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ORIGINAL PAPER

Multi-year two-stage generation and transmission expansion planning: intermittent renewable energy sources integration for Brazilian interconnected power system

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Abstract

The power system long-term expansion planning is a computer-intensive problem as demands a varied set of studies especially considering the increasing deployment of intermittent renewables. In the case of the Brazilian power sector planning, the responsible institutions mostly use proprietary software. This paper presents the multiyear two-stage academic generation and transmission expansion planning software, called CARTHER, developed by the authors in order to provide the academy an open-source and non-commercial software, with a friendly interface and with several applications for expansion planning of hydrothermal systems with high intermittent renewables penetration. CARTHER is then calibrated for a case study in the Brazilian power sector, considering the most recent governmental goals for renewable energies for the horizons of 2030, 2040, 2050 and 2060. The results demonstrate the functionality and the qualitative capacity of CARTHER optimization under the expansion's criteria of flexibility and reliability in the face of the intermittent renewables penetration.

Keywords Power system planning · Long-term generation Expansion planning · Optimization tool · Renewable energy integration · Brazil

Abbreviations

GEP	Generation expansion planning
VRE	Variable renewable energy
CGT	Open cycle gas turbine
CCGT	Combined cycle gas turbine

List of symbols

$X_{(i,w,j)}$	Installed capacity of technology i in subsystem w for horizon j, in GW
$e_{(i,j)}$	Hours of use in the year of technology i in horizon j
$CT_{(i,j)}$	Levelized cost of technology i, in horizon j, where the levelized cost covers the sum of capital, fuel, O&M and environmental costs
D_j	Energy demand in horizon j
$L_{(i,w,j)}$	Availability of fuel from technology i in subsystem w for horizon j
$k_{(i,j)}$	Conversion factor from MWh to unit of measurement of fuel of technology i in period j
$B_{(i,j)}$	Blocking binary variable of technology i in horizon j
$VREmin_{(i,w,j)}$	Minimum expansion of the VRE technology i in subsystem w in horizon j, in GW
$M_{(i,w,j)}$	Limit of use of technology i in subsystem w in horizon j, in GW
$t_{(i,w,j)}$	Portion of the generation of technology i in subsystem w destined for transmission in horizon j
$N_{(w,j)}$	Transmission usage limit, in TWh, of subsystem w in horizon j
$c_{(i,j)}$	CO_2 emission factor per unit of energy generated from technology i in horizon j, in Mton-CO_2/TWh

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$F_{(w,j)}$	CO_2 emission limit for subsystem w in horizon j
$D_{(w,j)}$	Demand from subsystem w in horizon j
$\alpha_{te(i,j)}$	Flexibility coefficient of dispatchable technology i in horizon j
$\alpha_{\mathrm{VRE}(i,j)}$	Flexibility coefficient of VRE technology i in period j
$\alpha_{\mathrm{load}(j)}$	Load flexibility coefficient in horizon j

1 Introduction

Stimulated by international agreements between several countries, such as the Paris agreement, their respective government institutions are opting for renewable power sources to expand the infrastructure of their power sectors. According to the International Energy Agency—IEA, renewables generated 26% of electricity worldwide in 2018 [1]. Based on the widespread adoption of incentive policies in favour of renewables, this share may reach up to 45% in 2030 [2].

Amid accelerated transition of the panorama of the countries electrical matrix, the variable or intermittent renewable energy sources (VRE), solar and wind energy, whose variability presents new challenges to the electricity sector, concerning reliability, flexibility and operational stability. Currently, the solutions used to mitigate the impact of the VRE intermittency to the system range from demand response, operating reserve; interconnection with other grids; curtailment of intermittent technology; energy storage; complementarity between renewable sources; demand-side management [3].

In this sense, planning and research institutions around the world seek to address this challenge of VREs, starting directly with the long-term planning of future investment decisions, called generation expansion planning (GEP).

The GEP consists of identifying the optimum configuration of installed capacity based on the generation technologies available, from an economic perspective, to meet the expected demand for the planned horizon. Several models are known internationally for their contribution to the GEP studies development. It is worth mentioning the electric generation expansion analysis system—EGEAS, precursor model that gave rise to several models that are currently used, such as system optimizer, PLEXOS, Aurora, UPLAN e ENPEP (WASP). In addition to these, it stands out the OPTGEN model from PSR Consulting, which has been applied in a diverse range of countries from the Balkans and South America [4, 5].

The mathematical optimization methods for GEP vary: linear programming (LP) [6], mixed integer linear programming (MILP) [7], non-linear programming (NLP) [8], dynamic programming [9] and metaheuristic techniques [10–13].

Therefore, decision-makers have developed considerable knowledge on how to address the impacts of VREs on long-term models, within the parameters of firm capacity [14, 15], flexibility [16, 17] and GEP case studies with high penetration of VREs for regions, states and countries, considering their systemic characteristics [18–20]. In [21], the increase in the VRE's penetration in Iran's national power grid (INPG) is investigated, through a MILP model of dynamic multi-objective planning. The authors of Bhuvanesh et al. [22] use a model based on a multi-objective genetic algorithm for GEP in the state of Tamil Nadu in India, in order to minimize the total cost of expansion, the GHG emission and investigate the penetration of VREs.

In Brazil, it highlights the *Modelo de Expansão de Longo Prazo*—MELP, developed by the *Centro de Pesquisas de Energia Elétrica*—CEPEL. The MELP is intended for the long-term GEP of horizons between 20 and 30 years, used in the study *Plano Nacional de Energia 2030* (PNE 2030) by *Empresa de Pesquisa Energética*—EPE [23].

Currently, EPE uses the investment decision model (MDI) for expansion studies over the ten-year horizon and, in partnership with PSR Consulting, uses the OPTGEN model for future long-term studies considering the entry of VREs [24, 25]. In the technical literature, researches are also developed evaluating several aspects of the VRE's penetration in the Brazilian Interconnected Power System—BIPS for the long-term horizon [26–28], from studies for the planning of a 100% renewable electrical matrix [29] to studies of the complementarity between VRE and dispatchable renewables [30].

However, the main softwares used by CEPEL and EPE for long-term BIPS's GEP are proprietary softwares and are not open source. Thus, the benefit of this work is to contribute to the development of LT GEP studies presenting a computational tool to help in the understanding and in preliminary studies considering the GEP problem. This article presents the functionality of the open-source multiyear two-stage academic generation expansion planning software, called CARTHER developed by the authors. CARTHER is a tool capable of optimizing the long-term expansion of any multi-regional hydrothermal system, which can be divided into up to four interconnected subsystems. In addition, the model allows: to optimize up to four different time horizon scenarios, simultaneously and independently and these scenarios may have differences in any user input parameters; accurate analysis of VRE penetration due to the representation of the VRE generation profile curve and the load curve in hourly levels; the insertion of up to two new generation technologies in addition to the existing ones; measure CO2 emissions; and importing existing system technologies in an automated manner.

