791 MW. Even though that made up only 3.1% of the current matrix, it signaled a movement of diversification in generation, with another 14 plants already approved for building that will add another 436.5 MW (ANEEL, 2023). Fossil power had only a slight increase in installed power capacity, but the number of plants had a significant increase of 190, more than in any of the other sources. This means a proliferation of small-scale, self-production plants, which actually have been producing more energy than the main plants of the state (ONS, 2023). Hydraulic energy saw only a minor increase of 70 MW in the period, and what also stands out is that wind energy remained stagnant with only one plant of 2 kW installed in the state.

3.2 Effects of the Water Crisis in Electric Generation

Figure 1 presents the mean live storage for the reservoirs in the main generation basins for the state of São Paulo: Tietê, Paraná, Paranapanema, and Grande. The live storage of reservoirs corresponds to the volume between the maximum and minimum operational levels. It is conceived as the stored volume necessary to maintain a regularized discharge in critical hydric stress scenarios, and, therefore, many hydroelectric plants can keep operating below their live storages, as the water intake is located some meters below the operating minimum (Galvão et al., 2015). These four basins have hydroelectric generation chains comprising dams with large conventional reservoirs and run-of-the-river dams, which rely on regularization provided by the larger reservoirs. In our data we included only the main reservoirs from each basin. It is also important to note that the Tietê and

Paranapanema are tributaries of the Paraná River, and that the Paraná River is a continuation of the Grande River as it merges with the Paranaíba River. Therefore, the Paraná River can be affected by the other three rivers.

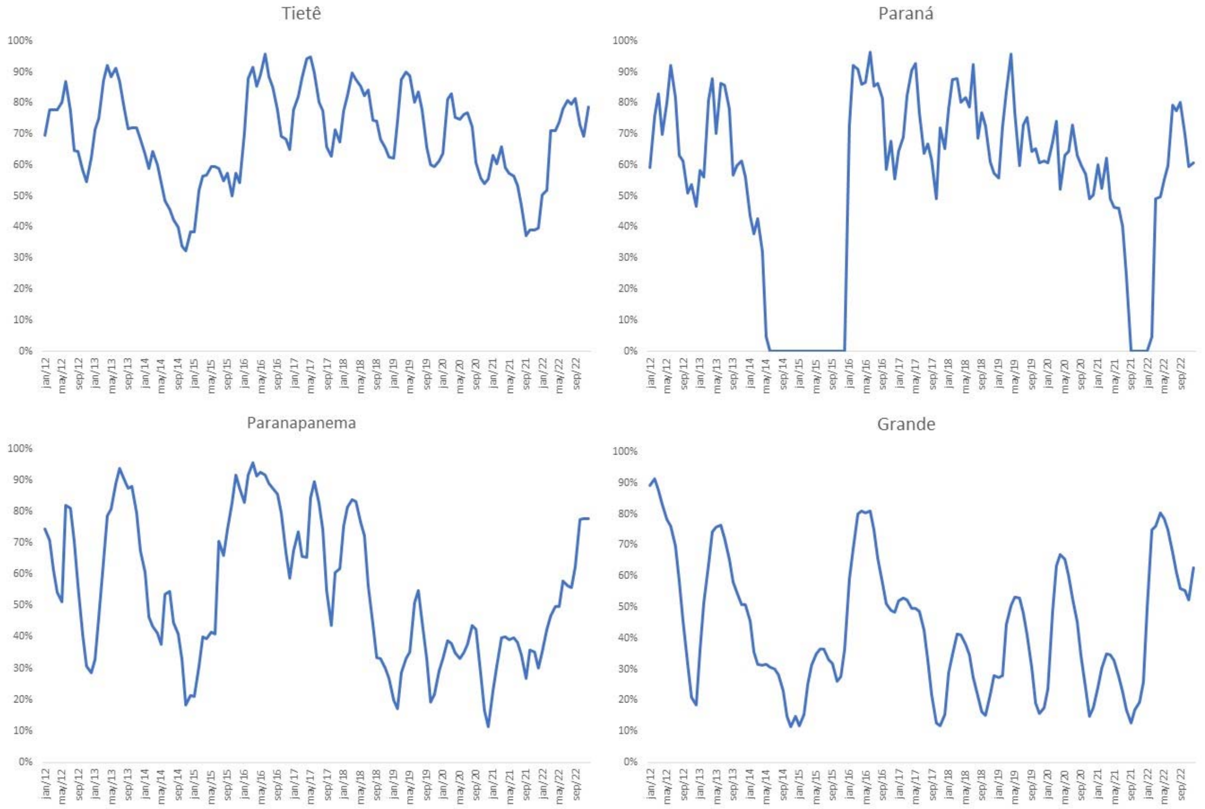

Figure 1. Mean live storage of reservoirs in São Paulo's basins between 2012 and 2022.

