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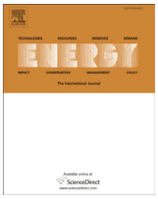

The trade-off between demand growth and renewables: A multiperiod electricity planning model under CO_2 emission constraints[☆]

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ABSTRACT

Under the Paris Agreement, each participant country established its Nationally Determined Contribution aiming at reducing its CO_2 emissions. This makes the trade-off between the electricity capacity expansion planning to meet the increase of demand and the reduction of greenhouse gas emissions a challenge, specially for developing countries, which require a higher rate of economic growth. To consider this trade-off, and identify the feasibility of the targets of the electricity expansion planning, a multiperiod optimization model is proposed considering the seasonality of supply and demand and the peak period demand. The goal is to minimize the total cost, satisfying demand constraints, the maximum CO_2 emission constraints and the power expansion supply restrictions for each source. An analysis of the Brazilian electricity matrix for the years 2020–2033 is performed considering two scenarios for the growth of the demand and two scenarios for the CO_2 target emissions The numerical simulations indicate that the present Brazilian electricity expansion planning seems adequate to meet the Nationally Determined Contribution only under a mild economic growth rate scenario. A higher economic growth rate would require a stronger economic policy related to the power expansions of the renewable sources.

1. Introduction

Each participant country of the Paris Agreement has established its Nationally Determined Contribution (NDC) to mitigate global warming. For that several actions and sectoral plans have been promoted over the last decade aiming at reducing emissions in order to achieve the NDC targets. Increasing the share of sustainable biofuels in the energy mix, enhancing policies regarding the forests and expanding the use of renewable power sources, are among the adopted strategies. For instance, to attain the NDC reduction goals (see Refs. [1]) the Brazilian government intends to achieve at least 23% of the share with renewable sources by 2030 ([2]). However in several developing countries the economic growth is associated with burning fossil fuel as CO_2 emissions decreases in times of GDP reduction (see, for instance, Bastida and Mc. Isaac [3] for the Brazilian case). Thus, achieving the commitment of reducing greenhouse gases under economic growth can be a challenge. On one hand the use of renewables sources play an important role regarding emissions reduction but, on the other, their capacity factors during peak hours as well as the seasonality in supply have to be into account in the electricity planning in order to assure energy security (see Ref. [4–6] and the references within). In Ref. [4] the authors use Integrated Assessment Modelling techniques to analyze future macroeconomic and energy scenarios for Brazil in a global context, aligned with the Brazilian NDC, and comment on the advantage of the addition of non-hydro renewables. Li et al. in Ref. [5] developed a fuzzy-stochastic simulation-optimization model for planning electric power systems considering peak demand under uncertainty. Staffell and Pfenninger ([6]) consider the gross demand after subtracting weather-dependent

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PV and wind generation and discuss decarbonization with renewable electricity.

The use of multiperiod optimization models for energy planning under environmental constraints has been receiving lately a great deal of attention. A small sample of papers dealing with these models includes [7], which presents a deterministic multiperiod mixed-integer linear programming (MILP) model for the power generation planning of electric systems and considering CO_2 emissions [8], which introduces a mathematical framework for planning an energy supply system taking into account factors affecting the total cost of supplying commercial energy such as market prices and waste disposal costs. In Refs. [9] it is proposed a multiperiod optimization problem for the integrated electricity expansion plan for Lesotho, with focus on the security of supply at national level. A multi-year stochastic generation capacity expansion planning model to investigate changes in generation building decisions and CO_2 emissions under environmental energy policies is proposed in Ref. [10], by using a scenario tree reducing to improve computation performance. In Ref. [11] a stochastic MILP model is introduced to address the problem of the optimal planning of a power system at an annual level in competitive and uncertain power markets. A MILP is also used in Ref. [12] to analyze the impacts on the power system expansion planning of implementing CO_2 and local pollutant emission taxes under five different policy-relevant scenarios. In Ref. [13] it is proposed a dynamic carbon-constrained equilibrium programming framework for the generation development planning on electricity markets over a multi-period horizon. A Pareto frontier for the multi-objective generation expansion planning problem that explicitly considers availability of the system components over the planning horizon and operational dispatching decision is proposed in Ref. [14]. The authors in Ref. [15] propose a tri-objective linear programming problem for generation expansion planning taking into account the total power generation, the total system cost, and the total CO_2 emission. Other related papers are [16] which addresses the long-term planning of electric power infrastructures considering high renewable penetration and using MILP [17], which proposes a generic mathematical model for developing a multiperiod CCS retrofit planning [18], which introduces the use of robust portfolio optimization for electricity planning, and [19] which presents a survey on optimization models for the solution of planning problems related to power distribution systems. Most of the aforementioned papers deal with the annual average production and demand of electricity.

In order to derive a more reliable model for a country highly dependent on renewable sources, it is important to consider the seasonality of supply and demand, as the complementarity between wind, water and bioelectricity during dry and wet seasons can provide a better optimization of these resources ([20]). The role of weather patterns has been treated in the literature under different approaches. Thornton et al. ([21]) discuss how wind power can contribute to the supply during high and peak demand. The intermittence of wind and solar power plants makes the peak power supply an important variable, both in long and short run planning, as they increase the uncertainties in the system [22], resulting in a higher use of non renewable sources. Thus, peak demand shall be a concern in electricity capacity planning when renewables are considered as to promote decarbonization. As a sample of works dealing with the electricity planning during the peak hours the reader is referred to the papers [5] (already mentioned above) and [23–26] and the references within. In Ref. [23] the authors analyzed the residential response to electricity critical-peak pricing. In Ref. [24] it is presented a methodology for the application of a critical peak pricing electricity demand response program for the manufacturing enterprises, and [25] proposes a Bayesian Network complex system model to analyze a residential peak demand reduction program. A mixed-integer approach for energy resource scheduling in smart grids considering that the peak load is scheduled in terms of day ahead, hour ahead and 5 min, is proposed in Ref. [26].

Bearing all these factors in mind this paper proposes a multiperiod linear programming model for the power generation planning of electric systems taking into account CO_2 emissions and the power expansion supply restrictions for each source. Differently from previous multiperiod electricity planning papers which deal with an annual average production and demand, the present paper focus on an intermediate approach, balancing supply and its cost in the dry and wet seasons. As a case study, the model will be applied to the electricity planning in Brazil for the years 2020–2033 (14 years).

In the power sector, Brazil is heavily dependent on renewable sources, which account for around 80% of the power generating capacity. Although predominant in the Brazilian electricity mix, the country faced a reduction of the hydropower share during the last few years as a result from droughts and also from policies that increased the share of other renewables (solar, wind and biomass). A key issue in Brazil is the increase of fossil fuel thermoelectric plants to assure the reliability of the system, thus reducing CO_2 savings. For example, in 2018, the average demand for power plants supervised by the Brazilian National Operator (ONS - Brazilian acronyms, see Ref. [27]) was 63,293 average MW. On the other hand, during the 3 regulatory hours of peak period the demand was 71,175 average MW, and the highest instantaneous demand in 2018 reached 84,976 average MW. In this way, the generation and its transmission network must be able to meet these demands, and also have enough left over to compensate for eventual failures of generation and transmission equipment at this time.

Summing up, the main contributions of this paper are:

1) A multiperiod optimization model is developed to plan the electricity matrix that meets the expected electricity demand under CO_2 constraint targets and power expansion supply restrictions for each source. The model is formulated as a linear programming problem and yields to the optimal expansion of the electricity matrix as well as the optimal dispatch from each technology in each season.
2) This model will be applied for the electricity planning in Brazil for the years 2020–2033, considering the peak period and the dry and wet seasons. Constraints related to the CO_2 emissions and power expansions are also taken into account.
3) Based on this model an analysis of the feasibility of achieving the Brazilian NDC goals under alternative economic scenarios is performed considering costs, CO_2 target emissions, expected electricity demand, and power expansion of the sources.

The paper is organized as follows. In Section 2 it is presented the multiperiod optimization model, formulated as a linear programming problem, to plan the electricity matrix under CO_2 constraint targets. Section 3 presents a case study, applying the model for the electricity expansion planning in Brazil for the years 2020–2033. Section 4 presents and discusses the obtained results. The paper is concluded in Section 5 with some final conclusions.

2. The optimization model

The main purpose of the model is to decide on new expansion in capacity and on the dispatch strategy for different power sources (hydro, wind, thermo, nuclear, solar) considering various generation technologies, aiming to attend the peak demand of the country during different annual seasons. The deterministic discrete multiperiod electricity planing model considers a finite time horizon, in years, and assumes two different yearly seasons: wet (w) and dry (d). The construction time of each technology is assumed to be known and no delays are considered. The goal is to decide on new expansions for each technology and to obtain the optimal despatch to meet the electricity demand during the peak period in each season. Without loss of generality, the decision of building a new plant is taken always at the beginning of the year and the plant is operational at the beginning of the year after the construction lag time is completed. The model considers variable and fixed operating costs, the latter being proportional to the generation capacity. The total cost is linear and the objective is to find the minimum cost capacity expansion planning. The electricity demand is deterministic, and shall be attended in each period. To achieve a more realistic planning, for each technology, constraints on the power expansion and lower bounds for generation due to contracts already active are adopted. Upper bounds for the CO_2 emissions are also taken into account.

In summary, the inputs, constraints and outputs of the model (to be detailed in the next sub-section) are as follows:

- Inputs: Fixed and variable operating costs, volume of greenhouse gases emission, construction times, installed generation capacity with its lower bound, increase in power generation capacity with its lower bound.
- Constraints: Electricity demand, maximum CO_2 emission, generation lower bound, expansion supply restrictions.
- Outputs: Capacity of new power stations, electricity power expansion, dispatch of each technology with its lower bound.

