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Photovoltaic systems: a review with analysis of the energy transition in Brazilian culture, 2018–2023

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Abstract

Countries all over the world have been seeking ways and methods so that their electrical matrices can stand out using clean and renewable energy sources. In this context, this article presents a review with analysis of sector legislation on photovoltaic solar energy in Brazil. This study was grounded in four steps: (i) sample definition; (ii) theoretical basis; (iii) network analysis; and (iv) content analysis in two stages of research. Initially, a systematic literature review was carried out in order to map all the major and most cited works. The second stage consisted in reading and performing a critical analysis of government documents and reports from the energy sector in Brazil using a few bibliometric resources for such a purpose. Its results reveal that photovoltaic solar energy in Brazil has grown and expanded to different applications, since floating solar plants and subscription to solar energy are becoming increasingly attractive. Furthermore, a possible replacement of photovoltaic solar generation for thermoelectric plants has been investigated once there are a few positive aspects yet to be found thereof. As samples of the results obtained, we have that the replacement of works would allow the photovoltaic solar energy source to increase by 1% in the electrical matrix and would stop emitting 10,738,478 tons into the atmosphere, there would be a progressive decrease in the use of tariff flags (which affect directly to the final consumer) and a reduction in operating costs would also be achieved.

Keywords: Photovoltaic solar energy, Renewable energy, Energy transition, Energy management, Solar energy

Introduction

Use of energy is one of the most critical issues regarding sustainable development nowadays. Countries around the globe strive for ways and methods to make their electrical matrices increasingly attractive using clean and renewable energy sources. Solutions to energy generation issues must be compatible with the economic realities of a country, thus there must be a comprehensive economic analysis to exert a significant impact on the major problems of society.

Hydroelectric generation stands out if compared to other Brazilian electricity generation sources, as it accounts for 51% of the nation's overall electricity production. Hydropower plants are important elements in expanding the supply of electricity in Brazil

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(EPE & Brasil 2018). Although they are considered clean energy sources, there are some associated environmental impacts thereof. As for other sources, 15% of electricity is generated by fossil fuel and nuclear plants, but these are expensive and cause environmental pollution, mainly on account of CO_2 emissions. One of the main sources of fossil fuels are thermoelectric plants, which use such fuels in their generation process and generally opt for fuel oils derived from petroleum, due to their low cost and ease of storage. Being characterized by a non-renewable source, the greatest environmental impact produced by thermoelectric plants are gases, many of which are greenhouse gases. Sulfur oxides and dioxides, nitrogen oxides, carbon monoxide and dioxide, other gases and particulates are produced (Coelho Junior et al. 2022; Nogueira et al. 2021). Only about 11% is represented by photovoltaic solar energy (EPE (Brasil) 2021; ABSOLAR 2023), therefore there is ample room for the development of photovoltaic solar energy sources in the Brazilian territory. Nonetheless, cleaner sources are being sought other than hydropower generation, since Brazil has one of the most abundant renewable energy sources worldwide (Lima et al. 2020).

Photovoltaic solar energy has the greatest capacity to generate low-cost electrical energy if compared to solar thermal, geothermal, wind and biomass energy (Hosseini and Wahid 2019; Laviola de Oliveira et al. 2022), thus it is the object of study herein. According to the Ten-Year Energy Expansion Plan 2032 developed by Energy research company, regarding Centralized Energy Generation, photovoltaic solar technology remains the main source in this segment, as it accounts for about 97% of the overall expansion of distributed generation in Brazil (EPE—Brasil 2021; EPE & Brasil 2022).

Recent high-impact research published in journals report a brief description of the state of the art in the topic addressed herein. In a couple of studies, the authors state that adequate spatial planning is required for the expansion of solar and wind sources. According to these authors, energy transition requires planning policies, in addition to a change in energy sources, therefore there must be diverse incentives so that these renewable energies can be inclusive and benefit low-income populations and communities, thus reducing energy poverty. Energy policies, programs and plans should take into account interdependencies with other sources and sectors in which energy generation takes place (Breyer et al. 2017; Werner and Benites Lazaro 2023; Rodrigo de Freitas 2022). Lampis et al. (2022) have found that Brazil cannot be considered a country on a sustainable path towards carrying out an adequate energy transition, thus further emphasizing the importance of a study corroborating the topic nationwide.

In another approach, it is stated that despite a diversification of the Brazilian energy matrix, it does not seem to be in a complete energy transition stage. The fact of using fossil fuels having also been increased in a few sectors demonstrates that such a transition is not associated with a significant reduction in greenhouse gas emissions. Literature reveals that there is a need for governance and energy planning, not only through multilevel governance, but also through intersectoral planning. Furthermore, results reveal that local and regional governments play a crucial role in implementing relevant public policies towards energy transition (Lazaro et al. 2022; David et al. 2023).

Bradshaw and Jannuzzi (2019) point out that a policy environment at national level in Brazil supporting state participation in energy planning can foster the development of renewable energy projects through national public support programs. The importance

of local action can be redefined as cementing a more collaborative relationship with federal energy agencies to overcome broader problems such as those regarding transmission. Saccardo et al. (2023) also report that there is a lack of studies on a transition from fossil fuel to photovoltaic solar energy generation and the investment required for effecting such a change.

Therefore, this article presents a review with analysis of sector legislation on photovoltaic solar energy in Brazil, initially by performing a literature review so as to highlight an overview and identify the greatest insights regarding the research topic (from 2018 to 2023), and then by reading and carrying out a critical analysis of government documents and reports about the Brazilian energy sector. This article is based on two stages of research. The first concerns a systematic literature review in which all the major and most cited works have been mapped, whilst the second consists in reading and performing a critical analysis of government documents and reports from the energy sector in Brazil. Four main steps were taken to answer its research questions: (i) sample definition; (ii) theoretical basis; (iii) network analysis; and (iv) content analysis.

Such results allowed acquiring information on the benefits (economic, environmental and socioeconomic aspects) obtained from the expansion of solar sources and as a consequence of a reduction in the number of thermoelectric plants. It is worth highlighting that the relevance of this study is ensured once other works on this field have not presented this type of analysis having detailed focus, as it was presented in the article. This article is divided into four sections in addition to its introduction. The following section presents its method, as well as the steps taken to achieve its objective. The third section presents the main results and discussions and the fourth section draws its conclusion.

Methods

There are some important environmental and economic reasons to prompt a literature review on energy policies. One of which is based on such an incessant search for better energy generation practices, given that it is one of the pillars of several studies around worldwide. Therefore, this article is motivated by the following research questions:

(1) What are the main contributions/approaches in the literature on energy transition in Brazil?
(2) What mechanism or policy can assist the Brazilian government in managing energy transition and enhancing its positive impacts?

This article is based on two stages of research. The former concerns a systematic literature review in which all the major and most cited works have been mapped, whilst the latter consists in reading and performing a critical analysis of government documents and reports from the energy sector in Brazil.

Four main steps were taken to answer its research questions: (i) sample definition; (ii) theoretical basis; (iii) network analysis; and (iv) content analysis.

