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Economic overview of the use and production of photovoltaic solar energy in brazil

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A R T I C L E I N F O

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A B S T R A C T

The technology of photovoltaic power generation has been increasingly regarded in many countries as an alternative to reduce the environmental impacts associated with climate changes and dependence on fossil fuels. Countries such as Germany and other European countries have been developed specific regulatory mechanisms to encourage its use either by government programs or by financial and/or tax incentives. In Brazil, despite the large existing solar potential, the encouragement to technology is still incipient. This paper aims to demonstrate the key aspects of the evolution of regulatory incentives to use photovoltaic solar energy in Brazil and present the technologies and characteristics of photovoltaic power generation.

1. Introduction

The increase of the demand and consumption of energy resulting from technological progress and from advancement in human development are seen as the most important factors in the acceleration of climate and environmental changes observed and described by the scientific community. Recent studies have shown an upward trend in energy demand as a result of economic recovery in developing countries. The current growth trend suggests that probably in the second decade of this century, energy consumption in developed countries will be exceeded by consumption in developing countries due to the improvement of socio-economic parameters in these countries [1,2].

According to data from the International Energy Agency and Key World Energy Statistics [3], Brazil, Russia, India and China account for 32% of world energy demand. Among them, the highlight is China with 2417 million toe (tons of oil equivalent), which corresponds to 19% of the world energy demand. Russia comes next with 701 million toe (6% of world demand), after India with 692 million toe (5%) and finally Brazil with 265 million toe (2%). About this, see also [4–13].

Although China presents the greatest world's energy demand, its per capita consumption (1.81 toe/person) is below the world average (1.86 toe/person). Similarly, India, even reaching 5% of world demand, has a low per capita consumption (0.59 toe/person). On the other hand, Russia presents a per capita energy consumption (4.95 toe/inhabitant) of developed country. Brazilian consumption (1.36 toe/inhabitant) is in an intermediate position among the BRICs, down slightly from Chinese consumption.

Petroleum is the major commodity in the Brazilian energy matrix, representing about 60% of the total consumption energy sources, used mainly to provide much of the energy demand in the transport sector. It is also important to denote that about 40% of the energy comes from sugarcane bagasse and traditional biomass, as shown in Fig. 1.

Currently hydropower is the main source of energy for electricity generation in Brazil, accounting for 62.44% of production, as shown in Fig. 2.

Hydropower is considered renewable and clean, however its application is restricted due to the environmental impacts caused by the flooding of large areas, by the emission of methane (CH_4) resulting from the anaerobic degradation of organic material submerged by flooding, and due to hydrological dependence of the region to be implemented [16].

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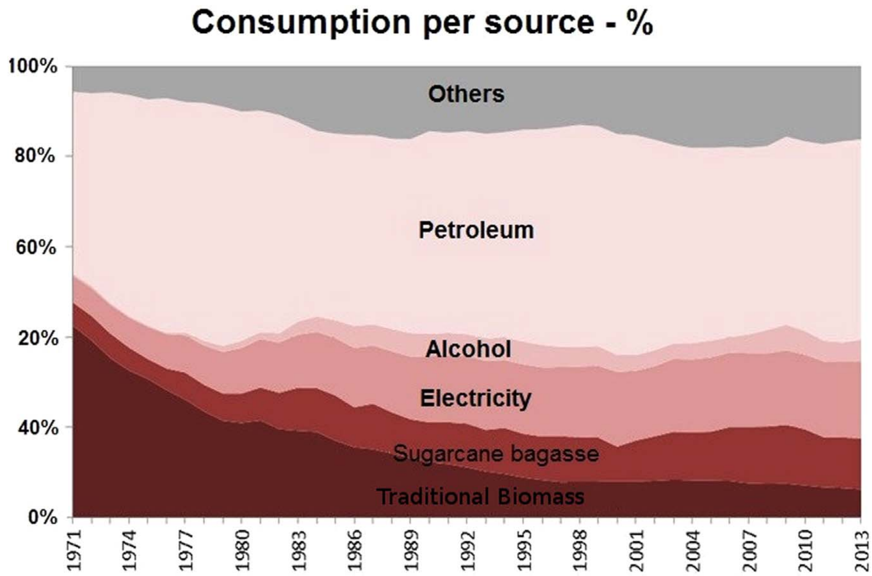

Fig. 1. Brazil's energy matrix versus time. Source: MME, 2014 [14].

