Renewable Energy 162 (2020) 1684–1702

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

When is the sun going to shine for the Brazilian energy sector? A story of how modelling affects solar electricity

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A R T I C L E I N F O

Article history:
Received 26 November 2019
Received in revised form
14 August 2020
Accepted 19 September 2020
Available online 21 September 2020

Keywords:
Large-scale solar energy
Energy modeling
Cost-effectiveness
Brazil

A B S T R A C T

The energy sector has a vital role in climate change mitigation. In Brazil, the electricity generation sector is strongly dependent on hydropower generation, but thermoelectricity contribution has increased leading to a more carbon-intensive electricity mix. This trend will be aggravated with the expected significant increase in the electricity demand until 2050 and with the potential limitation of hydropower generation expansion due to environmental constraints. The extent of the role of solar power to overcome these challenges in the future has been hidden by energy modelling assumptions. A review on how solar energy has been considered in different models, was performed. The research further assessed the relevance of assumptions by developing an optimization model to explore the cost-effectiveness of solar electricity large-scale deployment up to 2050. The work found that most published solar energy assessments based on long-term energy modelling for Brazil currently are not updated regarding several assumptions, leading to models results where solar appears with a marginal role. The energy modeling exercise shows solar PV is cost-effective for Brazil, providing more than 36% of total electricity in 2050. This is a different conclusion from the energy and power modeling exercises conducted until now, where solar deployment has been underestimated.

1. Introduction

The current climate change crisis imposes on society the need to implement an energy transition towards a low carbon energy system [1]. This implies that current energy systems must become more efficient, more electrified and consuming more renewable energy sources (RES) [1], such as hydropower, wind and solar. On the other hand, the deployment of RES energy sources has to overcome many market, social, technical and policy barriers [2,3]. Among these, solar photovoltaics or solar PV (and wind) is a more recent technology, with a very important role to play globally [4,5], whereas hydropower is a well-known and more established RES technology [6].

Therefore, the required large scale deployment of solar power requires a technical-institutional paradigm shift [7] to overcome the aforementioned barriers. This is especially the case for countries with less experience with solar power, where other RES (as for example hydropower) are seen as more reliable [3,6]. Thus, for such countries, for solar deployment to occur it is thus necessary to transition between rival paradigms (from a fossil fuels and/or hydropower one to a solar and/or wind-based paradigm). According to Ref. [8] such transition cannot be gradual.

In this context, this paper contributes to the debate on the possible shift from the current hydro-fossil paradigm in electricity generation to a new one that includes large-scale use of solar energy until 2050, for the case-study of Brazil. To do so, this work investigates how the role of solar energy has been dealt with in the scientific literature on long-term energy planning in Brazil, and proposes data updates within an integrated energy system modelling tool to assess the potential of solar energy in the country.

Brazil is a relevant case-study as it is the biggest country of Latin America, the eighth biggest global economy and the seventh global emitter of greenhouse gases emissions (GHG). Since the Brazilian development pattern is similar to other countries, the insights and conclusions from this work may have relevant impacts for other developing economies.

Within the Paris Agreement, Brazil proposed a reduction of 43% of national GHG emissions in 2050, relative to 2005 [9]. In the last decade, the electricity mix has undergone a significant increase in

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https://doi.org/10.1016/j.renene.2020.09.091
0960-1481/

Abbreviations

ACR	*Ambiente de Contratação Regulada* – Regulated contract environment
ANEEL	*Agência Nacional de Energia Elétrica* – Electricity regulation agency
CNPq	*Conselho Nacional de Desenvolvimento Científico e Tecnológico* – National Council for Scientific and Technological Development
COP 21	21st yearly session of the Conference of the Parties of United Nations Framework Convention on Climate Change
CSP	concentrated solar power
EPE	*Empresa de Pesquisa Energética* - Brazilian energy planning enterprise
FEC	Final energy consumption
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatts
IEA	International Energy Agency
INPE	*Instituto Nacional de Pesquisas Espaciais* – National Institute of Spacial Research
kt	thousands of tons
LCOE	Levelized Cost Of Energy
LEN	*Leilão de Energia Nova* – New energy auction
N_2O	Nitrous oxide
PCH	*Pequena Central Hidrelétrica* – Small hydropower plant
PDE	*Plano Decenal de Expansão de Energia* – 10-year energy expansion plans for Brazil
PNE	*Plano Nacional de Energia* – National energy plan
PV	Photovoltaic
RES	Renewable Energy Source
TWh	Terawatts hour
UHE	*Usina Hidrelétrica* – Hydropower plant
US	Utility scale

GHG emissions intensity, from 63 $ktCO_2$/TWh in 2006 to 159 $ktCO_2$/TWh in 2014 [10–12], due to the deployment of thermal power plants fueled by gas, coal and oil. The dryer years, like 2014, tend to be more carbon intensive, in 2016 and 2017 the intensity decreased to 104$ktCO_2$/TWh. The 2030 carbon intensity of electricity is expected to be 63$ktCO_2$/TWh, according to oficial projections [13]. Electricity generation was the third largest GHG emitter in 2016 in terms of total emissions (19%), behind land-use change (51%) and agriculture (22%) [14]. Brazil is currently on a critical moment regarding energy planning: addressing climate change mitigation while facing an increasing demand for electricity, which is expected to grow more than 110% between 2010 and 2030 [15]. Moreover, the expansion of hydropower appears limited due to the high environmentally sensitive Amazon region [16].

Regarding the increasing demand, although the pace of growth of the Brazilian economy has dropped in 2015 and 2016, due to the political and economic crisis, the cyclic recuperation of economy is expected to restore the annual growth rate of the GDP to 2.5% until 2026 [17], meaning a cumulative growth of 50% between 2006 and 2026, leading to an average projected annual increase rate of 2.2% between 2013 and 2050 [18].

Regarding the Amazon hydropower, in 2007 up to new 80 GW could potentially be built [15], whereas currently, this potential is considered to be only a quarter of the total potential identified [16]. Socio-environmental issues faced by the Belo Monte dam construction show the particular sensitivity of the region has to be taken into account within the energy planning process [19]. Therefore, some hydropower plants will no longer be constructed, while others have been adapted to operate in a run-of-river mode, with corresponding decreases in productivity [16]. Limiting hydropower in Amazon is currently once again being politically questioned and debated following the 2018 elections in Brazil. Therefore, revisiting cost-effective alternatives to hydropower (as solar power) is even more relevant now in order to thoroughly and objectively address the transition. Moreover, the vulnerability of hydropower to climate change is becoming more relevant, and there are concerns that hydropower might not be as effective in the future as in the past years, both in Brazil [20,21] and in other parts of the globe.

Despite the global push towards solar deployment [4], in Brazil, solar energy is currently very low with 2.2 GW of solar PV installed by September 2019, 0.6 GW under construction and 3.5 GW planned [22]. Solar PV is expected to represent only 2% of power generation in 2027 [23], according to national plans [24]. The role of solar source up to 2050 is perceived as modest, according to existing scientific literature [25–27]). Following [28], the large-scale deployment of renewable technologies that could allow an energy transition is necessary, but historically, the adoption of new energy technologies used to be a slow process with many barriers, namely associated with the regional diffusion. In our study, the focus is on the main barriers for solar deployment in large scale in Brazil. Our hypothesis is that the perceived marginal role for solar energy in the future energy matrix of Brazil may be explained, at least partially, by the fact that solar energy has not been properly assessed in energy planning models used to assess it. This aspect was investigated firstly by reviewing approaches and assumptions taken in previous modelling exercises that include solar power in Brazil and secondly, by testing its deployment with different plausible assumptions using the technology optimization model TIMES-BR_light representing the Brazilian energy system up to 2050.

This paper is structured as follows: after this introduction, section two reviews some solar energy modelling approaches for Brazil, followed by an overview of the TIMES-BR_light energy system model and the alternative approaches used to test the role of solar power in the country. Section four presents the results of the energy modelling exercise regarding generated electricity, final energy and GHG emissions and the last section concludes.

2. Review of solar energy modelling approaches in Brazil

This section presents an overview of current status regarding the main barriers that have hindered the large-scale deployment of solar power in Brazil and globally, followed by an analysis on how these have been considered in the existing long-term energy planning literature for Brazil.

2.1. Main barriers affecting solar energy deployment

A set of barriers to solar power expansion were cited by Ref. [24] and can be divided in technological (intermittency of the resource and the quality of the projects) and economic-regulatory barriers (electricity production costs, lack of a specific regulatory framework for solar PV, lack of local industry, and access to capital). One of these barriers is the high cost of electricity production from PV utility-scale plants [24], which has been decreased substantially [29]. For example, at the 27°LEN (new energy auction) in Brazil [30] the electricity contracted from the new natural gas power plants had higher costs than PV centralized plants (64.73US$/MWh and 35.51US$/MWh, respectively). In the auction of June 2019 [31], the price for 1 MWh of PV electricity was set at 17.61US$.

Moreover, the relevance of the traditional barriers for PV deployment, as cost and lack of subsidies, are questioned [7], which suggests the focus should be on overcoming concerns: (i) the social acceptance and readiness (workforce knowledge) to deploy utility-scale PV plants, (ii) the environmental sensitivity of possible location, and (iii) the existence of transmission lines. One pioneering project for solar deployment market research was described by Ref. [32], proposing that an ecolabel could be used to influence the decision of consumers and consequently the power companies' decision in adopting PV electricity in the free market.

The International Solar Energy Society [3] launched in 2019 a set of infographics demystifying the most common myths on the difficulties of large-scale integrating solar energy into the grid. The work highlights the myth that the increase of RES power reduces the grid security, which is contested [33] through energy models showing that the growth of solar and wind power in the grid will in fact increase grid reliability.

Currently, most barriers for solar PV deployment seem to have become less relevant. Thus, we argue that the reason why solar energy has had a marginal role in the future energy system planning literature for Brazil refers to how it has been considered in the energy modelling exercises. To confirm this hypothesis, this research follows with a review on how solar has been assessed with energy models in Brazil.

2.2. Review of energy modelling literature regarding solar power

This section presents a review of scientific papers addressing solar energy and energy modelling for Brazil, regarding the assumptions and approaches used for solar power, and assessing how these are affecting the future role of solar in the Brazilian energy system. The literature review was structured in three steps: (i) the definition of a protocol for research, (ii) the selection of relevant papers and finally (iii) the inclusion of official reports from national and international bodies (as the International Energy Agency or IEA) regarding large-scale solar energy deployment in Brazil.

Fig. 1 shows the research protocol with the research question, a strategy of research and the temporal horizon of research. In the right upper part, Fig. 1 presents a list of reasons to reject a number of papers. In the middle of the figure, additional sources used in the review are presented, while in the bottom the relevant aspects used to assess the papers are listed.