(i) Sample definition

Data search was performed using the Scopus database, as it is the major source of literature data on the area of research approached herein. It is aimed at mining publications

by analyzing the topics of general aspects of photovoltaic solar energy, applicability in Brazil, energy transition, energy reform and energy management. The following clusters of keywords were used in the search, divided into the following Boolean operators:

(1) 866 documents

("solar energy" OR "photovoltaic") AND ("brazil" OR "brazilian");

(2) 34 documents

("solar energy" OR "photovoltaic") AND ("brazil" OR "brazilian") AND ("energy management" OR "energetic management")

(3) 23 documents

("solar energy" OR "photovoltaic") AND ("energetic transition" OR "energy transition") AND ("brazil" OR "brazilian")

(4) 186 documents

A secondary search was also performed using the keywords ("sustainable development") AND ("renewable energy") AND ("brazil" OR "brazilian")

The keywords "solar energy" and "photovoltaic" should be found in the title and the remaining others in titles, abstracts or keywords. Only publications having the following characteristics were included: year of publication between 2018 and 2023 and only publications in English were considered.

Studies were selected according to elimination criteria by reading the title and abstract of articles. The objective of the first stage was to highlight an overview and identify the main insights of the research topic.

The second stage of research consists in reading and performing a critical analysis of government documents and reports from the energy sector in Brazil. This part of the research was classified as exploratory. At this stage, specific features of national legislation and government plans regarding photovoltaic solar energy were sought. The documents obtained in this step are those made available by the Ministry of Mines and Energy of the Brazilian government. The following documents were analyzed: Ten-Year Energy Expansion Plan; Brazilian Energy Balance; Studies on the Ten-Year Energy Expansion Plan; NORMATIVE RESOLUTION No. 482, OF APRIL 17, 2012. Brazilian Electricity Regulatory Agency—ANEEL and Energy Research Office, EPE. Summary Report.

These two actions together, searching for articles in the Scopus database and Brazilian government regulatory documents, aimed to Understanding the scientific ground of political decisions and assess the consistency between science and political trends.

(ii) Theoretical basis

Before going to the Network analysis and Content analysis steps, some concepts and theoretical basement on the topic were discussed in order to connect information that is explored in steps (iii) and (iv). Identified by items "ENERGY CONSUMPTION

IN BRAZIL; "HISTORICAL CONTEXT IN BRAZIL—PHOTOVOLTAIC SOLAR ENERGY" and "ADVANTAGES OF SOLAR POWER PLANTS" of chapter 3.

(iii) Network analysis

Sample metadata were analyzed to identify the most frequent journals and cited articles in the sample. Then, the software VOSviewer was used to analyze the co-occurrence of keywords based on the same methodological framework used by Martinho (2018). The VoSviewer is used to draw maps based on network information so as to view and analyze them more easily. These maps include items (terms, publications or authors) with links between them (the strength of each link is indicated by a value). In this context, co-occurrences are links between keywords and the strength of links (co-occurrences), which reveals the number of publications in which the keywords are found together. The software represents each item in the co-occurrence map by means of a label and a circle, and its size depends on the weight of each item and the lines between items represent the links. On the other hand, the distance between items shows their relationship. Each piece of information was more carefully analyzed in order to provide an initial overview of the article sample. In particular, the network of keywords was relevant for identifying thematic groups, thus making it easier to monitor the research stage related to the categorization and qualitative analysis of articles. Out of the titles and abstracts of these 1109 articles analyzed herein, 114 keywords being cited ten times or so were extracted (except for those that are impertinent to the study). This step was identified by item "CO-OCCURRENCE ANALYSIS—VOSVIEWER" of chapter 3.

(iv) Content analysis

This qualitative stage was aimed at investigating/assessing scientific discoveries. It is the main stage, as its results are the core of this study. An overview of articles was provided based on qualitative analyses, mainly by observing studies focusing on the main topic of this article. With this step it was possible to obtain a detailed discussion on the topic of the article, data on the Brazilian energy panorama and possible discussions and perspectives on the energy transition in Brazil. With such analyzes obtained from government articles and publications implicitly and explicitly in their texts, it was possible to outline and comment on future perspectives for the energy transition favoring photovoltaic solar energy.

The selection criteria for the chosen studies were based on a complete analysis of the article with a focus on characteristics that addressed important aspects of energy management in Brazil, photovoltaic solar energy in Brazil and the energy transition in Brazil. For the article to be selected for the study, it had to obtain some of these characteristics that required a critical analysis. The scientific relevance of the studies was also analyzed. In detail about the analysis process, the title was read, if it was not relevant to the characteristics sought it was discarded, if after reading the title there was any doubt, the abstract was then read. If, after reading the abstract, its relevance was found based on what was sought, the article was read in its entirety, otherwise it was discarded. And finally, after fully reading the article based on this selection method, it was selected and cited with the parts of interest for the study.

There are methodological limitations in this work. Although it is a review, its main topic is thoroughly aimed at the Brazilian territory so as to obtain more singularities in the study. In this sense, a study aimed at a given sample becomes more specific in several aspects, in addition to contributing to its applicability in other countries having similar territories and characteristics to those of Brazil. It is also worth mentioning the limitation regarding years of study, which were only 5 years, thus obtaining the most recent updates and information on the topic. This stage was identified by items "TECHNOLOGIES AND APPLICATIONS OF PHOTOVOLTAIC SYSTEMS"; "POLITICAL ASPECTS"; "LEGISLATION REFORM—LAW OF 2023" and "ANALYSIS OF SOLAR PV ENERGY EXPANSION ALONG THE BRAZILIAN TERRITORY" of chapter 3.

Results

Energy consumption in Brazil

A growing use of global energy has raised concerns about supply shortages, depletion of energy resources and strong environmental impacts such as damage to the ozone layer, global warming, and climate change for years to come (Pérez-Lombard et al. 2008). In contrast, energy demand in Brazil has been increasing significantly for quite some time. It can be observed in Fig. 1 that there has been an energy increase for the last 10 years measured in MWh, which is equivalent to an approximate increase by 14% in 2022 if compared to 2012 (EPE 2023), thus being one of the reasons for population growth (Kannan and Vakeesan 2016).

As for energy use in Brazil, the industrial and freight and passenger transport sectors account for approximately 65% (transport 32.5% and Industry 32.3%) of the country's overall energy consumption. Moreover, 10.9% is used by the residence sector, 9.5% by the energy sector, 5% by the agricultural sector, 4.8% by the services sector, and 5.1% is not even used (ABSOLAR 2021).

Concerning Brazilian sources of electricity generation, hydroelectric plants are the most prominent if compared to other sources, which altogether account for 51% of the nation's overall generation. Hydropower exploitation is a decisive element in increasing the Brazilian electricity supply. The potential of its northern region to boost electricity

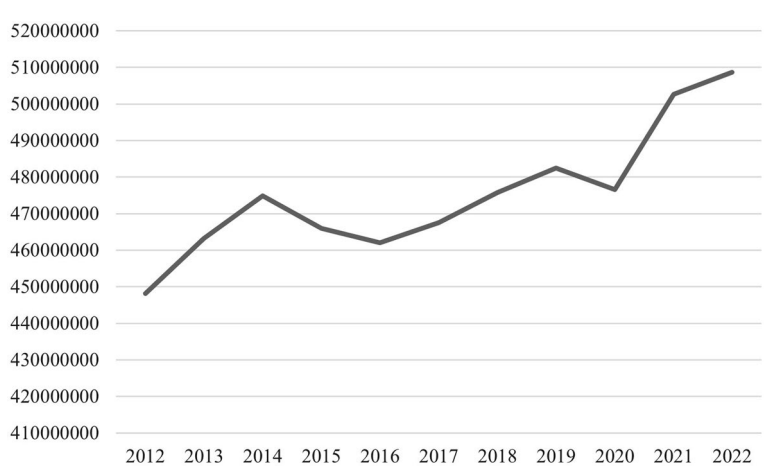

Fig. 1 Energy demand in Brazil over the last 10 years. Source: EPE 2023

supply is still unexploited. Nonetheless, it is worth mentioning that there are multiple challenges yet to be faced, mainly those concerning environmental conservation. Figure 2 shows an exact description of how the country's division is made according to energy sources (EPE & Brasil 2018).