In Figure 1, it is possible to observe the effects of the 2014–2015 and 2021 water crises on the leading hydroelectric chains of the state. The hydroelectric reservoirs in the Tietê River had their lowest live storage in November 2014, when it reached 32%. The effects of the drought can be seen from the beginning of 2014, when instead of an expected ascendant movement, the mean live storage started to fall, and in the middle of the year, the crisis fully manifested when storage dropped to 49% in June, in comparison to 91% in the same month of 2013. Storage in 2015 was relatively more stable, with mean live storage remaining between 50% and 60%. The recovery happened only at the beginning of 2016, with mean storage reaching 88% in February. In the 2021 crisis, the most critical point for the Tietê reservoirs was in September, when the storage stayed at 37%, slightly higher than the 2014 low. The crisis can be observed starting from the beginning of the year, when the filling of the reservoirs was below the level expected in the summer months, and manifested itself strongly after August, when the mean storage dropped below 50% and stayed that way for six months, before recovering at the beginning of 2022. It is also worthy of notice that for the Tietê River reservoirs, there was a slight but consistent decrease in live storage levels from 2016 to 2020. As each year passed, the maximum and minimum storage registered was slightly lower than the year before, which may indicate a long-term phenomenon.

The Paraná River chain was severely affected in both cases, with its live storage drained to zero for 19 months between 2014 and 2015 and for five months in 2021. In both cases, a consistent recovery was observed following the drought events, with levels rising quickly and stabilizing in the subsequent rainy seasons. Unlike the others, the Paranapanema River chain felt the crisis in 2021 in a more challenging way than the previous one. Its effects were also felt sooner than in the other rivers, with the lowest registered storage level at 11% in December 2020. The 2014–2015 crisis's lowest register was 18% in November 2014. The stress was visible from the beginning of 2014, with storage levels decreasing in the summer. In February, mean live storage was already at 47%. In this case, the recovery was observed sooner than in the other basins, with a rapid increase starting in July.

For the 2021 crisis in the Paranapanema, the reservoirs were already experiencing hydric stress in late 2018. The mean live storage levels registered in February 2019, 17%, were already lower than the worst point of the 2014–2015 crisis. Since then, consistent recovery was observed only in 2022, with all storage levels in the intervening years staying almost below 50%. As observed in the Tietê River, this scenario might indicate a long-term phenomenon.

Lastly, a notable difference from the start for reservoirs in the Grande River is that its mean live storage levels tended to periodically reach low levels at the end of the year, despite hydric stress being present. The lowest levels registered in the 2014–2015 crisis—12% in November 2014 and January 2015—were also seen in November 2017. Still, the effects of this crisis can be seen in the middle of the period,, when levels were expected to be higher but stayed below 40% in both 2014 and 2015. In 2021, the crisis's impact can also be better observed in the middle months, when the reservoirs' recharge remained low and did not surpass 40%. Some stress can already be perceived in the middle months starting from 2018, with the recharge being significantly lower than in other "normal" years. An increase can be observed in 2019 and 2020, but consistent recovery was seen only in 2022 when storage levels reached 79% in May. This, as is the other cases, may also indicate a phenomenon with a more prolonged duration.

Figure 2, elaborated from data by ONS (2023), shows the monthly electricity generation in the state of São Paulo between 2012 and 2017 by source, including hydraulic, fossil, and biomass. Solar and wind were not included because neither managed to generate more than 1 GWh in a month. The effects of the water crisis are visible in 2014 and 2015, with a sharp drop from January to June in 2014 and a small recovery in the summer of 2015, dropping again during winter.