In this way, CARTHER offers a range of applications, such as analysis of the technical–economic impact of policies to encourage VRE penetration, evaluation of fuel price and fuel availability policies in the different subsystems, evaluation of environmental policies to reduce emissions of CO2 and identification of transmission bottlenecks between subsystems.

Through the CARTHER calibration for the representation of hypothetical scenarios of long-term BIPS expansion, the case study investigates techno-economically the maximum solar PV and wind penetration in the BIPS for the horizons of 2030, 2040, 2050 and 2060.

The main contributions of the present paper are:

- The development of an open-source software with adequate VRE representation to LT GEP Studies.
- Considers a real data from a real large-scale system.
- A study case considering different VRE penetration scenarios in the BIPS.

The remainder of the present paper has been represented as follows: Sect. 2 presents the CARTHER methodology and functionalities, followed by the description of its objective function and constraints. Section 3 refers to the BIPS expansion planning case study, presenting the input data calibration of the load and VREs curves. Finally, in Sect. 4, the results and the performance of CARTHER are investigated and the conclusions are presented in Sect. 5.

2 CARTHER model

CARTHER is defined by its developers as a multiyear two-stage academic generation expansion planning software, whose motivation is to make available to the academic community this free, open-source software for long-term GEP (LT GEP) studies of any hydrothermal power system.

The objective of this tool is to optimize power systems expansion scenarios represented by the user, from an economic perspective, in other words, it presents the configuration of low-cost generation technologies for the proposed scenarios, considering the costs associated with the plant's construction, operation and maintenance, costs for mitigating externalities, in addition to considering existing operational constraints [31].

CARTHER carries out the expansion planning considering several types of generation technologies available in four regions. The mechanism that allows comparing such different power sources is the levelized cost of electricity—LCOE. The LCOE represents the average revenue per unit of energy production, in $/MWh, which would be required by the project owner to recover all investment and operating costs, also considering a specified return on investment over the plant's life cycle [32, 33].

The software is classified as multiyear because it can independently optimize up to four scenarios in parallel, and these scenarios can be in different horizons, with differences in any user input parameters, such as fuel availability, electrical constraints among several other characteristics. This computational tool also qualifies as multi-regional, the electrical system can be divided into up to four interconnected subsystems, electrical areas. This first version of the software is modelled for the BIPS, with the definition of the electrical areas according to the existing division in Brazil, which are south (S), southeast/midwest (SE-CO), north (N) and northeast (NE), as shown in Fig. 1.

Fig. 1 The four subsystems of CARTHER

Nevertheless, CARTHER has applicability not only for the BIPS, but also for optimizing the expansion of any other multi-regional hydrothermal system, with: representation of the load and VRE generation profile curves in hourly levels for each subsystem, the possibility of insertion of up to two new types of generation technologies, the measure of the CO2 emission from the expansion and the import of the existing system in an automated way. With this, the model can be used for different applicabilities: technical–economic analysis of incentive policies for VRE penetration, evaluation of fuel price and availability policies in the different subsystems, evaluation of environmental policies to reduce CO2 emissions and identification transmission bottlenecks between subsystems.

The computational tool's programming platform is excel's *Visual Basic for Applications* (VBA) from Microsoft®. The model optimization is performed through the MILP tool called *COIN Branch and Cut solver* (CBC) executed by *OpenSolver* from excel.

2.1 Description of the CARTHER model methodology

In this section, the general methodology and the main equations of the model are presented. It is intended to raise a global understanding of the performance and correlation between the various data and variables in the model optimization process. Figure 2 shows a macro view of the CARTHER modelling structure for a scenario through a general flowchart, while the sub-items address the equations in more detail.

Figure 2 the methodology is divided into 5 steps: *User Data Inputs*, *1st Data Preparation*, *1st Simulation Stage*, *2nd Data Preparation* and *2nd Simulation Stage*.

The representation of a scenario starts in the *User Data Inputs step*, where the user enters information about: the load forecast; load and VRE profiles curves; operating parameters of each of the technologies; data on the costs of construction, operation, maintenance and externalities linked to the technologies; and data that sets the scenario constraints.

Then, in the *1st Data Preparation*, the tool calculates, for each technology, its LCOE, thus building a basis for economic comparison between the different forms of power technologies.

In the third step, *1st Simulation Stage*, after calculating the LCOE of each technology and having the input data for the scenario, the first simulation is carried out, in which the PLIM CBC optimization provides parameters on the VRE generation, presenting a proposal for solar PV and wind installed capacity expansion for the scenario.