It can be seen that 15% of electricity is generated by fossil fuel and nuclear plants which are expensive and cause environmental pollution, mainly due to CO_2 generation, and only about 11% is represented by photovoltaic solar energy plants (ABSOLAR 2023; EPE & Brasil 2022). Therefore, there is ample room for the development of photovoltaic solar energy plants in its territory. Even though Brazil has one of the matrices with the highest incidence of renewable sources, an increase in other clean sources is sought, except for hydroelectric ones. In two studies published in 2018 and 2019 respectively, the authors highlight the importalnce of solar energy for the composition of Brazil's future energy (Luz et al. 2018; Viviescas et al. 2019).

Photovoltaic solar energy has grown significantly in Brazil, but its disadvantages still outweigh its great advantages. Figure 3 shows the evolution of Photovoltaic Solar Energy Source in Brazil in installed capacity from its inception to 2022 measured in MW (ANEEL 2012). The most significant increase occurred after 2012 due to Normative Resolution No. 482 put forward on April 17, 2012, which establishes the general conditions for microgeneration and distributed minigeneration access to electricity distribution systems, the electricity compensation system, among others (EPE & Brasil 2022; ABSOLAR 2023).

Distributed Micro- and Minigeneration, which are small local electricity generation plants operated based on renewable sources or qualified cogeneration, presented an 84% increase in 2021 if compared to 2020, and only the solar source reached an increase by 88.3% if compared to the total amount generated. Figure 4 shows such an increase in solar source compared to other renewable sources (Ferreira et al. 2018).

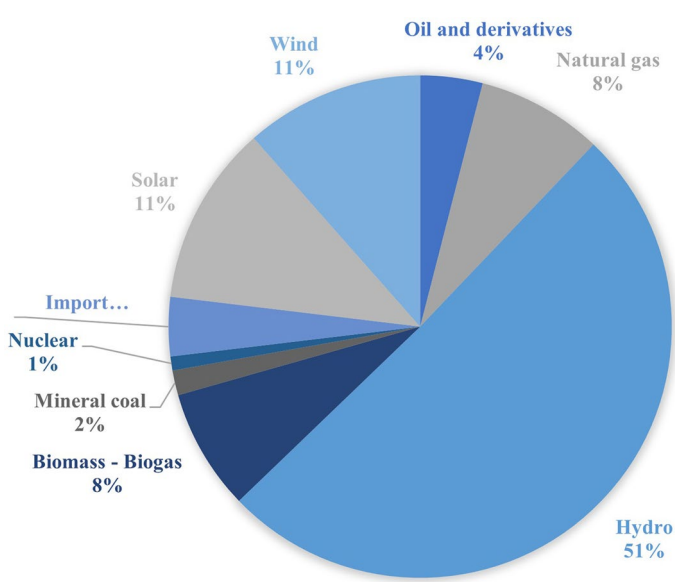

Fig. 2 Brazilian Electrical Matrix, 2023—Percentage of participation of each source

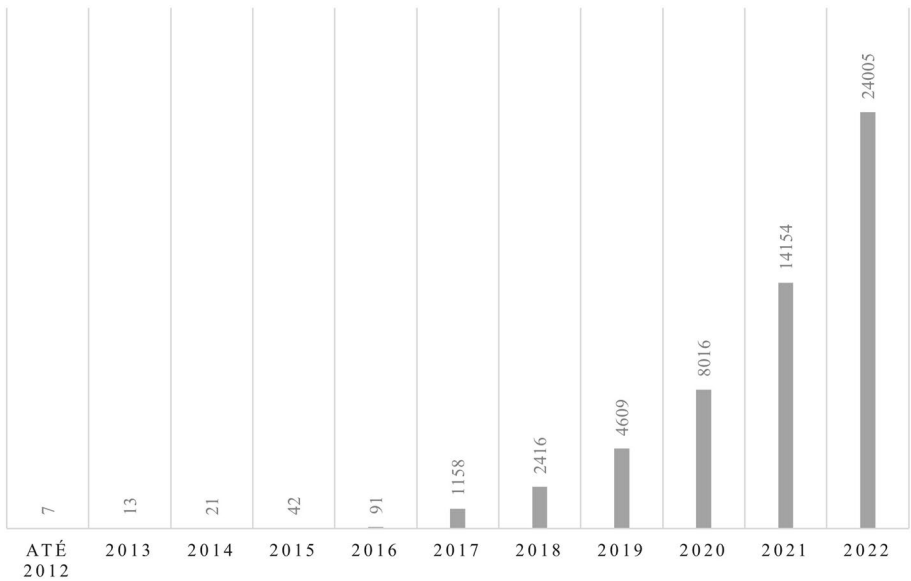

Fig. 3 Evolution of Photovoltaic Solar Source in Brazil—Installed capacity, 2023

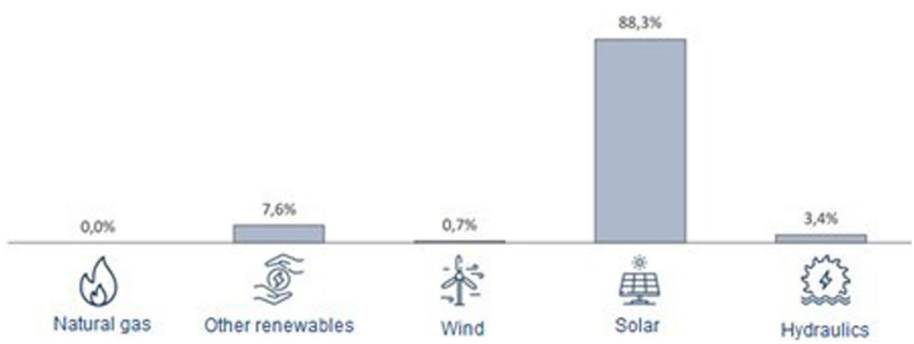

Fig. 4 Increase in solar source compared to other renewable sources

The growth of distributed micro- and minigeneration of electricity has been encouraged by regulatory actions, such as the one establishing the possibility of compensating for the surplus energy produced by smaller systems (net metering). In 2020, distributed micro- and mini-generation reached 9810 GWh with 8965 MW of installed capacity, mainly from the photovoltaic solar source with 9019 GWh and 8771 MW of generation and installed capacity, respectively (EPE—Brasil 2021).

Historical context in Brazil—photovoltaic solar energy

Since Brazil has favorable natural characteristics such as high levels of solar irradiation and large reserves of quality quartz, it offers an important competitive advantage in high-purity silicon production, thus some German universities and research institutes developed an interest in initiating scientific collaborations in this area in the 1970s. Then, a considerable number of other groups also started out their activities in Brazil, both in scientific research and technological advancement of solar cells and materials. In the following years, an applied research was carried out on solar thermal collectors,

refrigeration, ovens, stoves, dryers and distillation, and the manufacture of photovoltaic modules and silicon. The period after 1994 was marked by greater research development and implementation activities. In the 2000s, there was greater emphasis on the field deployment of photovoltaic systems (ABSOLAR 2023). Table 1 depicts a few details about some milestones regarding the solar source (Solangi et al. 2011).