In the definition of the protocol, it was identified a research question, a strategy of research, keywords and a temporal horizon definition (i.e. the last five years). The focus point of the literature review was on how solar energy in Brazil has been considered in long-term energy models, resulting in the research question: "Is solar energy properly assessed in energy modelling exercises for the future Brazilian power sector?" The search strategy used three keywords <solar>, <Brazil> and <energy model > that appear in different article components (abstract, title or keywords) and the platform used was *Web of Science*. About 100 potentially relevant papers published in the last five years were identified, which were scrutinized and resulted in a final selection of only ten papers suitable for this research purpose. Additionally, it was included six other papers published more than five years ago, as they were found especially relevant and suggested by experts in the field. Finally, the plausibility of the results obtained from the analysis of the scientific publications was tested by comparing them with findings of related official reports from the IEA ad the Brazilian energy planning enterprise (EPE).

To assess how solar energy has been considered in Brazilian energy system modelling studies, six model assumptions were focused: (i) investment cost of PV generation at utility-scale (PV-US), (ii) maximum solar plants deployment potential, (iii) maximum hydropower plants deployment potential, (iv) coal power plants deployment trends from current situation, (v) temporal granularity of the model (e.g. hourly or annual), and (vi) spatial granularity (e.g. Brazil modelled as one single region or with higher geographical resolution). This analysis is discussed in the following sections and summarised in Table 1 for the 16 papers covering 13 different models generating results on the medium-long term role for solar PV in Brazil.

2.2.1. PV-US investment cost

Considering the solar PV investment cost in the initial year, the assumptions for the 16 studies and 13 models, vary widely, from 578US$/kW [37] to 4560 US$/kW [40]. The former is based on international costs (e.g. Ref. [45]) and the latter is from the simulation with the System Advisor Model – SAM. The investment cost for the final modelled year, reflecting the considered learning curve of technology, have a smaller range, from 301 US$/kW [5] to 3100 US$/kW [40]. Of the eight papers that present solar PV investment cost, three consider 4300 US$/kW in the initial year and 1300 US$/kW in the final year. It is not straightforward to identify the sources of the PV cost assumptions in the models [25]. state that PV costs are from the IEA Solar Technology Roadmap [4] but their values differ from the ones in this publication: the IEA's solar PV cost average range, in a high-renewable scenario, is around 2000-1000 US$/kW (p.23) and the cost in selected countries ranges between 1400 and 3300 US$/kW, for PV utility scale system prices (p.16). The same occurs in Ref. [44] that presents a PV cost ranging from 4300 to 1300 US$/kW, also based on [46], although with different values. In all papers, it is not clear to what year the costs are reported, thus hampering the comparison. Fig. 2 shows the investment cost for utility-scale PV in the initial years for the 16 reviewed studies.

Finally, the considered solar PV-US investment cost, in one of the preparatory documents of the Brazilian national 2050 energy plan [47], was between 1350 and 800 US$/kW. In Ref. [24], the investment cost for centralised PV generation is between 1400 and 2100 US$/kW, and for [16] this value is around 1300 US$/kW. Therefore, it seems that the PV investment costs used to assess the solar potential have been rather high.

2.2.2. Solar deployment potential

The assumptions on the maximum solar potential that can be deployed are considered from different perspectives in the 16 reviewed articles. Some studies [39] consider the total availability for solar energy deployment is of 794 GW of installed capacity in Brazil, while other [37] consider the potential so high that it is treated as unlimited. Some authors [36,41], divided the solar energy potential in PV utility-scale, PV distributed and concentrated solar power (CSP). In the former paper, the total solar potential ranges between 570 and 770 GW, whereas in the second the potential is only 46 GW. This same author in previous work [48] considered the potential for PV would be of 40 GW. The assumption on solar potential appears to be constantly changing, revealing a high uncertainty.

2.2.3. Hydropower deployment potential

With more than two-thirds of the current power matrix relying on hydropower generation [49], it is natural that the first option of expansion of the power supply would be exploring the remaining potential. However, this is mostly located in the Amazon region and other environmentally sensitive regions, thus limiting this expansion. In the reviewed studies, new hydropower potential ranges

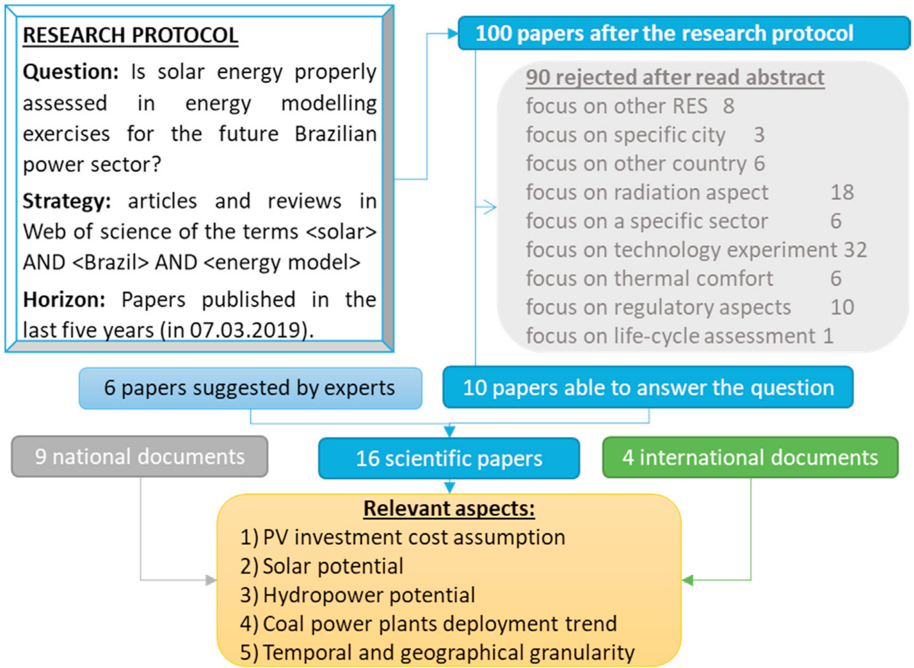

Fig. 1. Literature review methodology overview.

Table 1
Summary of the parameters selected to assess how solar energy has been assessed in Brazilian energy system models.

Ref.	Model	CAPEX PV-US (US$/kW)	Solar maximum potential (GW)	Hydropower maximum potential (GW)	New coal power plants deployment trend	Temporal Granularity	Spatial Granularity (No. of regions)
[34]	LUT	NA	NA	NA	NA	Hourly	5
[5]	LUT	1278–301	NA	Stable	Decreasing	Hourly	1
[35]	TIMES	NA	NA	NA	NA	Year divided in 288 time-slices	2
[36]	MESSAGE	NA	730–930	ND	Increasing	Year divided in 20 time-slices	4
[25]	REMIX	4300–1300	NA	Stable in Northeast Region	Increasing	Year divided in 168 time-slices	2
[37]	REMIX	578	Unlimited	109	Decreasing	Hourly	7
[38]	MESSAGE, TIAM, POLES, EPPA, GCAM, Phoenix	NA	NA	NA	NA	Varies from hourly	1
[39]	Other	NA	794	260	Decreasing	Hourly	1
[40]	MESSAGE	4560–3100	12.8	42	Stable	Year divided in 20 time-slices	3
[26]	MESSAGE	NA	NA	42	STABLE	Year divided in 20 time-slices	2
[41]	TIMES	4300–1000	46	85	Increasing	Year divided in 192 time-slices	29
[27]	MESSAGE	4300–1300	NA	NA	Increasing	NA	1
[42]	MESSAGE	NA	NA	14	Increasing	NA	1
[33]	No name	NA	NA	20	Stable	Hourly	1
[43]	No name	1900–600	NA	Stable	Decreasing	Hourly	1
[44]	MESSAGE + TIMES + REMIX	4300–1300	NA	Increasing	Increasing	Year divided in 432 time-slices for TIMES and 20 for MESSAGE	1

NA - not available.

from 14 to 260 GW. Whereas some studies consider such limited expansion in its models assumptions [5,43,44], others assume an increased hydropower potential [33,37,39–42]. Some increasing hydropower thresholds are incremental variations, between 14 GW [42] and 45 GW [40], while others consider expansions up to 85 GW [41] or 109 GW [37], that are unavailable outside the Amazon region.

In the *National Energy Plan 2030* [15], the hydropower expansion potential was of 96 GW, of which 74 GW would be located in the Amazon region. It should be mentioned that, in the decadal plans of 2024, 2023 and 2022 [50–52], the potential expansion was of around 30 GW. However, in the 2026 decadal plan, it decreased to 14 GW [16], and in the 2027 plan only 3 GW were considered for large hydropower plants and 2.7 GW for small power plants [23]. Regarding potentials referred in the *National Energy* Plan 2050 [53], the potential for large hydropower plants is set at 52 GW, with only 12 GW assumed to be located in environmental sensitivity areas. Depending on the potential taken into the energy model, the results could vary substantially due to the relevance of that source to the Brazilian electricity mix in terms of availability, low production costs and GHG emissions.

2.2.4. *Coal deployment trends*

The increase of coal power generation, a carbon-intensive technology, is very significant for the expansion of Brazilian power supply in the majority of the reviewed papers

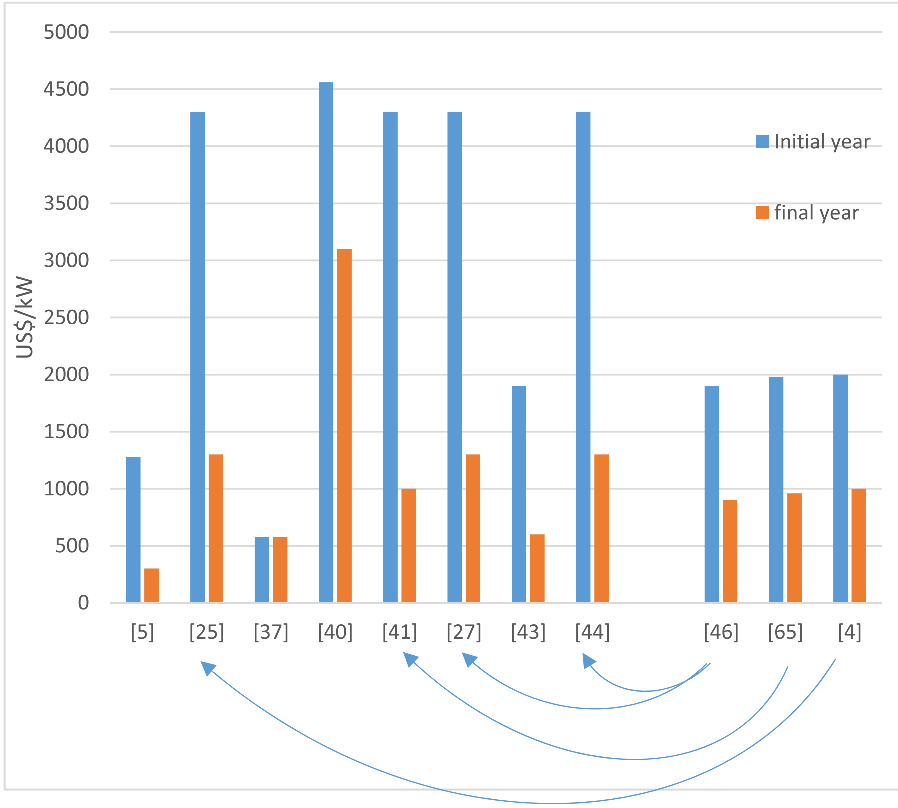

Fig. 2. Utility-scale solar PV investment cost considered in various studies, including cross-references. Arrows illustrate the origin of the source reference to several studies.