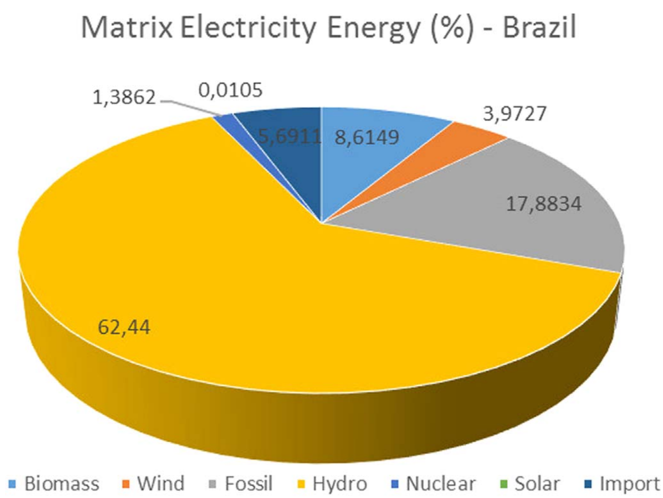

Fig. 2. Brazilian energy matrix. Source: ANEEL, 2014 [15].

On the other hand, Brazil, as a country located mostly in the intertropical region has great potential for solar energy utilization throughout the year. The use of solar energy brings long-term benefits for the country, enabling the development of remote regions where the cost of electrification by conventional network is too high in relation to the financial return on investment, regulating the energy supply during drought periods. There is a wide range of possibilities in the medium and long-term use of this abundant form of renewable energy, ranging from small independent photovoltaic systems to large power plants that use concentrated solar power [17].

According to Rüther [18], the solar photovoltaic systems, especially those integrated with urban buildings and connected to distribution system, offer several advantages to the electrical system, many of which relate to avoiding costs, which are not yet considered or quantified, such as: a) reduction of losses due to transmission and distribution of energy, as electricity is consumed where it is produced; b) Reduction of investment in transmission and distribution lines; c) buildings with integrated photovoltaic technology does not require dedicated physical area; d) solar photovoltaic buildings provide larger volumes of electricity at times of peak demand; e) When strategically distributed, photovoltaic generators offer minimal idle generation capacity for its great modularity short term installation, providing speed on the demands of adding generating capacity.

However, nowadays this energy still has an incipient participation in the Brazilian energy matrix - thermal solar energy for water heating has aroused interest in the domestic market, mostly for the use between classes A and B of society, in the industry and hotel services.

Much of the potential investors and producers in the energy sector do not have information or knowledge, with the necessary scientific background, about the options in renewable energy sources, and because of that, they tend to avoid the economic and financial risks associated with the development of projects in this area [19].

The present article aims to supply part of the demand for information about the solar energy availability in Brazil, government incentives and overview of the current legislation. Specifically for the case of the present review, it has been possible to observe that the generation of photovoltaic energy is an alternative to the diversification of the Brazilian energy matrix. It will be seen that although the country come trying over the years to encourage the photovoltaic source, as a renewable source, this incentive is still very modest to increase its share in the national energy matrix. The projects installed through government actions use autonomous systems and focus on isolated houses, far from the distribution networks. To comprehend such picture, firstly the paper will review in Section 2 technologies and applications of photovoltaic systems, and it will be addressed in Section 3 the main information about costs and learning curve and in Section 4 the potential use. In Section 5 it will be discussed some historical aspects of the development of solar energy in Brazil, mainly in what concerns to photovoltaic systems and the current situation of National fomentation programs. Section 7 will discuss the main actual government incentives and the Brazilian regulatory panorama, and in Section 8 it will be made some final considerations.

2. Technologies and applications of photovoltaic systems

All photovoltaic systems can be characterized into five groups:

i) Connected to the network: the photovoltaic system connected to the network, usually installed on house roofs and buildings, consists of a photovoltaic panel that converts the sun energy into electricity (direct current) in which the presence of an inverter is required, which converts direct current into alternating current with tension and frequency compatible with the electric grid standards to which the system is connected. The main advantages of this type of system are high productivity, the absence of battery bank and automatic shutdown in the event of network power shortage, avoiding isolation phenomenon [20].

ii) Isolated: isolated or independent photovoltaic systems are installed in areas of difficult access to the power grid, usually rural areas. In this case, photovoltaics is the only source of electricity and some storage is necessary, as in batteries [21].

iii) Hybrid - photovoltaic generation works in conjunction with others, such as wind turbines or diesel. They are considered more complex, such systems require a control able to integrate different forms of energy generation. These systems can be connected to the network, alone or have the support network [15].

iv) Solar power plants - These systems also connected to the network, produce a lot of electricity in a single point. The size of the plant varies from hundreds of kilowatts and megawatts.

v) Applied in consumer goods - photovoltaic cells can also be applied in various electrical equipment such as watches, calculators, toys, battery chargers or solar roofs for charging electric cars, irrigation systems, signage on highways, poles or public phones, among others.