Regarding centralized generation projects, the first Photovoltaic Plant was launched in 2011 by private initiatives with 1 MWp in the municipality of Tauá located in northeast Brazil. In 2013, solar photovoltaic generation projects were allowed to participate in an Energy Auction for the very first time, although no project was launched. In 2012, the first legislation regulated by the National Electric Energy Agency (ANEEL) was enacted through Normative Resolution No. 482/2012 which establishes the General Conditions to grant access for micro- and mini-generation distributed plants to main electricity distribution systems and the electrical energy compensation system (Marcelino et al. 2015). In 2022, it underwent several changes that divided opinions as to whether it became more attractive to the end consumer or not.

Advantages of solar power plants

After the historical context presented, mainly in relation to centralized generation projects, it is worth commenting on the advantages of solar plants. Solar energy is one of the few cleanest energy sources that does not affect or contribute to global warming. The sun radiates more energy in a second than people have ever been able to use it. The availability of cheap and abundant energy with minimal environmental damage associated with its production and use is one of the several important factors for a desirable improvement in people's quality of life. Solar energy is has great potential to be used in future years, although it currently satisfies only a small amount of global energy demand (Baños et al. 2011).

As the majority of the Brazilian territory is located between tropics, daily sunshine reaches 8 h in some regions. Despite its diverse climate characteristics throughout its territory, solar radiation is relatively uniform. Its annual average daily global horizontal solar irradiation is greater than in most countries having more installed capacity (Kannan and Vakeesan 2016). The main advantages of on-grid systems are their high productivity, absence of a battery bank and automatic shutdown in the event of a power failure in the grid, thus avoiding isolation phenomena (Ferreira et al. 2018).

Table 1 Significant milestones regarding the solar source—Between January 2018 and August 2019

Period	Event
January—2018	Photovoltaic solar energy reaches its first gigawatt of installed capacity in Brazil
May—2018	ANEEL—National Electric Energy Agency opens public consultation number 10/2018 to review the rules for distributed solar photovoltaic generation in Brazil
January—2019	Centralized solar photovoltaic generation reaches 2 gigawatt of accumulated installed capacity and becomes the seventh largest source of electricity in Brazil, surpassing nuclear
June—2019	Distributed photovoltaic solar generation reaches its first gigawatt of installed capacity
August—2019	All Brazilian states adhere to ICMS Agreement number 16/2015

Source: Solangi et al. (2011)

Solar energy is very advantageous from an environmental perspective if compared to any other energy source and it is considered the core of any sustainable development program. Some of its advantages are that it does not deplete natural resources, there are no CO_2 emissions, no other gases are released into the atmosphere, nor generates liquid or solid waste; moreover, there is a reduction in the amount of transmission lines in the electrical grid; there is an increase in energy independence; there is diversification and security of energy supply; acceleration of rural electrification (Brazil is one of the largest countries with a large territorial extension, the fifth largest on the planet); in addition to the fact that energy supply by the conventional grid is still scarce in some regions (Martins et al. 2022).

Co-occurrence analysis—VOSviewer

Based on the keyword analysis, some elementary knowledge has been acquired about the frequency at which keywords related to the main topic of this article are found, which lays a solid foundation for performing a co-occurrence analysis of keyword frequency. A title and abstract co-occurrence network (Fig. 5) was produced based on articles on solar energy and energy transition using data from the Scopus database and VOSviewer. The text mining function of VOSviewer was used to mine keywords from titles and abstracts. This function creates a co-occurrence network of keywords (adjectives and nouns) and displays it on a two-dimensional map. Two keywords are said to co-occur if they are

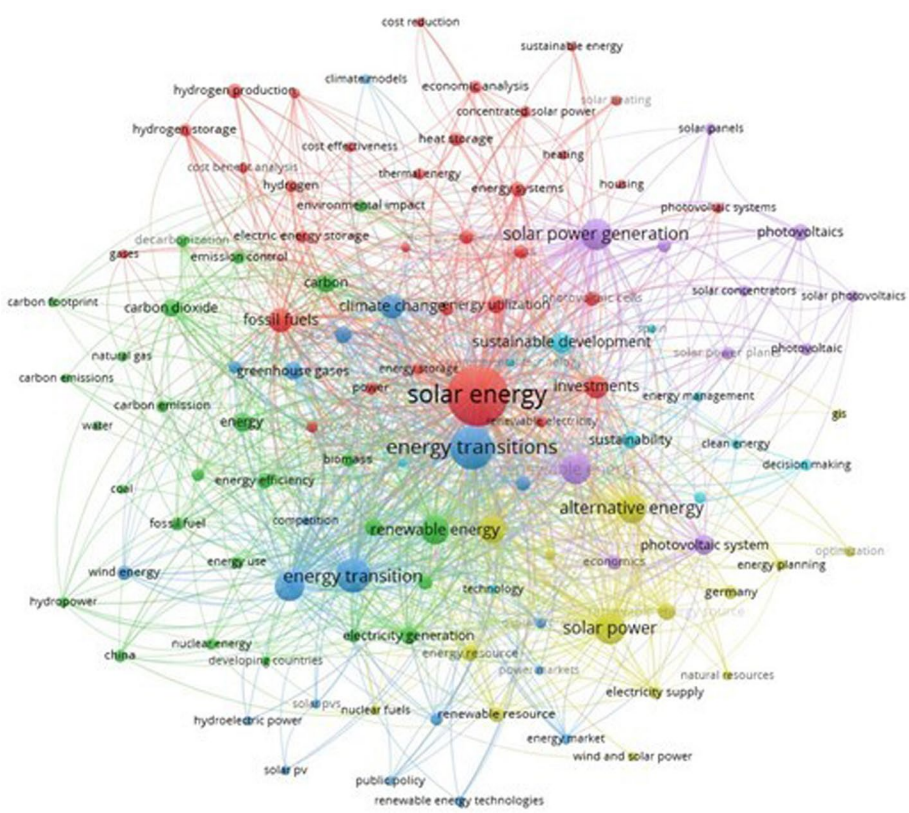

Fig. 5 Co-occurrence analysis

both found in the same title/abstract, and keywords at a higher rate of co-occurrence tend to be found closer together.

In this study, the following settings were used to create the co-occurrence network using VOSviewer: use of binary counting, a keyword must be found at least ten times, and the number of clusters was determined based on interpretability ratios. Keywords which are irrelevant to this analysis were manually excluded and words structuring abstracts (e.g. "case studies", "theory" or "review") were disregarded.

Out of the titles and abstracts of these 1109 articles analyzed herein, 114 keywords being cited ten times or so were extracted (except for those that are impertinent to the study). As it can be seen in Figs. 5, 6 clusters were created, and cluster 1, with 32 keywords, refers to those which are basically about an economic analysis aimed at cost reduction, decreasing pollution by fossil fuels, sustainable development and solar energy, thus corroborating the expectations of authors the search for renewable sources that are also less expensive. Cluster 2 (26 keywords) addresses environmental aspects such as reducing carbon dioxide emissions collaborating with issues involving the replacement of thermoelectric plants with a solar energy source, which does not emit any pollution from polluting gases. Cluster 3 (20 keywords) and cluster 4 (15 keywords) address renewable energy technologies, cluster 5 (11 keywords) is mainly on efficiency and solar cells and, finally, cluster 6 (with 10 keywords) keyword), which cannot be seen in Fig. 5, is only about energy management. The co-occurrence network analysis reveals that there are 3997 nodes and 15,330 connections between them, and the keyword co-occurrence network clearly reveals the main aspects addressed in the area, in addition to broadening horizons for further research.