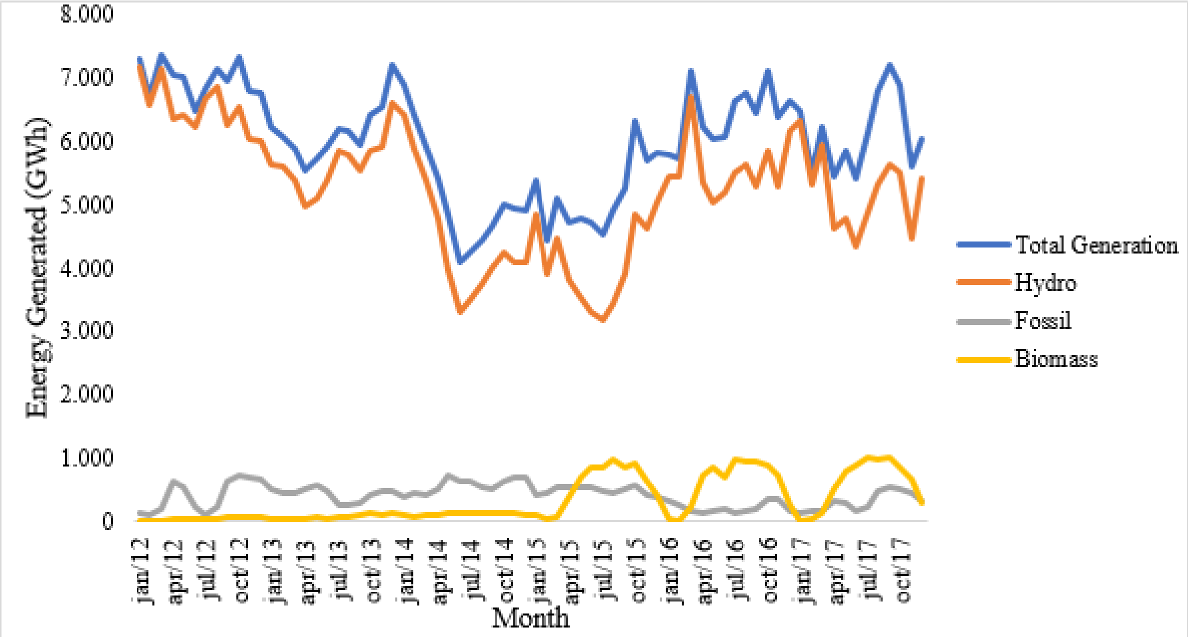

Figure 2. Electricity Generated in São Paulo between 2012 and 2017 by source.

Observing the hydroelectric generation in July, one of the driest months, we see the impact on generation: it went from 6,672 GWh in 2012 to 3,191 GWh in 2015, a drop of 52%. Total generation closely followed hydroelectric generation, especially in the first years. From 2015 on, more significant gaps started appearing, getting more prominent in the winter months. This was due to the behavior of the biomass generation data, which showed a considerable increase in cyclic peaks starting in 2015. These peaks were due to the sugarcane harvest between April and November, reaching 980 GWh in July 2015. The data from several sugarcane biomass plants, which were already in operation, is lacking before December 2014, and thus these cycles started appearing only in 2015. Therefore, it is reasonable to assume a similar pattern was also present before 2015.

Generation from fossil thermal plants was the least impressive, with 485 GWh in July 2015 and a top output of 731 GWh in May 2014. It is vital to notice that this generation value for fossil plants includes only the state's leading public service thermal plants, excluding small and self-production plants. The hydraulic dependency of the state's matrix is clear from the data, as is the impact a drought can have. Even with fossil plants turned on and biomass generation at its peak, as in July 2015, the generation was insufficient to counteract the effects of the drought. Total generation only reached 4,542 GWh in the month, while the monthly average electricity consumption in 2015 was 12,092 GWh (São Paulo, 2022a).

Figure 3, also created through data from ONS (2023), shows the monthly electric generation in the state of São Paulo in the subsequent period, between 2018 and 2022, by source, including hydraulic, fossil biomass, and solar. Solar was included as it started to present a significant output, but wind was left out as it still did not surpass 1 GWh in a month (an obvious fact that no new power was installed). The effects of the water crisis can be seen starting from the beginning of 2021 with a sharp drop in total electric and hydraulic generation.

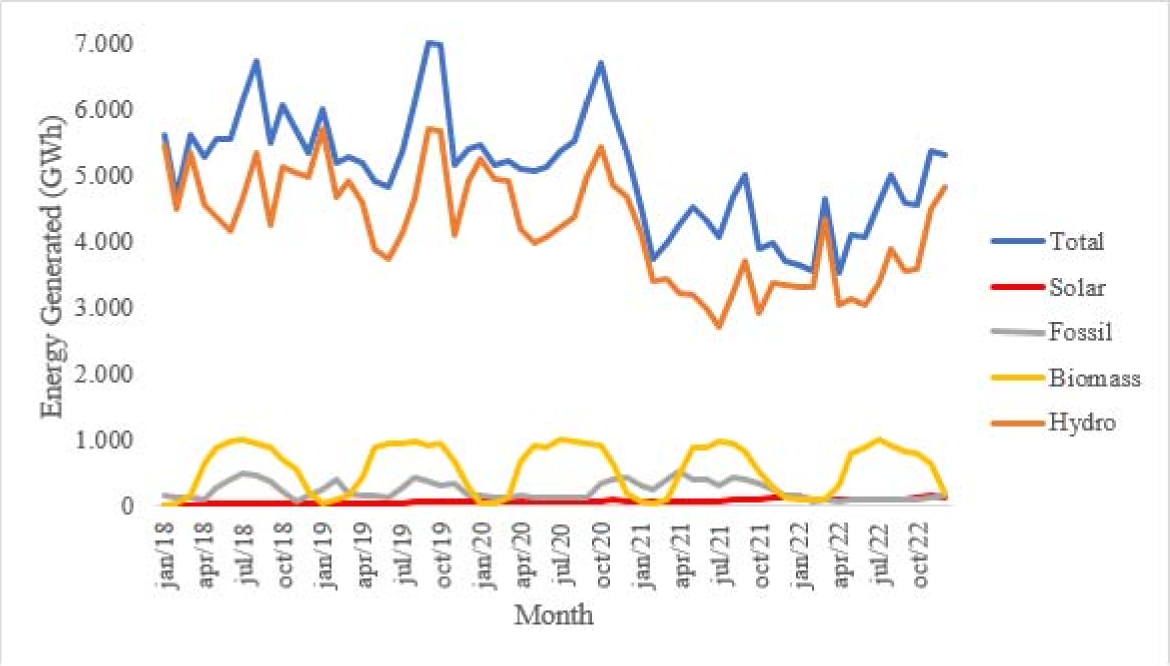

Figure 3. Electricity Generated in São Paulo between 2018 and 2022 by source.