2.1. Nomenclature

In this sub-section it is presented the nomenclature used to define the optimization model. The indexes and sets associated to the optimization model are as follows:

- H: Time horizon (in years).
- $\mathscr{H} = \{1, \dots H\}$.
- $t \in \mathscr{H}$: superscript index for the time period (in years).
- N: Number of available technologies.
- $\mathscr{N} = \{1, \dots N\}$.
- $i \in \mathscr{N}$: subscript index for the technology.
- $s \in \{d, w\}$: superscript index indicating the dry season ($s = d$) or the wet season ($s = w$).
  Next it is presented the input parameters of the optimization model.
- F_i^t: Fixed operating cost for technology i at period t (in \$/MW).
- C_i^t: Variable operating cost for power generation using technology i during period t (in \$/MWh).
- G_i: Volume of greenhouse gases emission by MWh for the source i, in gCO_2/MWh.
- $D^{t,s}$: Electricity demand during period t (MWh/year) and season s.
- $E^{t,s}$: Maximum CO_2 emission during period t (MWh/year) and season s, in gCO_2/year.
- $S_i^{t,s}$: Lower bound for generation through technology i at period t and season s.
- $V_i^{t,s}$: Installed generation capacity for technology i at period t and season s[1].
- T_i: Construction time for a plant using technology i.
- Δ_i^s: Increase in power generation capacity when technology i begins operation during season s (in MWh/year for each installed capacity in MW).
- Γ_i^s: Increase in power generation lower bound (due to contract obligation) when technology i begins operation during season s (in MWh/year for each installed capacity in MW).
- $R_i^{t,s}$: Expansion supply restrictions of each source i, during season s at the year t (in 10^3 MWh/year).
  The decision variables of the optimization model are presented below:
- y_i^t: Capacity of a new power station using technology i (in MW), which begins the operation at year $t + T_i$, $i \in \mathscr{N}$, $t = 1, \dots, H-1$.
- $v_i^{t,s}$: Expansion for the electricity power available for technology i, during season s and at the year t (in 10^3 MWh/year), $i \in \mathscr{N}$, $t = 2, \dots H$, $s \in \{d, w\}$.
- $s_i^{t,s}$: Dispatch lower bound due to the expansion for technology i, during season s and at the year t (in 10^3 MWh/year), $i \in \mathscr{N}$, $t = 2, \dots, H$, $s \in \{d, w\}$.
- $w_i^{t,s}$: Dispatch for technology i, during season s and at the year t (in 10^3 MWh/year), $i \in \mathscr{N}$, $t \in \mathscr{H}$, $s \in \{d, w\}$.

Notice that the decision variables y_i^t goes from $t = 1$ up to $H-1$ since, due to the time-lag, it would be useless to install a new power station in the last year. Notice also that these variables don't depend on the season s.

It will be convenient to define $v_i^{1,s} = V_i^{1,s}$, $s_i^{1,s} = S_i^{1,s}$, $i \in \mathscr{N}$, $s \in \{d, w\}$. The following auxiliary parameters are defined, which gives the power increment ($\zeta_i^{t+1,s}$) and lower bound dispatch increment ($\phi_i^{t+1,s}$) of new stations which were already planned to be built or plants that have to be shuttled down. For $t = 1, \dots, H-1$ set[1]

$$\zeta_i^{t+1,s} = V_i^{t+1,s} - V_i^{t,s}$$

$$\varphi_i^{t+1,s} = S_i^{t+1,s} - S_i^{t,s}$$

2.2. Optimization Model

The optimization problem that is proposed in this paper is defined as follows:

$$\min \quad \sum_{i=1}^{N} \Big(\sum_{t=1}^{H-1} F_i^t y_i^t + \sum_{t=1}^{H} C_i^t \left(w_i^{t,d} + w_i^{t,w} \right) \Big), \tag{1}$$

$$\text{subject to}: \ v_i^{t+1,s} = v_i^{t,s} + \zeta_i^{t+1,s}, \ \text{for}\, i \in \mathscr{N}, t = 1, \dots, T_i, \ s \in \{d, w\}, \tag{2}$$

$$\begin{gathered} v_i^{t+1,s} = v_i^{t,s} + \Delta_i^s y_i^{t-T_i} + \zeta_i^{t+1,s}, \\ \text{for } i \in \mathscr{N}, t = T_i + 1, \dots, H-1, \ s \in \{d, w\}, \end{gathered} \tag{3}$$

$$s_i^{t+1,s} = s_i^{t,s} + \phi_i^{t,s}, \quad \text{for } i \in \mathscr{N}, t = 1, \dots, T_i, \ s \in \{d, w\}, \tag{4}$$

$$\begin{gathered} s_i^{t+1,s} = s_i^{t,s} + \Gamma_i^s y_i^{t-T_i} + \phi_i^{t+1,s}, \\ \text{for } i \in \mathscr{N}, t = T_i + 1, \dots, H-1, \ s \in \{d, w\}, \end{gathered} \tag{5}$$

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[1] Note that this includes expansions already contracted and plants to be shuttled down.

$$s_i^{t,s} \le w_i^{t,s} \le v_i^{t,s}, \quad \text{for } i \in \mathscr{N}, t \in \mathscr{H},\ s\in\{d,w\}, \tag{6}$$

$$\sum_{i=1}^{N} w_i^{t,s} \ge D^{t,s}, \quad \text{for } t \in \mathscr{H},\ s\in\{d,w\}, \tag{7}$$

$$\sum_{i=1}^{N} G_i w_i^{t,s} \le E^{t,s}, \quad \text{for } t \in \mathscr{H},\ s\in\{d,w\}, \tag{8}$$

$$\sum_{k=T_i+1}^{t} \Delta_i^s y_i^{k-T_i} \le R_i^{t,s} \quad \text{for } t = T_i+1, \ldots, H,\ s\in\{d,w\}, \tag{9}$$

$$y_i^t \ge 0,\ i\in\mathscr{N},\ t=1,\ldots,H,\ w_i^{t,s} \ge 0,\ i\in\mathscr{N},\ t\in\mathscr{H}, s\in\{d,w\},$$
$$v_i^{t,s} \ge 0,\ s_i^{t,s} \ge 0,\ i\in\mathscr{N},\ t=2,\ldots,H,\ s\in\{d,w\}.$$

Next it is presented an explanation for each of the equations (1)–(9).

a) Equation (1) represents the value function to be minimized, the fist term $\sum_{t=1}^{H-1} F_i^t y_i^t$ is the fixed cost for providing an expansion of y_i^t MW for the technology i at time t, which will start operation at time $t+\ T_i$, and the term $\sum_{t=1}^{H} C_i^t (w_i^{t,d} + w_i^{t,w})$ is associated to the running cost for dispatching $w_i^{t,s}$ (in 10^3 MWh/year) using the source i at time t and during the season s.

b) Equations (2) and (3) are related to the expansion for the electricity power available for technology i, during season s and at the year t (in 10^3 MWh/year). Notice that new plants will only be included in the matrix after the time lag T_i, so that a decision taken at time t will only be account to the energy expansion at time $t+T_i$ (equation (3)). Before that the adjusts are only to the decisions already taken before time $t\ = 1$.

c) Equations (4) and (5) are related to the increase in power generation lower bound (due to contract obligation) for technology i, during season s and at the year t (in 10^3 MWh/year). Similar reasoning concerning the time-lag T_i as in item b) applies here.

d) Inequalities (6) represent the lower and upper bound for the dispatch $w_i^{t,s}$ from the source i at time t and during the season s (in 10^3 MWh/year).

e) Equations (7) and (8) are related to meeting the electricity demand and maximum greenhouse emissions at time t and during the season s (in 10^3 MWh/year and gCO_2/year respectively).

f) Equation (9) is related to the expansion supply restrictions of each source i, during season s at the year t (in 10^3 MWh/year).

3. Case study: The Brazilian electricity expansion planning

Despite the great complexity of its electricity generation system, due to the territorial extension and the diversity of the country, Brazil is a successful example of using renewable sources for electricity generation. The regulation of the Brazilian power sector is controlled by the government through the Brazilian Electricity Regulatory Agency (ANEEL), responsible for contracting the generation. Thus, to provide long terms energy contracts the Brazilian government conduces electricity auctions as part of the mechanisms to ensure supply. ANEEL also establishes the peak period as a period of 3 consecutive daily hours with high electricity consumption. Based on the period of maximum demand along the year, this study adopts the period from 5 p.m. to 8 p.m. as the peak period.

The Brazilian power sector is highly dependent on hydroelectricity, leading to a high vulnerability to droughts (see, for instance Ref. [28]). In the past the power generated could meet the demand even during peak periods. Given the good hydro resource in reservoirs, the system could meet the flexibility requirements of the system by ramping up and down when needed. In this way the hydro resource was able to compensate for any sudden changes in demand or fluctuations in the production of the so-called intermittent power plants, whose production undergoes random variations. But due to environmental constraints this has changed since new hydroelectric plants do not have reservoirs, so that the hydroelectric generation's own predominance in the system is diluting and the participation of intermittent sources has increased considerably. Due to that, currently thermoelectricity has been the main alternative to meet this critical peak demand, yielding to the use of fossil fuel technologies. Fig. 1 shows the evolution of electricity demand as well as the maximum level of the reservoirs of the Brazilian hydroelectric system (year 2000 = 1, for both), illustrating this affirmation. It can be seen that while demand has grown by approximately 70% over the past two decades, water storage capacity has grown just over 20%.

Fig. 2 illustrates the generation of electricity by source: hydro, thermal, wind, nuclear and photovoltaic, confirming the last argument regarding the greater participation of intermittent renewable sources. It can be noticed that hydropower generation has already represented more than 90% of the Brazilian electricity generation but, however, in recent years it has been around 70%.