It is worth noting that co-occurrence analysis focuses on identifying the relationship based on the frequency of appearance of items within the same context, without explicitly considering their strength. Therefore, it is worth saying that the method uses the co-occurrence map as an isolated step in the analysis process and not as the only means of interpretation. The map serves as a valuable starting point for identifying prominent relationships between keywords. These visualizations provide a high-level overview of interconnection, helping this study identify relevant themes and clusters within the dataset.

Technologies and applications of solar photovoltaic systems

Solar energy is the radiant energy produced by the sun. Direct solar radiation is considered one of the best energy sources in multiple areas around the globe. To design

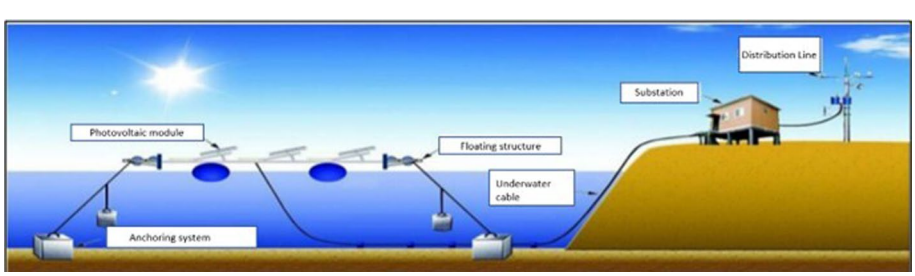

Fig. 6 Floating photovoltaic plant—composition

solar energy systems, radiation data on the studied location are needed, which is usually measured through networks of radiometric stations having low spatial resolution. Some interpolation/extrapolation techniques are often used to measure radiation, but they are valid for places where spatial variability of radiation is not significant, in addition to the fact that they are less accurate in complex terrains between radiometric stations. Notwithstanding such a great development in solar radiation data prediction, there is a gap in mining pertinent information from these data, therefore some methods have been proposed to identify and optimize statistics representing solar radiation availability (Rigo et al. 2022).

Silicon is the element used as a semiconductor in solar photovoltaic systems, which consists of many components such as cells, modules and panels for energy generation. The principle of the whole process is to activate electrons to supply energy, as it is based on the fact that electrons are activated from their lowest to their highest energy state by the addition of energy from sunlight. This activation, in turn, creates a number of holes and free electrons in the semiconductor, thus providing electricity. Furthermore, various means of regulation and control, electronic devices, electrical connections and mechanical devices are used for improving operation efficiency (Portal Solar 2023).

In Brazil, technology applications are mainly classified into four groups: on-grid, systems connected to the grid; off-grid systems, hybrid systems and solar plants, and centralized generation (Ferreira et al. 2018).

1- On-grid systems: a solar photovoltaic system connected to the grid, usually installed on the rooftops of houses and buildings consisting of photovoltaic panels able to convert solar energy into direct current electricity, or into alternating current with voltage and frequency compatible with the electrical grid standards to which the system is connected. It is the most commonly used modality in Brazil regulated by Law 14,300 of 2022.

Distributed micro- and mini-generation is currently considered a technological innovation in global electricity markets. Amidst the evolution of digital technology, a reduction in the costs of decentralized renewable energies and the spread of distributed energy resources has changed the role of consumers in the electricity market (EPE & Brasil 2020).

2- Off-grid systems: isolated or independent solar photovoltaic systems generally installed in areas of difficult access to the electricity grid, such as rural areas. In such a case, batteries must be used. However, such technology is still seldom used due to their high cost. It is widespread in Brazil in rural areas with small solar pumping systems or just to supply low-voltage electrical appliances with power in isolated and remote locations with no access to the electrical grid. It is generated direct current energy by the photovoltaic panel, which is stored in a stationary DC battery and later used for electricity supply.
3- Hybrid systems—photovoltaic generation is coupled with others such as wind or diesel turbines. As they are more complex, such systems require the capability of integrating different forms of electricity generation.

4- Solar energy plants—these systems, also connected to the grid, produce a large amount of electricity at a single point. Plant generation capacity ranges from hundreds of kilowatts to megawatts. Thus, these plants are usually capable of large-scale generation and can be bought in auctions promoted by the National Electric Energy Agency (ANEEL) (Siqueira et al. 2022).

A solar photovoltaic energy generation plant is composed of several components such as arrays and modules of solar cells, means of control or regulation of systems for electrical and mechanical connections. These plants are designed in such a way as to provide higher conversion efficiencies (Kannan and Vakeesan 2016). Table 2 contains details about the largest solar plants in Brazil (Canal Solar 2023).

Another Brazilian plant worth mentioning is a floating photovoltaic plant. The main difference between a conventional solar photovoltaic system (on land) and a floating photovoltaic plant (on water) is that a floating platform requires support structures for attaching the photovoltaic modules, cables and also inverters in a few cases, together with anchoring and mooring.

Basically, a floating photovoltaic plant consists of (Fig. 6): (i) Photovoltaic modules; (ii) Floating platforms: support structure for installing photovoltaic modules in water, which provides stability and buoyancy, in addition to supports for electrical cables and inverters in a few cases; (iii) Anchoring and mooring: for fixing the floating platform on the banks and/or the bottom of the body of water, which must be able to withstand the effects of tide variation and the wind; and (iv) Electrical cables: which may include underwater cables (PV Magazine 2023).

Floating solar plants have some advantages over those set up on the ground, such as the use of existing transmission infrastructure when installed on the premises of hydroelectric plants; better performance due to the cooling effect of water and less impact of dirt on the panels; they are typically close to demand centers and in areas that are normally idle; less water evaporation from reservoirs, which is especially interesting in areas where water is used for agricultural purposes in order to supply the general population with water or wherever fresh water is a limited resource; reduced or zero expenses in civil works and earthworks, which may exert great environmental impacts in some cases. In Brazil, there is an increasing search for floating photovoltaic systems, mainly in the

Table 2 Largest solar plants in Brazil

Plant	MW
São Gonçalo	475
Pirapora	321
Nova Olinda	292
Ituverava	292
Lapa	168
Juazeiro Solar	156
Guaimbê	150
Apodi	132
Paracatu	132
Tauá	1

Source: Canal Solar (2023)

northeast region where the greatest potential is found (Abe et al. 2019). The addition of large photovoltaic plants to compensate hydropower plants could reduce the variability and intermittency of the photovoltaic power source and improve power quality, which is one of the biggest obstacles for large-scale applications in power systems (Motta Silvério et al. 2018).

Compared to other countries, Brazil is the third country with the greatest floating solar plant potential, as it is able to generate 865 TWh of electricity a year, in addition to supplying more than 100% of the country's overall electricity demand. This is largely due to an enormous opportunity for hybridization using hydroelectric plants, as the country has a large representation of such a source, as aforementioned in subsection 3.1 (Hoffmann and Henriques de Carvalho 2019; Rodrigo de Freitas 2022; Câmara Legislativa 2022).