[25,27,36,38,41,42,44]. A contrasting view, with a decreasing coal deployment trend, is seen in Refs. [5,37,39,43]. It is worth to highlight that the official National Energy Plan for 2030 [15] in 2007, coal-based power generation was expected to grow substantially up to 2030 (Fig. 3, PNE 2030 green dots and linear trend curve). Such expectation was based on: (i) the high availability of endogenous coal resources, and (ii) the trend (at the time) of increased coal thermoelectricity in some non-OECD countries. The PNE2030 (2007) estimated an increase of installed coal capacity of 10 000 MW. However, the most recent official 10-year energy expansion plans for Brazil (published in 2012, 2013, 2014, 2016 and 2017) do not consider the same high growth of coal-based electricity. Fig. 3 shows the difference of the expected coal-based electricity between the trend published in 2007 [15] and after 2013 in official energy planning reports [16,23,50–52].

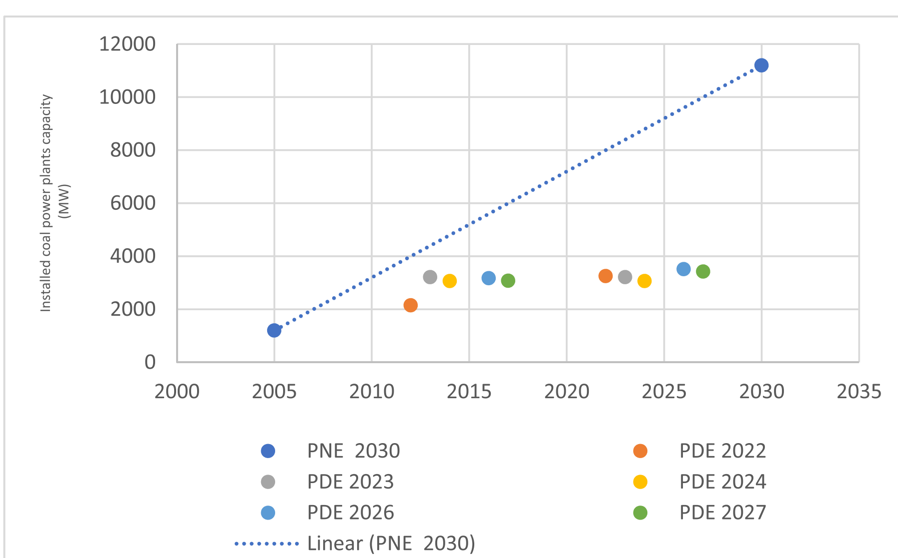

Fig. 3. Coal-based thermoelectricity trends in official Brazilian energy planning reports from EPE.
PDE-10-year energy expansion plans for Brazil; PNE- National energy plan); Sources: PNE2030 [15]; PDE2022 [50]; PDE2023 [51]; PDE2024 [52]; PDE2026 [16]; PDE2027 [23].

The main barriers for coal deployment pointed in the 10-year energy plans include environmental concerns, the lack of financial resources for coal made available by the national financing organizations in Brazil and the low heating value of the national coal resources. Moreover, the official document (2018) on the potential for power generation in 2050 [23] in Brazil, states that the three most recent national coal power plants are currently using imported coal at the expense of the national coal due to poor quality. The last coal power plant was contracted through an auction in Brazil in 2014. Therefore, we may state the majority of reviewed papers does not consider the recent developments regarding more conservative assumptions on coal power plants deployment in Brazil.

2.2.5. Temporal and spatial granularity

Considering the intraday variability of solar resource and its load, the best way to assess the solar PV potential would be by considering an hourly time resolution in Ref. [5,33,34,37,39,43]. None of them, however, used MESSAGE or TIMES energy system modelling tools. Considering the trade-off between increased complexity of interactions of technologies and sectors and better temporal granularity, other authors opted by having 24 h of a typical day for season, week, day or weekend as [35]who used 288 timeslices in TIMES model [25], with 168 time-slices modelling with REMIX [41], with 192 time-slices in TIMES and [44]with 432 time-slices. As the focus of this work is on solar energy and this source has an intraday variability, it is important to consider at least all hours in a representative day.

From a spatial scale perspective, the total Brazilian energy system has been considered as a unique region in most of the reviewed studies [5,27,33,38,39,42–44]. The exception was [41] that considered several regions to account for the bottlenecks in transmission lines.

2.3. How current modelling approaches affect the future role of solar in the Brazilian energy system

By analyzing how the six set of assumptions have been considered in the 16 reviewed papers on energy planning studies for Brazil, it was possible to find that solar energy has not been properly assessed in the energy modelling exercises. The technology investment costs in most of the literature was higher than in the recent official datasets and was obtained from a few similar sources. Regarding the PV potential, most of the studies (dated from 2013 to 2017) considered values substantially lower than recent official national documents [53], indicating that there is substantial uncertainty on PV potential for Brazil. Another important assumption refers to the potential of “competitors” technologies, i.e. hydropower and coal power. In all reviewed studies, the official forecasts of the Brazilian National Energy Plan (2007) from EPE were assumed. However, the forecasts from EPE from 2016 to 2017 have reviewed such deployment assumptions and hydropower and coal power plants potential is substantially lower. This serves to highlight again, the uncertainty on new technologies potential deployment and the importance of differentiating between technical and political potentials in modelling exercises. Ideally, both should be considered to better deal with the uncertainty around future technology deployment. Finally, the temporal and geographical granularity of the different reviewed modelling studies was not found to be the most determinant assumption critically affecting the role of solar power in their respective results.

Considering the importance of the identified assumptions on solar deployment, the authors built a new model representing the Brazilian energy sector in order to assess what would be the impact of changing such assumptions in the long-term role of solar energy in Brazil. In this model, the solar investment costs are updated, as well as solar, hydropower and coal power plants potentials. It was further investigated how variations in cost assumptions for solar PV and solar thermal affect overall solar energy deployment in Brazil, up to 2050. This research aims to explore how modelling assumptions have been influencing the results regarding the long-term role of solar energy for power production in Brazil and provide some insights on its possible role in the future electricity mix.

3. Overview of the TIMES _BR_LIGHT model

The cost-effective potential of solar power for the Brazilian energy system was assessed using a new model based on the TIMES-MARKAL model generator [54], the TIMES_BR_light model. TIMES-MARKAL is a partial equilibrium bottom-up optimization model generator, developed by the International Energy Agency that finds the most cost-effective technological options under integrated energy scenarios. The model generator has been implemented in different scales and is currently used to model different energy systems: global [55], Chinese [56], European [54], or Portuguese [57], South America [35] to name but a few.

The main objective of a TIMES model and of TIMES_BR_light, in particular, is to identify the energy supply and demand technologies that allow the satisfaction of the energy demand while minimising the total energy system costs through linear programming. The objective function of the model is:

$$NPV = \sum_{y \in YEARS} (1 + d_y)^{REFYR-y} . ANNCOST(y)$$

Where NPV is the net present value of the total costs, d is the discount rate, y is the year, and REFYR is the reference year. ANNCOST are the total annual costs and YEARS are the years for which there are costs [54].

As other TIMES models, the TIMES_BR_light model provides results on the most cost-effective technological alternatives for future energy system scenarios, the changes in fuel costs, emissions and total system cost, as well as the new investments required to supply projections of future energy services demand.

3.1. Model structure and overview

TIMES_BR_light represents the Brazilian energy system as one single region from 2013 to 2050, in five-year time steps. Each year is divided into 192 time-slices, representing each hour of a typical day, week and weekend, for each of the four seasons of the year. The model considers both the supply and demand sides of the energy system, and it models in detail the primary energy supply sector including RES and non-RES primary resource extraction, primary energy imports, crude oil refinery and other technologies in the transformation sector. It also includes the electricity generation sector and the residential sector (disaggregated into climatization, hot water, cooking and other appliances).

The following sectors are modelled as “black boxes” (i.e. inputs/outputs of final energy without detailing the technology stock): industry; commercial; public sector; agriculture, energy sector and transport. The energy sector is defined in the Brazilian energy system as the amount of energy used to generate more energy, by Ref. [58] “Final Consumption by Energy Sector – Energy consumed by Transformation Centers and/or by Energy Extraction and Transportation Processes, when the energy products are in their final form”. For these “black-box” sectors, it was assumed that the final energy mix for new technologies can result in a fuel shift up to 20% difference from the 2013 mix.

In TIMES_BR_light, the energy flow from primary energy supply, to generation, to final end-use occurs through a chain of processes linked by the commodities they use and produce. Fig. 4 shows the simplified structure of the model. The input information (left side of the figure) is the core data used by the model to produce a linear optimization objective: minimisation of the total cost of the system. At the right side, the outcomes of the model can provide an answer to a multiplicity of questions, for example: what is the installed capacity of each energy source? How much must natural gas be imported? What is the cost in different scenarios?

The TIMES_BR_light model deals solely with GHG emissions from combustion and production processes, which accounted for approximately 20% of national emissions in 2013 in Brazil [14]. At this stage, the biomass emissions from combustion are not considered as emitting GHG, following the Third National Emissions Report [59]. The model considers GHG emissions (CO_2, CH_4, and N_2O) from all fuels in all sectors, following the emission factors from Ref. [60], and with particular detail for the primary energy supply, electricity generation, and residential sectors. For these sectors, reducing GHG emissions is possible by replacing existing technologies with ones that are more efficient or with technologies that use less-carbon intensive fuels. For the other sectors, lowering GHG emissions is limited by the maximum 20% fuel shift exogenously defined. In this exercise, no target of GHG reduction for the future was imposed, since this research aims to analyze the cost-effectiveness of solar options without any shadow carbon cost related to fossil-based technologies.

It should be noted that, as other TIMES models, TIMES_BR_light does not model the economic interactions outside of the energy sector. It does not consider in detail demand curves nor non-rational aspects that condition investment in new, more efficient technologies. The model considers a homogeneous real discount rate of 8%. TIMES_BR_light was calibrated for the year 2013, according to the National Energy Matrix of the National Energy Balance [61,62].

