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Multi-objective power generation expansion planning with high penetration of renewables

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ABSTRACT

This paper presents a multi-objective model for expansion with a high share of renewable energy. The model considers three objective functions (minimizing the total cost, maximizing generation at the peak load, and maximizing the contribution of non-hydro renewable sources). The model was then applied to the Brazilian case, using the new government targets for renewable energy. The introduction of the objectives regarding peak load and non-hydro renewable generation lead to an increase of solar power generation.

In many studies about Brazil, solar power was not considered, or its participation was negligible, but in this paper the results show solar energy as the main non-hydro renewable source in 2030, due to its capacity to meet the peak demand, since its daily curve coincides with the peak load period. In this study, it was possible to meet 90% of the annual load with renewable sources (with 23% being ensured by non-hydro) and the solar power increased from 21 MW to 40000 MW by 2030.

1. Introduction

In recent years, concerns about environmental impact have increased exponentially, and as result most countries have objectives for the reduction in greenhouse gas (GHG) emissions. One way to reduce GHG emissions is by increasing the share of renewable energy sources (RES). For instance, by 2030 the European Commission intends to achieve a 40% cut in GHG emissions (when compared with 1990), ensured by a minimum increase on the share of RES to 27%, as well as a 27% improvement in energy efficiency [1].

Brazil, in the 2015 United Nations Climate Change Conference, 21st annual Conference of Parties (COP21), has committed to increase the share of RES to 45% by 2030. For the electricity generation, the goal is to achieve a 23% share of non-hydro RES [2]. In 2015, the share of RES in power generation reached 75.5% [3], Brazil being among the countries with the highest share of renewables in the power generation mix and one of the largest producers of hydropower. Despite the high share of renewable sources in Brazil's electric power generation system, there is a considerable dependence on hydropower (64% of the total generation in 2015) and the participation of non-hydro renewable generation is still low (11.5% in 2015), with 8% provided by biomass, 3.5% by wind, and only 0.01% by solar power [3]. Hydropower is considered a clean RES, but the construction of large power plants is a time-consuming process and causes irreversible environmental and social impacts. This dependence on hydropower also makes the energy system vulnerable to severe droughts, as has occurred in the recent past [4]. Additionally, in the near future, extreme climate events, such as droughts, are more likely to occur due to climate change.

According to the latest Brazilian National Energy Plan (NEP 2030), prepared by the Energy Research Company, the participation of non-hydro renewables in power generation, will not reach 5% in 2030 [5]. However, the wind power share has already exceeded the expectations of the NEP 2030. The NEP forecast for 2030 considers a installed capacity in wind power of 4.7 GW, but this was already exceeded in 2014, with 4.9 GW of installed capacity (7.6 GW in 2015) [3,6]. Additionally, the reduction in the cost of solar photovoltaic panels has been faster than predicted at the time of writing the NEP. Furthermore, the NEP 2030 was written before the current government environmental commitments (23% of non-hydro renewable generation) and therefore it does not contemplate these goals.

Some researchers and governmental or non-governmental institutions have presented projections for the Brazil's energy mix in 2030 [5,7–9]. However, such studies did not meet the goals of the federal government for reduction of GHG, since they were developed before COP21. Therefore, such studies do not consider the increasing planning complexity that is required to ensure a larger level of intermittent RES. Some of these studies do not even provide information regarding the participation of solar energy, as it was not considered competitive in the planning horizon. However, recent studies show that solar energy will be competitive in Brazil in the short term [10,11].

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In fact, Brazil urgently needs to re-establish its long-term planning to be able to meet the new targets for 2030. Given the need to address the current government targets and assess the impacts of a higher share of intermittent renewables, this paper presents a model for Multi-Objective Power Generation Expansion Planning with a high share of Renewable Energy. This model is then used to assess the optimum RES mix for Brazil. The time horizon of this plan is the same as the government's target (2030), with sub-periods of five-years, in order to encourage decision makers to reformulate energy plans to meet the new Brazilian context. This study considers the current government's goals and uses updated projections of demand growth and the price of electricity generation technologies.

The remainder of the paper is structured as follows. Section 2 gives a general overview of relevant studies that use multi-objective programming and that consider RES in expansion planning. The proposed model for the Generation Expansion Planning (GEP) of Renewable Energy is presented in Section 3. The data used in the case study for the Brazilian scenario is presented in Section 4. In Section 5 the results are presented, discussed and compared with other studies. Finally, Section 6 summarizes the paper and highlights its main conclusions.