Political aspects

Given the concerns about climate change and rising energy consumption rates, international agreements on reducing GHG emissions and the availability of solar energy, governments worldwide are setting national targets for electricity generation from renewable energy sources as an attempt to configure the various solar energy policies in multiple countries (Solangi et al. 2011).

In a study carried out in 2022 (Rigo et al. 2022), the authors comment on the following impeding aspects: the barriers to achieving success in deploying PV solar energy plants in Brazil, such as the lack of a domestic production of photovoltaic modules, expensive and slow logistics, the high cost of systems and difficulties for investors to finance them.

These barriers can be addressed through policies to encourage the development of the photovoltaic energy market. Thus, the main barrier identified was the lack of political incentives, which generates a cause and effect relationship with other barriers. According to this study, through policies to encourage photovoltaic energy, there are two additional paths to be taken towards success: a domestic production of modules (technological improvements ensuring that solar energy generation becomes even cheaper) and the availability of financing mechanisms. As a result, Brazil could use its quartz reserves and keep its capital within the country, without having to transfer money to developing countries. Thus, systems would be cheaper since they would reduce logistics, which is one of the greatest issues to be settled in the country.

Moreover, financing mechanisms are required for such an industry to have sufficient demand to operate. Consequently, at the end of this production process, during the period of replacing systems, these industries are able to recycle their solar modules. Otherwise, such waste is not going to be properly treated in Brazil, thus causing a negative impact on the environment.

Lack of accessible data on the details about the environmental licensing process and studies conducted on existing photovoltaic solar plants in Brazil not only hinders this type of research, but also the development of new projects. Lack of information about the main guidelines and challenges critically affects the licensing process, the decisions to be made by potential investors and, therefore, the future of photovoltaic projects in Brazil. It is worth issuing federal guidelines providing states with necessary support so as to define more coherent and consistent criteria. By adopting such measures, a licensing

process taking into account unique environmental considerations and constraints of each region can be developed; this would allow optimizing the licensing process and avoiding all significant obstacles to securing the necessary investments and boost solar energy generation in Brazil (Hoffmann and Henriques de Carvalho 2019). It is also worth making these details less bureaucratic for works to occur more smoothly.

Photovoltaic solar energy is the technology having the highest participation among residential distributed generation systems and net metering is one of the main incentive mechanisms adopted by multiple countries to urge its adoption. Its spatial distribution of photovoltaic panel capture is uneven and affected by several factors, among which one of the most relevant is settlement patterns. Brazilian authorities and policy makers must adopt other policies to democratize and bridge the gap between locations regarding residential PV adoption. This can increase adoption rates and contribute to more sustainable ways of producing electricity, boost the energy transition process in there nation and lower the price of its population's electricity bill, thus increasing its purchasing power (Breyer et al. 2017; Rodrigo de Freitas 2022; Castro et al. 2018).

Legislation reform—law of 2023

In Brazil, with regard to standards for distributed generation of solar energy, it was guided only by normative resolutions established by the National Electric Energy Agency (Aneel) until 2022. In January 2022, the legal framework for micro and mini-generation of energy, Law 14,300, was instituted. It states that microgenerators are those able to generate up to 75 kW of energy through renewable sources (such as photovoltaics and wind) and its minigenerators should have capacity ranging between 75 kW up to 10 MW (DOU 2022; ANEEL 2012).

Before such legal framework, the Electric Energy Compensation system was a procedure in which electric energy consumers install small generators in their consumer units and the generated energy was used to reduce the utility's electric energy consumption, with no fee impositions, but only a small amount charged for grid availability. After the legal framework, the payment of a tariff component that was not imposed upon a consumer having distributed micro and mini generation plants, i.e. the TUSD on Fio B, which refers to distribution costs (this is only charged based on the amount added to the utility grid) (DOU 2022).

For instance, as it was before the reform: a Photovoltaic system generated 200 kWh/month; it consumed 100 kWh/month during the day and the remaining 100 kWh/month was added to the grid, therefore the consumer has 100 kWh/month of credit, i.e. by assuming a rate of R$1, the consumer would have R$100.00 of credit for the following months.

After the reform: in Brazil, TE (energy tariff) and TUSD (distribution tariff) are on energy bills, as they are the existing tariffs and each has a percentage, taxation will be on Wire B, which is equivalent to the distribution tariff, i.e. 28%. Following the same previous example of generation and use of the grid and calculating the new fee, we have: TAXA = (28)*(0.15) = R$ 4.20, which would be R$ 100 − R$ 4.2 = R$ 95.80 of returns instead of R$100.00 according to the law (it is worth mentioning that this rate is progressive over the years, and that the first year starts at 15% and will have reached 90% in 2028). Among a few small changes and alterations, this taxation was primordial.

In energy generation, the term LCOE is commonly used to compare the costs of energy sources. It is defined as the Levelized Cost of Energy. The average LCOE increases by 22%, while the average return time increases by 29%. This is due to the fact that compensation is no longer made through all components of the tariff, as there must be payment for transportation called Fio B. Thus, the economic viability of investing in photovoltaic systems is affected, as it leads to a reduction in the expected number of adopters of this technology. On the other hand, a reduced growth on the distributed generation market leads to a reduction in revenue losses expected by distributors by up to 42%. This is a notable impact from the new Law 14,300. Nonetheless, it is still possible to notice an annual growth in the total number of consumers over the years (Iglesias and Vilaça 2022).

Analysis of solar PV energy expansion along the Brazilian territory

The Energy research company, whose purpose is to provide services to the Ministry of Mines and Energy (MME) in the area of studies and research aimed at subsidizing the energy sector planning periodically issues a Ten-Year Energy Expansion Plan in which methodological criteria, assumptions and guidelines for the simulations of supply alternatives are described so as to ensure a safe service with respect to energy load and demand.

The Ten-Year Energy Expansion Plan is a relevant alternative, therefore, its functions are: (i) to facilitate access to relevant information for agents to make better decisions; (ii) subsidize decision-making on the execution of auctions and planning of sectors of the generation system; (iii) and sanction public sector policies (EPE & Brasil 2018).

The planning process transforms this input information into indications of what are the needs of the electrical system to ensure compliance with the requirements of economy and security in energy supply. These needs may include, for example: technologies having a high degree of flexibility at low variable costs and reduced environmental impacts. It is up to society to confront the view of planners and thus determine a more economically feasible way to meet demand and contest the plan proves an important way of dealing with information asymmetry. It fulfills both the function of facilitating direct access to information, as well as identifying the needs of the electrical system under different future realizations (EPE & Brasil 2018). Therefore, studies and analyzes aimed to promote and complement the ten-year energy expansion plan become quite relevant.

One of the problems arising from the energy crisis in Brazil has been caused by lack of rain and a low volume of hydroelectric reservoirs, thus directly affecting the country's energy production and resulting in an increase in electricity bills through tariff flags (increase in the value of energy to be passed onto the final consumer, depending on electricity generation conditions), when thermoelectric plants are operational (ANEEL 2023).

Brazil has a high rate of using thermoelectric power sources which generate environmental impact and lead to a seasonal increase in the cost of electricity through tarrif flags. Compared to the most commonly used source, i.e. hydroelectric plants, the cost per kWh is higher. In percentage terms, regarding what will be charged to the final consumer when the thermoelectric plant is replaced by a hydroelectric power source,

ANEEL established that 63.7% of the total amount is represented by tariff flags (ANEEL 2023).