The worst point of the 2021 crisis was also in the month of July, when hydroelectric generation in the state hit the lowest point considering both of the periods, with 2,703 GWh generated in the month, 15% lower than the worst point of the 2014–2015 crisis registered in July 2015, and 59% below the generation registered in July 2012. Total generation in July 2021 stayed at 4,046 GWh, seeing greater participation of biomass in the month with 981 GWh, 24% of the total against 66% of hydroelectric. The worst point for total generation was observed in February 2022 with 3,537 GWh, as the drought persisted through the latter months of 2021, and the biomass generation hit its low point. In that month, hydraulic generation had an output of 3,300 GWh, 93% of the electricity generated in the state, attesting once more to the utter dependence on hydroelectricity for the state's generation. Considering the biomass generation in the period, it is essential to note that there has been no increase in total output on the peak months with the passing of years, despite the addition in generation capacity from this source as presented above. This could mean the newly added capacity was composed primarily of small-scale plants for self-production, and the data were not included in the ONS database.

As for solar generation, the increase experienced during these years was significant, from only 3 GWh in January 2018 to its highest point in November 2022, with an output of 141 GWh, 47 times more. Still, the contribution from solar to the grid remains timid, and it hardly could be considered a tool to counteract water crisis effects at that stage. Lastly, for the fossil generation in the state, the scenario remains similar to the previous period, with the average fossil usage decreasing. In July 2021, the output of fossil electric generation was 301 GWh, against the 485 GWh of July 2015. Still, as in the previous case and the case of the biomass plants noted above, it is important to consider that a significant number of plants are not included in this data, and therefore, this may not be representative of the output of the new fossil plants added in the grid, mostly small-scale and oriented to self-production.

3.3 Effects of the Water Crisis in Costs and Tariffs

Both water crises influenced costs and tariffs in the Brazilian electric system, notably in São Paulo and the Southeast/Central-West electric subsystem. The taxes in Brazil have been submitted to a "Tariff Flag" system since February 2015, which operates through five different levels of pricing (Green Flag, Yellow Flag, Red Flag 1, Red Flag 2, and Water Scarcity Flag) that are defined according to the availability of electricity from hydroelectric sources (Brazil, 2015). Specifically, the ANEEL defines it through the settlement price of differences, which is calculated through models and published daily by the Electric Energy Commercial Chamber. This value is closely related to the marginal cost of operation, which represents the cost of generating the next unit of energy (MWh) the system requires to meet its demand. The marginal cost of operation will increase when thermoelectric plants are turned on, as they are more expensive to operate, and will decrease when hydroelectric generation is abundant. Therefore, there is an adherence between the tariffs and the marginal cost of operation. It is important to note that the marginal cost of operation is published only for the subsystems that constitute the National Interconnected System, and so the data encompass the whole Southeast/Central-West subsystem, in which São Paulo is located.

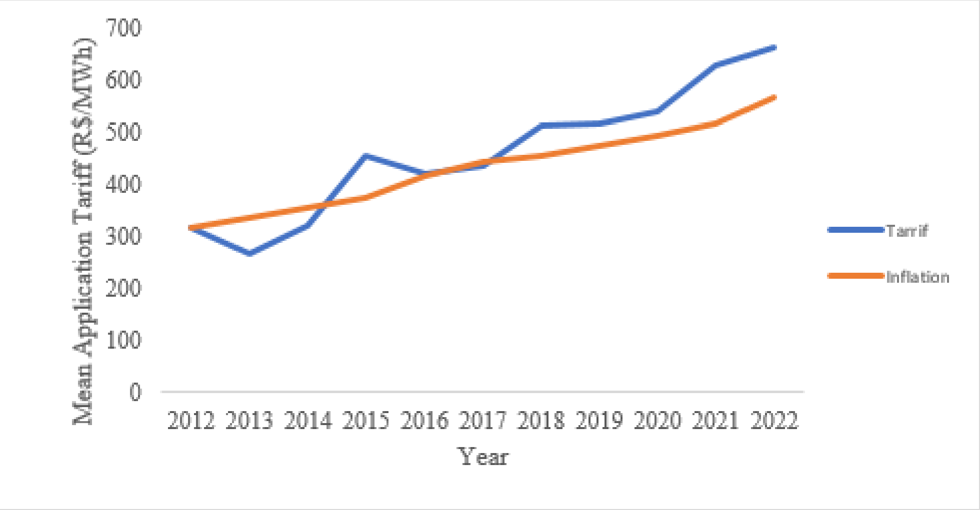

Figure 4. Mean application tariff for residential consumers in São Paulo between 2012 and 2022 and tariff corrected by inflation