3.2. Exogenous final energy demand

The evolution of the energy demand in the Brazilian energy system was calculated outside TIMES and input into the model. The main source of data considered to estimate the final energy demand was the official projections of the Brazilian energy planning company EPE [18]. To the residential sector, this demand was disaggregated per energy uses (climatization, cooking, water heating and other appliances). In industry, commercial, agriculture, transport, public and energy sectors, the estimate for energy demand was taken as the final energy demand.

For the residential sector, the end-use energy demand adopted the information available on [18,62], as well as a survey from Eletrobrás [63] on the ownership and use of devices split in four energy uses: climatization, water heating, cooking and other appliances, including lighting. The relative share of these final uses of the base-year was kept to the future. For climatization, it was assumed electricity was the only energy supply form, although the authors are aware space cooling supplied via solar air conditioning could be considered in the future. Water heating can be provided via electricity, natural gas and direct solar energy. Cooking can use natural gas, wood, charcoal and electricity. For other appliances (lighting, refrigeration, clothes washing, iron, TV, computers) the electricity use is the only possibility.

For the other end-use sectors, the base-year final energy consumptions correspond to the values reported in Ref. [62], and the evolution of the exogenous final energy consumption was based on the research conducted by EPE – *Empresa de Pesquisa Energética* regarding energy demand till 2050 [18] as shown in Table 2. According to these projections, a growth of more than 126% in final energy demand until 2050 is expected.

The hourly data of demand in the residential sector is based on the information provided by National Operator of the System for 2013 [64] for total load, combined with the proportion of the consumption of the sector in the year [62] and divided by energy uses in each hour [63]. Due to the lack of detailed information, it

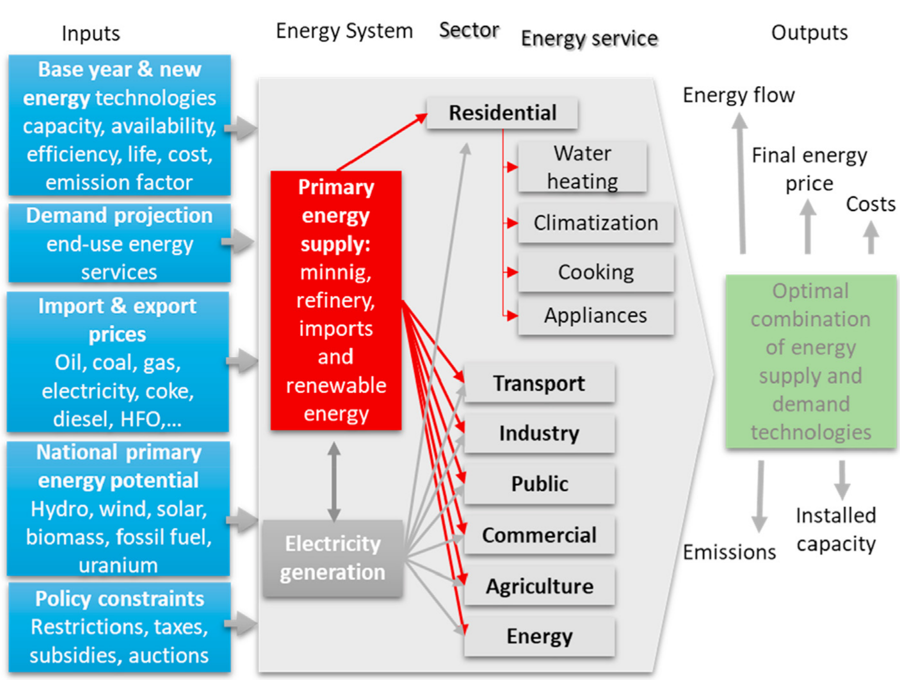

Fig. 4. -Structure of the TIMES_BR_light: Energy system description with inputs and outputs used in the model.

Table 2
- Exogenous energy demand estimated by EPE [18] by sectors and considered in TIMES_BR_light.

[Mtoe]	2013	2016	2020	2030	2040	2050
Industry	88	84	101	138	174	199
Energy sector	26	26	35	48	53	75
Agriculture	11	10	13	15	18	23
Commercial	8	8	11	16	25	38
Public	4	4	5	8	11	17
Transport	83	83	115	152	175	176
Residential – total	**24**	**25**	**28**	**34**	**39**	**43**
Residential- Appliances	6	7	6	9	10	11
Residential - Climatization	2	3	2	3	4	4
Residential – Cooking	13	15	13	18	21	23
Residential – Water Heating	3	3	3	4	5	5
Total	**263**	**268**	**309**	**424**	**527**	**611**

was assumed the same hourly share of the energy demand for both weekdays and weekends and all the four seasons based on [63]. For the other sectors, the demand in each sector is proportional to the time-slice duration, i.e. if the first hour in a spring day weekday represents 0.742% of the total duration in the year, the demand in the first hour of spring in the weekday will be 0.742% of the annual demand.

3.3. Technological detail and assumptions

The model considers 202 technologies for electricity generation (including solar, described in the following section), refineries, oil, coal and gas extraction, production of biomass and demand technologies for residential sector (climatization, cooking, water heating and other electric appliances). The technologies of electricity generation are represented by 45 processes, including current and new technologies. The main sources considered for power generation include hydro, wind, solar, biomass from sugar cane products, biomass from forest byproducts, natural gas, coal, nuclear and oil. For each technology, the following techno-economic parameters are considered: capacity, maximum capacity factor, efficiency, life, cost, and CO_2 emission factor.

A technology cost curve up to 2050 was assumed, as shown in Table 3 for some of the power generation technologies, as well as an efficiency evolution. For mature technologies like gas-fueled power plants or hydropower plants, it was assumed a stable cost in the future. For RES based technologies, a decrease in the future investment cost was estimated, as follows. For wind power technologies, a reduction of 10% for each ten-year from 2020 was considered, while for solar technologies the cost projections were adopted from Ref. [65] until 2040 followed by a linear projection until 2050. This resulted in a reduction of 55% for PV utility-scale, and more than 65% for PV distributed residential individual and PV distributed commercial, compared with current costs.

The cost data was validated with the investments from recent Brazilian auctions for solar, wind and biomass, namely the auction of December 2017 (18/12/2017) for biomass (A-6 26°LEN), wind (A-6 26°LEN), and solar (A-4 25°LEN). As new energy contracted after the availability of the source, the investment cost for biomass-based on sugarcane bagasse was 959.13US$/kW, for solar energy in utility-scale was between 1509 and 2468 US$/kW with an average cost of 2037US$/kW, and for wind power was 1753US$/kW as average [30]. The values were taken for the entire country because the majority of the new capacity contracted is in the ACR (regulated contract environment), within the centralized framework.

The charcoal to cook is assumed to participate with maximum 10% of the energy demand for cooking in 2050 and a linear projection for intermediate years. The charcoal use is limited but cannot be avoided by the model due to the cultural reason (barbecue). The wood for cooking must be reduced during the period. In TIMES_BR_light, the share of electricity in final energy consumption (FEC) is assumed to be always at least the same share of sector FEC as in 2013 for industry, agriculture, energy, public and in the commercial sector.

3.4. Solar energy options in TIMES_BR_light

In TIMES_BR_light, seven solar technologies options are considered as in Fig. 5 - PV for electricity generation (distributed in rooftops and centralized in utility-scale) and solar thermal energy for heat (water heating in the residential sector) and electricity production via CSP. Solar energy enters the system as a commodity that can have four uses; centralised or decentralised electricity production through PV panels or CSP and water heating.

For solar energy, the distributed options were divided into five different technologies: PV residential individual, PV residential

Table 3
Technological portfolio for future electricity generation considered in TIMES_BR_light and correspondent investment costs (US$$_{2015}$/kW).

Fuel	Technology	2016	2020	2030	2040	2050	Source
Natural Gas	Simple Cycle	803	803	803	803	803	[66]
	Combined Cycle	1105	1105	1105	1105	1105	
	Internal Combustion Engine Alternative - open cycle	693	693	693	693	693	
Coal	Pulverized Coal Combustion System - Subcritical cycle	3513	3513	3513	3513	3513	
	Fluidized bed	3513	3513	3513	3513	3513	
	Integrated Gasification Combined Cycle	3292	3061	2756	2480	2232	
Nuclear	Nuclear - Third generation plant	4215	4215	4215	4215	4215	
Biomass	Sugar Cane -Bagasse - Steam with condensation	1151	1093	1038	986	936	[24,65]
	Wood - Steam with condensation	1146	1089	1035	983	934	
	Black Liquor	1146	1089	1035	983	934	
	Residual products - Urban solid waste – biogas	2008	1908	1813	1722	1636	
Hydro	Amazon Rivers	1074	1074	1074	1074	1074	[24]
	PCH	1671	1671	1671	1671	1671	
	UHE (non-Amazon Rivers)	1831	1831	1831	1831	1831	
Wind	Onshore	1326	1393	1323	1258	1194	[24,30]
Solar	PV Utility Scale - Polycrystalline Silicon	1460	1003	803	722	650	[24,29,30,65,67,68]
	PV Distributed Residential Individual- Polycrystalline Silicon	2681	1345	1076	968	871	
	PV Distributed Residential Non-Individual - Polycrystalline Silicon	2681	1345	1076	968	871	
	PV Distributed Commercial - Polycrystalline Silicon	2143	1019	815	734	660	
	PV Distributed Other sectors - Polycrystalline Silicon	1784	846	676	609	547	
	Concentrated Solar Power (with 6 h storage)	8823	5560	5004	4504	4054	[24,69,70])

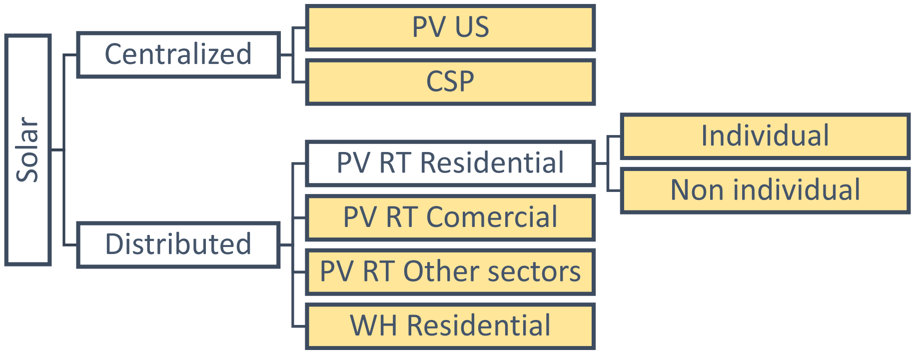

Fig. 5. Solar energy technological options in the model.