2. Generation expansion planning models

Electrical energy is increasingly fundamental to the modern society, in order to meet human needs such as heating, cooling, lighting, and cooking, as well as to supply industrial processes, being its continuity of supply a crucial factor to ensure the sustainable development. Electric mobility, which is likely to sharply increase in the next decades, will further increase the role of electricity. Therefore, sustainable energy planning is essential to ensure the continuity of energy supply with the predetermined quality standards at the lowest cost, lowest risk, and lowest environmental and socioeconomic impacts. The lack of proper energy planning can bring consequences such as higher costs and degradation on the quality of service, leading for instance to energy rationing, oversizing of the installed capacity, generation deficit, etc.

Before the 1973 oil crisis, the energy planning was only used to determine the type, capacity, location and timeframe of the needed power plants to meet the growing energy consumption [12]. During this period, the GEP was a single objective problem, only focused on the optimization of an economic indicator. In Brazil, during many years the electric utility Eletrobras used the Linear Programming (LP) method in the expansion of the energy generating capacity [13]. The Long-Term Generation Expansion Planning Model was used in the last NEP, applying large-scale mixed-integer linear programming to minimize the total cost of the power system expansion [5]. After it, the MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) was used to validate the results. The same model that uses LP to minimize the total cost was also used in [7,8,14].

Nowadays, due to the increasing environmental, energy security and policy goals, the GEP began to involve multiple objectives [15]. In a review study, Iqbal et al. [16] identified fourteen goals used in the literature. Some authors present an expansion planning model using three minimization goals: total cost, environmental impacts associated with the new power plants and environmental costs of electricity generation [15]. Tekiner et al. [17] also applied the multi-objective optimization in a IEEE test system with three objectives: minimization of costs; minimization of CO_2 emissions and NO_x emissions.

Multi-Criteria Decision Making techniques have been used in recent years, mainly in systems using non-hydro RES [18]. Chedid et al. [19] used two objective functions to find the mix between solar and wind in an isolated system with backup batteries and diesel generators. Meza et al. [20] considered geothermal and wind power with four objective functions: minimization of the total cost, minimization of CO_2 emissions, minimization of fuel imports and minimization of energy price risk (related to price change of fuel). Moura and de Almeida [21] made the expansion planning of the RES to the Portuguese case considering five objectives: minimization of the total cost; minimization of intermittence between years and between months in an average year; maximization of the contribution of intermittent renewable sources to the peak load in winter and summer.

There are several approaches used by researchers in GEP and several criteria for selecting the energy mix. However, most studies use a multi-criteria decision and include the minimization of the total expansion cost. Regarding the environmental impact and energy security objectives, there are many possible objective functions. This work will consider three objective functions: minimizing the total cost (using the classic approach), maximizing generation at the peak load [21] and maximization of non-hydro renewable sources. This last criterion will be inserted in this model to consider the new goals of the federal government.

3. Model formulation

A problem of GEP is formed by decision variables (independent or dependent), constraint functions and objective functions, and the decision maker should be able to find a solution within the feasible region. The planning horizon can be divided into long-term or short-term studies. In this work a long-term study will be presented to a horizon until 2030, with sub-periods of five years, to find the best composition of the power generation mix and its evolution. The sub-periods can be solved separately (static type) or, as in this work, a global solution for all sub-periods (dynamic type) can be found. The modeling of the problem depends on the tools and algorithms available for solving it, the required accuracy, the possible simplifications, etc. In long-term studies, there is no need to detail every element of the system and simplifying the model can facilitate the solution [12]. Therefore, in this model, the transmission system will be ignored.

This Multi-Objective Linear Problem (MOLP) model considers the following structure:

- three linear objective functions (total expansion cost, capacity of non-hydro renewable resources and energy security);
- three categories of restrictions (goal of annual energy generation through renewable resources, maximum exploitable capacity for each technology and maximum increase of each technology, by sub-period);
- four decision variables for sub-period representing the powers to be installed in the considered technologies (hydro, wind, solar and biomass).

3.1. Objective function

In the design of long-term expansion of power generation systems, several authors have used the Levelized Cost of Electricity (LCE) to represent the total cost, since it already includes the initial investment and operating and maintenance costs [21].