The module is the main element of a photovoltaic system. It is comprised of a set of photovoltaic cells, which in turn has the purpose of obtaining electric energy through the conversion of the energy of the solar radiation.

The main technologies that are available today in the market for photovoltaic solar energy production can be divided according to the raw material used in photovoltaic cells such that: Crystalline silicon (c-SI), hydrogenated amorphous silicon (a-Si), cadmium telluride (CdTe), copper diselenide (gallium) and indium (CIS and CIGS), colored modules and High Power Modules [22].

According to [23], the main raw material used in the world for the production of photovoltaic cells is silicon, which is used as semiconductor element. The silicon has four electrons in its last layer, shared by covalent bonds, however this compound is not a good conductor of electricity requiring thus be doped with other elements such as phosphorus which has five electrons in the last layer, which will remain a free electron, shared not forming a silicon semiconductor N-type negative charge. When silicon is doped with an element that has less electron than it in its valence layer as, for example, the boron which has three electrons in the last layer, it is formed a silicon semiconductor P-type positive charge, and the combination of the P-N generates a charge imbalance thereby generating an electric field. The sunlight has the role to excite the electrons generating a flow that produces an electric current and a difference in electrical potential.

The crystalline silicon (c-SI) has been established as the main source of raw material according to the robustness and reliability. These cells may be of two types: monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si). Besides being the oldest photovoltaic technology, the monocrystalline silicon (m-Si) it produces cells with greater efficiencies in commercial applications. This cell is produced by pulling a kind of seed crystal in an extremely slow way (in cm/hour order) and uniform from a molten silicon bath of high purity (Si = 99.99% a 99.9999%) in reactors under controlled atmosphere, producing a cylinder with two thin edges. Next, the crystal is cut into sections using four cuts along its entire length. Finally, the crystal is cut into hundreds of blades (wafers) by wire or diamond saws. This will be the pre-product used in the production of solar cells, which involves stoning, chemical baths, polishing, diffusion/doping processes and deposition of conductive mask of the electricity generated. Finally, cells will be interconnected in series to obtain the photovoltaic module [24].

According to [25], polycrystalline silicon (p-Si), as its name implies, is made up of several crystals, which are subsequently melted and directionally solidified. Precisely because the edges of the crystal particles that the efficiency of polycrystalline cells is smaller than the monocrystalline. On the other hand, they cost much less to be produced, requiring less material and energy. All this reflected in the final cost of the cells, which ends up being less than the monocrystalline, which makes the technology holds the largest share of the solar module market to a long term. The theoretical efficiency of a silicon cell reaches 33%, however on a commercial scale it is 18–20%, while the polycrystalline silicon cells reaches 15–16% [26].

Even though conventional solar cells of crystalline silicon are more expensive, they still account for 90% of the market share due to its greater energy efficiency. The conversion rate of light energy into electricity (relation between the amount of photons falling on the cell and the amount of electricity converted) called photoconversion is 24.7% for these cells. The other 10% of the market corresponds to the inorganic thin films of amorphous silicon cells, polycrystalline silicon or microcrystalline and sulphate of copper-indium-gallium (CIGS), although less efficient than traditional cells (photoconversion 18.8%), they are cheaper to produce [27–30].

In an attempt to overcome these barriers, extensive research has been developed in Brazil and globally in search of new materials and solar cell manufacturing processes more efficient and less costly.

Thus, the development of a new line of solar cell with production costs lower than that of silicon wafers currently used in conventional modules is known as solar cells of third generation (the silicon are the first generation and the inorganic films are the second), that are mainly of two types: organic (OPV, which stands for organic photovoltaic) or sensitized dyes (DSSC, which stands for dye-sensitized solar cell) [27].