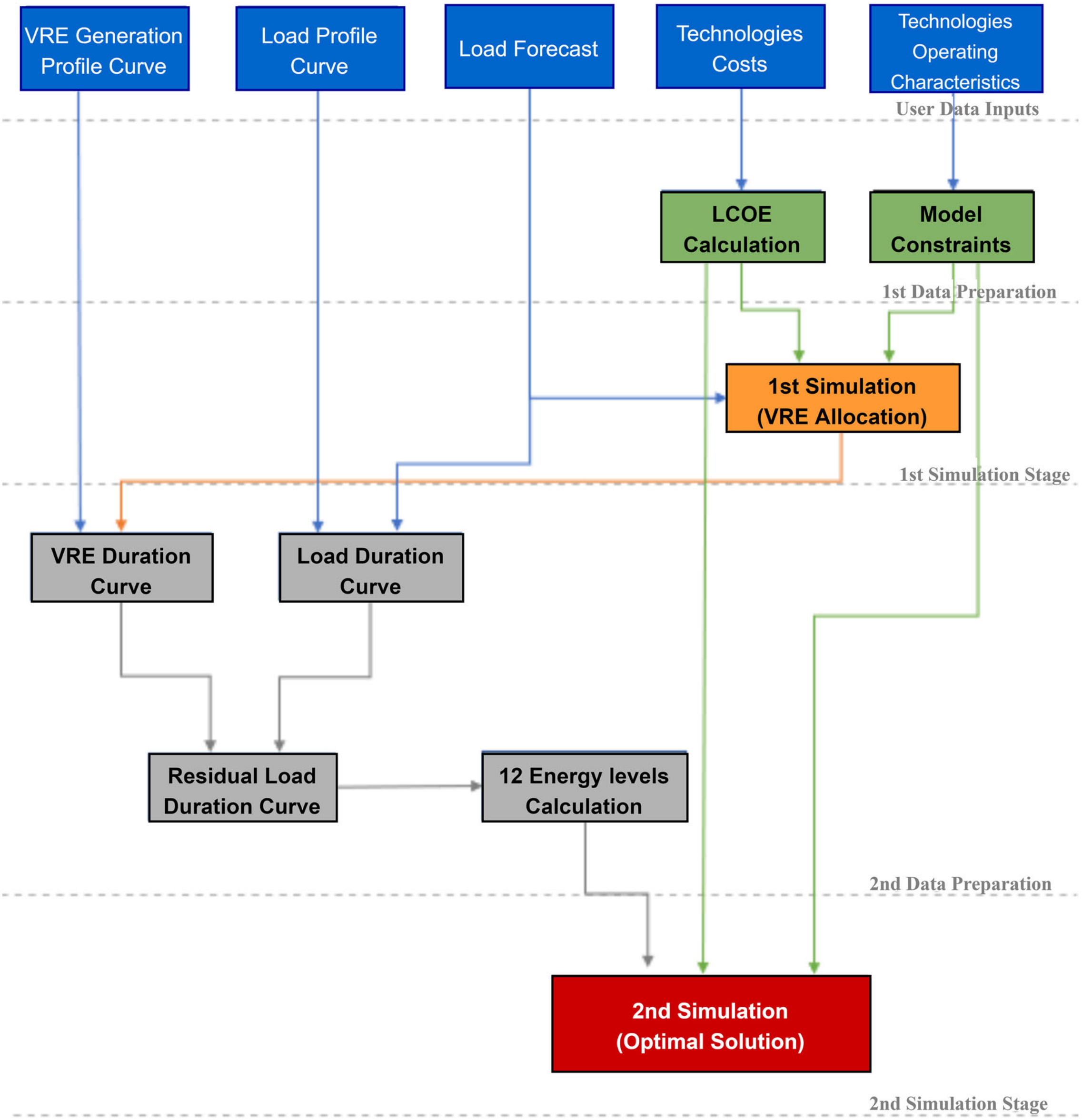

Fig. 2 CARTHER operation flowchart

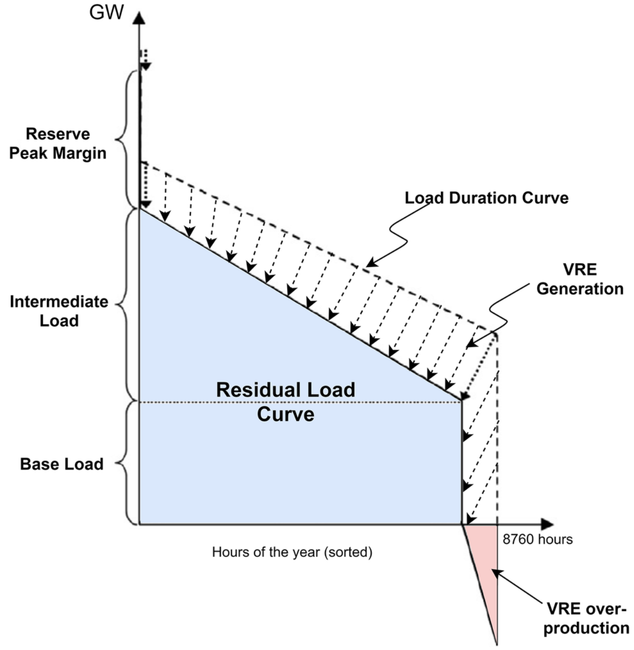

Fig. 3 Residual load duration curve

In the *2nd Data Preparation*, a new data preparation takes place, considering the results obtained in the first simulation. With the result of the VREs installed capacity in GW, average FC input data, solar PV and wind profile curves, the renewable duration curve is constructed. Similarly, with the load predicted in TWh and the annual variability profile of the load curve, the load duration curve is drawn up. With this, the VRE duration curve is subtracted from the load duration curve, resulting in the residual duration load curve, as shown in Fig. 3.

The residual load duration curve, area in blue, represents the energy profile that must be met by conventional generating units (non-intermittent) in the last step. Before the last step, the residual curve is divided into 12 energy levels.

Finally, in the *2nd Simulation Stage*, the 12 energy levels of the residual curve are optimized, starting from the first level (base of the curve) to the peak (last slice of energy), so that the plants satisfy all conditions/characteristics/constraints from the energy level whose optimization is underway. In this way, the *2nd Simulation Stage* optimizes the residual curve, considering the input parameters and all the constraints that set the scenario, and finally provides an optimal solution to the scenario proposed by the user.

2.1.1 Optimization: minimizing costs

The objective of the proposed computational model is to minimize the expansion costs for the scenario horizon, making available to the user how much installed capacity per source must be installed. This optimization process is based on the objective function and constraints described in Eqs. (1)–(10).

$$\min \sum_{i=1}^{NI} \sum_{w=1}^{NW} \sum_{j=1}^{NJ} CT_{(i,j)} e_{(i,j)} X_{(i,w,j)} \tag{1}$$

s. a

$$\sum_{i=1}^{NI} \sum_{w=1}^{NW} e_{(i,j)} X_{(i,w,j)} = D_j, \quad \forall j \in \{1, \ldots, NJ\} \tag{2}$$

$$k_{(i,j)} e_{(i,j)} X_{(i,w,j)} \le L_{(i,w,j)}, \quad \forall i \in \{1, \ldots, NI\}, \quad \forall w \in \{1, \ldots, NJ\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{3}$$

$$X_{(i,w,j)} \ge 0, \quad \forall i \in \{1, \ldots, NI\}, \quad \forall w \in \{1, \ldots, NJ\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{4}$$

$$B_{(i,j)} X_{(i,w,j)} = 0, \quad \forall i \in \{1, \ldots, NI\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{5}$$

$$X_{(i,w,j)} \ge VRE\,min_{(i,w,j)}, \quad \forall i \in \{1, \ldots, N2\}, \quad \forall w \in \{1, \ldots, NJ\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{6}$$

$$X_{(i,w,j)} \le M_{(i,w,j)}, \quad \forall i \in \{1, \ldots, NI\}, \quad \forall w \in \{1, \ldots, NJ\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{7}$$

$$\sum_{i=1}^{NI} t_{(i,w,j)} e_{(i,j)} X_{(i,w,j)} \le N_{(w,j)}, \quad \forall w \in \{1, \ldots, NW\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{8}$$

$$\sum_{i=1}^{NI} c_{(i,j)} e_{(i,j)} X_{(i,w,j)} \le F_{(w,j)}, \quad \forall w \in \{1, \ldots, NW\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{9}$$

$$\sum_{i=1}^{NI-2} \alpha_{te(i,j)} e_{(i,j)} X_{(i,w,j)} + \sum_{w=1}^{NW-1} \sum_{i=1}^{NI} \alpha_{te(i,j)} t_{(i,j)} e_{(i,j)} X_{(i,w,j)} + \sum_{i=1}^{N2} \alpha_{\mathrm{VRE}(i,j)} e_{(i,j)} X_{(i,w,j)} + \alpha_{\mathrm{load}(j)} D_{(w,j)} \ge 0, \quad \forall w \in \{1, \ldots, NW\}, \quad \forall j \in \{1, \ldots, NJ\} \tag{10}$$

Equation (1) represents the objective function, that is, the equation to be minimized, which corresponds to the sum of the product between the additional installed capacity in GW, $X_{(i,w,j)}$, number of utilization hours in the year, $e_{(i,j)}$ and the

LCOE, $CT_{(i,j)}$, of the different technologies i, in subsystems w for horizon j.

Equations (2)–(5) form the set of fundamental constraints of the model, which are essential to obtain a solution that respects the primary technical and operational characteristics of a system. Constraint (2) requires that the sum of the energy generated by the technologies, $e_{(i,j)}X_{(i,w,j)}$, must be able to meet the increase in demand forecast, $D_{(j)}$, for the horizon j.