Eq. (1) presents the objective function for the costs minimization.

$$min\ f_1 = \sum_{t_a=1}^{T} \left\{ \sum_{t=1}^{t_a} \left[\sum_{i=1}^{I} (C_i^t P_i^t h_i) \right] \right\} \tag{1}$$

Where t is the index of sub-period within the planning period (t = 1, ..., T); t_a is an auxiliary index to integrate all sub-periods (t_a = 1, ..., T). Therefore, the cost of a plant installed in the first sub-period, is also considered in the last sub-period; i is the index of unit type of renewable technology for additions (i = 1, ..., I), being hydro = 1, wind = 2, solar = 3 and biomass = 4; C_i^t is the LCE (in \$/MWh) of the technology i installed in the sub-period t; P_i^t is the decision variable representing the total capacity (in MW) of the power generation units of type i installed in the sub-period t; and h_i is the yearly full load hours (in h/year) of the power plants of type i.

In order to promote the growth of non-conventional RES (wind, solar and biomass), the second objective, given by Eq. (2), is to maximize the generation from such sources. The result of this equation corresponds to the generation of non-hydro RES in the last studied period, ensured by the new power plants.

$$\max f_2 = \sum_{t=1}^{T}\left\{\sum_{i=1}^{I}[Q_i^t h_i]\right\},$$

$$\text{where } Q_i^t = \begin{cases} 0 \quad , \quad if \quad P_i^t \in (\text{hydropower}) \\ P_i^t \qquad\qquad\quad , \ otherwise \end{cases} \tag{2}$$

Eq. (3) aims to maximize the system security, by prioritizing power plants with the highest power available in peak hours. Based on the daily curve of generation it is possible to establish the average available power at peak times. This function will assess the power (in MW), of new power plants, available at peak hours, at the end of the planning period.

$$max \ f_3 = \sum_{t=1}^{T}\left\{\sum_{i=1}^{I}[\epsilon_i P_i^t]\right\} \tag{3}$$

Where ϵ_i is the available capacity (in %) of the power plant units of type i, at peak hours.

3.2. Restrictions

This work considers as energy commitment the achievement of the annual energy consumption within the planning horizon using renewable sources. Therefore, classical restriction using the Load Duration Curve must be replaced by a power generation restriction. Eq. (4) presents the electricity generation commitment restriction through RES. This equation defines the annual generation of RES in the sub-period t.

$$\sum_{i=1}^{I}\left\{\left[PI_i + \sum_{j=1}^{t} P_i^j\right]h_i\right\} = \beta_t E_t \quad , \quad \forall \ t \tag{4}$$

Where E_t represents the forecasted electricity consumption (in MWh/year) to the sub-period t; β_t is the contribution (in %) of RES to meet the electricity consumption in the sub-period t; PI_i represents the power initially installed (in MW) with power plants of type i.

It is not desirable, and even possible to implement, to concentrate all the expansion in a single technology, since diversified RES supplies have higher robustness in minimizing generation fluctuations. Therefore, Eq. (5) provides the restriction of growth by technology, for each sub-period.

$$0 \le P_i^t \le p_i^{max}, \forall t, \ i \tag{5}$$

where p_i^{max} is the maximum power (in MW) that can be installed in power plants of type i in each sub-period (5 years).

The last set of equations (Eq. (6)) is related to restrictions of maximum expansion for each technology, due to the maximum exploitable potential in the country.

$$PI_i + \sum_{t=1}^{T} P_i^t \le P_i^{max} \quad , \quad \forall \ i \tag{6}$$

where P_i^{max} is the potential (in MW) of maximum exploitable technology i.

4. Brazilian scenario

Currently, Brazil is an emergent country, showing in the last 10 years an annual growth rate of 2.61% on the Gross Domestic Product (GDP) and an annual population growth of 0.98%. In 2015, Brazil had a GDP of US$ 1.77 trillion, occupying the 9th place in the world ranking. Nowadays, Brazil's population exceeds 200 million and the forecast for 2030 is 220 million [22]. Although the country is entering a recession, the population, as well as the energy demand, will continue to grow. In 2015 the yearly electricity consumption was 522.8 TWh and the forecast for 2030 is 965 TWh [3,23].

Table 1
Projection of energy consumption and renewable generation.