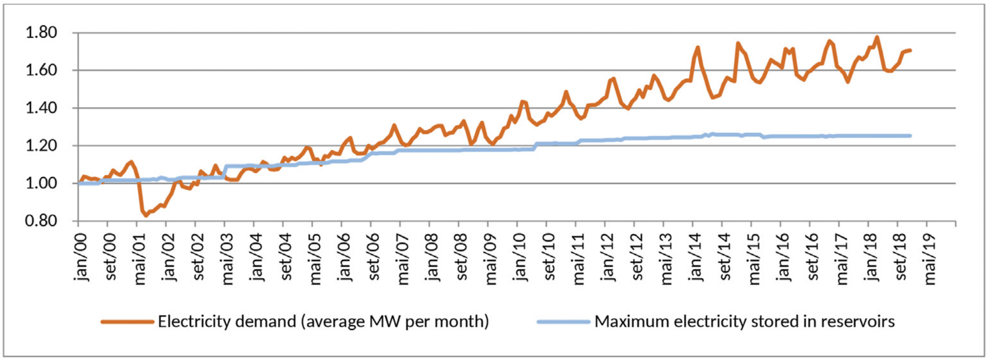

Fig. 1. Electricity demand and maximum energy stored in the reservoirs. Source: [27].

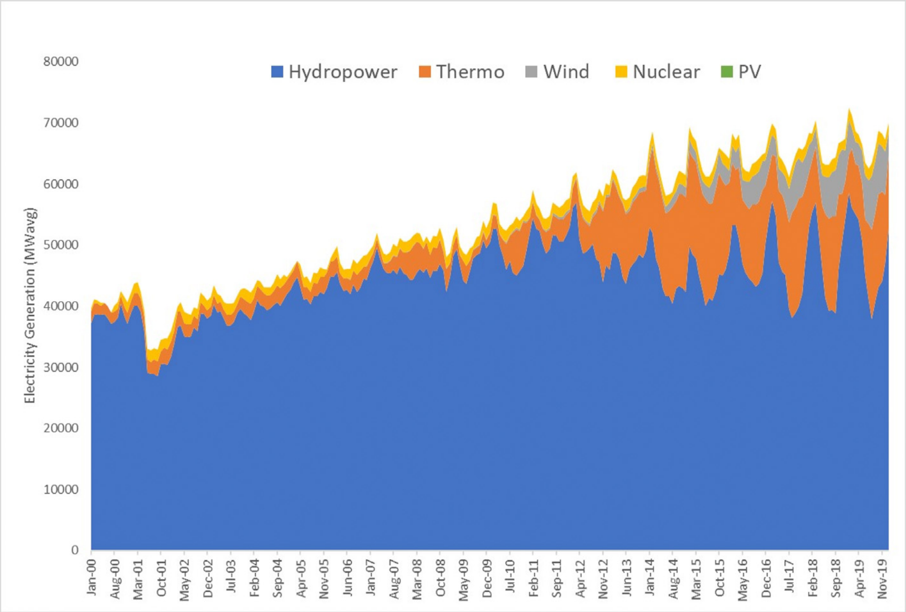

Fig. 2. Electricity generation by source. Source: [27].

3.1. *Demand and supply*

This study focus on the electricity demand and supply for the wet and dry seasons. This separation was done because the Brazilian electricity matrix is highly hydroelectric (see Fig. 1), and both demand and supply present different profiles according to the season. On one hand there is greater use of air conditioning during the wet season (summer is hot and rainy in the southern hemisphere), on the other hand, there is an increased use of electric shower during dry winter. Fig. 3 presents the average demand profile of the year 2018, in average *MW* per hour, during both the wet and dry periods.

With a very similar behavior, the electricity supply also presents seasonality and differs significantly during wet and dry seasons. For hydroelectric power plants, the highest generation is obviously in the wet period, approximately 24% higher than dry period. Fig. 4 shows the maximum hydroelectric generation during the period of 1 h, for each month of the year. Regarding the wind generation, there is a huge difference between the dry and wet seasons: in the first one, the average wind capacity factor (average MW generation divided by installed capacity) from power plants into operation in Brazil is 56%, while during the wet season (summer) it is only 34%, as can be noticed from Fig. 5. Sugarcane biomass electricity generation in its turn also shows a very seasonal profile, with a predominant generation in the dry period (see Fig. 6).

The reliability in the operation of power systems depends on the capacity of attending peak demand. Although promoting renewable generation technologies shall be a concern regarding emissions reduction, the capacity factor during peak hours must always be taken into account. Solar photovoltaic generation, for instance, is a renewable power source with a very distinct behavior throughout a daily cycle being unsuitable to attend peak demand. It usually reaches its maximum availability value in the periods of average load that usually occurs from 1:00 p.m. to 3:00 p.m., and is null in periods of heavy load, which usually occurs from 7:00 p.m. to 9:00 p.m. ([27]). The sugarcane biomass electricity generation, in its turn is continuous (flat) during the dry period, since this is the cogeneration of the ethanol and sugar industry, but during the wet

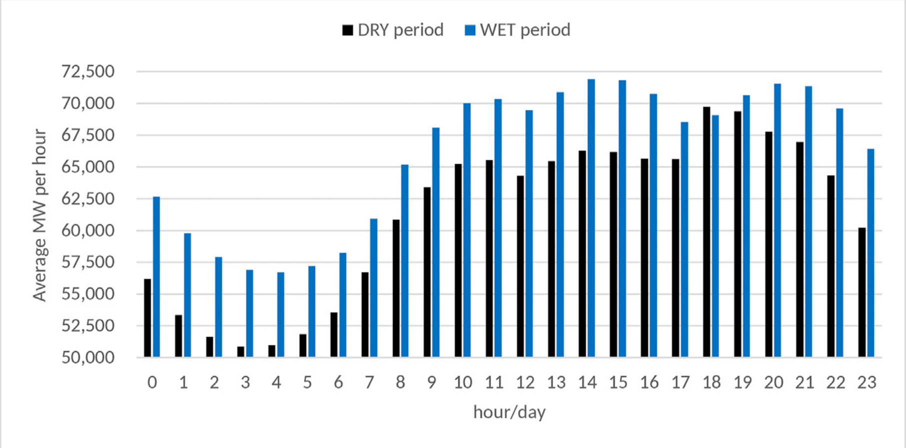

Fig. 3. Average electricity demand per hour of the day, during wet and dry seasons. Source: [27].

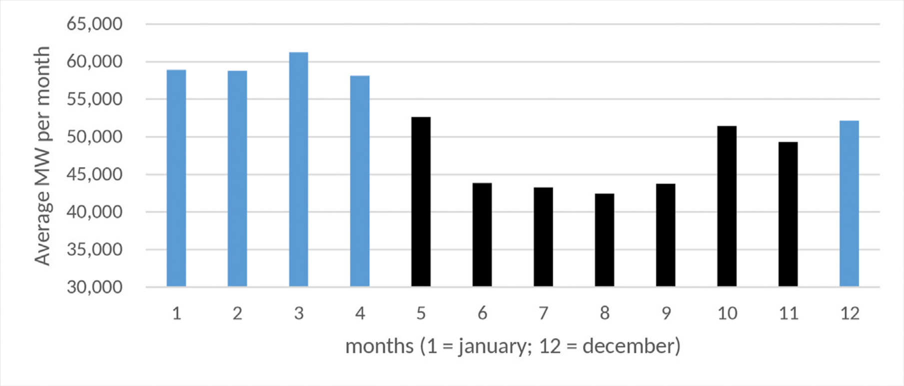

Fig. 4. Seasonality of hydropower generation - top hourly generation [black bars: dry period; blue bars: wet period]. Source: [27]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

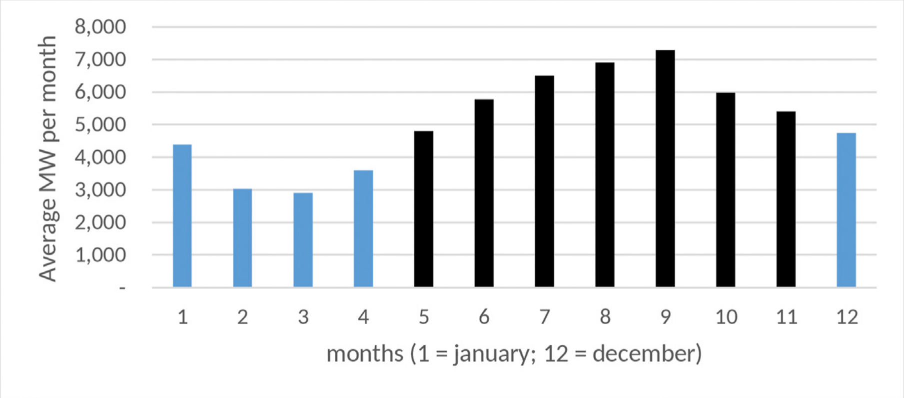

Fig. 5. Seasonality of wind generation [black bars: dry period; blue bars: wet period]. Source: [27]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

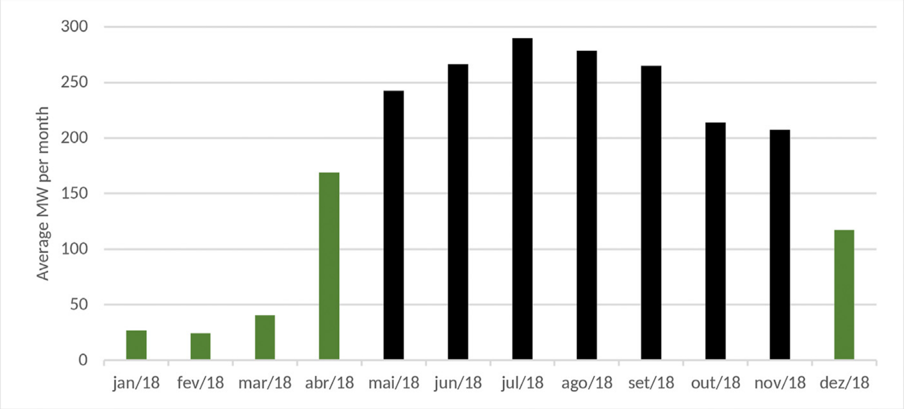

Fig. 6. Seasonality of sugarcane biomass electricity generation. Source: [27].

periods, at the end of the harvest season, this reduces to zero. CO_2 emissions increase strongly with thermal power plants such as oil, gas and coal-fired, but their operational flexibility allows their use regardless the season.