Additionally, the generation, $e_{(i,j)}X_{(i,w,j)}$, of technology i must be such that the fuel consumed, $k_{(i,j)}e_{(i,j)}X_{(i,w,j)}$, does not exhaust the available fuel supply, $L_{(i,w,j)}$, for subsystem w in horizon j, composing Eq. (3).

Equation (4) ensures that the additional installed capacity per power source, $X_{(i,w,j)}$, must assume positive values.

Equation (5) consists of a blocking technology constraint, where only technologies that have a viable capacity factor (CF) to meet the level of demand of the residual curve are considered as solution options ($B_{(i,j)} = 0$). That is, if $B_{(i,j)} = 1$, it means that the technology does not have a viable CF to meet the level of demand and the expansion of this technology to this level of demand must be null, $X_{(i,w,j)} = 0$.

The equations from (7) to (10) are called complementary equations. Equation (7) allows the user to define the minimum expansion, $VRE\,min_{(i,w,j)}$, in GW, of the VRE technology i to be installed in subsystem w of horizon j. Equation (7) limits the expansion capacity, $M_{(i,w,j)}$, in GW, of technology i to be installed in subsystem w of horizon j. Equation (8) restricts the subsystem's ability to exchange in TWh, $t_{(i,w,j)}e_{(i,j)}X_{(i,w,j)}$ in subsystem w the period j, in $N_{(w,j)}$. Equation (9) allows the constraint of the amount of CO2 to be emitted, $c_{(i,j)}e_{(i,j)}X_{(i,w,j)}$, equal or less than $F_{(w,j)}$, by subsystem w in horizon j. Finally, constraint (10) represents the flexibility balancing equation for each subsystem, based on the equation developed for the MESSAGE model [34], where α_{load} determines the portion of flexible energy required by the load, $\alpha_{\text{load}(j)}D_{(w,j)}$ and $\alpha_{\text{VRE}(i,j)}$ determines the portion of the energy generated by the VREs of subsystem w that requires flexibility. The $\alpha_{te(i,j)}$ indicates the generation portion of each dispatchable technology in the subsystem w and the generation derived from interchange capable of providing flexibility.

3 Case study

This work performs a GEP analysis for BIPS, which investigates the techno-economic impact for different VREs, solar PV and wind, insertion scenarios in CARTHER, comparing the so-called reference scenarios with the scenarios of maximum VRE penetration.

Therefore, in this section, the calibration of the BIPS 2019 base year scenario and the parameters for planning the expansion of the BIPS to 2030, 2040 2050 and 2060 time horizons are presented, composing the reference scenarios. And, from the simulations of the reference scenarios, alternative scenarios of VRE expansion are carried out, seeking the maximum VRE penetration in the system, with no spilled energy.

Table 1 Expected additional demand for horizons

Total demand (TWh)	2030	2040	2050	2060
N	17.31	38,31	66,01	102,51
NE	34.29	75,92	130,80	203,13
SE/CO	122.79	271.87	468.37	727.36
S	36.25	80.26	138.27	214.73
BIPS	210.64	466.36	803.45	1247.73

The data that set the economic parameters, demand, technologies and constraints, were established based on documents referring to the main institutional agencies responsible for managing the Brazilian power and energy system [35–38].

3.1 Demand

The demand refers to the BIPS[1] load discounted of imports, that is, it comprises all electrical energy requirements made available to the country, via centralized generation only. The demand forecast is based on the following assumption of CARTHER's operation, the base year power system, that is, the existing system is considered in balance between supply and demand, meeting the criteria of stability and flexibility. In other words, CARTHER analyses the power sector exclusively in the scope of the expansion. Therefore, CARTHER does not use the expected total demand for the study horizon as an input, but rather the expected increase in demand in relation to the base year for the study horizon. In this way, the expected additional demand for the study horizons is shown in Table 1.

3.2 Load curve and VRE generation curves profiles

The load curve profiles, Table 2, and generation of wind and solar PV technologies, Tables 3 and 4 are based on data provided by ONS [39–41].

3.3 Technologies

The database on economic and performance characteristics for each of the technologies in the reference scenario for the time horizons is listed in Table 5.

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[1] BIPS load—all energy available to the country, via centralized generation and import. Excluding demands related to isolated systems, distributed generation and self-production not injected into the network [37].

Table 2 Daily load curve profile by subsystem

Demand (GWh/h)												
Subsystem	00–02 h	02–04 h	04–06 h	06–08 h	08–10 h	10–12 h	12–14 h	14–16 h	16–18 h	18–20 h	20–22 h	22–00 h
Southeast	34.15	32.14	32.71	37.29	42.13	43.71	44.36	45.54	42.18	43.96	43.58	39.74
North	5.64	5.37	5.18	4.94	5.57	5.67	5.87	6.07	5.64	5.83	5.99	6.06
Northeast	10.49	10.09	9.42	10.3	11.43	11.54	11.66	11.94	11.1	11.14	11.72	11.35
South	9.26	8.83	9.36	11.56	12.94	13.54	12.99	13.45	13.12	13.48	12.81	11.11

Table 3 Annual wind curve profile by subsystem

Capacity factor (%)												
Subsystem	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sudeste	42	39	36	44	46	55	62	64	70	64	60	47
Norte	55	28	40	20	23	49	57	66	85	80	84	56
Nordeste	38	37	32	40	42	50	58	60	65	57	54	42
Sul	35	27	33	36	33	32	37	36	41	44	37	35

Table 4 Daily solar PV curve profile by subsystem

Generation (GWh/h)												
Subsystem	00–02 h	02–04 h	04–06 h	06–08 h	08–10 h	10–12 h	12–14 h	14–16 h	16–18 h	18–20 h	20–22 h	22–00 h
Southeast	0	0	0	100	250	337.5	325	275	175	0	0	0
North	0	0	0	300	800	966.5	966.5	833.5	700	0	0	0
Northeast	0	0	0	275	625	725	725	600	400	0	0	0
South	0	0	0	300	800	966.5	966.5	833.5	700	0	0	0

The North and South subsystems have only distributed PV generation or microgeneration. In this case, the PV solar generation curve profile adopted for these subsystems is based on the BIPS average hourly solar generation curve as a whole

Table 5 Generation technologies characteristics

Parameters	Capital cost (US\$/kW)	Fixed O&M cost (US\$/kW)	Variable O&M cost (US\$/kWh)	Cost of externalities (US\$/ton-C)	Capacity factor (%)	Energy efficiency (%)	Life cycle (years)	Coef. of flexibility (α)
Large hydro (≥ 1000 MW)	1352	12.91	–	–	38–85	–	30	0.5
Medium hydro (≥ 300 MW)	1816	12.91	–	–	38–85	–	30	0.5
Small hydro (≤ 300 MW)	2661	7.75	–	–	38–85	–	30	0.3
Coal	2500	25.82	0.00357	15	40–91	30	25	0.15
OCGT	775	43.90	0.00516	15	0–93	38.5	20	1
CCGT	970	69.72	0.00516	15	40–93	56	20	0.5
Fuel oil thermal	1070	25.82	0.00108	15	0–85	30	20	1
Nuclear	5000	110	0.00042	–	70–95	–	60	0
Biopower	1200	23.24	30	–	20–80	30	20	0.3
Wind	1500–1300	100	–	–	45	–	20	− 0.08
Solar PV	1350–800	5.16	–	–	30	–	20	− 0.05