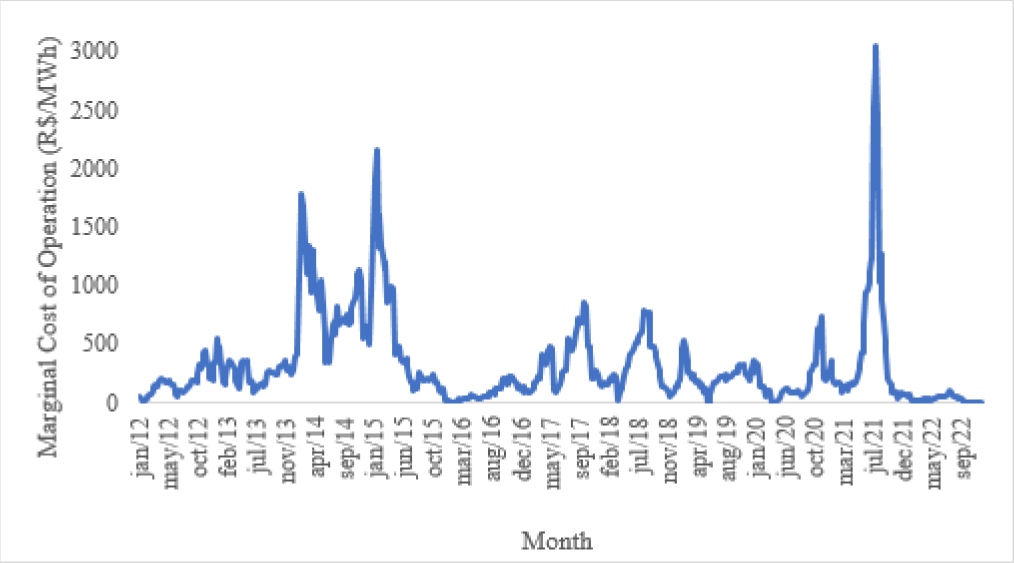

Figure 5. Marginal Cost of Operation in the Southeast/Central-West subsystem between 2012 and 2022.

In Figures 4 and 5, it is possible to see the evolution of the values mentioned above in the period between 2012 and 2022. One can visualize both events on the marginal-cost-of-operation graphic, with the first two peaks in February 2014, when it reached 1,777.54 R$/MWh, and in February 2015, even higher at 2,158.57 R$/MWh. In the following years the average cost was much lower, with some smaller peaks occurring, until peaking again in late 2021, reaching the historic maximum of 3,044.45 R$/MWh in August. This shows how both water crises were felt well beyond the state of São Paulo, and that in the whole Southeast/Central-West subsystem the 2014–2015 event was more prolonged, while in 2021 it was shorter but more acute. Already in the beginning of 2022, the cost had reached a low and stable level, signaling the normalization of hydraulic generation in the subsystem.

Looking at the mean application tariff for residential consumers in São Paulo in the same period, the impact of both events is also visible. The tariffs increased 21% from 2013 to 2014 and in the next year had an incredible increase of 42%. From 2020 to 2021, an increase of 16% was observed and for the following year it increased by another 5%. Both events can be visualized in the data presented, but the impact on the tariffs was different from that observed in the marginal cost of operation. The highest impact in mean tariffs happened in the 2014–2015 crisis. Even with the marginal cost of operation reaching higher levels in 2021, the increase in tariffs was much more modest.

4. Discussion

4.1 Energy Planning in São Paulo and Its Outcomes

The scenario we have presented reveals many challenges for an energy transition that seeks to gradually phase out fossil fuels while keeping the system resilient and secure to maintain electric availability and affordability. The last published state energy plan in São Paulo dates from 2012 and has 2020 as its horizon (São Paulo, 2012). The plan already considers the goals established by the state's Climate Change Policy, the principle being an emissions reduction of 20% from 2005 standards by 2020. The goal was largely unaccomplished, and the emissions in 2020 were calculated as being 0.7% lower than in 2005 (São Paulo, 2022b). While it could be said that a 20% reduction was unrealistic, its inclusion in the 2012 planning means the plan already had incorporated some transition goals. The actions envisioned for reducing emissions were mainly focused on the transport sector, which, as we already noted, is by far the greatest consumer of fossil fuels in the state and, therefore, ends up being the most significant GHG emitter. The objective was to increase the use of ethanol and biodiesel by motor vehicles, and while it fell short of the goal of having the flex fleet use alcohol 90% of the time, some advances were visible. Gasoline consumption in the transport sector fell from 8.2 billion liters in 2012 to 6.5 billion in 2021, while ethanol use rose from 4.1 billion liters in 2012 to 5.6 billion in 2021, peaking at 7.2 billion liters in 2019, when it surpassed gasoline (São Paulo, 2022a). This advance was slowed due to federal government subsidies on gasoline between 2011 and 2014. While helping maintain security and affordability in a country with huge road-transport dependency, the subsidies made ethanol less competitive (Costa & Burnquist, 2016).

With regard to planning for the electricity sector, we first note that the plan does not aim at any decrease in fossil thermal generation. Because it views thermal plants as a security measure against climatic events that could lead to decreased hydroelectric generation, it intends to increase installed capacity in the state and to transition from fuel oil to natural gas (São Paulo, 2012a). It mentions two planned large gas-thermal plants to be constructed starting in 2017: Canas, with 500 MW, and Pederneiras, with 279 MW. These plants, however, have not been installed to this date (ANEEL, 2023). Instead, the enormous Lins thermal plant, with 2,000 MW, is planned for 2025 and has already been granted a license in 2019 (São Paulo, 2019).