3.2. Parameters

This sub-section describes the main parameters considered in the Linear Programming multiperiod electricity planing model introduced in Section 2. It is based on the data obtained from Refs. [27,29–34] as well as on discussions with experts on the matter in the Brazilian energy sector.

3.2.1. Lifetime, construction periods and costs ($F_i^t C_i^t$, T_i)

This paper considers that a power plant has two revenues (and so, two costs to consumers): fixed revenue (BR$ per year) and

Table 1
Economic assumptions. Source: Based on [29].

Technology (i)	BR$/year ($F_i$)	BR$/MWh ($C_i$)	Time (years) (T_i)	Lifetime (years)
1-Hydro	484, 741	9.95	5	80
2-Itaipu Hydro	–	9, 95	–	–
3-Small hydro	715, 373	15.13	2	60
4-Wind	444, 446	20.46	2	25
5-Biomass	416, 165	20.63	2	25
6-PV	400, 001	16.91	1	25
7-Nuclear	1, 532, 613	24.94	7	50
8-Natural Gas (50% flexible)	327, 921	263.82	4	30
9-Coal	747, 673	199.59	4	40
10-Oil	348, 488	509.84	2	30
11-Diesel	219, 530	810.00	2	30
12-Natural Gas (100% flexible)	327, 921	316.09	4	30

variable revenue (BR$ per MWh of electricity generation). The first one comprises the cost of capital, debt interest, financial fees, taxes, connection charge, fixed operations and maintenance (O&M) costs, and general administrative expenses, while the latter comprises the fuel and variable O&M costs.

Capital expenditure and annual generation from each source were obtained from Ref. [29], which publishes the data of which power plant has sold electricity in regulated procurement electricity auctions for new ventures (electricity supply expansion procurement auctions). Variable costs were obtained from Ref. [27], since ONS is the Brazilian organization responsible for the system dispatch by merit order.

Besides, it was considered the lifetimes and construction periods given in the Table 1. Four different WACCs were considered (from each different unlevered beta given by Ref. [35] - but the same risk free, market risk premium, country risk premium, cost of debt and leverage were considered): 10.11% p.y. for non-conventional renewables (PV, wind, sugarcane biomass and small power plant); 11.18% p.y. for coal power plants; 10.19% for oil and gas power plants; and 8.47% p.y. to other sources - hydro and nuclear power plants.

It is important to highlight that for the construction period, it was considered the total period between decision investment date and the beginning of commercial operation, which includes time for obtaining both environmental licenses (considering that all environmental studies were already done and pre-approved), and regulatory licenses and agreements with: (i) ANEEL (also considering that the engineering project was already done and pre-approved by this agency); (ii) ONS ([27]) regarding connection agreement to the grid, and CCEE (Electric Energy Trading Chamber [29]) in order to connect the power plant to the metering and billing systems.

Table 2
Greenhouse gases emission. Source: Based on [32].

Source	(G_i) gCO_2/MWh
Hydro	16, 150
Itaipu Hydro	6, 300
Small hydro	6, 300
Wind	2, 500
Biomass	8, 400
PV	8, 200
Nuclear	2, 500
Natural Gas	106, 000
Coal	206, 000
Oil	149, 000
Diesel	149, 000

3.2.2. *Volume of greenhouse gases emission* (G_i)

The values of the greenhouse gases emission (parameter G_i, for the source i), based on the data from Ref. [32] and discussions with experts, are summarized in Table 2.

3.2.3. *Power generation capacity* (Δ_i^s, Γ_i^s)

Table 3 presents the increase in power generation capacity (in MWh/year) when 1 MW of installed power using technology i begins operation at period t (Δ_i^s) as well as the increase in the power generation lower bound (Γ_i^s), due to contract obligation.These parameters take into account the capacity factor for each technology i during season s.

3.2.4. *Power supply* ($V_i^{t,s}$, $S_1^{t,s}$, $R^{t,s}$)

As this study considers the electricity demand and supply during the 3 h-peak period for the wet and dry seasons, it is necessary to specify the capacity parameters. The average of the maximum

Table 3
Increase in power generation capacity (Δ_i^s) and lower bound (Γ_i^s) in MWh/year for 1 MW of installed power. Source: Based on [29].

Technology (i)	MWh/year (Δ_i^d)	MWh/year (Γ_i^d)	MWh/year (Δ_i^w)	MWh/year (Γ_i^w)
	Dry Season	Dry Season	Wet Season	Wet Season
1-Hydro	320	0	283	0
2-Itaipu Hydro	0	0	0	0
3-Small hydro	359	359	318	318
4-Wind	304	304	133	133
5-Biomass	401	401	0	0
6-PV	0	0	0	0
7-Nuclear	462	462	330	330
8-Natural Gas (50% flexible)	520	0	372	0
9-Coal	520	0	372	0
10-Oil	520	0	372	0
11-Diesel	520	0	372	0
12-Natural Gas (100% flexible)	520	0	372	0

hydro generations for both dry and wet seasons was considered as supply for the peak periods. Besides, according to Ref. [27], during the periods of heavy load, the wind generation is on its daily average, so, this article is going to consider the capacity factor as shown in Fig. 5. As discussed in sub-section 3.1, the sugarcane (biomass) electricity generation is continuous, and this article will consider for the peak periods, the values shown in Fig. 6 for each month in the dry period, and, with a more conservative approach, 0 in the wet period. Solar generation was not considered since its maximum availability does not coincide with peak-demand periods. Besides, wind power, sugarcane bagasse electricity, small hydropower plants (power plants lower than $30MW$ and without reservoir by Brazilian regulation) and nuclear power plants are inflexible, that is, they do not store electricity. Notice that nuclear plants are considered inflexible since, in the most economical and technically simple mode of operation, it may take many hours, if not days, to startup or to change their power output, primarily due to the fact that they require a long period of time to heat up the nuclear steam supply system and the turbine-generator to operating temperature. On the other hand, for thermal power plants such as oil, gas and coal-fired, operational flexibility was considered since they are able to ramp up or shut down relatively quickly so that hourly modulation is possible regardless of the season. Due to that it was considered for thermal power plants during the peak period a capacity factor of 95%.

In Table 4 it is presented, based on [33,34], the maximum peak period electricity power available ($V_i^{t,s}$), all in 10^3 MWh/year, during the dry season ($s = d$) and wet season ($s = w$) at the year t, starting at the year 2020 and going up to year 2033. Note that the increase or decrease in the power availability is due to ongoing expansion projects that were decided in the past with conclusions in the next 4 years or plants that will be shuttled down. The dispatch lower bound for the large hydro ($S_1^{t,s}$) due to contract obligations, is $5,749$ 10^3 MWh/year in the dry season and $4,106$ 10^3 MWh/year in the wet season along all the years from 2020 up to 2033. All the other renewable sources as well as the nuclear power are inflexible, so that everything that is produced has to be dispatched. For the fossil fuels the dispatch lower bound is zero.

One of the most important constraints of the portfolio model is the expansion supply restrictions of each source, denoted by $R^{t,s}$ (in 10^3 MWh/year) in (9). It is presented in Table 5 the values for the expansion supply restrictions of each source. This data was based on some interviews with Brazilian energy experts and [33,34], and adopting the following assumptions:

- hydropower: this article considered the expansion capacity that is planned by the government company EPE-2018 (see Ref. [33]), which is the possible technical and environmental potential. Since hydrological expansion is concentrated in the Amazon region, environmental constraints strongly limit the expansion of this source.
- small hydroelectric plants: the annual construction limit set by EPE-2018 ([33]) was also used.
- wind: this paper considered 125% in the first years up to 200% in the tenth year of the total annual megawatts that wind energy associations ask for the government, as public policy, to be contract in regulatory procurement electricity auctions of new power plants.
- biomass: this article considered the annual capacity requested by the sugarcane association to be contracted into electricity auctions.
- natural gas: the paper considered the total capacity of the electricity procurement auction that contracted the most from this source as annual limit. It happened in 2014, and this value has not been exceeded yet.
- oil and coal: as annual limit, this paper considered the average of the four largest years of hiring these sources in electricity procurement auctions - those years were at the end of the last decade.

4. Results and discussion

To analyze the feasibility of moving to a cleaner electricity system, the optimization model was run under different scenarios, considering both the demand growth rate and the CO_2 target emissions, as summarized in Table 6.

In terms of the demand growth rate, two main scenarios are considered: Moderate Economic Growth and Optimistic Economic Growth. The difference between them lies from small to major advances in the national regulatory framework, analyzing a poor investment flow to a more significant increase over time, creating a context of return to normality and stability of legal-institutional regulations. In a very favorable environment, the Optimistic scenario, investment is expected to increase more intensively, highlighting the increased competitiveness of the Brazilian economy; through the continuity and deepening of policies to stimulate innovation (R&D) and improvements in education, resulting in higher levels of productivity. The macroeconomic framework would land to more stable levels, based on a clean floating exchange rate, with controllable inflation and low interest rates, as well as the return of consecutive primary surpluses, reducing the public sector net debt, making the economy more robust to the eyes of domestic and foreign investors. In this sense, it will be assumed that under the Moderate scenario the Brazilian economic growth will yield to an increase of the electricity demand, on average, of 1%

Table 4
Maximum peak period electricity power available ($V_i^{t,s}$) for technology i, during season s and at the year t (in 10^3 MWh/year) Source: Based on [33,34].