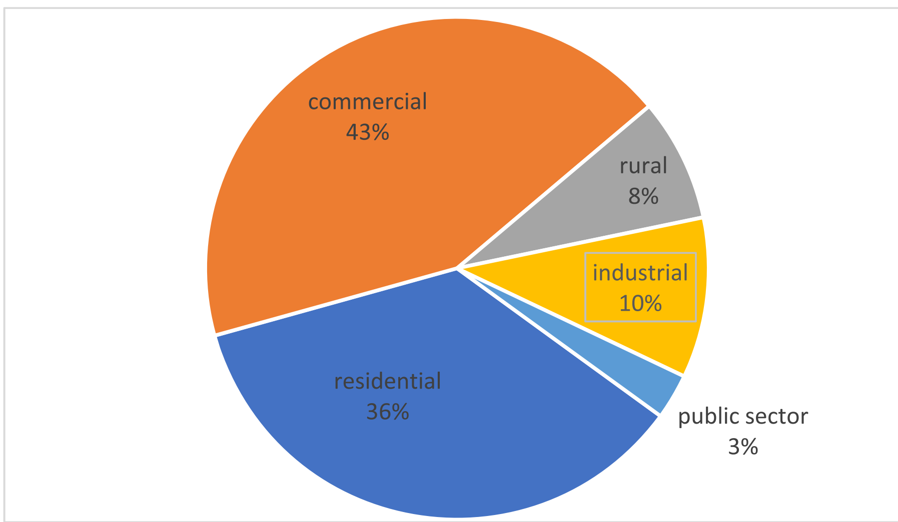

Fig. 6. Distributed photovoltaic installed capacity by sector in Brazil in February 2019.
Source: ANEEL.

non-individual, PV commercial and PV other sectors (industrial, agriculture, public sector) and solar hot water. The rationality of this split is a large participation of the non-residential sector in new installed capacity, mainly in the commercial sector that represents 43% of installed capacity of decentralised PV in February 2019 [71], as in Fig. 6. Between 01.02.2019 and 30.09.2019 the total installed capacity of distributed generation units based on solar radiation increased from 657 MW to 1485 MW in the ANEEL database. Residential sector installations are currently 40% of total solar PV with commercial representing 39%, and the other sectors (agriculture, industrial and public sectors) 21%.

For solar domestic water heating, the maximum solar energy that could be used is limited by the number of dwellings that could have solar energy systems for water heating, based on [18] multiplied by the net energy transferred to the solar collector in a regular residence (1355 kWh/year) with data of [72]. This estimate is similar to Ref. [73]. The estimation of the potential to use solar energy directly for the provision of water heating in the residential sector using the two indicators, and the differences, can be seen in Table 4.

3.5. Energy supply assumption: power generation and primary energy resources

In this section, the estimates of the maximum potential of primary energy sources and power generation (RES and non-RES sources) are presented. Table 5 summarizes the potential up to 2050 for the different energy resources.

The total installed capacity of hydropower potential was defined as in the contracted in the auctions of new energy until April 2018 in the ACR [75], plus all the plants considered in PDE2026 [16]. For new hydropower plants, three types of technologies were considered: large hydropower plants in Amazon region, large hydropower plants outside the Amazon region and small hydropower plants (PCH – Portuguese acronym), as detailed in Annex I[1]Table 14. The total foreseen new hydropower installed capacity in ACR and PDE2026 is assumed to be the upper limit of installed capacity potentially deployed in TIMES_BR_light.

The potential for solar PV centralized is 307 GW, corresponding to the use of anthropized areas with radiation above 6000 Wh/m^2.day. If all the anthropized lands with radiation above 4 400 Wh/

[1] For the Amazon region hydropower plants, it was considered a total of installed new capacity of 23.30 GW in 2020 as a maximum upper limitation, which represents the fourteen projects contracted in auctions for new energy. For 2030, it was additionally considered the three new plants in Refs. [16] summing 1.198 GW new capacity for Amazon large hydropower. For hydropower plants outside the Amazon region, it was considered a potential for new hydropower up to 0.782 GW contracted by auctions with operation beginning until 2020 and 1.868 GW identified in Ref. [16] as additional potential. Up to 0.926 GW new-installed capacity is contracted by auctions for 88 small hydropower plants, a potential addition of 0.3 GW per year until 2050 [53] is also considered.

Table 4
Potential of water heating from thermal solar energy.

	2020		2030		2040		2050	
Source	1000 Dwellings	Solar energy (PJ)	1000 Dwellings	Solar energy (PJ)	1000 Dwellings	Solar energy (PJ)	1000 Dwellings	Solar energy (PJ)
[72]	6 197	30	11 361	55	15 847	77	19 931	98
[73]		38		69		97		122

Table 5
Current power generation and primary energy supply and future technical potentials.

Technology/energy resource	Unit	Current values (year)	2020	2030	2040/ 2050	Source
Primary energy assumptions						
Primary energy resources maximum extraction						
Oil extraction	PJ	4466 (2013)	6174	7605	9036/ 10467	[18,62]
Coal (mining)	PJ	138 (2013)	157	157	157	[62]
Natural gas (mining)	PJ	957 (2013)	1955*	2336	2336	[58,62,74]
Sugar-cane by-products production	PJ	2064 (2013)	3500	4000	4200/ 4500	[24,62] and own interpolation
Power generation assumptions						
Maximum Installed capacity potential						
Hydropower	GW	86.00 (2013)	112.38	118.51	121.51/ 123.38	[16,75]
Wind power	GW	12.70 (2018)	143.00	157.30	173.00	[24] plus assumed extra 10% considering improvement turbine design
Solar PV – distributed	GW	0.24 (2018)	1.40	9.36	25.00/ 43.50	Current values*** from Refs. [22]), potential assumed 10% of value from Ref. [24] for residential and assumed same proportion of expansion for commercial and other sectors
Solar PV – distributed – resid. ind.	GW	0.58 (2019)	0.52	3.48	9.27/ 16.26	
Solar PV – distributed – resid. no ind.	GW	0.002 (2019)	0.04	0.28	0.75/ 1.30	
Solar PV – distributed – commercial	GW	0.57 (2019)	0.60	4.00	10.80/ 18.60	
Solar PV – distributed – other sectors	GW	0.31 (2019)	0.24	1.60	4.26/ 7.34	
Solar PV – utility size	GW	1.12 (2018)	50.00	75.00	220.00/ 307.00	[24] and own assumptions
CSP	GW	0.00 (2018)	10.00	20.00	150.00/ 203.30	[24]
Coal power plants	GW	3.40 (2013)	Not limited	Not limited	Not limited	[62] for 2013
Gas power plants	GW	11.60 (2013)	Not limited	Not limited	Not limited	[62] for 2013
Nuclear power plants	GW	1.99 (2013)	1.99	3.40	3.40	[53,62]
Oil power plants	GW	9.40 (2013)	9.40	9.40	9.40	[53,62]
Electricity generated from RES thermal sources						
Sugar cane	PJ	107.00 (2013)	288.00	346	378.00/ 392.00	[62,75]
Forest biomass	PJ	35.00 (2013) 79.00 (2015)	79.00	169	212.00/ 248.00	[62,75]

*In 2026, the natural gas national gross production is estimated by Ref. [74] in 55805ktoe, this value was used to the future years. To 2020 was used an average between the historical value of 2016 and this projection. This amount considers the contingent reserves and includes a projected increasing demand for natural gas for reinjection.
**This is the projection of proven reserves in 2026 after [16] around 1.74 trillion of m^3, converted to PJ using 1trilion m^3 = 37681.2 PJ.
***Position in 30/10/2019 in .

m^2.day were used for solar PV power generation, the potential would be 28 519 GW [24]. The solar thermal power plant potential was estimated at 203 GW [24].

For decentralised electricity production, there is a lack of information on the distributed solar PV, especially in sectors other than residential. Thus, some simplifications were made, as follows:

(i) the share as in the beginning of 2019 (01.02.2019) of distributed PV per sector will be the same in the future (37% residential individual, 3% residential non-individual, 43% commercial and 17% other sectors [71];
(ii) in 2050, 10% of the total solar potential[2] will be implemented for the residential sector and other sectors (total potential as in Ref. [24]). As detailed in Table 6, two historical values (2016 and 2017 [71]) were considered plus the two

[2] In UK and Germany, in most recent data around 4% of the households have PV installations [82–85].

Table 6
Assumptions to projections of distributed PV generation potential.

Source	Sector	Generation (GWh/year)	
[24]	Residential	**287 505**	Used to calculate 10% of the total in 2050
[76]	Residential + commercial	5 339	Intermediate value to 2024 – considered total installed capacity of 3208 MW and availability factor of 19% (sectorial proportion not used).
[23]	All sectors	**9 940**	Intermediate value to 2027
[71]	All sectors	**166**	Historical value for 2017
[71]	All sectors	**54**	Historical value for 2016

intermediate projections (2024 and 2027 [23,76]) for the total distributed PV production to derive a trend line ($y = 0.1923x^2 + 0.6986x - 1.2591$). Finally, the intermediate values for the total amount of distributed PV electricity was interpolated until 2050 and split by sectors.

Regarding wind power generation, the TIMES_BR_light model assumes a maximum technical potential of 143 GW in 2020, considering 50 m towers and wind speed higher than 7 m per second based on (EPE, 2016a). In this paper, it was further included an increase in wind power capacity of 10% by 2030 and more 10% by 2040, considering the possibility of installing further wind power plants in regions with 6.5 m per second of wind speed that could be economically feasible with 50 m towers and/or higher towers. The minimum installed capacity of wind power is the current installed capacity (April 2018) corresponding to 502 units with 12.7 GW. For the case of electricity generation from marine energy or from geothermal, no technical potential was considered.

The potential for cane bioelectricity was estimated by Ref. [24] per sub-product, namely 151 PJ, 198 PJ, and 21 PJ for bagasse, tips, and vinasse, respectively, via steam condensation or combined cycle. The total of sugarcane available for generation of electricity may increase by 63% in 2050, compared with 2013 [24]. Forest biomass availability for electricity production has a potential for an increase from 79 PJ in 2015 to 248 PJ in 2050 [24]). Steam-condensing turbine using the black liquor combustion is the technology corresponding to 80% of the current total installed capacity of forest-based power generation, although two-thirds is for auto consumption [24]. However, this feature is not accommodated in the model since there is no distinction between auto producers and grid producers. Tables 7 and 8 present the national reserves of non-RES resources and RES energy potential, respectively.

Regarding non-renewable sources, the third nuclear power plant of Brazil, Angra III was considered as starting operation in 2026, and no new nuclear potential is included in the model. Also, no new investment is considered for oil and coal-based electricity generation plants from 2021 onwards, to be coherent with Paris Agreement. Regarding coal, the assumption is based on the fact that only six projects were presented in the new electricity auction, in December 2017, and just one showed minimum conditions to participate in the bid and lost it. Additionally, under the ongoing revision of the power system regulatory framework [77], the incentives for the national coal mining [24] have been reduced, which may imply an increase of the coal costs and a bottleneck for new private investments.