In alignment with [36], the VRE capital costs, wind and solar PV, show a great tendency to decline. The other technologies have their costs considered constant in the study horizons. Fonte: [36, 37, 42]. Load flexibility coefficient adopted is $\alpha = -0.1$

OCGT Open cycle gas turbine, *CCGT* Combined cycle gas turbine

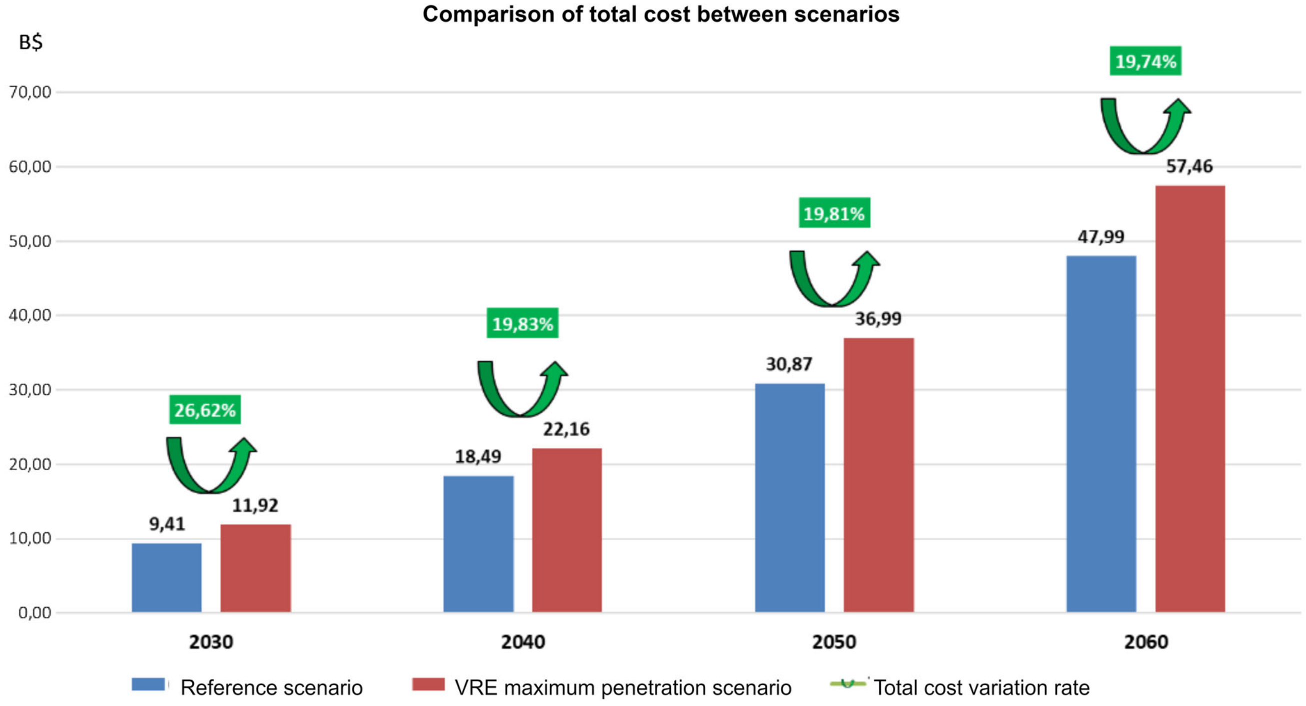

Fig. 4 Total cost comparison

4 Results

This section presents the results of the BIPS GEP, performing a comparative economic analysis between the reference expansion and maximum VRE penetration scenarios.

The result of the optimal mix of technologies and their respective expansions of installed capacity in MW for the reference scenarios and maximum penetration VRE of 2030, 2040, 2050 and 2060 are shown in Tables 6 and 7.

It is noteworthy that for the studies of scenarios from 2040 to 2060, only the hydraulic potential inventoried outside environmental protection areas is considered, plus an additional margin of 200% as an expansion limit, thus providing an extra GW capacity which allows the model to take his own expansion preferences. With this, it is observed that CARTHER, both for the reference scenarios and maximum VRE integration scenarios, uses the availability of medium-sized UHEs in their totality, 3600 MW, indicating a possible favourable economic viability for the hydraulic expansion in greater scale if there was an even greater expansion limit. In other words, an update of the outdated studies of hydraulic potential inventoried, as pointed out by [38], would allow a greater medium and large hydraulic expansion, which would result in a greater participation of renewable sources in the expansion. In addition, it is worth mentioning the coal and petroleum[2] derivatives technologies were passed over by CARTHER in favour of the biopower, CCGT and OCGT technologies, thus demonstrating a greater economy on the part of these technologies, in line with the expectation cited by the study [43], that gas technologies assume an important role as a transition technology for a future power sector matrix with high costs for the emission of pollutants, where the gas plants stands out, mainly, due to its infrastructure already built, low cost of adaptation for gas of the industrial facilities of plants that use more polluting fuels, such as coal and petroleum products, and the expected growth of the national supply of fuel from the pre-salt.

From an economic point of view, the scenarios of maximum VRE penetration and the reference scenarios are compared through Fig. 4.

It is noted that the increase in the VRE representation in the composition of the BIPS matrix, in the maximum VRE scenarios, results in an extra financial contribution for all horizons, varying between 19.7 and 26.6%.

From the expansion optimized data by CARTHER plus the installed capacity of the existing BIPS in 2019, we have the final BIPS matrix composition for the study horizons of the reference and maximum VRE penetration scenarios, as shown in Fig. 5.

For the reference scenarios, the growth of the participation of the VREs stands out, starting from 10.48% of the matrix in 2019 (base year) and reaching a representation of 26.61% of the total installed capacity for 2060. In addition, among the VREs, there is a more significant growth in the share of solar

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[2] Fuel oil thermal plant was utilized only in the expansion of the NE subsystem of horizon 2030.