Season	Dry				Wet			
	2020	2021	2022	2023	2020	2021	2022	2023
Hydro	32,659	32,659	32,704	32,704	28,915	28,915	28,955	28,955
Itaipu	3011	3011	3011	3011	2151	2151	2151	2151
Sm. Hydro	2391	2391	2499	2499	2117	2117	2212	2212
Wind	5370	5920	6469	6469	2352	2592	2833	2833
Biomass	5444	5694	5881	5881	0	0	0	0
PV	0	0	0	0	0	0	0	0
Nuclear	920	920	920	920	657	657	657	657
NG (50%)	7631	7631	7631	8411	5451	5451	5451	6008
Coal	1828	1828	1828	1828	1306	1306	1306	1306
Oil	1935	1935	1935	923	1382	1382	1382	659
Diesel	796	796	796	318	568	568	568	227
NG (100%)	0	0	0	0	0	0	0	0

Table 5
Expansion supply restrictions ($R_i^{t,s}$) of each source i, during season s at the year t (in 10^3 MWh/year), starting at the year 2021 (zero before that). Source: The authors.

Dry	21	22	23	24	25	26	27	28	29	30	31	32	33
Hydro	0	0	38	112	252	421	645	870	1094	1318	1542	1766	1990
Itaipu	0	0	0	0	0	0	0	0	0	0	0	0	0
Sm. Hydro	144	180	287	395	503	610	718	826	934	1041	1149	1257	1365
Wind	212	423	1184	2097	3010	3923	4989	6054	7119	8184	9250	10,315	11,380
Biomass	0	13	214	414	615	815	1016	1216	1417	1617	1818	2018	2219
PV	0	0	0	0	0	0	0	0	0	0	0	0	0
Nuclear	0	0	0	0	0	649	649	649	649	649	649	649	649
NG (50%)	0	780	780	1560	2341	3121	3901	4681	5461	6242	7022	7802	8582
Coal	0	260	520	780	1040	1300	1560	1820	2080	2341	2601	2861	3121
Oil	0	260	1533	1793	2053	2313	2573	2833	3093	3353	3613	3873	4133
Diesel	0	260	998	1258	1518	1778	2038	2298	2558	2818	3078	3338	3598
NG (100%)	0	780	1560	2341	3121	3901	4681	5461	6242	7022	7802	8582	9362
Wet	21	22	23	24	25	26	27	28	29	30	31	32	33
Hydro	0	0	33	100	223	373	571	770	968	1167	1365	1564	1762
Itaipu	0	0	0	0	0	0	0	0	0	0	0	0	0
Sm. Hydro	127	159	254	350	445	541	636	731	827	922	1017	1113	1208
Wind	93	185	519	918	1318	1718	2185	2651	3118	3584	4051	4517	4984
Biomass	0	0	0	0	0	0	0	0	0	0	0	0	0
PV	0	0	0	0	0	0	0	0	0	0	0	0	0
Nuclear	0	0	0	0	0	464	464	464	464	464	464	464	464
NG (50%)	0	557	557	1115	1672	2229	2786	3344	3901	4458	5015	5573	6130
Coal	0	186	372	557	743	929	1115	1300	1486	1672	1858	2043	2229
Oil	0	186	1095	1281	1466	1652	1838	2024	2209	2395	2581	2767	2952
Diesel	0	186	713	898	1084	1270	1456	1641	1827	2013	2199	2384	2570
NG (100%)	0	557	1115	1672	2229	2786	3344	3901	4458	5015	5573	6130	6687

Table 6
Scenarios considered for analysis.

		Economic Growth	
		Moderate	Optimistic
CO_2	Full emissions	S1: Reference Scenario	S3: Intensive Emissions
	Constrained	S2: Emissions Reduction	S4: Relatively Constrained

p.y. in real terms, and under the Optimistic scenario, the country's electricity demand growth will be, in real terms, of 3% p.y. on average.

4.1. Moderate economic growth

As explained at the beginning of this section, for the moderate economic growth an annual increase of 1% for the electricity growth rate was assumed. This will affect the input parameter denoted in (7) by $D^{t,s}$ (in 10^3 MWh/year), with t representing the year and s the dry ($s = d$) and wet ($s = w$) seasons. In 2019 the electricity power demand (in 10^3 MWh/year), during the 3 regulatory hours of peak was $57,798$ for the dry season and $42,837$ for the wet season, based on data from Ref. [27]. Two scenarios regarding the maximum CO_2 emission (denoted by the parameter $E^{t,s}$ in (8), in GtCO_2/year) are considered, as described next.

4.1.1. Scenario S1: Reference Scenario

Under the Reference Scenario, referred to as scenario S1, a constant value along the 14 years is considered, as obtained from the emissions of the 2019 Brazilian electricity mix. According to this mix, the carbon intensity in the Brazilian electricity generation (in Kg CO_2/MWh) is 31.544 for the dry season and 32.193 for the wet season. The value in the dry season is smaller than in the wet season due to the fact that it is only considered the biomass participation in the mix in the dry season. From that and the initial electricity demand it was fixed a constant value for $E^{t,d} = 1.823$ GtCO_2/year for the dry season, and $E^{t,w} = 1.379$ GtCO_2/year for the wet season (see Table 7).

4.1.2. Scenario S2: emissions reduction

Under the Emissions Reduction scenario, referred to as scenario S2, a decreasing value for the emissions, within the goals of the Paris agreement, which aims at reducing in 43% the total emissions from 2005 to 2030, is considered. In this case a decreasing factor of around 0.9778 per year is assumed, which would correspond to a decrease of around 43% of the initial value in 25 years. The values are presented in Table 7.

Table 7
Maximum CO_2 emission $E^{t,s}$, in GtCO_2/year, during the season s and at the year t, Scenarios S1, S2, S3 and S4.

Year	S1	S1	S2	S2	S3	S3	S4	S4
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
2020	1.823	1.379	1.783	1.348	2.086	1.578	2.086	1.578
2021	1.823	1.379	1.743	1.318	2.149	1.625	2.149	1.625
2022	1.823	1.379	1.704	1.289	2.214	1.674	2.214	1.674
2023	1.823	1.379	1.666	1.260	2.280	1.725	1.960	1.638
2024	1.823	1.379	1.629	1.232	2.348	1.776	2.019	1.687
2025	1.823	1.379	1.593	1.205	2.419	1.829	2.080	1.738
2026	1.823	1.379	1.558	1.178	2.491	1.884	2.142	1.790
2027	1.823	1.379	1.523	1.152	2.566	1.941	2.207	1.844
2028	1.823	1.379	1.489	1.126	2.643	1.999	2.273	1.899
2029	1.823	1.379	1.456	1.101	2.722	2.059	2.341	1.956
2030	1.823	1.379	1.423	1.077	2.804	2.121	2.411	2.015
2033	1.823	1.379	1.392	1.053	2.888	2.184	2.484	2.075
2032	1.823	1.379	1.361	1.029	2.975	2.250	2.558	2.137
2033	1.823	1.379	1.331	1.007	3.064	2.317	2.635	2.201

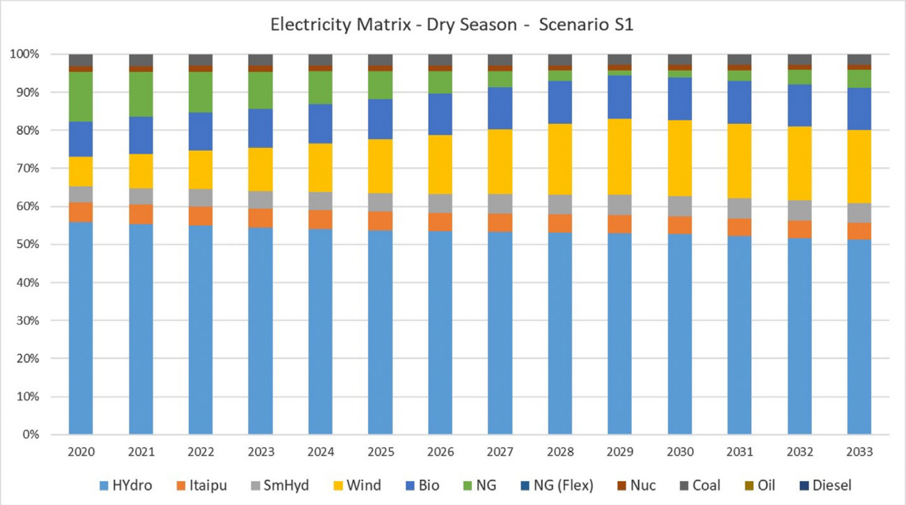

Fig. 7. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Dry Season, Scenario S1.

4.1.3. *Results for the moderate economic growth*

Considering the mild moderate economic growth scenario both problems were feasible. Figs. 9 and 10 present the electricity matrix along the years for the dry and wet seasons, under the Emissions Reduction scenario (scenario S2, corresponding to a decreasing value for the emissions). The case for the Reference Scenario (scenario S1), with constant value for the emissions, has a similar electricity matrix, as can be seen from Figs. 7 and 8, the main difference being the greater participation of the wind power generation in the former, in response to the CO_2 emission restrictions. For instance, in the year 2033 and dry period (wet period), the wind share in the scenario S2 is 22.4% (15.6%) while in scenario S1 it is 19.2% (13.7% respectively). It should also be noticed that the wind power is the source with the highest increase along the 14 years, starting with a participation of 7% in the dry and wet periods and reaching the values mentioned above in the year 2033.

Hydropower generation has a high but decreasing share in the matrix along the 14 years, starting with 66% in the dry season (77% in the wet season) and decreasing to 62% (73% respectively) in the year 2033. Similar behavior happens for the scenario S1. This is due, as pointed out before, to the environmental constraints that strongly limit the hydrological expansion.