Year	2020	2025	2030
Energy consumption [TWh]	685	825	965
Renewable generation [TWh]	548	701	869
Renewable generation [%]	80	85	90

In this work, the planning horizon will have three sub-periods (2020, 2025 e 2030). Having as reference the objective defined by of the federal government to increase the use of RES, an increase of the renewable share to 80%, 85% and 90% in consecutive sub-periods will be proposed. Table 1 presents the energy consumption projections [23], as well as the required renewable energy generation level to ensure the objective.

Table 2 presents the installed capacity in 2014 and the capacity of the system that will be achieved after completing the projects under construction and the projects that have not started their construction yet, but that have already been approved (scenario 2015+). To estimate the potential available for each technology (Table 2), several inventories and reports conducted by government institutions were used as reference, for hydropower [24], wind power [25] and solar power [26]. For solar, the maximum potential was estimated considering an occupancy rate of 0.1% of the Brazilian territory, a useful area of 75% of the solar panel and a efficiency of 14% [27].

As previously explained, for technical and environmental constraints, the maximum growth of each technology will be restricted (Table 2). To such restriction, the largest hydropower plant in Brazil (Itaipu: 14000 MW) was used as reference. Such power plant supplies 17% of the consumption in Brazil and its installed power is more than the current installed power in wind, solar and biomass [3]. Itaipu was built in almost 10 years, therefore with a rate of about 1400 MW/year. Additionally, from 1985 to 2015, the hydropower capacity has increased with a rate of 1800 MW/year (54.6 GW were installed in 30 years) [3]. It was therefore considered that, with the strong need to increase the renewable generation capacity, it is possible to increase such rate by a factor of about 4, when comparing it with the baseline scenario of Itaipu construction, ensuring a rate of 5600 MW/year. Therefore, each technology will have a maximum growth restricted to 28000 MW for each sub-period of 5 years.

This study used the average capacity factor during 2014 for hydropower, wind and biomass power plants. This was a dry year in Brazil, being therefore a pessimist value for hydropower [30]. For solar power plants, the historical average (1995–2005) capacity factor was used [26].

The contribution of each technology for the peak power will also be assessed in this work (Table 2). Due to the storage capacity of hydropower and biomass power plants, it was considered that these technologies can reschedule the maximum generation to the hour of peak load. In dry years, the annual power generation is reduced, but the maximum generation can always be rescheduled to peak load, saving water for this period. For the case of wind and solar power, the energy generation depends on the availability of wind speed and solar radiation. The shape of the daily load curve in Brazil has been changing in recent years, and currently the peak load occurs in the early afternoon (Fig. 1). Fig. 2 presents the daily average curve of wind speed and solar radiation in Brazil. Based on Figs. 1 and 2, the solar and wind power contribution to the peak was estimated.

In Brazil, the power auctions do not use the LCE, due to the large share of hydropower, being used a methodology developed by the market operator. Such methodology, called Cost Benefit Index (CBI),

Table 2
Brazilian electrical system data.

Type	Installed power 2014 (MW) [6]	Installed power 2015+ (MW) [28,29]	Estimated potential (MW)	Maximum growth for sub-period (MW)	Capacity Factor	Contribution to the peak
Hydropower	89,193	105,081	260,000	28,000	0.49	100%
Wind	4888	11,447	143,000	28,000	0.38	10%
Solar	15	21	793,898	28,000	0.18	83%
Biomass	12,341	13,854	–	28,000	0.44	100%

also considers the operation and investment costs. However, when comparing the CBI of the last auction held in Brazil [33] and the LCE presented by some authors [10,34,35] to Brazil and South America, the results are quite similar. Thus, for the LCE, the average results of CBI in the 2015 auctions were adopted. Such values were also used as reference for the projection for the analysis period, using the same rates presented in [11] for solar and wind power and [27] for hydropower and biomass. Table 3 presents the LCE projection, being such values aligned with the values that can be found in literature [11,27]. Such LCE values are more expensive than some specific auctions, because they are average results for Brazil, considering several power plants.

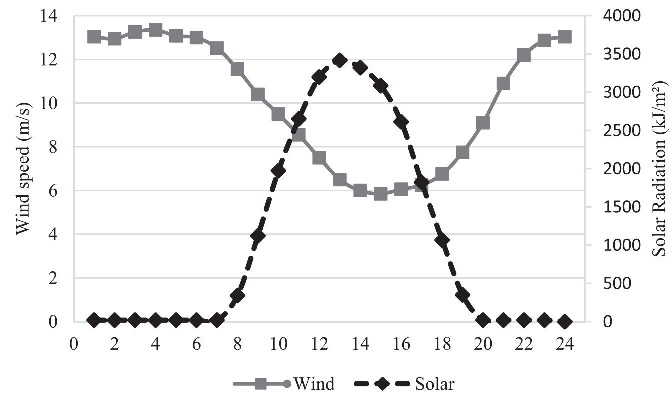

Fig. 2. Daily average curve wind speed and solar radiation in Brazil [32].