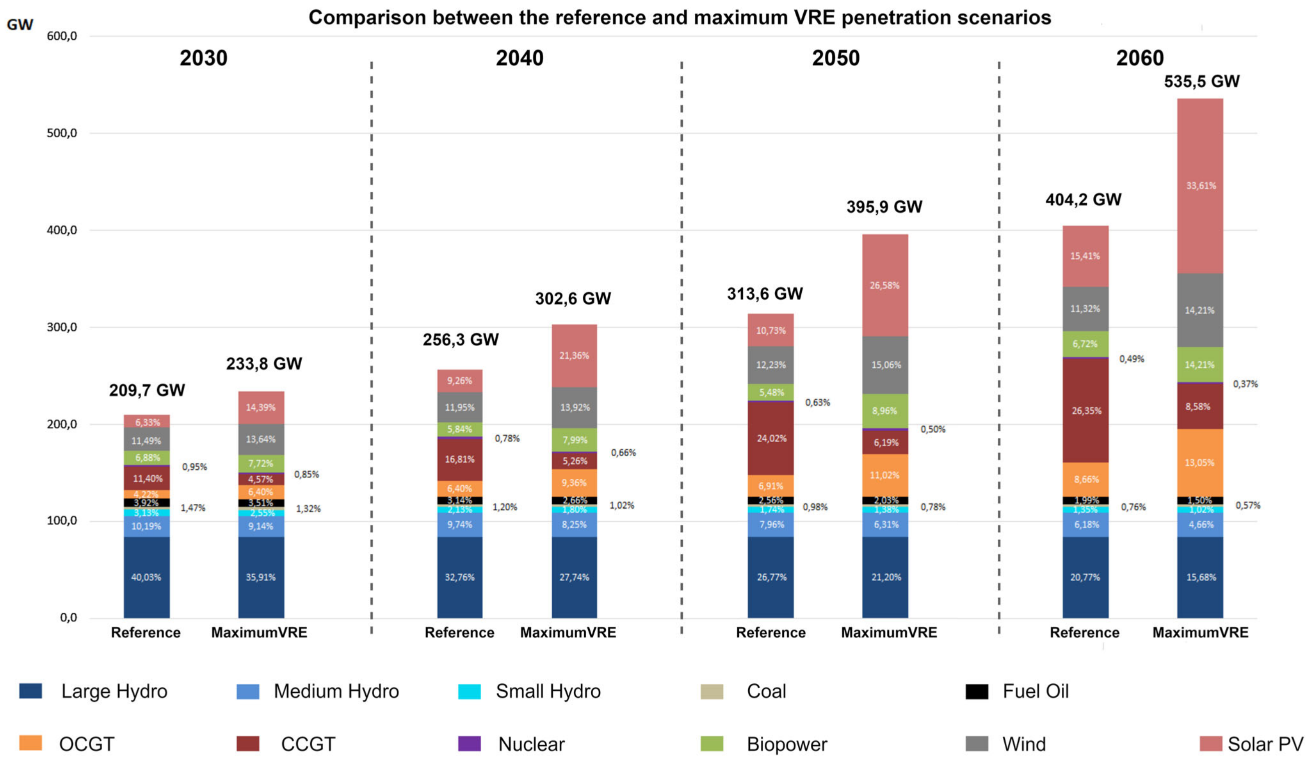

Fig. 5 Electrical matrix comparison

PV compared to wind, justified by being the most economical technology between both of them. Based on Fig. 5, some common behaviours are identified across all horizons. First, in general, the significant increase in the BIPS's total installed capacity from the reference scenario to the maximum VRE scenario. Since the objective is the maximum insertion of VRE, this difference in the final amount of installed capacity of the system is natural, as it is known that the average CF of operation of the VREs is lower than the majority of dispatchable generation technologies, thus requiring a higher installed capacity to meet the same demand.

Second, in the maximum VRE scenarios, it appears that the growth in VRE penetration is also accompanied by greater representativeness of OCGT and biopower technologies in the matrix followed by a reduction in the percentage of CCGT when compared to the reference scenario. It highlights the representativeness gain of the biomass renewable technology in the role of the plant responsible for providing despachability in a greater presence of VRE technologies in the system, demonstrating the capacity for complementarity between renewable sources, as discussed [30]. This fact is shown in CARTHER through the difference between the residual curve profiles of the reference and maximum VRE scenarios, exemplified by the residual curves for 2060 in Fig. 6.

Comparing the residual curves of the reference and the maximum VRE scenarios for 2060, there is a natural reduction in the amount of energy in the residual curve as a whole for greater VRE penetration in the system. However, there is mainly a change in the profile of the residual curve. In the reference scenarios, the shape of the residual curve has the largest portion of the energy required during almost all hours of the year, the base of the curve (dotted region of the graph), with a reduced portion of peak energy. In the maximum VRE scenario, this configuration of the energy distribution in the residual curve changes. The amount of energy required at the base of the curve is decreased, as the dotted regions of the graphs are compared. With this, the CCGT, whose LCOE is more economical than the biomass plants for the required demand above 8030 h per year, has a reduced portion of the load curve with economic advantage for expansion. That is, for energy demand in periods of less than 8030 h in the year (with CF below 91.7%), the expansion of biopower is more economically advantageous, justifying the choice of the model for the dispatchable renewable technology, biopower units, to complement the expansion of VRE. In addition, in the scenario of maximum VRE, it is noteworthy that despite the model opting for the expansion of the biopower technology, whose $\alpha = 0.3$, in detriment of the CCGT technology, whose flexibility coefficient is greater, $\alpha = 0.5$, the model increases the penetration of OCGT, whose $\alpha = 1.0$, demonstrating the qualitative response of the model in the scope of the flexibility and reliability of the expansion in the face of a large-scale VRE expansion.