Electricity generation of electricity from gas and for coal in 2020 and 2025 was established with a minimum of operation of 35 000 GWh and 27 222 GWh for gas and 7 222 GWh and 5 555 GWh for coal. This assumption was supported on the security of supply concern, considering the lifetime of existing installed capacity The TIMES_BR_light includes the costs per unit of energy (extracted or imported) of primary energy resources. Table 9 presents the cost of energy by source and activity.

3.6. The hourly granularity of supply technologies for power generation

The TIMES_BR_light model considers an hourly granularity of electricity production to tackle the variability of RES supply of the power systems, for the following 192 time-slices: each hour of one typical day in each season, taking a weekday and a weekend day. Data for wind and hydropower was gathered from the National System Operator in each hour of the year [64]. Regarding solar energy, and because hourly data of production is unavailable, the used data came from meteorological station of INPE [78] for the city of Petrolina-PE (09° 04′ 08" S, 40° 19′ 11" O), selected due to its location in the neighbored of several PV power plants in operation and construction. The Fig. 7 shows the SONDA meteorological stations with radiation information and the localization of photovoltaic generation units. Observing both Petrolina and Caicó are the stations with more photovoltaic units nearby. However, Caicó has no information to 2013, the base year of TIMES_BR_light.

The global horizontal radiation average, in Wm^{-2} per minute for the year 2013, was taken from Ref. [78], then aggregated into hours and then into those time-slices. The maximum electricity production value observed in that period was taken and the availability of the solar resource for each hour in relation with this maximum was considered, combined with an assumed efficiency of 24% [24]. This value is coherent with the observed production of the installed plants in Brazil, around 28% [79].

The first step was to obtain the solar resource in each hour of a year, in kWh per square meter. The relevant information for TIMES model is the hourly availability of the resource relative to the maximum potential (i.e. the maximum incidence of solar radiation or the greatest value of the 8760 h of the year). Then, the 8760 data of hourly availability were organized in 192 time-slices (24 h of 8 typical days: 4 seasons, weekdays and weekends) as shown in Fig. 8.

Table 7
– Assumptions on national reserves.

Reserves			
Natural gas	**PJ**	65 565	[16]
Crude Oil	**PJ**	371 106	[23]
Uranium U3O8	**PJ**	17 997	
Steam Coal	**PJ**	117 974	

Table 8
Renewable energy potentials.

Renewable energy source yearly potential			
Wind power	**PJ**	1 184	[24] and own assumption
Biomass	**PJ**	643	[24]
Solar PV Centralized	**PJ**	157 885	
Solar PV Distributed	**PJ**	1 035	
Hydro	**PJ**	1 983	[16,75]

Table 9
Cost of energy - primary and secondary sources.

Energy source	Activity	Cost US$2013/GJ	Activity	Cost US$2013/GJ	Activity	Cost US$2013/GJ
Wood	mining	14.18				
Sugar Cane Products	mining	13.79				
Black Liquor	mining	13.79				
Crude	mining	18.56	import	18.74	export	18.56
Uranium U3O8	mining	3.01	import	3.01		
Uranium UO2	import	3.01				
Electricity	Import	59.62	Export	59.03		
Steam coal	mining	13.79	import	31.03		
Metallurgical coal	import	3.23		0.00		
Natural gas	mining	16.55	import	16.55		
Coke	Import	18.23		0.00		
Diesel	Import	29.54	Export	29.25		
Kerosene	Import	20.76	Export	20.55		
LPG	Import	31.08	Export	30.77		
Gasoline	Import	39.86	Export	39.46		
Heavy Fuel Oil	Import	12.52	Export	12.40		
Other secondary of petroleum	Import	20.55	Export	20.34		

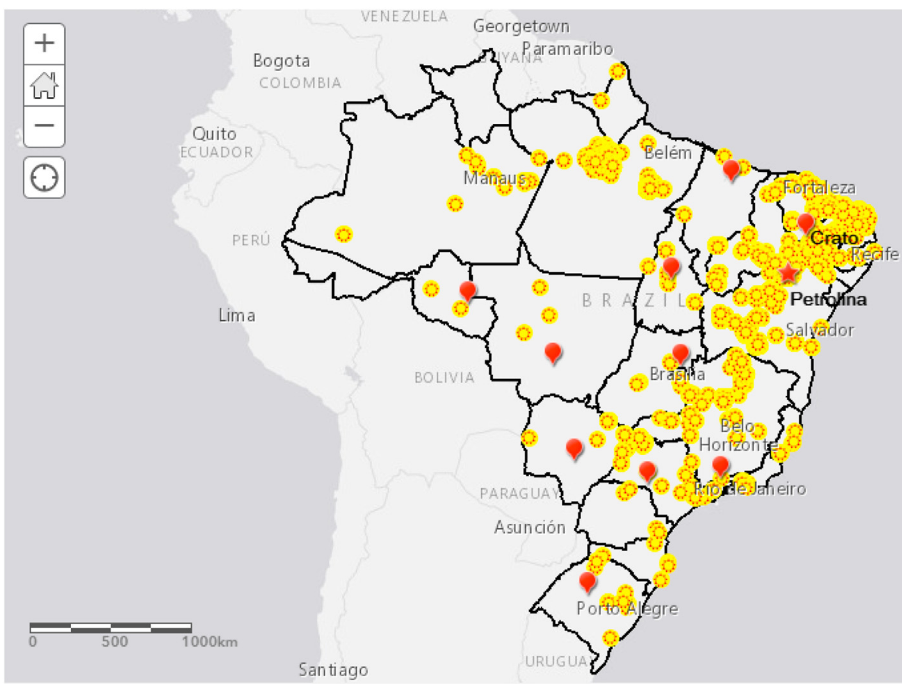

Fig. 7. Meteorological stations (SONDA net) with radiation data and photovoltaic units (INPE and SIGEL-ANEEL).

4. Results and discussion

This section presents and discusses the results regarding the potential role of solar energy in the Brazilian energy system up to 2050. The analysis focuses primarily on solar energy technologies deployment, by assessing the participation of solar on the electricity generation mix both in terms of electricity production and final energy consumption (including solar thermal for water heating) and emissions from the power sector.

4.1. Electricity production

The results of the TIMES_BR_light show a paradigm shift in the electricity mix in 2050, when compared to the current situation, with a high increase of solar and wind power, and also with hydro, biomass and natural gas playing an important role in the system. The results of the TIMES_BR_light, as in Table 10, shows a 173% increase of electricity generated from 2017 to 2050, mostly from RES, as a cost-effective strategy to satisfy the future energy demand of Brazil. Natural gas-based electricity production is likely the only non-RES technologies to increase. It increased by 35% compared to its base year value. Solar power appears as the most cost-effective electricity generation technology with the highest growth rate largely justified by the decreasing investment costs and the high potential of Brazil. It should be noted that the wind power installed capacity between 2006 and 2017 grew from 342 GWh to 42 373 GWh [10,12] meaning that a speedy growth of solar PV could also be plausible.

The optimization results show us that by 2040 the solar energy will likely play a major role in the Brazilian electricity mix and by 2050 will likely have a larger share than hydropower (Table 10). This result supports the hypothesis of this paper on the effective potential role of solar, and that the prospects of the its role for power production should be reviewed. Most probably, the

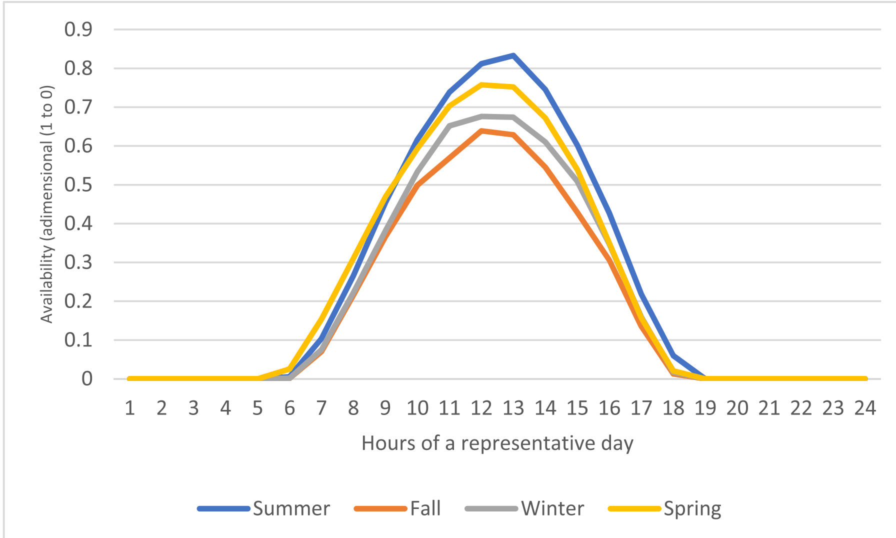

Fig. 8. Daily solar resource availability by season.

assumptions, namely on the evolution of investment costs, used by other energy modelling exercises, explain the limited deployment of solar energy published until now.

Contrarily to the literature review, this research finds that by modifying the model assumptions regarding solar investment costs, hydropower potential and coal power plants assumed deployment (i.e. in the case of TIMES_BRlight, coal power plants are only deployed if cost effective), solar has an important role in the future of the power system in Brazil (9% of generated electricity in 2030 and 40% in 2050).

Table 11 shows a comparison of the TIMES_BR_light results with several other energy modelling exercises using different tools and assumptions for Brazil. Although 16 studies were reviewed in section 2, herein the results are compared with the most similar models and studies of these 16, namely: TIAM BASE, TIAM 50% CAP and POLES BASE models [38]; Message 2DS model [44]); and IEA 2DS and IEA 6DS [65]. The total electricity generated by TIMES_BR_light and other model exercises are quite similar, which may validate the performance of the model. However, solar energy in 2050 is much higher in TIMES_BR_light model than in the other models. These differences are explained mainly by the higher share of hydropower which in turn is caused due to the considered hydropower potential assumed as substantially higher in almost all other modelling studies. The exception to this role of hydropower versus solar expansion is in the case of the TIAM BASE model, that relies strongly on fossil fuels power.

For all the studies, a high range in the potential hydropower deployment in 2050 is visible, from 1 332 PJ to 2 880 PJ. This means that, for most of the studies, the socioenvironmental restrictions affecting the expansion of Amazon hydropower are not considered in 2050, and subsequently the hydropower potential is larger (TIAM 50% CAP, POLES BASE, MESSAGE, IEA 2DS and IEA 6DS). Also, fossil fuels and nuclear deployment in the long term present a very wide range, which translates the very high uncertainty of these sources. The results of TIMES_BR_light model fall within this range, with coal and oil power plants declining along the time horizon and in 2050 will not be part of the electricity mix in Brazil. The results regarding wind power from the TIMES_BR_light model show the largest participation of this source in comparison with other studies.