Table 3
LCE projection.

	Hydropower	Wind	Solar	Biomass
Baseline year	LCE (US $/MWh)	LCE (US $/MWh)	LCE (US $/MWh)	LCE (US $/MWh)
2015	48.00	56.11	92.70	69.91
2020	48.00	55.37	79.40	69.70
2025	48.00	54.27	70.81	69.56
2030	48.00	52.07	64.38	69.35

5. Results and discussion

To solve the multi-objective linear problem presented in Section 3, the package *iMOLPe* (Interactive MOLP Explorer) was used [36]. The real and updated data from the Brazilian electrical system, as presented in Section 4, was used to obtain solutions for the power GEP model.

Table 4 presents the achieved optimum for each objective function individually (payoffs) and Table 5 presents the power to be installed for the payoffs. Solution 1 is the optimum point of the cost function, which seeks to meet the restrictions of the problem at minimal cost. Solution 2 is the optimum point of the function that maximizes the use of non-hydro renewable generation and solution 3 is the optimum point of the function that maximizes the contribution to peak load.

As can be seen in Table 5, by minimizing the cost function (solution 1), there is a preference by the use of hydropower, since it is the technology with lowest cost in this study. For this solution, the average cost was 49.24 US$/MWh.

By maximizing the use of non-hydro renewable generation, wind, solar and biomass power plants were enough to ensure the demand, without any need of new hydropower plant (solution 2).

By maximizing the peak load contribution, the preference is given to the use of solar energy, since this source operates mainly at peak load hours. The second option to meet the peak load is biomass, because it is a dispatchable technology, which can shift the maximum output for peak load hours. Hydropower is dispatchable, but its capacity factor is larger than for the biomass. Therefore, it is necessary to install a smaller hydropower capacity to have the same annual generation, resulting in a lower contribution to the peak load.

The multi-objective problems representing real problems involve

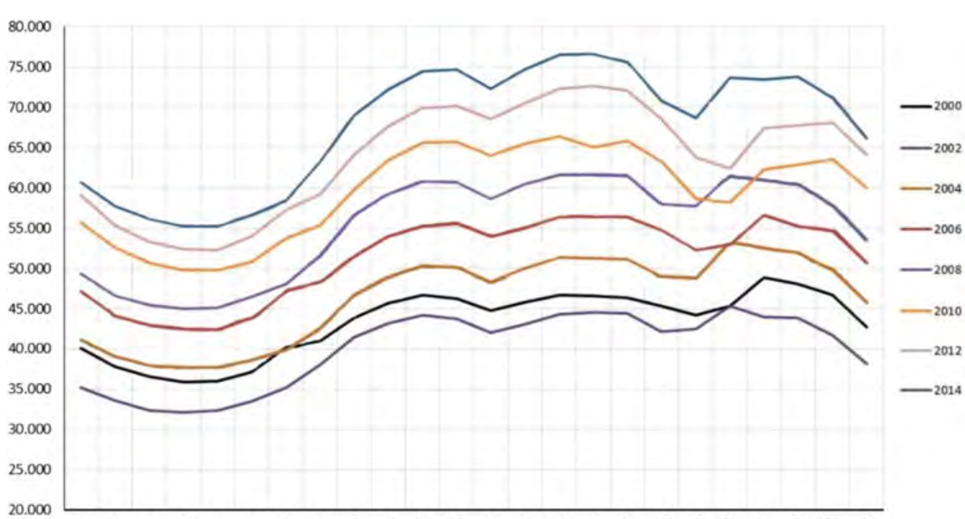

Fig. 1. Evolution of daily load curve in Brazil in the summer, from 2000 to 2014, in GW [31].

Table 4
Optimum of each objective functions individually (payoffs).