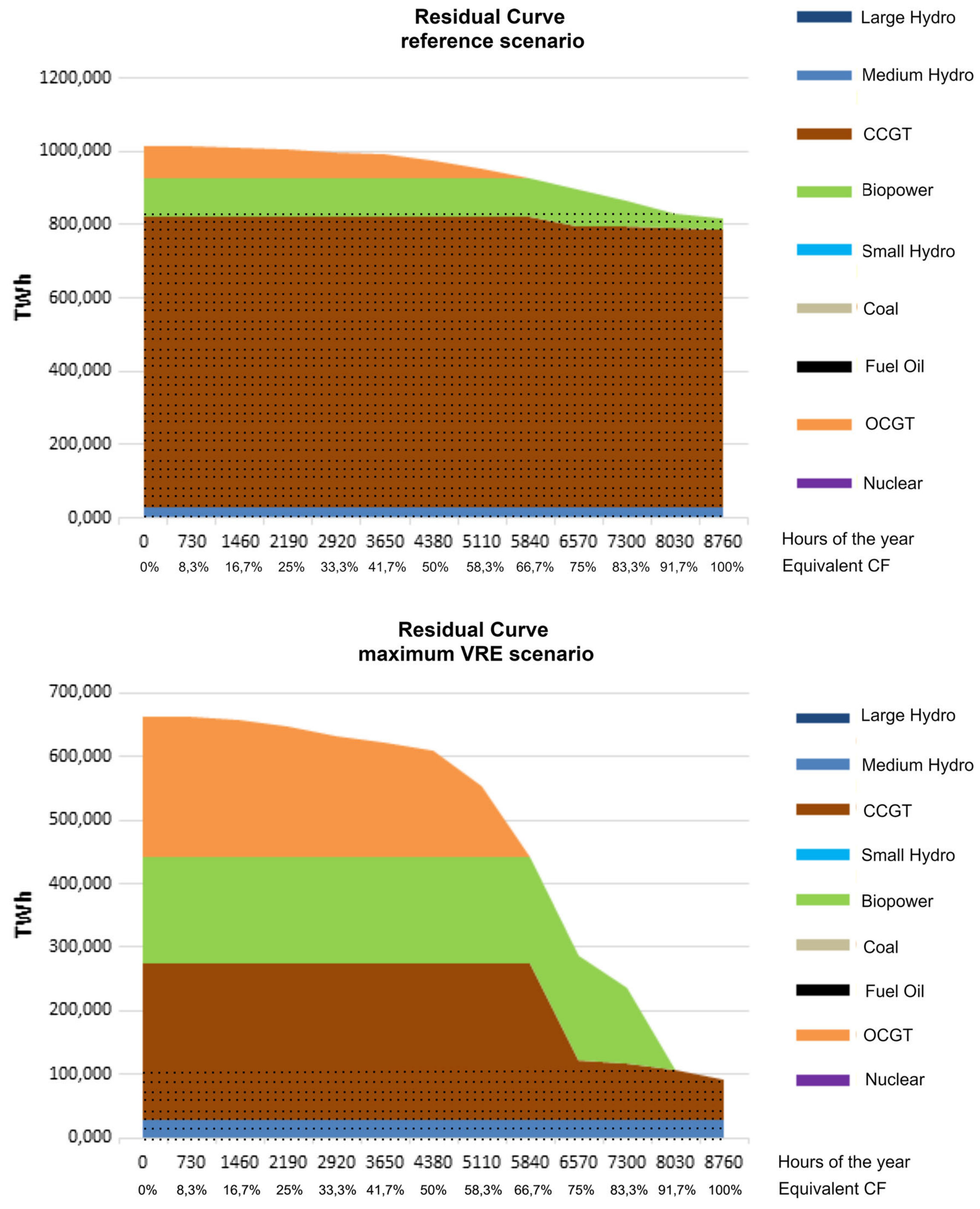

Fig. 6 BIPS residual curves for 2060

Table 6 Expansion of installed capacity in MW for the reference scenarios

Horizons	2030	2040	2050	2060
Large hydro ($\geq$ 1000 MW)	0	0	0	0
Medium hydro ($\geq$ 300 MW)	0	3600	3600	3600
Small hydro ($\leq$ 300 MW)	1122.2	0	0	0
Coal	0	0	0	0
OCGT	175.16	0	0	0
CCGT	3871.5	11426.6	16143.9	30038.5
Fuel oil thermal	15993.5	35163.8	54694.1	98614.2
Nuclear	0	0	0	0
Biopower	2931.5	3480.3	4442.1	15658.8
Wind	8993	15500.8	22657.8	30662.5
Solar PV	11043	21492	32300	60064.6

Table 7 Expansion of installed capacity in MW for maximum VRE share scenarios

Horizons	2030	2040	2050	2060
Large Hydro ($\geq$ 1000 MW)	0	0	0	0
Medium Hydro ($\geq$ 300 MW)	0	3600	3600	3600
Small Hydro ($\leq$ 300 MW)	500	0	0	0
Coal	0	0	0	0
OCGT	175.16	0	0	0
CCGT	9900.1	23340.7	37011.9	64876.7
Fuel oil Thermal	2776.3	7989.1	15593	38037.8
Nuclear	0	0	0	0
Biopower	6552.8	12678.7	19744.6	24638.3
Wind	16768	27000	27000	61000
Solar PV	31392	62400	101900	177700

5 Conclusion

In this work, the main objective is to present the methodology of an open-source, two-stage, multiyear computational tool and its range of applicability for LT GEP studies of hydrothermal systems with high intermittent renewables penetration, whose studies are calibrated in this article for BIPS expansion scenarios.

Through the case study, the adequate performance of the model is verified concerning the main parameters of the system impacted with a large-scale VRE insertion: flexibility and reliability. In general, the need for an extra financial contribution proportional to the greater integration of VRE in the system was noticed. Among the VREs, there is a more expressive growth in the share of solar PV compared to wind power, justified by its greater economy between the two. In the reference scenarios, the results of the BIPS matrix for all horizons present the same characteristic, which consists of a more sustainable expansion, prioritizing gas plants over coal and oil products technologies, in line with expectations de [43], where gas technologies assume the role of transition technology towards a more sustainable future power sector matrix. In the scenarios of maximum VRE penetration compared to the reference scenario, there is the loss of space of the CCGT technology for an increase in the representativeness of the biopower in the matrix, demonstrating the capacity of complementarity between renewable technologies, agreeing with [30]. In addition, it is noteworthy that although the model opts for a more sustainable expansion, biomass, whose $\alpha = 0.3$, to the detriment of CCGT, whose flexibility coefficient is greater, $\alpha = 0.5$, the model increases OCGT penetration, whose $\alpha = 1.0$, demonstrating the qualitative response of the model in the scope of the flexibility and reliability of the expansion in the face of a large-scale VRE expansion.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. IEA (2020) Renewables—International Energy Agency (IEA). https://www.iea.org/fuels-and-technologies/renewables
2. IRENA (2017) REthinking energy 2017: accelerating the global energy transformation. International Renewable Energy Agency (IRENA), Abu Dhabi
3. Das P, Mathur J, Bhakar R, Kanudia A (2018) Implications of short-term renewable energy resource intermittency in long-term power system planning. Energy Strategy Rev 22:1–15. https://doi.org/10.1016/j.esr.2018.06.005
4. EPRI (2015) Electric power resource planning: EGEAS software overview. Electric Power Research Institute (EPRI). https://eea.epri.com/pdf/NG%20Planning_EPRI_EGEAS_Webcast_041615_Final.pdf
5. PSR (2020) OptGen—model for generation expansion planning and regional interconnections. https://www.psr-inc.com/softwares/?current=p4038
6. Gupta N, Khosravy M, Saurav K, Sethi I, Marina N (2018) Value assessment method for expansion planning of generators and transmission networks: a non-iterative approach. Electr Eng 100:1405–1420. https://doi.org/10.1007/s00202-017-0590-7
7. Dehghan S, Amjady N, Kazemi A (2014) Two-stage robust generation expansion planning: a mixed integer linear programming model. IEEE Trans Power Syst 29(2):584–597. https://doi.org/10.1109/TPWRS.2013.2287457