The OPV cells carry that name because they use carbon-based semiconductor materials to convert light energy into electrical. As for the DSSC run through a chemical oxidation-reduction reaction. Also called hybrid, as they are made of inorganic and organic materials, they are built between two glasses and contain a liquid electrolyte, typically a solution comprising an iodine salt. The cells activated by dyes absorb solar radiation, allowing the phenomenon of separation of charges (positive and negative) for the production of energy. Neither the organic cells or hybrids are marketed on a large scale in the world [28,29].

Because they are lightweight, flexible and semi-transparent, the range of applications of OPV and DSSC cells is wider than those of previous generations. However, for these cells to become commercialized, two major challenges remain: the low efficiency and reduced lifespan of the new devices. The photoconversion of third generation cells is still very low. The maximum efficiency ratio, though not certified, already obtained for OPV cells was 12, 1% and for the DSSC, 11.4% [27–30].

The low yield of organic cells is explained by no light absorption in the infrared region, with a wavelength greater than 900 nm, and energy losses caused by recombination of electric charges. On the other hand, the reduced lifespan of these cells is a result of the presence of oxygen or moisture inside them. With the incidence of light, especially ultraviolet portion (UV, the presence of oxygen and humidity generate unwanted elements that react with the organic semiconductor changing its chemical structure and functionality [30].

However, recently, semiconductors known as organometallic trihalides of perovskite have the formula (CH_3NH_3) PbX_3, where X can be iodine, bromine or chlorine, it has attracted attention in the scenario of photovoltaics due to its simple architecture and lower cost, the photoconversion rate of 15% [31–37].

Organometallic of perovskite had been introduced in [33] as absorbent materials in solar cells sensitized by dye (DSCs) based on a liquid electrolyte [32].

A rapid development in these devices, perovskites have been applied as coatings over a surface of a thin film of nanoparticles of titanium dioxide (TiO2). Thus, it has been observed that perovskite serves not only to collect light but also playing the role of carriers of the collected charges, which has eliminated the "wet" part of the dye-sensitized solar cells - precisely the weak link of this technology.

In these solar cells last generation of perovskites, the perovskite is simply pressed between the electrodes electrons (negative charges) and holes (positive charges) the same configuration used in conventional planar solar cells [31–37].

The great advantage is that they are very thin - about 300 nm, compared to 150 µm of silicon cells – what gives them flexibility and transparency [31–37]. However, recent disclosures show the use of ferroelectric perovskite, base metal oxides, as potential candidates for the application of solar cells [38].

The perovskite material described in Nature, by Grinberg et al. [39], has properties that could lead to solar cells that can convert more than half of the sun's energy directly into electricity. Furthermore, the new material is also the first to respond well to visible light, making solar cells twice efficient than those available on the market.

In this scenario, the perovskite promise to be an encouraging material for solar low cost energy, due to stable mechanic al chemical and thermal conditions these materials present and can be manufactured using low-cost methods, such as sol-gel of thin film deposition, sputtering [40,41].

Although there are many advantages in cost and efficiency linked to perovskite, this material has some environmental concerns related mainly to the toxicity of lead. In this respect, one of the actual key scientific challenges is to replace the lead in the perovskite crystal with a less toxic metal. Possible replacements for Pb in the perovskite are Sn and Ge, also members of the group 14 metals. For example, CH3NH3SnI3 is a possibility [42]. However, the leading complication with the use of such metals is their chemical instability. Important efforts to solve this problem are being made (see, for example, the experiments described by [42–51]).

3. Costs and learning curve

Despite disposing high levels of insolation, Brazil does not convert this resource into energy. The main explanation for this phenomenon is the high cost compared to traditional energy sources [52–54].

In the first half of 2013, the installation of a photovoltaic system in Germany was around 1684 euros per kilowatt of installed capacity (kWp). In Brazil, during the same period, the cost ranged from 7000 to 10,000 reals per kWp, that is equivalent to 2000–3000 euros per kWp (in that period).

Studies of the European Photovoltaic Industry Association (EPIA) have shown that the competitiveness of photovoltaic energy will be reached soon. The main factors that can contribute to this result are the public policy incentives, investment in technologies that can reduce the costs of cells and investments in research to increase the conversion of systems. Fig. 3 shows the decrease of the unit cost of photovoltaic silicon cells of 99.6% from 1977 until 2015.