Solution	*Cost* (10^9 US$)	*Renewable* (TWh)	*Peak power* (GW)
1	**24.13**	80.1	59.7
2	33.80	**325.9**	105.8
3	33.72	309.6	**109.1**

multiple points of view to be evaluated, which in turn are conflicting (there is not in general a solution that simultaneosly optimize all purposes). Therefore, the final solution (the set of individual solutions) will be a choice of the decision marker, taking into account their preferences. Given this fact, some solutions can be presented (in scenarios) based on economic, technical, environmental and policy preferences, using the tools available in *iMOLPe*. With the *ε-constraint* technique, it is possible to select one of the objective functions to be optimized considering the other objectives as constraints by specifying the inferior levels. With the *Pareto Race* method, it is possible to drive the non-dominated region and choose which function goal must be improved. With the *STEM* method, it is possible to define which objective functions can be relaxed in each iteration and to define the value of this relaxation to try to improve the other goals [36].

Through of the *ε-constraint* method, it was possible to select the function cost to be optimized restricting the minimum value of the non-hydro renewable function, to meet the government's goal of 23% (221.95 TWh) in 2030. However, Eq. (2) (*Renewable*) only provides the generation of the new non-hydro renewable power plants, so it is necessary to include the value of the existent generation (after the planning) in the goal. The existent non-hydro renewable generation that was considered is 91.54 TWh, thus the government's goal to new plants is 130.41 TWh. Thus, Solution 4 (Tables 6 and 7) meets the government's goal for non-hydro renewables, with the minimum cost (49,73 US$/MWh). With this scenario, the cost increased 1% when compared with Solution 1 (payoff of the cost function).

Solution 5 was found using the same technic as for Solution 4, but in this case the peak load function was restricted to meet 90% of peak demand (by new and old renewable power plants), optimizing the cost. With the *Pareto Race* method, it was possible to find solutions 6 and 7, being Solution 6 an intermediate solution, where the government's goal was relaxed to 20% and the peak demand's goal to 80%. Solution 7 was found starting with Solution 6, by freezing the cost function, seeking to meet the government's goal. With the *STEM* method, Solution 8 was obtained, which seeks to meet the government's goal (23% of non-hydro renewable) and meet 90% of the peak load with the mix of hydro, wind, solar and biomass. Solution 9 shows a result above of the government's goal, obtained by *Pareto Race*.

In multi-objective problems, to improve a non-dominated solution, it is necessary to degrade the value of, at least, one other objective function. As can be seen in Fig. 3, to improve the non-hydro renewable, the cost must be degraded. In solution 4, the renewable contribution (hydro, wind, solar and biomass) to the peak load was 43%, but the improvement of this goal resulted in an increase on the cost function or reduction on the non-hydro renewable generation. Solution 5 met 90% of peak demand, but it did not meet the government's goal and the cost was 10.5% larger than Solution 1, since in order to meet the peak demand it was necessary to increase the use of solar power. Solution 6 seeks to reduce the function cost while meeting part of the goals. In this case, the cost increased 5.8% (52.07 US$/MWh) when compared with Solution 1. To increase the non-hydro renewable (in almost 30%) without increasing the cost, it is necessary to degrade (in 8.8%) the function peak. Solution 7 shows such case. In Solution 8, all goals are met and in this case the cost increased 12.9%. To improve the non-hydro renewable participation above of the goal (Solution 9), the cost increased 20% (59.11 US$/MWh).

Table 6
Objective function values.

Solution	*Cost* (10^9 US$)	*Renewable* (TWh)	*Peak Power* (GW)
4	24.37	**130.41**	49.47
5	26.66	94.82	**102.97**
6	25.52	101.10	88.73
7	25.52	**130.85**	80.93
8	27.23	**130.52**	**103.23**
9	28.96	**224.08**	100.41

The increased contribution to the peak load is achieved with more solar power (e.g. Solution 5, 8 and 9), since this source has a low capacity factor and its use implies an increase on installed capacity to have the same yearly energy generation. When the objective is to ensure the peak load at a minimal cost, the most favorable technology is hydropower, because it is the technology with lower cost and due to its storage capacity can be 100% available at peak load hours. However, due to the high capacity factor, the choice of hydropower results in a reduction of the installed power and, therefore, a reduction on the contribution to peak power. For this scenario, the optimal combination is the use of solar along with hydropower (Solution 5). In this case, hydropower has the function of baseload generation and solar ensures the peak load. Despite the higher cost of solar power (in the first two sub-periods), its use is compensated by hydropower (technology with lower cost). In the last sub-period, hydropower and solar reached the limits of installation per sub-period, therefore others sources were needed to meet the load.