In justifying the building of the plant, the plan claims that it would fulfill a demand of the nationwide energy expansion plan, which set up the goal of a 5,000 MW expansion by 2026 (UTE Lins, 2018). Looking at the 2012–2022 data, it is clear that additions were not made to fossil generation in large public service plants, as the generation in the state shows no growth in the period. This implies that most of the plants added in the period are small-scale plants focused on self-generation. The Brazilian law divides the plants by the power capacity of the plant. Small plants of up to 5 MW need to be registered only after implantation, while plants above 5 MW require authorizations or concessions and more complex procedures (Brazil, 1995).

Electricity distribution in Brazil is divided into two markets: the captive market and the free market. In the captive market, users have no choice but to purchase energy from the concession supplying a particular region, while in the free market, there is a possibility of choice among different suppliers. Only larger consuming units, with demand above a specific load determined by regulations, are able to access the free market. This means it excludes most users, favoring only companies with large installations: the most significant consumers on the free market are from the metallurgy and non-metallic minerals sector, the chemical industry, and the cellulose industry (Machado, 2007). The main benefits to companies of migrating to the free market are the reduced electricity prices provided by the renewables subsided by PROINFA, as tariffs were found to be up to 20% cheaper in the free market (Cardoso & Rocha, 2017).

Lastly, the plan to expand the system has no explicit goals for biomass and hydraulics. The fundamental role they play in the system is acknowledged, but as noted before, the hydroelectric potential in the state is almost exhausted. The actions proposed focused on increasing the efficiency of the existing structure (São Paulo, 2012a). The state's relationship between hydraulics and biomass shows the same lack of vision in making alternative renewables a public service. As demonstrated by the data, biomass electricity has a significant role in the state's generation, even greater than that of the public-service fossil plants. The own producer uses some of the energy, the remaining being sold in the market. Biomass electricity in the state could be used for counterbalancing water crisis effects and helping control tariffs (Galvão et al., 2015), but instead is also entirely privately appropriated, with a total lack of plans to distribute benefits from this source more equally.

Even though there has yet to be a clear initiative to consistently develop alternative renewable sources in the state, the options and capabilities for this endeavor are already known. Research concerning the wind, solar, biomass, and hydraulic potential in the state have been conducted by the state's government, showing many possibilities for expansion and diversification of the matrix that, if executed with the public interest as its goal, can help build a secure grid beyond fossil fuels that shares the benefits of renewables with equity. Evaluation of the wind potential in São Paulo that was carried out by the initiative of the state's government in 2012 shows a potential for installing at least 4,734 MW in the state, which could generate up to 13 TWh yearly (São Paulo, 2012b). Setting up such capacity would require 1,134 km² in area, undoubtedly a large extent, but would be localized only in certain regions of the state, some of which are offshore. In comparison, the Ilha Solteira Hydroelectric Plant, the sixth largest in Brazil, located on the border of São Paulo and Mato Grosso do Sul, has a flooded area of 1,195 km² and a capacity of 3,444 MW, lower than the wind potential (ANA, 2022). For solar, the potential for development in the state is even more significant. Considering only areas with peak solar incidence, the calculated potential for new power is 9,100 MW, which could generate up to 12 TWh yearly (São Paulo, 2013). The area needed for installing this new capacity would be 732 km², representing a higher efficiency in the usage of space than the wind and hydroelectric examples shown. This reveals how, despite the growth in solar capacity, it is still an underdeveloped source.

As for biomass, which plays an increasingly important role, a survey conducted by the state in 2016 showed potential for an additional 1,498 MW considering only forestry biomass (São Paulo, 2016a). This study focused on forestry and did not include generation potential from the sugarcane agroindustry, which already plays a significant role, given the sector's relevance in the state. The potential for sugarcane bagasse generation stills needs a more profound evaluation, as a similar study has not been conducted for this potential source. The expansion envisioned for forestry biomass would demand 17,145 km² in area, by far the largest of all. Still, this area was selected among lands such as degraded pastures, barren lands with small shrub vegetation, and lands with high forestry potential so that it would be an opportunity for reforestation and productive rehabilitation.

For the remaining hydroelectric potential, it was found that there is still another 1,452 MW in 637 possible locations. This potential is composed of small-scale plants of up to 30 MW in power, with the majority of identified places being able to support only plants up to 3 MW (São Paulo, 2016b). This reveals that, while there is still room for development in many areas, the hydraulic potential of the state has already been largely exploited. Considering all the remaining potential from these renewable sources, it is clear that the state has the natural resources available for conducting a transition on its electric matrix. The state's government, however, would not be able to shift this transition toward greater distributional justice on its own, as the regulations that shape the electric sector in Brazil are at the national level

4.2 Water Crisis and Distributional Justice

Both water crises are visible in the present data, affecting reservoir levels, electricity generation, costs, and tariffs. Starting from the reservoir levels, it is possible to encounter the social impacts of the events, with problems of distributional justice regarding the equity in multiple uses of reservoir water resources. Such concerns, even if not referring directly to energy distribution, are essential in a broader environmental justice vision, being fundamental in a fair energy transition approach. The 2014–2015 water crisis led to the emptying of many reservoirs in the state, with some being drained below their dead storage because of the decision of companies operating plants and state organs to maximize electricity production, as was the case with the Ilha Solteira plant in the Paraná River. Many of the adjacent settings, ultimately leading to the judicialization of one of the conflicts between the company operating the reservoir and fish farmers, felt the impact caused by the drainage of these reservoirs. As a reservoir was drained, it was impossible for the fishing to continue; this led to businesses shutting down, with a rise in unemployment and impoverishment of the population as incomes fell (Galvão et al., 2015).