8. Akbari T, ZolfaghariMoghaddam S, Poorghanaat E, Azimi F (2017) Coordinated planning of generation capacity and transmission network expansion: a game approach with multi-leader-follower. Int. Trans. Electr. Energy Syst. 27(7):e2339. https://doi.org/10.1002/etep.2339
9. Andreoni AM, Garcia-Agreda A, Strada TJ, Saraiva JT (2007) "Strategies for power systems expansion planning in a competitive electrical market. Electr Eng 89:433–441. https://doi.org/10.1007/s00202-006-0022-6
10. Martínez-Villaseñor L, Ponce H, Marmolejo-Saucedo JA, Ramírez JM, Hernández A (2018) Analysis of constraint-handling in metaheuristic approaches for the generation and transmission expansion planning problem with renewable energy. Complexity 2018:1–22. https://doi.org/10.1155/2018/1438196
11. Pereira AJC, Saraiva JT (2011) Generation expansion planning (GEP)—a long-term approach using system dynamics and genetic algorithms (GAs). Energy 36(8):5180–5199. https://doi.org/10.1016/j.energy.2011.06.021
12. Rajesh K, Bhuvanesh A, Kannan S, Thangaraj C (2016) Least cost generation expansion planning with solar power plant using differential evolution algorithm. Renew Energy 85:677–686. https://doi.org/10.1016/j.renene.2015.07.026
13. Ashraf M, Malik T (2020) A hybrid teaching–learning-based optimizer with novel radix-5 mapping procedure for minimum cost power generation planning considering renewable energy sources and reducing emission. Electr Eng 102:2567–2582. https://doi.org/10.1007/s00202-020-01044-0
14. Ueckerdt F, Pietzcker R, Scholz Y, Stetter D, Giannousakis A, Luderer G (2017) Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. Energy Econ 64:665–684. https://doi.org/10.1016/j.eneco.2016.05.012
15. Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W, (2016) Impact of the level of temporal and operational detail in energy-system planning models. Appl Energy 162:631–643. https://doi.org/10.1016/j.apenergy.2015.10.100
16. Denholm P, Hand M (2011) Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 39(3):1817–1830. https://doi.org/10.1016/j.enpol.2011.01.019
17. Ueckerdt F, Brecha R, Luderer G, Sullivan P, Eva S, Bauer N, Böttger D, Pietzcker R (2015) Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves. Energy 90:1799–1814. https://doi.org/10.1016/j.energy.2015.07.006
18. Pereira AJC, Saraiva JT (2013) A long term generation expansion planning model using system dynamics—case study using data from the Portuguese/Spanish generation system. Electr Power Syst Res 97:41–50. https://doi.org/10.1016/j.epsr.2012.12.001
19. Kotb S, Sadat A, Adly A (2020) A proposed optimization scheme for the Egyptian electrical network generation mix based on cost reduction. Electr Eng 102:401–408. https://doi.org/10.1007/s00202-019-00883-w
20. Ko W, Park J-K, Kim M-K, Heo J-H (2017) A multi-energy system expansion planning method using a linearized load-energy curve: a case study in South Korea. Energies 10(10):1663. https://doi.org/10.3390/en10101663
21. Javadi MS, Esmaeel NA (2019) Multi-objective, multi-year dynamic generation and transmission expansion planning—renewable energy sources integration for Iran's National Power Grid. Int Trans Electr Energy Syst 29(4):e2810. https://doi.org/10.1002/etep.2810
22. Bhuvanesh A, Jaya Christa ST, Kannan S, Karuppasamy PM (2019) Multistage multiobjective electricity generation expansion planning for Tamil Nadu considering least cost and minimal GHG emission. Int Trans Electr Energy Syst. 29(2):e2708. https://doi.org/10.1002/etep.2708
23. CEPEL. MELP—long term generation expansion model. http://www.cepel.br/en_us/products/melp-long-term-generation-expansion-model-1.htm
24. EPE (2018) Estudos para a Expansão da Geração—Modelo de Decisão de Investimentos para Expansão do SIN—PDE 2027 Version. http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-332/topico-425/NT_MDI_EPE-DEE-RE-52-2018_r1.pdf
25. EPE (2019) Workshop stochastic programming models and algorithms for energy planning—ILAS 2019
26. Santos MJ, Ferreira P, Araújo M, Portugal-Pereira J, Lucena AFP, Schaeffer R (2017) Scenarios for the future Brazilian power sector based on a multi-criteria assessment. J Clean Prod 167:938–950. https://doi.org/10.1016/j.jclepro.2017.03.145
27. Schmidt J, Cancella R, Pereira AO (2016) An optimal mix of solar PV, wind and hydro power for a low-carbon electricity supply in Brazil. Renew Energy 85:137–147. https://doi.org/10.1016/j.renene.2015.06.010
28. Gils H, Simon S, Soria R (2017) 100% Renewable energy supply for Brazil—the role of sector coupling and regional development. Energies 10(11):1859. https://doi.org/10.3390/en10111859
29. Luz T, Moura P, De Almeida A (2018) Multi-objective power generation expansion planning with high penetration of renewables. Renew Sustain Energy Rev 81:2637–2643. https://doi.org/10.1016/j.rser.2017.06.069
30. Luz T, Moura P (2019) Power generation expansion planning with complementarity between renewable sources and regions for 100% renewable energy systems. Int Trans Electr Energy Syst. https://doi.org/10.1002/2050-7038.2817
31. Torres C, Melo R (2020) Manual of CARTHER academic expansion planning software. http://www.ppgeet.uff.br/site/wp-content/uploads/2021/06/Ranther-Melo.pdf
32. EIA (2013) Levelized cost of electricity and levelized avoided cost of electricity methodology supplement. U.S. Energy Information Administration (EIA). https://www.eia.gov/renewable/workshop/gencosts/pdf/methodology_supplement.pdf
33. NREL (2020) Simple levelized cost of energy (LCOE) calculator documentation. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/analysis/tech-lcoe-documentation.html. Accessed 01, 2020
34. Sullivan P, Krey V, Riahi K (2013) Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Rev 1(3):157–163. https://doi.org/10.1016/j.esr.2013.01.001
35. ANEEL (2020) Sistema de Informações de Geração da ANEEL—SIGA. https://www.aneel.gov.br/siga
36. EPE (2006) Plano Nacional de Energia 2030—PNE 2030. Empresa de Pesquisa Energética—EPE. http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Nacional-de-Energia-PNE-2030
37. EPE (2018) Premissas e Custos da Oferta de Energia Elétrica no horizonte 2050—Série: Estudos de Longo Prazo- Empresa de Pesquisa Energética (EPE)
38. EPE (2019) The ten-year energy expansion plan 2029—PDE 2029 (Portuguese acronym). Empresa de Pesquisa Energética. http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2029
39. ONS (2020) Curva de Carga Horária. Operador Nacional do Sistema Elétrico (ONS). http://ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/curva_carga_horaria.aspx
40. ONS (2018) Boletim Mensal de Geração Eólica dezembro/2018. http://www.ons.org.br/AcervoDigitalDocumentosEPublicacoes/Boletim_Eolica_dez_2018.pdf

41. ONS (2018) Boletim Mensal de Geração Solar Fotovoltaica dezembro/2018. http://www.ons.org.br/AcervoDigitalDocumentosEPublicacoes/Boletim_Mensal_%20Gera%C3%A7%C3%A3o_Solar_201812.pdf
42. ANEEL (2018) Relatório de Acompanhamento da Implantação de Empreendimentos de Geração N11 março 2018
43. EPE (2018) Considerações sobre a Participação do Gás Natural na Matriz Energética no Longo Prazo. http://www.mme.gov.br/web/guest/secretarias/planejamento-e-desenvolvimento-energetico/publicacoes/relatorio-do-pne-2050/-/document_library_display/bGHIG0XSkBz4/recent?p_r_p_564233524_categoryId=&p_r_p_564233524_tag