Natural gas has a decreasing participation in the mix when emission is reduced, moving from 12% to 0% in 2033 during the dry period, and from 11% to 9% in the wet period. When emissions are assumed constant (scenario S1), this reduction is smaller, with a participation of 5% in 2033 during the dry period, and 11% in the wet period. This is due to the fact that a more severe constraint on CO_2 induces a greater participation of the wind power, and less of natural gas. Notice also that, as pointed out in sub-section 3.1, during the wet season, the biomass is not considered available, being partially replaced by natural gas. On the other hand, during the dry season, biomass is available, so that the natural gas share can be reduced during this season, explaining why its participation goes to 0% and 5% for the scenarios S2 and S1 respectively.

Comparing the emissions, when the goals of Paris agreement are considered, the emissions from the electricity matrix obtained for the year 2033 are around 25% lower than those obtained without this constraint (scenario S1). When the whole period is considered, the cumulative volume of emissions for the scenario S2 is around 7.5% lower than for the scenario S1. On the other hand, the total cost for the scenario S2 is around 2% higher than for the scenario S1.

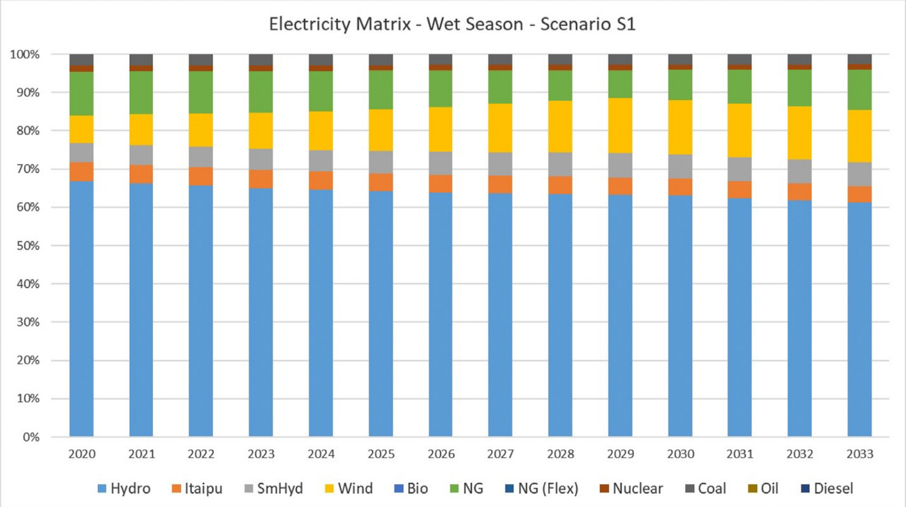

Fig. 8. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Wet Season, Scenario S1.

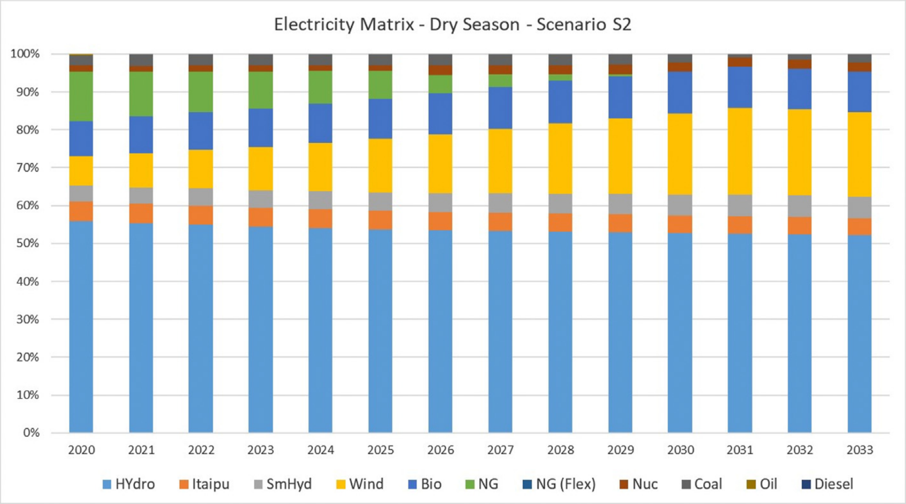

Fig. 9. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Dry Season, Scenario S2.

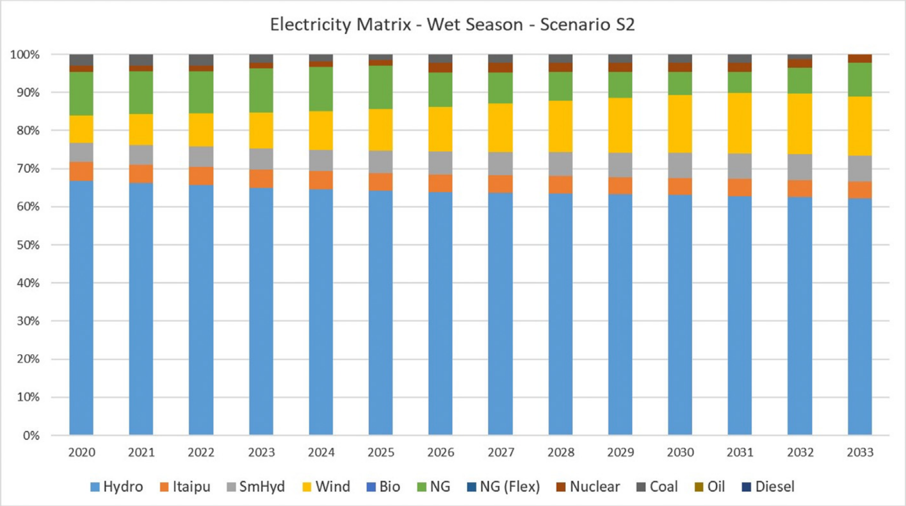

Fig. 10. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Wet Season, Scenario S2.

The electricity mix in terms of the installed capacity for the scenarios S1 and S2 are presented in Figs. 11 and 12 respectively. Again it should be noticed for both scenarios S1 and S2 the decreasing participation of the hydropower generation and increasing participation of the wind power.

In conclusion, under this mild basic electricity growth scenario, it seems that it is worth to consider more strict CO_2 constraints, bearing in mind that with the current electricity expansion planning it is possible to reduce the CO_2 emissions in 25% at the year 2033, at a total cost of around 2% more than the case with no CO_2 reductions.

4.2. Optimistic economical growth

In this sub-section an annual increase of 3% for the electricity growth rate is adopted, following the Brazilian optimistic economical growth scenario, as explained at the beginning of this section. In this case for the 14 years horizon, starting at the year 2020 up to the year 2033, the initial demands are as in the sub-section 4.1, that is, $57,798$ (dry season) and $42,837$ (wet season) and the final demands are $87,425$ (dry season) and $64,794$ (wet season), all in 10^3 MWh/year, representing an increase of around 51%.

This stronger electricity demand growth rate substantially changes the electricity planning problem, so that it is no longer realistic to consider a constant (or reduction) CO_2 emissions constraints as considered in sub-section 4.1. An attempt to solve the problem with these constraints will yield to unfeasible problems. Therefore, considering a more realistic scenario, the CO_2 constraints in this sub-section will aim at controlling the increase of the emissions, at a price of increasing the wind power expansion supply of the portfolio model (as little as possible to stay closer to the more realistic initial expansion planning), so that the problem becomes feasible. It was chosen the wind power since that, among the renewable sources, it is the one that has more possibility of increasing its availability along the next years in Brazil.

Bearing in mind the points raised above, two cases for the values of the maximum CO_2 emission $E^{t,s}$ were considered: Intensive Emissions (Scenario S3) and Relatively Constrained (Scenario S4), as presented in Table 6.

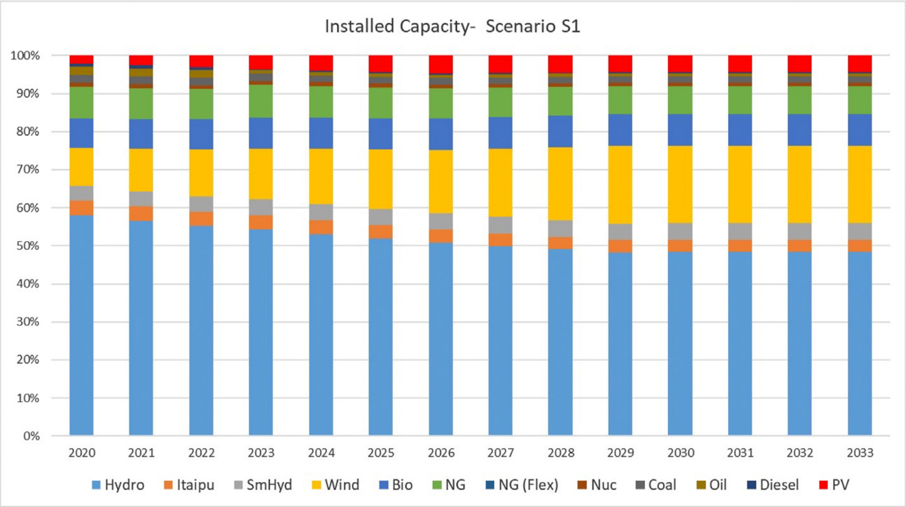

Fig. 11. Elect. mix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex), PV in terms of installed capacity, Scenario S1.