Hydropower is the technology with the lowest cost during the horizon of the study. Therefore, solution 1 has the lowest cost, since it uses mainly hydropower. This solution has the smallest installed capacity (81.3 GW) because hydropower has the highest capacity factor of this case study. In solution 4, the use of non-hydro RES had to increase to meet the government's goal. In this scenario, part of hydropower was replaced by wind power. With the increase of wind power, the power to be installed increases to 84.7 GW, as this technology has lower capacity factor than hydropower. Although the installed capacity has increased, the peak load contribution declined, since the contribution of wind power to the peak load is very low.

In all scenarios, the share of RES (hydro, wind, solar and biomass) in the last sub-period was 90%. Thus, solution 8 seeks to meet the government's goal (23% of non-hydro renewable) and meet 90% of the peak load with the mix of hydro, wind, solar and biomass. This scenario also ensures greater system security, in terms of intermittence, due to the increased participation of dispatchable sources (hydropower and biomass), but does not include wind power in all the planning period. This scenario is not interesting because it does not promote wind power development. In order to promote all non-hydro renewables, a new solution is presented, Solution 9. In this scenario, these sources are included in second and third sub-periods.

Table 5
Power to be installed (MW) for the payoffs (the index refers to the sub-period).

Solution	$Hydro_1$	$Solar_1$	$Hydro_2$	$Wind_2$	$Solar_2$	Bio_2	$Hydro_3$	$Wind_3$	$Solar_3$	Bio_3
1	1,261		28,000	9,934			28,000	14,140		
2		3,433		353	28,000	28,000		4,559	28,000	28,000
3		3,433	274		28,000	28,000	3,536		28,000	28,000

Table 7
Generation additions (MW) for the solutions (the index refers to the sub-period).

Solution	$Hydro_1$	$Solar_1$	$Hydro_2$	$Wind_2$	$Solar_2$	Bio_2	$Hydro_3$	$Wind_3$	$Solar_3$	Bio_3
4	1,261		27,036	11,177			17,251	28,000		
5	422	2,284	25,418		28,000		28,000	28,000	28,000	757
6	1,261		28,000	3,035	14,564		23,116	7,174	28,000	
7	1,261		28,000	4,101	12,315		16,184	16,113	28,000	
8	1,025	644	25,418		28,000		19,080		28,000	10,690
9	1,261		22,463	2,029	28,000	1,538		4,559	28,000	28,000

Figs. 4 and 5 present the evolution of the electricity system in the planning horizon for solutions 7 and 9. These solutions were chosen because they meet the government's goal and are technically viable. Both solutions have a large share of solar power at the end of the planning horizon. In Solution 7 the share of solar power exceeds wind power and it does not have new biomass. Solution 9 includes biomass, increasing the non-hydro renewable participation and peak demand, and decreasing the hydropower and wind power share.

Table 8 compares some results of this study with the results of other researchers for the Brazilian power generation mix in 2030. As can be observed, there is a reduction in the growth of hydropower when compared with most studies, since the other studies did not consider the current government's goals to increase the share of non-hydro renewables. The actual results also point to a higher share of solar power to meet the peak demand, but due to its low capacity factor, it is necessary to increase the installed power, being wind power the cheapest solution (i.e. Solution 7). Solution 9 presents a very different result from other works, since this scenario considers the maximization of the peak load contribution and non-hydro renewable generation, a perspective that was not addressed in other studies. Although biomass power plants are more expensive than wind power, its dispatchability contributes to the peak demand and its high capacity factor to base power. This solution promotes the diversification in the generation matrix and greater security.

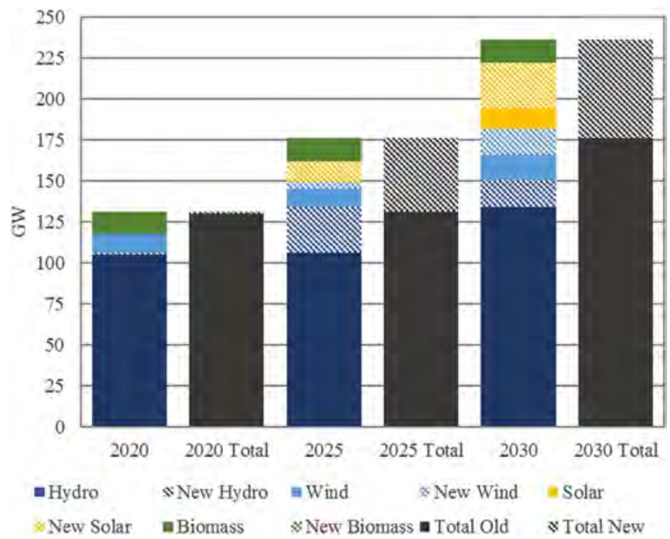

Fig. 4. Evolution of generating capacity in the planning horizon for the solution 7.