4.2. Impact of solar deployment in final energy consumption

Regarding the whole energy system, if the modelled assumption on solar investment costs and hydropower and coal power plants deployment are modified, the solar thermal energy grows more than 1000%- from zero PJ in 2013 to 713 PJ in 2050. This fits within a total final energy consumption evolution for Brazil, from 10 212 PJ in 2013 to 24 041 PJ in 2050, an increase of 135%. Part of this increase will be satisfied by biomass, that increases 109%, part by electricity consumption and part by fossil fuels as well.

Table 10
Electricity generation by source along the modelling time horizon in TWh.

Energy carrier/Scenario	2017	2020	2030	2040	2050	Evolution 2050/2017 (%)
	[12]	Results of TIMES_BR_light				
Non-RES	123	85	60	85	99	−20%
Coal	16	7	2	2	0	−100%
Natural Gas	66	35	39	70	89	35%
Oil	25	18	0	0	0	−100%
Nuclear	16	25	19	13	10	−38%
RES	465	652	932	1222	1508	224%
Hydro	371	506	500	479	460	24%
Biomass	51	36	72	90	136	167%
Solar	1	3	91	384	643	>1000%
Wind	42	107	269	269	269	540%
Total electricity generated	**588**	**737**	**992**	**1307**	**1607**	**173%**

Table 11
Comparison of the electricity generated by TIMES_BR_light model and by similar studies for the case of Brazil.

Energy Source	Unit	2020			2050						
		TIMES_ BR_light REF	IEA 2DS	IEA 6DS	TIMES_ BR_light REF	TIAM BASE	TIAM 50% CAP	POLES BASE	Soria Message 2DS	IEA 2DS	IEA 6DS
ref>		**own work**	[65]		**own work**	[38]			[44]	[65]	
Coal Natural Gas Oil Nuclear	PJ	306	328	458	356	2952	360	2088	1080	287	1142
Hydro	PJ	1822	1663	1661	1656	1332	2520	2178	2880	2616	2845
Biomass	PJ	130	180	183	490	756	1404	288	288	288	367
Solar	PJ	11	18	17	2315	0	1044	702	72	160	204
Wind	PJ	385	230	230	968	0	360	612	648	511	544
Total electricity generated	PJ	**2654**	**2419**	**2549**	**5785**	**5040**	**5688**	**5868**	**4968**	**3862**	**5102**

In Fig. 9, it is possible to observe an increase of 190% in the final energy consumption of electricity. As the final energy consumption-growing rate was 135%, that increase translates the electrification of the system. It may be stated that electricity becomes more cost-efficient than other sources, and the solar electricity generation leads to electricity growing by 2030. These two drivers, electrification and fast-growing solar PV, are a result of the optimization model.

Solar electricity will likely have a significant impact on the final energy consumption of the country in 2050 and could represent 10% of final energy consumption. Biomass will represent a quarter of final energy consumption and electricity from other sources besides solar will correspond to 13% of final energy consumption in 2050.

4.3. Impact of solar deployment on emissions

A larger deployment of solar energy means a greater share of RES in the electricity generation mix. The results show that the RES deployment for electricity generation will increase from 465 TWh in 2017 to 1 508 TWh in 2050. Meanwhile, the absolute value of non-renewable sources will decrease from 123 TWh to 99 TWh between 2017 and 2050 (Fig. 10).

The power sector GHG are proportional to electricity generation from non-renewable sources. The reduction of generation from non-renewable sources is declines until 2030 and increases in 2040 and 2050, due to the increasing demand and limited potential of other sources as hydropower (Fig. 11).

The power GHG emissions in power sector, follow the same trend, from 61 million tons CO_2e in 2017 (historical value) to 14 million tons CO_2e in 2030 and 32 million tons CO_2e in 2050.

The carbon intensity of generated electricity has a different trajectory from 101 ktCO_2e/TWh per TWh in 2017 to 20 ktCO_2e/TWh in 2050. When emissions increase in 2040 and 2050 the total electricity produced grows and thus, carbon intensity decreases significantly until 2030 and keeps almost the same level in 2050.

These results are an alternative perspective to those presented by EPE in the [13,23]where the GHG emissions reduction in the power sector are not considered. According to EPE energy models, it is expected a smaller reduction in carbon intensity of power generation from 101 ktCO_2e/TWh in 2017 to 71 ktCO_2e/TWh in 2027 [58]. Table 12 presents a synthesis of the differences between the document [13] used to build the National Determined contributions of Brazil for the COP 21 and TIMES_BR_light. This work considers less hydropower, less biomass and less non-renewable sources and more solar and wind power in 2030.

4.4. Levelized cost of electricity (LCOE): another approach

Table 13 presents the levelized costs of electricity using the same assumptions as TIMES_BR_light. Fossil fuels, natural gas and coal present a higher LCOE than the majority of the RES options, (hydro, wind and solar), except CSP. The distributed solar options present an LCOE above 100US$/MWh until 2025 but this cost declines to less than 80US$/MWh in 2050.

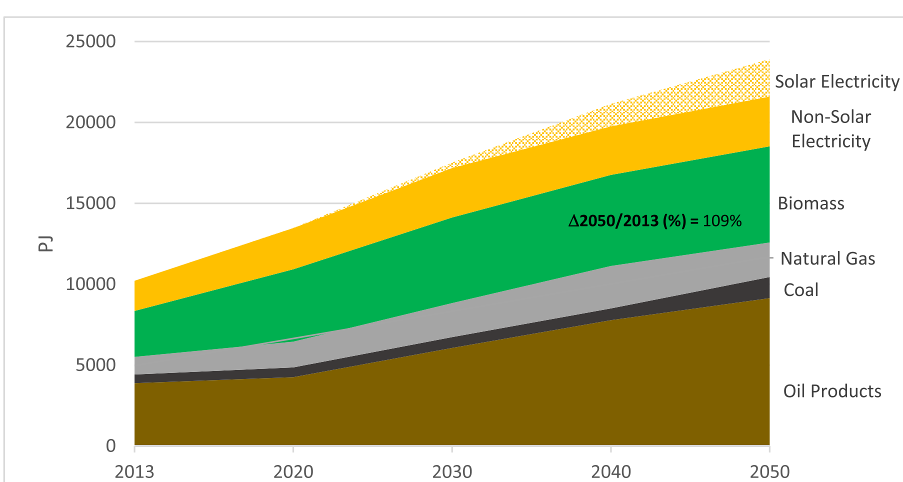

Fig. 9. Brazil Final Energy Consumption by fuel type as projected from TIMES-BR_light model.

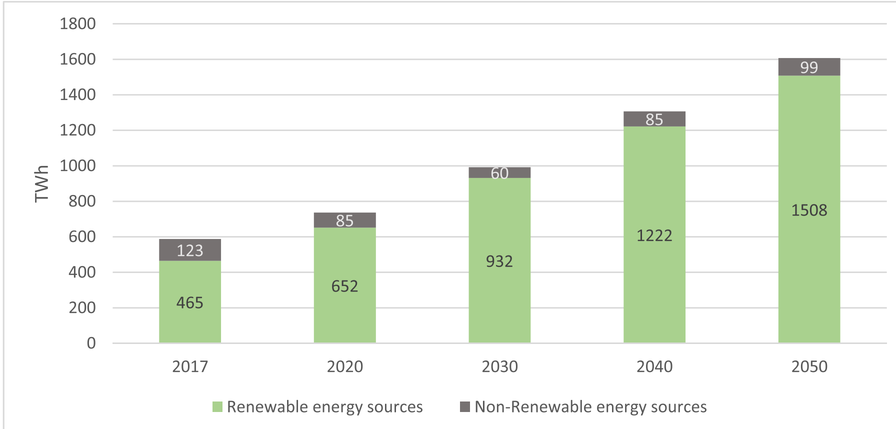

Fig. 10. Electricity generation from renewable and non-renewable energy sources.

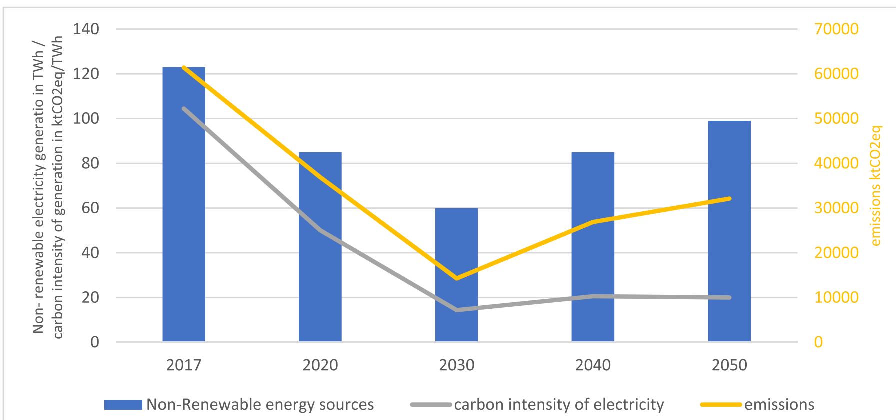

Fig. 11. Non-renewable electricity generation, GHG emissions and carbon intensity of power generation.

The main difference between the LCOE calculation and the model results presented before is that the latter considers the conditions of deployment, or near that, in terms of availability of reserves for primary energy resources, contracts stablished and the quantities of electricity that can be produced in future with the less annualized social cost for the whole energy sector, not only electricity. The two two approaches (LCOE and TIMES-BR_light) point to the increase in the competitiveness of solar energy compared to the other RES and fossil technologies.

5. Conclusions and policy implications

The objective of this paper was to explore how modelling assumptions have been influencing the results regarding the long-term role of solar energy for power production in Brazil and provide some insights on its possible role in the electricity mix. To do so, it was applied two approaches: firstly, it was extensively reviewed all major energy modelling studies addressing solar electricity in Brazil and have identified how the different approaches and assumptions have affected the resulting amount of solar PV and CSP deployment in Brazil till 2050. Secondly, it was studied how determinant these assumptions are by using in a newly developed energy system model for Brazil.

Regarding the review of modelling studies, it was identified the following main critical aspects that determine the future role of solar in existing modelling exercises for Brazil: (i) potential for new possible hydropower plants in the Amazon forest; (ii) potential for deployment of new coal power plants in the country and considered coal costs and (iii) considered solar PV investment costs for utility scale plants.

To identify the critical aspects it was developed an optimization model based on the IEA TIMES generator model, of the Brazilian energy system. This process was based on a set of assumptions along the modelling time horizon up to 2050, mostly supported by official data. The inclusion of solar power in a more detailed form in the energy modelling tool is a major innovative aspect of this work, namely in terms of temporal granularity and several technologies. A literature review was performed on that topic to understand why solar technologies have been taken as a marginal option in almost all published papers and reports. Another literature review [80]

Table 12
Comparison between TIMES_BR_light and EPE projections on electricity production and CO_2 emissions.