Conflicts between the national and state levels also arose, as the federal electric energy and water agencies demanded normalization of the levels, and the state organs and operating companies did not comply, leading to a judicial conflict. Today in São Paulo, most hydroelectric reservoirs have several uses, with thousands of use permits registered in these water bodies, with activities including farm irrigation, aquaculture, industrial services, mining, thermoelectric generation, and even human consumption (ANA, 2023). This case has shown that these activities and uses may be at risk in such hydric stress scenarios when there are agents with more political and economic power that can make one-sided decisions; in a clear case of environmental injustice, the less powerful being the most affected and the less heard in the process.

As shown in the data, in the 2021 crisis reservoirs also experienced some drastic level reductions. The Ilha Solteira reservoir drained below its dead storage in 2014 and 2015 and was once again emptied, only this time for a shorter period. As we noted, there is a tendency for a decrease in average live-storage levels in some of the basins spanning a more extended period, translated in the decline of hydroelectricity output during the period, which should be of concern and further investigated. This reveals how the hydroelectric generation system is still vulnerable to hydric stress events and that conflicts between multiple water uses remain imminent in such situations, which, as we have seen, would involve actors in uneven power relations.

Regarding affordability issues implied in the tariff raises due to the water crisis, as shown, the 2014–2015 crisis led to significant readjustments, which resulted in the creation of the tariff flag policy. Before the policy, readjustments occurred according to results from the previous year, so the goal was to control these readjustments through the flags that allowed for heavier tariffs in the moment of water stress situations. Comparing the changes in 2014 and 2015 with the ones in 2021 and 2022, the more moderate increase of the latter may be due to this control by the tariff flag policy, as in the old policy, losses in 2021 would be compensated in 2022. Still, the mean application tariffs in São Paulo increased above inflation in the period after the start of the tariff flag policy, as shown in Figure 4. Figure 6 shows the application of tariff flags from the policy approval in 2015 until 2022. In applying the policy, it is possible to see certain relations with the data from the marginal costs of operating from Figure 5. Still, it is essential to note that the tariff flags are applied nationwide, while the data refer only to a fraction of the Brazilian electric system, so discrepancies are expected.

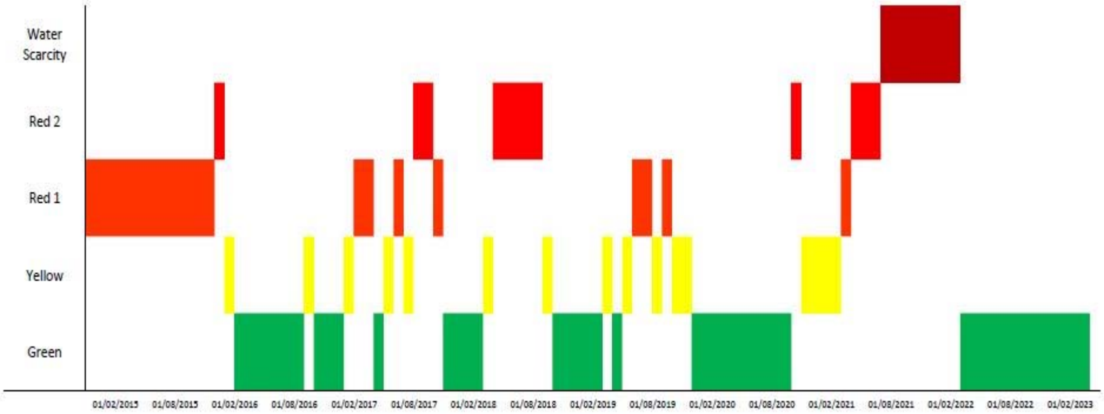

Figure 6. Tariff flags between 2015 and 2022

The tariff flag policy started in the middle of the water crisis with its first flag on Red 1, briefly reaching Red 2 until normalizing in 2016. Afterward, two peaks were encountered in 2017 and 2018, when the Red 2 flag was decreed. These correspond to the two smaller peaks in the marginal cost of operation in the same years, as seen in Figure 5. While the scenario of all other subsystems concurs with the definition of the flag, this shows that the water stress experienced does not have to be as severe as the 2014–2015 crisis for higher tariffs to be applied. For the following years, 2019 came to apply Red 1 on two occasions, 2020 saw a brief period of the Red 2 flag, and in 2021 the water crisis was again visible through the application of a new tariff flag, the "Water Scarcity" flag. This flag was created in consequence of the event that, as shown, led the marginal costs of operation to a historic high. The history of the application of the flag policy is more evidence of the dependence of the electric system of the whole country on hydraulic and fossil generation, with the high frequency of the application of higher tariffs exposing the users to elevated prices.