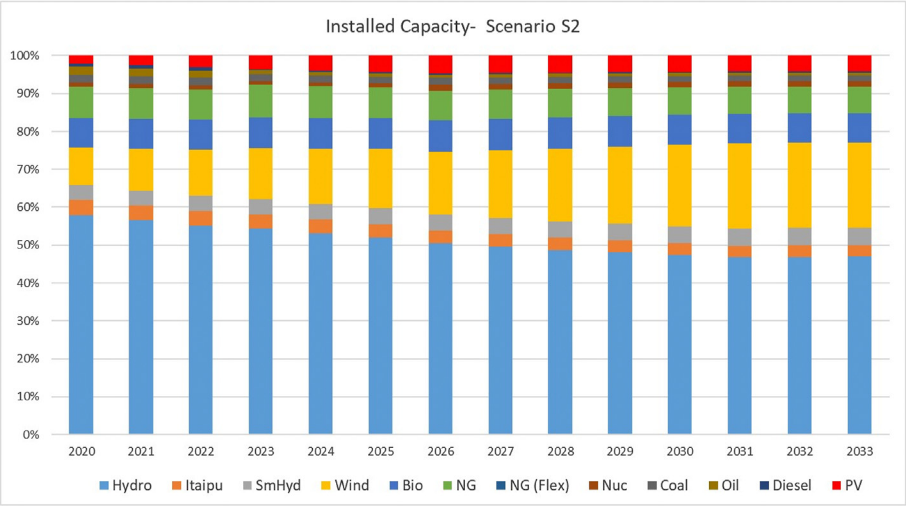

Fig. 12. Elect. mix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex), PV in terms of installed capacity, Scenario S2.

4.2.1. *Scenario S3: Intensive Emissions*

In this scenario an increasing value of emissions was obtained from the carbon intensity based on the 2019 Brazilian electricity mix generation multiplied by the expected electricity demand along the years. Since an annual increase of 3% for the electricity growth rate was assumed, this value is also applied to the emissions growth rate. The values are shown in Table 7.

4.2.2. *Scenario S4: Relatively Constrained*

For the first 3 years the same values for the maximum CO_2 emissions as in the previous scenario were considered, with annual growth rate of 3%. The reason for that is that in the first 3 years the capacity of expansion is very limited due to the time-lag for the construction of new projects, so that all the demand has to be met with existing projects. From the year 2023 on a reduction of14% the values of the maximum CO_2 emissions with respect to the values of the scenario S3 was considered for the dry season, and of 5% for the wet season. This choice was a trade-off between a reasonable reduction and increase in renewable sources so that a feasible solution could be obtained. The reason for the difference of 14% in dry season and 5% for the wet season is the biomass participation in the mix in the dry season, which allows to reduce the carbon emission during this period. The values are shown in Table 7.

4.2.3. *Results for the Optimistic Economic Growth*

Even considering increasing values for the maximum CO_2 emissions in the Optimistic scenario, the resulting problems were unfeasible as the expansion supply restrictions are too strong. To analyze this constraint, the wind power expansion supply was increased up to a point that the problems would become feasible. For the scenario S3 it was necessary to increase the wind power expansion in 45% and for scenario S4 in 70% (that is, multiply the values in Table 5 by 1.45 and 1.7 for scenarios S3 and S4 respectively). Notice that there is a great potential for increasing the wind power in Brazil and these values could be achieved, provided that there would have a strong investment for the construction of new wind power plants. Therefore this expansion would be possible and the main idea was to consider, under a strong growth in demand, what could be done in the electricity mix expansion to reduce the increase of CO_2 emissions. Since it is analyzed only the electricity sector, this increase of CO_2 emissions due to the strong growth in the electricity demand would have to be compensated taking

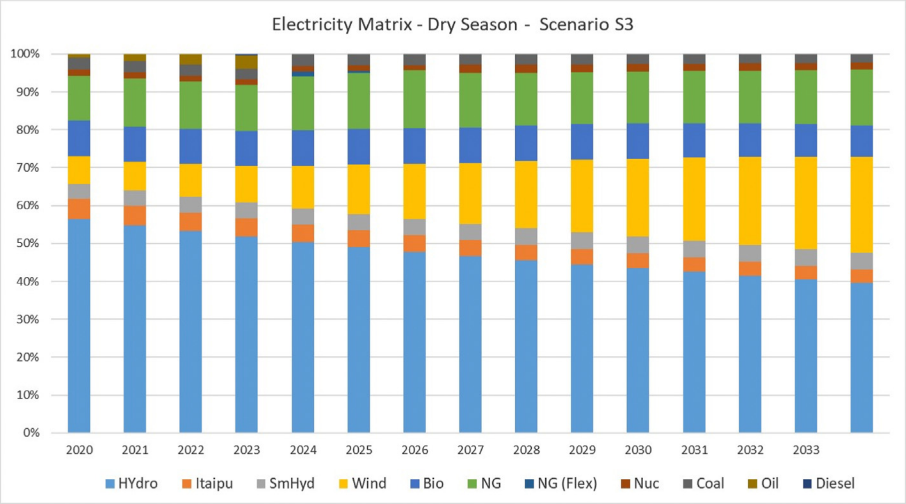

Fig. 13. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Dry Season, Scenario S3.

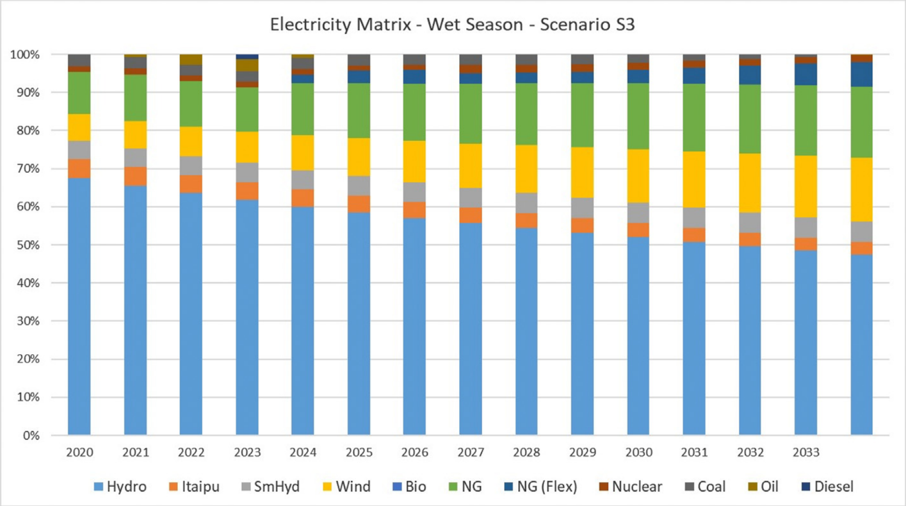

Fig. 14. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Wet Season, Scenario S3.

actions in other areas in order to meet the NDC agreement.

Figs. 13 and 14 present the electricity matrix along the years for the dry and wet seasons, corresponding to the scenario S3, while Figs. 15 and 16 show the results for scenario S4 (with a reduced increasing value for the emissions). The electricity mix in terms of the installed capacity for the scenarios S3 and S4 are presented in Figs. 17 and 18 respectively. As in sub-section 4.1 the main difference is the greater participation of the wind power generation under scenario S4, in response to the more restrictive CO_2 emissions constraint. For instance, for the year 2033 and dry period (wet period), the wind share in the scenario S3 is 25% (17%) while in the scenario S4 it is 29% (19% respectively).

The hydrological expansion is strongly limited since it is concentrated in the Amazon region, which is under several environmental constraints. Due to that and the increase of the electricity demand with respect to the framework studied in sub-section 4.1 it can be noticed (for both scenarios) that the share of hydro generation decreases from 66% (dry season) to 48%, and from 77% (wet season) to 56%. To meet the increasing electricity demand up to 2033, the wind generation increases its participation from 7% (dry and wet season) to 29% (dry season) and 19% (wet season). Natural gas had also a relevant increase in the matrix share in the wet season, going (scenario S4) from 11% to 23%, while in the dry season it keeps its share in 12% (similar results apply to scenario S3). Among the fossil fuels, natural gas is the most relevant one, with a contribution between 75% and 85% in the dry period, and 80% and 95% in the wet period (similar comments apply for the scenario S3). These points can also be observed from the installed capacity in Figs. 17 and 18.

Regarding the emissions, it follows that for the year 2033 the emissions from the electricity matrix obtained for the scenario S4 in the dry season are around 13% lower than the one for the scenario S3, and 5% lower in the wet season, in agreement with the fact that the scenario S4 is more restrictive about the CO_2 emissions. If it is considered the whole period of 14 years, it follows that the total emissions for the scenario S4 is around 5% lower than the one for scenario S3 with a total cost around 2% lower than for the scenario S3.

In conclusion, under this stronger electricity growth scenario, some effort to increase the expansion of renewable sources is crucial to reduce the increase in the CO_2 emissions. The numerical simulations presented in this sub-section indicate that an increase

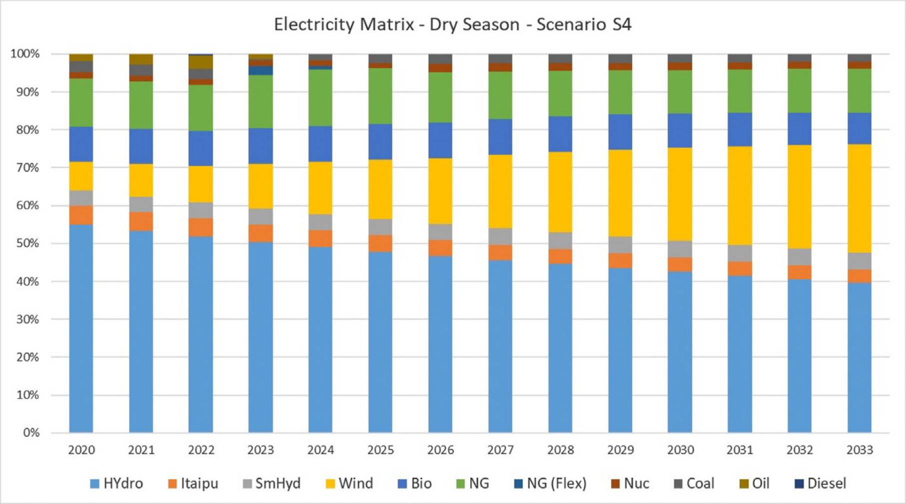

Fig. 15. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Dry Season, Scenario S4.