Energy carrier	Unit	[13]	TIMES_BR_light
Hydro 2030	TWh	697	500
Biomass 2030		134	72
Solar 2030		35	91
Wind 2030		105	269
Non-renewable sources 2030		180	60
Electricity generation in 2030		1151	992
Emissions from power sector 2030	$MtCO_2eq$	73	14

Table 13
Levelized cost of energy in US2013/MWh.

Power Plant	2013	2020	2025	2030	2035	2040	2045	2050
Natural Gas - Simple Cycle	134	134	134	134	134	134	134	134
Natural Gas - Combined Cycle	167	161	160	156	156	156	156	156
Natural Gas - Internal Combustion Engine Alternative - open cycle)	175	165	159	159	159	159	159	159
Steam Coal - Conventional Subcritical	298	301	297	291	291	284	283	283
Steam Coal - Pulverized Coal Combustion System - Subcritical cycle	269	272	266	262	262	255	254	254
Steam Coal - Integrated Gasification Combined Cycle	321	291	270	262	262	174	174	174
Hydro - PCH (non-Amazon Rivers)	44	44	44	44	44	44	44	44
Hydro —Amazon Rivers	29	29	29	29	29	29	29	29
Hydro - UHE (non Amazon Rivers)	48	48	48	48	48	48	48	48
Wind - On shore	59	62	61	59	58	57	55	54
Solar - Photovoltaic Distributed Residential - Polycrystalline Silicon	189	120	108	97	91	87	83	79
Solar - Photovoltaic Distributed Commercial - Polycrystalline Silicon	152	83	74	66	63	59	57	54
Solar - Photovoltaic Utility Scale - Polycrystalline Silicon	103	72	65	57	54	51	48	47
Solar - Concentrated Solar Power (with 6 h storage)	415	199	186	175	167	156	148	138

found that the main assumptions considered in energy models to integrate renewable energies could be the net present value of the system, las the output of TIMS-BR_light, or the levelized cost of electricity. In this work, the former was considered as the most appropriate parameter to have an overview of the whole energy system. However it was also performed an LCOE which was found to be coherent with the model results. It was found that solar power can provide around 9% of the electricity demand in 2030 and more than 40% after 2040. The cost-effectiveness of solar power, when compared with other power sources, is due to two main reasons: the expected decrease of its investment costs and the limitation of the technical potential of other sources. Environmental reasons in ecologically sensitive areas, like the Amazon watershed, limit the technical potential of hydropower, while market reasons justify the very limited interest in new coal power units.

The large-scale solar use in Brazil, changing the dominant paradigm of hydro-fossil power, could become a win-win strategy, providing affordable energy and reducing negative environmental impacts. This study shows that large scale solar PV power in the Brazilian energy system in the next decades is cost-effective from a system perspective.

The TIMES _BR_LIGHT model considers relevant aspects of official energy planning as the energy demand until 2050, the available options for new power supply, the import/export and extraction and mining tendencies to name but a few. It shows that solar energy could supply, in the mid and long-term, more than one-third of the national load in Brazil even with storage only CSP electricity generation. More than representing an implementation pathway, this work intends to contribute as an exploratory approach in the process of a paradigm shift for a decarbonised world and having presented a reflection on what kind of energy transition is being envisioned when it is assumed possible to explore the potential hydropower boundary in the Amazon region. It should be stressed that for this exercise, no GHG emission cap was considered, to assess the cost-effectiveness of solar technologies, even in the absence of a carbon cost.

This work presents some limitations. One refers to the impact of solar technologies on the performance of the transmission and distribution grids, which will require new investments to add intelligence to the grids in order to manage properly the intermittency and daily variability of the solar power production. The absence of hydrogen as an alternative energy carrier is also a limitation. As an exercise of long-term energy modelling, TIMES-BR_light is not a dispatch model, and further dispatch challenges could arise with the limited storage considered (just 6 h in CSP) and absence of batteries in PV installations. Another limitation refers to considering energy production and regional consumption homogeneously throughout the country. The diversity of situations in the country is not taken into consideration at this stage. The main objective of this work was to test if, from the whole national energy system perspective (considering not only power production, but also primary energy resources availability and its conversion, as well as end-use sectors as buildings, transport and industry), solar energy could be cost-effective. Future work should improve the model by including regional differences; further detailing power transmission and distribution infrastructure, storage options for solar PV, detailing the end-use sectors commercial, public buildings and industry (now modelled as black boxes).

The main conclusion of this work is that solar energy is not only a plausible option but is also necessary for the future of the energy system in Brazil. The main drivers for the large deployment of solar are the expected power demand increase associated with the reduction of the technology cost and the limitation in the potential of other sources. The assumptions and results found here differ from the literature review as well as official projections and intend to be "food for thought" for energy planning.

For complex problems as the future of the power supply in a country, there is no silver bullet. Usually, the solutions involve a wide range of alternatives. This work aims to contribute to discuss such alternatives. Large-scale deployment of solar energy in Brazil could bring new challenges for the transmission system operator due to the variability and the geographic position in the system of the deployment, as the integration of other sources brings the same or different challenges. Nevertheless, improving forecasting and appropriate system planning can contribute to overcoming this. As large scale solar PV deployment is not business as a usual, although cost-effective, public policies are required to make it happen. The design of these policies is determinant for the future success of solar energy use in Brazil, and future work must also cover this topic.

CRediT authorship contribution statement

Juliana Barbosa: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Luís P. Dias:** Methodology, Validation, Formal analysis, Writing - review & editing. **Sofia G. Simoes:** Conceptualization, Validation, Formal analysis, Writing - review & editing. **Júlia Seixas:** Supervision, Writing - review & editing.

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.

Acknowledgements

CNPq supported the research with a doctoral scholarship for Juliana Barbosa (process number (207070/2014-8) in the program Science without Borders. The authors would like to express the gratefulness to *Empresa de Pesquisa Energética* for the partnership, interviews and data information, as well as to the National System Operator for the interviews and data availability. The authors are grateful to CENSE colleagues, especially for Katherine Mahoney for her kindly help. The authors want to thank the anonymous reviewers for their valuable comments and suggestions.

Appendix

Annex I — Detailed Expected expansion of hydropower

Table 14
New hydropower considered in the model

TYPE	Situation	Assumption	Plant name	Installed capacity MW
UHE AMAZON REGION	Power plants that participate in auctions (PPA) and were not in operation in 2013 (base year of the model)	Expected until 2020	FERREIRA GOMES	252
			LAJEADO I	902
			LAJEADO II	902
			LAJEADO III	902
			SANTO ANTÔNIO	418
			SANTO ANTÔNIO DO JARI	73
			TELES PIRES	1820
			UHE BELO MONTE	11233
			UHE CACHOEIRA CALDEIRAO	219
			UHE JIRAU*	3750
			UHE STO ANTÔNIO*	1785
			UHE SÃO MANOEL	700
			COLIDER — MT	300
			SALTO APIÁCAS —MT	45
		SUBTOTAL		23303
	New potential plants after [16]	Expected increase between 2020 and 2030	UHE CASTANHEIRA	140
			UHE TABAJARA	350
			UHE BEM QUERER	708
		SUBTOTAL		1198
	TOTAL			24501
UHE OUTSIDE AMAZON REGION	Power plants that participate in auctions (PPA) and were not in operation in 2013 (base year of the model)	Expected until 2020	Tibagi	32
			UHE Santa Branca	62
			Baixo Iguaçu	350
			Itacoara	150
			Batalha	52
			São Roque	135
		SUBTOTAL		782
	New potential plants after [16]	Expected increase between 2020 e 2030	Apertados	139
			Comissário	140
			Davinópolis	74
			Ercilândia	87
			Telemaco Borba	118
			Foz do Piquiri	93
			São Miguel	58
			Buriti Queimado	142
			Itapiranga	725
			Maranhão Baixo	125
			Porteiras 2	86
			Porto Galeano	81
		SUBTOTAL		1868
	TOTAL			2650
PCH	Power plants that participate in auctions (PPA) and were not in operation in 2013 (base year of the model)	Expected until 2020	116 SMALL PLANTS	926
	New potential plants after [16]	Expected increase between 2020 e 2030	Pch 300 MW/year	3000
		Expected increase between 2030 e 2040		3000
		Expected increase between 2040 e 2050		3000
	TOTAL			9926

* These two plants were in operation in 2013 but were included as a new capacity to accommodate a difference between the [62,81].

Annex II — Imports, exports and mining assumptions

The imports, exports and national production, through mining activities, are key boundaries for the planning of future energy systems. In energy models, it is necessary to have assumptions on these, which could be based on official projections and historical values (as in Table 15).

For the TIMES_BR_light model, these aspects are imposed exogenously, as in Table 15. No changes in the future capacity of imports of natural gas were considered based on the forecast of [16]. In particular, the contracted imports from Bolivia trough the gas pipeline and the current ports of regasification are kept constant during the horizon of the model. Currently two thirds of the natural gas imports come as liquid natural gas in three ports of regasification, Pacém (CE), Baia de Todos os Santos (BA) and Baia da Guanabara (RJ) with 7, 14 and 20 millions of cubic meters per day of capacity, respectively. The third remaining comes from Bolivia.

Regarding oil extraction, the possibility of an increase by almost three folds in 2050 relative to 2013 is considered. Consequently, it is assumed an increase in the exports of oil and a reduction in imports. However, following [16] there are no investments foreseen in the oil refinery sectors than the secondary products of oil are considered to keep the same tendency of historical data (2017). After [16,24], self-sufficiency in the national production of nuclear fuel ab 2026 and the reduction of imports from electricity, namely from Paraguay, was assumed in the model.

Table 15
Imports and exports assumptions by energy source along the modelling horizon in PJ

	Activity	Limit	Current values (2013)	2020	2030	2040/2050	Source
Natural gas	Import	upper	625	959	959	959	[16,53,62]
Crude	Import	upper	853	314	314	314	Own assumption
Crude	Export	lower	859	2255	2255	2255	based on the 2017
Metallurgical coal	Import	upper	328	358	358	358	imports/export [58]
Steam coal	Import	upper	176	223	223	223	
Coke	Import	upper	55	21	21	21	
Heavy fuel oil	Import	upper	4	3	3	3	
	Export	lower	355	280	280	280	
Kerosene	Import	upper	61	20	20	20	
	Export	lower	100	96	96	96	
Diesel	Import	upper	438	460	460	460	
	Export	lower	37	30	30	30	
Gasoline	Import	upper	120	145	145	145	
	Export	lower	11	23	23	23	
Other secondary of petroleum	Import	upper	193	81	81	81	
	Export	lower	15	17	17	17	
LPG	Import	upper	86	84	84	84	
	Export	lower	2	0	0	0	
Uranium U3O8	Import	upper	25	0	0	0	[24]
Uranium UO2	Import	upper	140	27	0	0	
Electricity	Import	fix	145	148	38	38	
	Export	fix	2	0	0	0	

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