Further addressing distributional justice concerns, it is legitimate to question if someone benefits from this crisis by applying greater tariffs. Research assessing the impacts of the 2014–2015 water crisis on economic indicators from companies in the electricity sector, including generation, transmission, and distribution, showed that there was primarily a favorable impact of the water crisis for generation and transmission companies, with net profits improved by 189% in the transmission sector due to the crisis (Falcão et al., 2019). For distribution companies, the impacts on economic indicators were mixed but very significant, with positive outcomes in some and negative in others. In general, the crisis was relatively favorable for the sector. This indicates that a continuation of the hydraulic and fossil dependence model for the electric system in Brazil might be of interest to companies in the electricity sector. Moreover, it is of interest to the petrochemical sector, as the periodic usage of thermal fossil plants during hydric stress and the ample use of small-scale fossil plants implies greater consumption of fossil fuels, what may be seen as an obstacle for the just energy transition.

5. Conclusion

Significant challenges are ahead for a fair energy transition in São Paulo and Brazil, as we have attempted to show with this focused analysis on the state's electric matrix. Even though Brazil achieved many advances in decarbonization (E+, 2020), the dependence on hydroelectric generation ultimately means fossil dependence. Current energy planning in São Paulo, while referring to the state Climate Change Policy (São Paulo, 2012a), does not show any strategies for tackling this dependence. In fact, in the last decade, the presence of fossil generation has only deepened in the state, mostly still in the form of smaller plants, and the construction of the future 2,000 MW Lins plant means a significant change in the matrix composition in terms of installed potential and a further consolidation of the hydraulic and fossil dependence system. The state's electric matrix improved diversification in the period, especially through the growth of solar and biomass, but advancements are still largely insufficient for tackling fossil dependence, and the state's renewables' potential remains wasted. With no concrete actions to develop alternative renewable electricity generation by the state's government, the sector was left mainly to a market dynamic where the benefits from renewables are privately appropriated by large companies, leading to the results showing for solar, wind, and biomass. In this scenario, one question is why the choice to install 2,000 MW in a public-service fossil plant and not on renewable alternatives was made. The reliability of fossil generation can no longer be an excuse, as many technically viable alternatives are already present.

The matrix's dependence on hydraulics and fossils implies several vulnerabilities and issues, as shown by the principles in energy justice of availability, affordability, and intragenerational equity (Sovacool & Dworkin, 2015) in the two water crisis events we have investigated. Impacts on electricity availability were felt as the total output in the state decreased over the pertinent period. While this does not necessarily imply shortages, as energy is imported from other states, it means a decrease in energy sufficiency and an increase in dependency. The state depends more on the national interconnected system while contributing less to its maintenance. In scenarios where the whole country may be affected by drought and hydric stress, as is feared because of deforestation in the Amazon (Marengo & Alves, 2016), this may lead to more severe consequences on electricity availability.

Affordability issues appeared at the peaks 1) in the marginal costs of operation when more expensive thermoelectric generation was used to guarantee availability, and 2) in tariffs applied in the state, leading to the creation of the tariff flag policy because of the 2014–2015 crisis. Tariffs were substantially readjusted in 2014 and 2015, and even though the tariff flag policy has managed to avoid these major readjustments to date, the tax applied in São Paulo still increased above inflation in the years after the creation of the policy. This context means a more significant impact that affects middle- and low-income households the most, as electricity expenses compose a more substantial fraction of their budgets.

The frequency of activating the Red 1 and 2 tariff flags and creating the water scarcity flag in 2021 reveals an exposed electric system that is often forced to burden its users with climatic variability. Issues regarding intragenerational equity appear entrenched in the very structure of the electric system, as well as in the manifestation of these structural aspects of the water crisis events. The structure of the country's electric system is one of dependence on hydraulics and fossils that favors market dynamics in the development of alternative renewables, unequally distributing its benefits while leaving ordinary users more exposed to this dependence. In the water crises we have studied, this led to inequity issues ranging from 1) conflicts in multiple water uses as the state pushed to continue electricity generation to 2) the possibility of companies in generation, transmission, and the petrochemical sector gathering economic benefits from crises.

In conclusion, a fair energy transition in São Paulo and Brazil requires pushing for significant structural changes in the established status quo of hydraulic and fossil dependence. The latest assessment report released by the IPCC

(2023) demonstrates that the severity and frequency of extreme climate events, including droughts, are virtually sure to increase with the rise in global temperatures, making the halting of emissions an imperative and exposing the necessity to build greater resilience in face of the climatic extremes. In the face of the imminence of this challenge, policies and planning remain insufficient for developing a large-scale renewable alternative for breaking the hydraulic and fossil dependence in a way that guarantees availability, affordability, and equity among the many different actors in the electricity system.

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