It is planned to replace the supply of thermoelectric plants powered by diesel oil and fuel, which will have reduced approximately 3000 MW from these sources by 2027 using natural gas plants, in addition to fact that operations at Angra 3 are goind to begin (nuclear power plant) (EPE & Brasil 2018). Therefore, thermoelectric plants could also be replaced by solar sources and the climate policies established for setting the government's energy transition path would be followed.

The Brazilian government provides detailed information about the works of systems that generate energy from all available sources. Monitoring of the expansion of the supply of electricity generation comprehends all projects implemented in the national territory, regardless of the source of energy. Such information relate to: works in operation, those under construction and those about to start construction. As a means to study the possibilities for expanding the photovoltaic solar energy source, data were collected from the thermoelectric plants measured in MW so as to perform an analysis in order to check whether all works under construction or about to start construction are able to be converted to photovoltaic generation (between about 2023 and 2030).

As a result, the capacity of photovoltaic solar energy sources would increase by almost 1%, an expansion from 16,297 MW to 22,279 MW. Considering that the current behavior of demand is maintained over the following ten-year, with load peaks in a few months of the year occurring at times when the solar contribution is significant, thus it would be necessary to add power in the order of 9500 MW (EPE & Brasil 2018), i.e. a value estimated by the Ten-Year Energy Expansion Plan and which would in turn be met by replacing 62.65%. In percentage terms, it may seem unattractive, but, financial aspects and socioeconomic aspects would be rather significant considering its environmental impacts.

Environmental—A socio-environmental analysis of energy expansion was carried out in order to discuss the main socio-environmental issues associated with production, generation and transmission of energy by observing policies related to energy and the environment. In view of such, climate policies for building the energy transition path in the Ten-Year Energy Energy Expansion Plan were suggested. Some emission reduction commitments signed by Brazil are shown in Table 3 (EPE & Brasil 2022).

The Brazilian government states that the main strategy for mitigating GHG emissions by the energy sector is to maintain a high share of renewable sources in its matrix in order to ensure that emissions resulting from the production and use of energy remain low (EPE & Brasil 2022).

Climate issues are typically associated with the energy sector, either regarding the mitigation of GHG emissions in the production and use of energy or concerning its need to adapt energy projects to climate change. As for mitigating GHG emissions, although Brazil stands out due to its highly renewable energy matrix, its wide availability of renewable natural resources and technologies, thus its energy sector assumes an important role in meeting commitments to reduce emissions.

According to the National Energy Balance—NEB 2022 (EPE & Brasil 2022), the total CO_2 emissions associated with the Brazilian energy matrix reached 445.4 million tons in 2021. The transport sector is the one the leads the emission rankings with 45% of the

Table 3 Emissions reduction commitments—climate policies

Emission reduction commitments signed by Brazil	Highlights
Update of Brazil's Nationally Determined Contribution, published in 2022	Reduction of 37% of Brazilian emissions in 2025 and 50% in 2030, using 2005 as the base year
Global Commitment on Methane Reductions, signed in 2021	Reduction by 30% of methane emissions in Brazil by 2030, with 2020 as the baseline
Guidelines for a national strategy for climate neutrality, developed in 2022	Some measures for the energy sector: • reach between 45 and 50% of renewable energies in the composition of the energy matrix in 2030 • expand the participation and consumption of biofuels • encourage the manufacture and use of electric and hybrid vehicles • promote efficiency gains in the energy and electricity sector • encourage the energy use of waste • reduce carbon footprint for the oil and gas and biofuels sector
Creation of the Interministerial Committee on Climate Change and Green Growth (CIMV), which deals with public policies related to climate change (Decree n. 10.845/2021)	Establishment of four temporary technical groups to support: • the implementation of the mechanisms of Article 6 of the Paris Agreement in Brazil • the implementation of the National Green Growth Program

Source: EPE & Brasil (2022)

total emissions, followed by the industrial sector with 18%. In both cases, initiatives to reduce GHG emissions are related to the replacement of fuels, mainly by biofuels, and measures to increase the energy efficiency of means of transport and industrial processes.

In the case of emissions linked to the production and transformation of energy, mitigation is particularly challenging for the entire chain of oil, natural gas and derivatives. Such a condition results from the expected significant expansion trend coupled with the marked emissions associated with exploration and production of oil, natural gas and derivatives, as well as the activities of transforming primary energy into secondary energy, such as in oil refining (EPE & Brasil 2022).

In 2021, total anthropogenic CO_2 emissions associated with the Brazilian energy matrix reached 445.4 million tons. In detail, the transport sector solely accounted for 44.4% of it, industries reached 17.4%, 4.22% were by residences and other sectors were responsible for 33.9% of emissions. The Brazilian electricity sector emitted only 118.5 kg CO_2 to produce 1 MWh on average, i.e. a very low rate if compared to European Union countries, the USA and China (EPE & Brasil 2022).

To cope with such a growth in demand in a safe and inexpensive way and with respect to its environmental legislation, Brazil has a remarkable energy potential, chiefly due to its abundant renewable energy sources (hydro, wind, biomass and solar sources) (EPE & Brasil 2018). Regarding the environmental impact resulting from such a transition, it is worth mentioning that it is found only in manufacturing processes and during the entire operation of a PV system, which can take over 25 years, in addition to the fact that it causes no pollution. Nonetheless, thermoelectric plants emit large amounts of polluting gases. With regard to CO_2 emissions, an expansion in order to replace thermoelectric plants with the solar power plants would prevent 10,738,478 tons from being emitted into the atmosphere.

From a financial standpoint, such an expansion would result in a growing decrease in the use of tariff flags (which directly affects the final consumer); there would also be a reduction in the cost of operation; less risk of a new energy crisis to arise from poor rainfall periods and provide the system with heightened security. In comparative terms, the average LCOE (R$/MWh) of the solar source is R$ 149.00 and the average LCOE of a single-cycle gas thermal plant is R$ 541.00, combined-cycle gas thermal unit is R$ 29,700 and Thermal biomass is R$ 247.00 (EPE & Brasil 2022). It is worth observing that the use of thermoelectric plants as a solution to the energy crisis would cost almost 4 times as much as the solar source.

With respect to energy losses, Brazil has a high associated index (Fig. 7 shows the sectors responsible for losses found in the country), therefore distributed solar power generation can reduce its transmission costs, since its generation takes place close to where it is going to be used, mainly during the peak hours in the afternoon, thus cutting down losses. Three sectors are responsible for 90% of losses found in the country: power plants, transmission and distribution of electricity and coal plants (EPE & Brasil 2022).

Furthermore, there are other ways of saving using photovoltaic solar energy such as its rental, and such subscriptions would lead to savings ranging between 20 and 30% of the amount spent by the end consumer, thus eliminating the initial purchase of equipment or any financing concerning the necessary contribution when the system has been acquired by the consumer, which would be an attractive alternative for consumers willing to save energy but cannot afford to purchase it from the system. For instance, let us consider a R$ 600.00 bill through the 30% savings plan: the new electricity bill would amount to R$ 50/month; a monthly subscription fee would be R$ 370/month; and the total energy expenses after the subscription would be R$ 420/month (R$ 50.00 + R$ 370.00) (Ramme Bortoluzzi 2022).