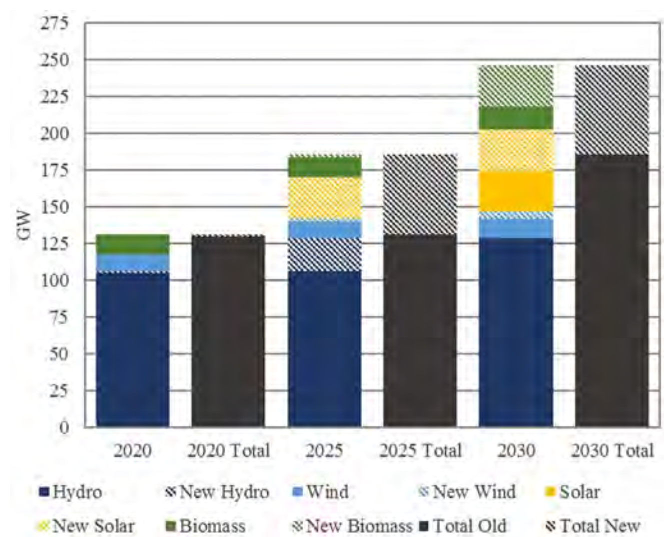

Fig. 5. Evolution of generating capacity in the planning horizon for the solution 9.

6. Conclusions

This paper presents a multi-objective model for expansion with a high share of RES, promoting the use of non-hydro RES. When the only objective was to minimize the cost, the solution was the use of hydropower. This trend was also observed in previous studies, but such results do not meet the new government's goals for generating electricity. The actual projections of costs and the use of daily average curve wind speed and solar radiation, led to very different results. The high use of wind does not help with the supply of peak demand, since its period of lower generation coincides with the period of higher consumption of electricity. When the objective was to meet the government's goals and the peak demand, solar power was the main non-hydro renewable source to ensure the expansion, since its daily curve, which coincides with the peak load period, favored its use.

In many studies, such as the National Energy Plan, solar power was not considered, or its participation was negligible. However, in this paper it was possible to realize the importance of solar energy to the

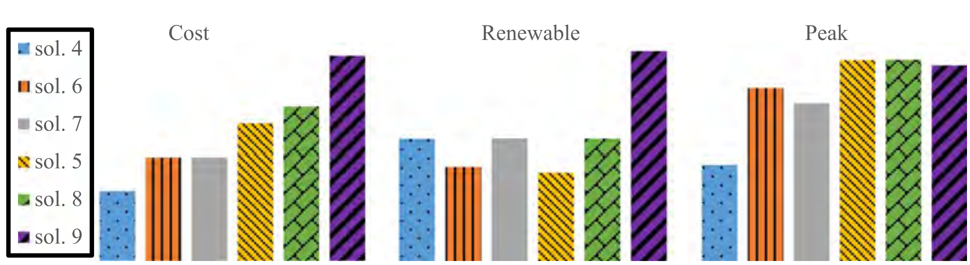

Fig. 3. Normalized values of objective functions, ordered according to the cost function.

Table 8
Comparison of results with other works (GW) – 2030.

Technology	Solution 7	Solution 9	NEP [5]	WEO [9]	Penalization of GHG [7]	Development first [8]
Hydro	150.5	128.8	164.1	141.0	178.4	169.8
Wind	31.7	18.0	4.7	19.0	3.9	others: 21.6
Solar	40.3	56.0	–	5.0	–	
Biomass	13.9	43.4	7.9	16.0	15.4	

composition of the Brazilian energy future. However, to have these changes that increase the share of solar and meet the government's goal, it will be necessary to reformulate the National Energy Plan. The government needs to continue with the programs that benefit the share of renewable to accelerate the reduction in the solar cost. This methodology can be applied in other countries to other scenarios and more objective functions can be added (e.g. minimization of intermittence between months in an average year or other government objectives).

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