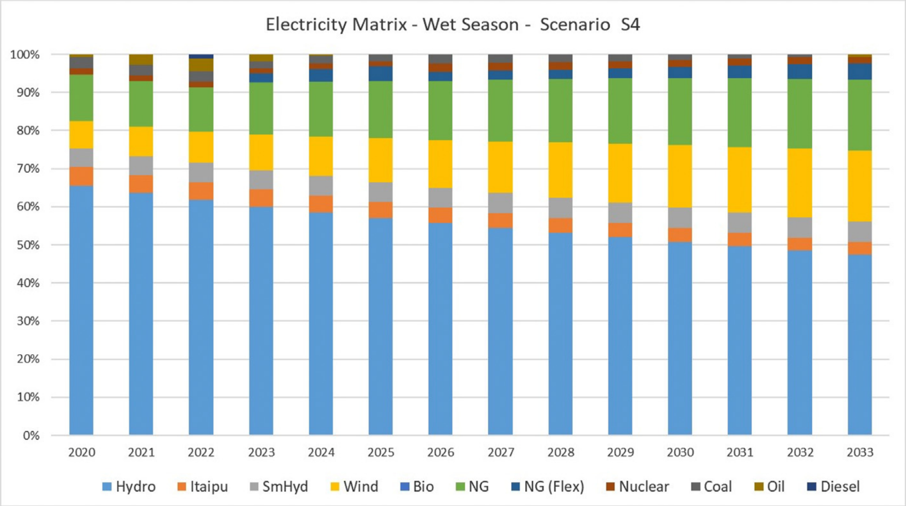

Fig. 16. Elect. matrix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex) - Wet Season, Scenario S4.

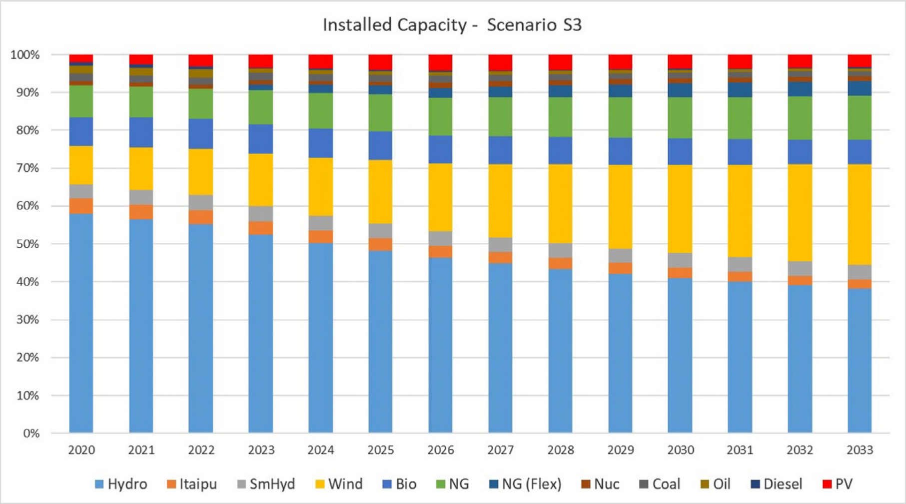

Fig. 17. Elect. mix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex), PV in terms of installed capacity, Scenario S3.

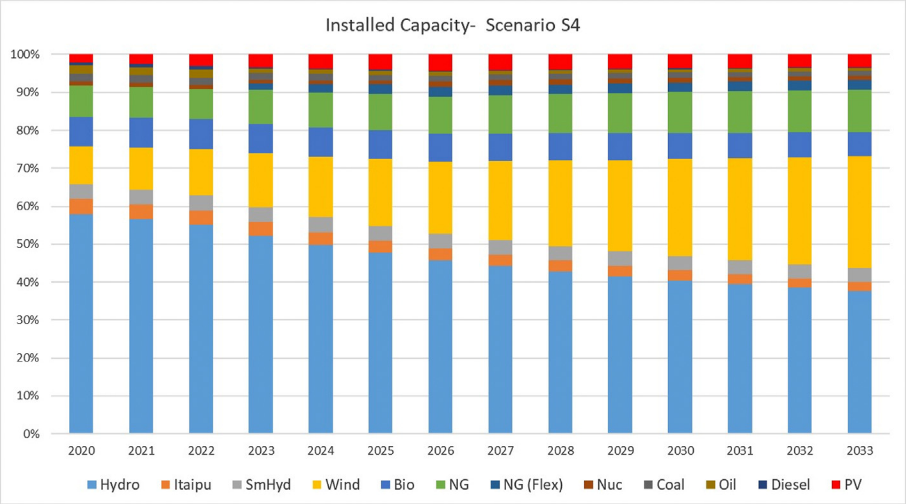

Fig. 18. Elect. mix 2020/33: Hyd., Itaipu, Small Hyd, Wind, Bio, Nuc, NG, Coal, Oil, Dies, NG (Flex), PV in terms of installed capacity, Scenario S4.

of around 45% in the wind power planning expansion would be required to limit the emissions to the values that would be obtained from the 2019 electricity matrix following the increase of the peak hour electricity demand. A further reduction would require an even stronger effort to increment the renewable sources expansion (in our simulations, an increase of 70% in the wind power planning expansion).

4.3. Final discussion

The following main conclusions for the electricity economic policy planning can be drawn from the results of this section, depending on the future economical scenario.

- Under a mild increase of the electricity demand, characterized by the 1% growth rate a year associated to the basic economical scenario discussed at the beginning of this section, the present policy for the electricity supply expansion seems adequate to meet the future electricity peak period demand as well as the maximum CO_2 emissions. In particular it was verified that in this case the participation of the hydropower remains high along the 14 years, with a contributions of around 60% and 70% in the dry and wet seasons. Moreover the wind power generation also significantly increases its participation in the electricity matrix, going from around 7% up to 22% and 16% in the dry and wet seasons respectively under scenario S2. Finally from the numerical simulations the results considering a decreasing CO_2 constraint emissions seems to be the best choice for the optimization problem bearing in mind that the increase in to total cost (around 2%) is compensated by the reduction in the CO_2 emissions (7.5% lower in the total value, and 25% lower in the final year of 2033).
- The situation changes substantially in the case of a stronger growth rate of 3% a year, associated to the optimistic economical scenario discussed at the beginning of this section. In this case the present policy for the electricity supply expansion does not seem adequate to meet a reduction in CO_2 emissions and, in fact, a more realistic situation is to consider a controlled increase in the CO_2 emissions. For that the increase in the supply expansion of renewable sources is a critical issue. In this paper it was considered as a benchmark the emissions obtained from the carbon intensity of the 2019 Brazilian electricity mix (less polluting due to the high hydropower participation), but considering the increase of the demand along the years (3%). A second benchmark with a more restrictive CO_2 emission constrains was to reduce these values in 14% (dry season) and 5% (wet season). To get feasible problems it was considered an increase in the wind power expansion supply in 45% for the first case, 70% for the second case. It was observed that, due to the strongly limited hydrological expansion, which is concentrated in the Amazon region and under several environmental constraints, the hydro generation has a strong decrease, going from 66% (dry season) to 48%, and from 77% (wet season) to 56%. On the other hand, to meet the increasing electricity demand up to 2033, the wind generation increases its participation from 7% (dry and wet season) to 29% (dry season) and 19% (wet season), under scenario S4 (similar observations can be made for scenario S3). Among the fossil fuels, natural gas is the most relevant one, going from 11% to 23% in the wet season, and staying in 12% in the dry season (for scenario S4, similar observations apply to scenario S3).

5. Conclusions

This paper proposes a multiperiod electricity planning optimization model considering seasonality of supply and demand during the peak period as well as restrictions of power expansion and CO_2 emissions. The model is formulated as a linear programming problem and yields to the optimal expansion of the electricity matrix as well as the optimal dispatch from each technology in each season. The model was applied to the electricity matrix planning in Brazil considering the 3 h peak period of demand in the dry and wet seasons, for the years 2020–2033. In the light of the high Brazilian dependence on renewable sources - mainly hydro, wind, solar and biomass - a planning strategy that takes into account the cycles of supply and demand during wet and dry seasons, as well as the complementarity of the sources, can provide a better way to use these resources. Furthermore, as the growth of the Brazilian electricity supply has been relying on the increase of the wind and solar power sources, the analysis of the peak demand becomes a primary concern in the electricity planning. From the numerical simulations presented in Section 4 it was observed that the present Brazilian electricity expansion planning seems adequate to meet the NDC only in a mild economic growth rate scenario of 1% a year. A higher economic growth rate of 3% would require a stronger economic policy related to the power expansions of the renewable sources, as for instance the wind power. Bearing in mind that a more realistic situation would be a growth rate between 1% and 3% in the peak hours electricity demand, it seems that more effort should be considered in electricity economic policy for increasing the supply of the renewable sources in the expansion planning, in order to reduce the CO_2 emissions during the peak hours in Brasil.

A future work along similar lines as the one presented in this paper would be to consider a planning strategy with emission restrictions of a more complex model that would include the whole energy sector as well as the main demands from the industrial, residential and transportation areas.

Credit statement

Erik E Rego: Data Curation, Writing- Original draft preparation. Oswaldo L V Costa: Software, Writing- Original draft preparation, Writing- Reviewing and Editing. Celma O. Ribeiro: Conceptualization, Methodology, Supervision. Roberto I Lima Filho: Investigation. Hellinton Takada: Validation. Julio Stern: Vizualitation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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