Regarding socioeconomic aspects, a comparison os sources allowed finding that the solar source generates an average of 30,000 jobs for each GW installed and thermoelectric sources generate about 20,000 jobs for each GW. In Brazil, photovoltaic solar energy is among the sources that generate the most jobs per installed MW, as it generated over 750,000 new jobs in 2022 alone (ABSOLAR 2023, 2021; SEMADESC 2018).

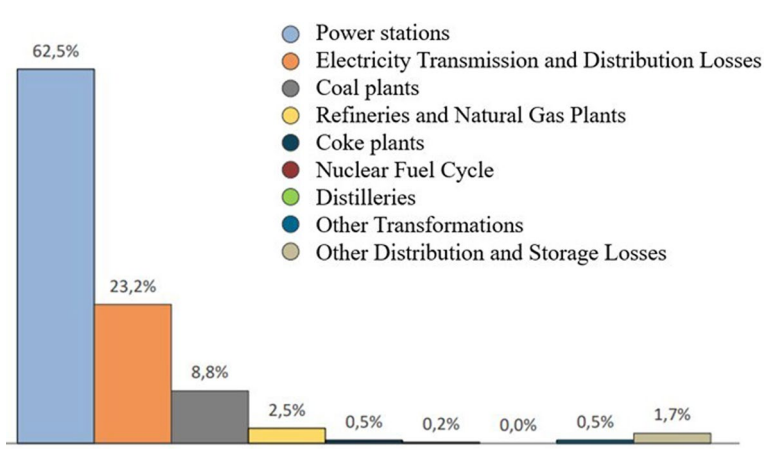

Fig. 7 Energy losses by sectors

It is also worth noting that photovoltaic solar energy has been greatly encouraged and a significant number of plants are under construction or about to start construction. In percentage terms, such an increase would represent 15.5% of participation in the electrical matrix.

Discussions

The study of solar energy as well as forms of energy storage is growing and increasingly. The study of solar energy as well as forms of energy storage is growing and increasingly gaining prominence in distributed generation options. Breyer et al. (2017) concluded through a review that photovoltaic solar energy and batteries will evolve as the most important energy technologies worldwide, with a continuous decline in their costs.

Despite Brazil having one of the cleanest energy matrices in the world, there are problems associated with generation through water sources, providing yet another justification for the energy transition to solar energy sources. According to Lima et al. (2020), recent changes in the hydrological cycle have compromised Brazil's capacity for hydroelectric generation. They also comment that the Brazilian electricity generation matrix has become vulnerable to climate change, making it necessary to expand and diversify the use of renewable energy sources. In the coming decades, climate variations may cause a significant reduction in rainfall, more frequent droughts and higher temperatures in the North and Northeast regions of Brazil compared to data from previous years. These impacts will trigger conflicts over water allocation and negatively affect hydroelectric energy production in these regions of Brazil (Jong et al. 2018; Luz and Moura 2019).

Thinking in a more detailed and optimized way, recent studies such as that by Desai et al. (2023) comment on some specific applications of how solar is considered essential, such as the emerging application in adapting to renewable energy, especially in remote locations where energy from local utilities is expensive or non-existent. The authors' work holds promise for bringing basic energy offerings to humans living in remote areas in growing countries consisting of solar photovoltaic, small hydropower, wind generator and energy storage system. The introduced concept is achievable to minimize poverty globally by improving health, education and financial burden of rural and neighborhood lives with cheap electricity.

With regard to thermoelectric sources, there were advantages when considering replacing the source with solar energy, proving its superiority in several aspects. It is worth highlighting that when it is not possible to completely replace thermoelectric plants with a solar energy source, the benefit of making combined use of such sources is indicated and proven, as explored in the article by Cavalcante et al. (2021).

In a comparative way, the study by Hassan et al. (2024) covers a general overview of renewable and non-renewable sources in some countries such as the United States, Canada, China and European Union countries. Several countries are expanding renewable energy and seeking the energy transition from their fossil fuel sources, corroborating this study and thus Brazil would be aligning itself with major global powers in the energy segment. The transition in the mentioned countries is based on public policies (to define new necessary infrastructure, economic feasibility studies, etc.) and government goals, making it a good path to follow in the national territory.

This literature review confirms the strengths of the energy transition in Brazilian territory, highlighting several positive factors in its application. Furthermore, this analysis suggests that the energy transition is possible in several other countries and scenarios, however this is beyond the scope of this review, but serves as a basis for future studies. Countries that have similar political characteristics to Brazil, or that are similar territorially, for example, can benefit from this study, characteristics that help in the application of the method of this article.

Conclusion

This article presents a literature review consisting in analyzes and suggestions for an energy transition in Brazil focusing on photovoltaic solar energy. It is found that, to the best of our knowledge, there is no study on the main topic researched herein, in addition to the fact that the greatest interest lies in contextualizing it so as to optimize energy generation processes.

A systematic bibliographical research was carried out and it was observed that photovoltaic solar energy in Brazil has grown and expanded to different uses and applications. The most significant factors concern, floating solar plants (assembled on fresh and salt bodies of water) and also subscription to solar energy programs.

Regarding the second aspect of the article's main topic, a possible expansion of the photovoltaic solar source being replaced by thermoelectric plants was explored and a few aspects have been identified: (1) the replacement of works would allow the photovoltaic solar energy source would raise by 1% in the electrical matrix, i.e. an increase from 16,297 MW to 22,279 MW; (2) such an expansion of the solar source to replace thermoelectric sources would stop emitting 10,738,478 tons into the atmosphere; (3) there would be an progressive decrease in the use of tariff flags (which directly affect the end consumer); one would also obtain a reduction in the cost of operation; (4) less risk of a new energy crisis due to lack of rain and offer more security for the system; (5) thermoelectric plants as a solution to the energy crisis cost almost 4 times as much as the solar source; (6) reduced energy transmission costs since generation takes place close to the place of consumption, mainly at peak hours in the afternoon, thus reducing losses; and (7) in Brazil, photovoltaic solar energy is among the sources that generate the most jobs per MW installed.

Another relevant aspect is based on the fact that the Brazilian system is thoroughly different from other those of countries, given such an enormous possibility of hydroelectric power plants. When thermoelectric plants must be used, which are quite expensive, it is as through all available water were stored on account of being generated in place of its source. Therefore, the idea of replacing thermoelectric sources with solar sources corroborates this problem, since there is solar generation and, if it were not enough, the hydraulic plants couple make up for this, and it would be performed rather quickly, unlike thermoelectric plants that take a long time to turn on.

Another aspect encouraging the expansion of solar sources is the hybridization of sources with existing projects (for example, photovoltaic solar energy generation in hydroelectric reservoirs or in existing wind farms), thus minimizing the need for new works and reducing the associated socio-environmental impacts.

It was possible to observe that, although there are many studies on the current topic, aspects would still be addressed so that a practical implementation of photovoltaic solar energy is disseminated throughout the country's territory. This article can also assist other countries with similar socioeconomic and territorial aspects to conduct specific studies aimed to increase the participation of solar source in the electric energy matrix, improve forms of energy management and reduce the consequences of uncertainties and restrictions in energy generation.

Author contributions
All authors listed have significantly contributed to the development and the writing of this article and All authors read and approved the final manuscript. TMD collected the generated data, participated in the study method as well as writing the article. PMSRR participated in the study method as well as writing the article. TMS participated in the study method as well as writing the article.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no competing interests.

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