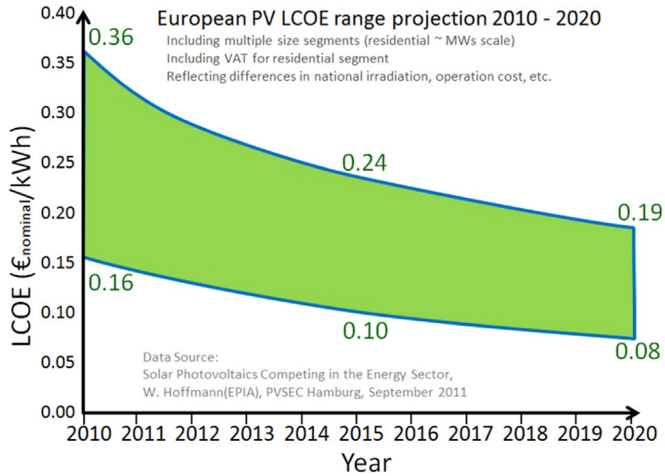

Fig. 4. The Photovoltaic learning curve for Europe. Adapted from [56].

It is possible to observe that the unit costs of photovoltaic dropped from 76.67 dollars per watt in 1977 to an estimated 0.36 dollar per watt in 2015 to crystalline silicon solar cells. This tendency allows validating the learning curve proposed by the Richard Swanson's law, which is similar to Moore's Law, which states that the solar cells cost drops 20% for each duplication of industry capacity.

According to the data published by Bloomberg New Energy Finance until 2011, the price of photovoltaic modules per MW has dropped by 60% since 2008, estimating that solar energy will have a competitive level of retail prices especially in sunny countries. Bloomberg also published a decline of costs of 75% from 2007 to 2012.

According to the European Photovoltaic Industry Association – EPIA, it is estimated that the learning curve will allow in 2020 Europe has an electrical energy cost approximately 50% more affordable than the 2010 costs, assuring solar energy a great alternative source of energy for its energy matrix, as shown in Fig. 4.

In Table 1 it is presented the costs to install a typical 1.5–2.0 kW photovotaic system for each Brazilian State, calculated from solar modules actual costs in Brazil, the regional solar irradiance and the regional installation cost [57–60].

In Brazil, the total installation cost is composed by the following items: PV modules (43%), inverters (24%), physical structure and security (16%), installation project (17%) [57]. Fig. 5 shows power electricity tariff versus cost of distributed photovoltaic generation at the end of 2015 in Brazil.

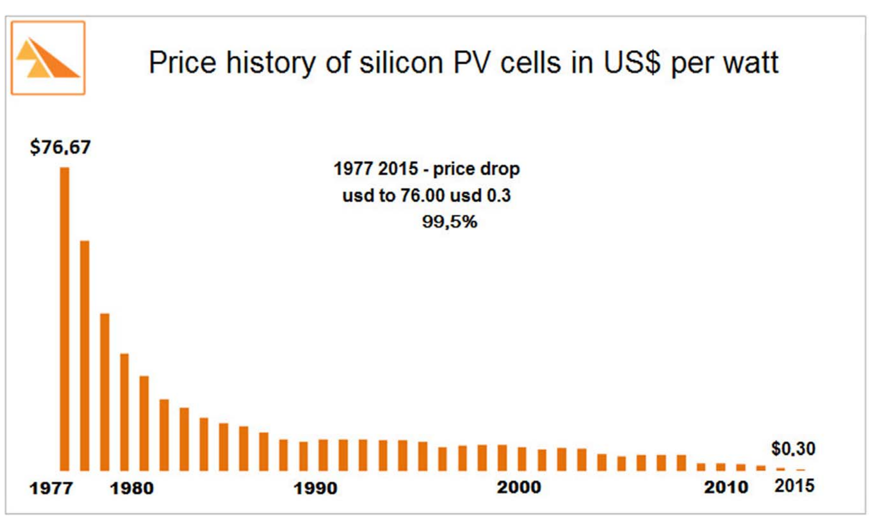

Fig. 3. Price history of silicon PV cells in US$ per watt. Source: Bloomberg. New Energy Finance (Adapted) [55].

Table 1
Maxim and minimum costs of a typical solar module in Brazil (by Brazilian State). Prices in Reals (R$ 1 ~ US$ 0.30). Adapted from [60].

State	Capital	Power of reference (kWp)	Min. price	Max. price
AC	Rio Branco	1.75	R$ 16,625.00	R$ 21,000.00
AL	Maceió	1.47	R$ 14,700.00	R$ 19,845,00
AM	Manaus	1.61	R$ 15,295.00	R$ 19,320.00
AP	Macapá	1.55	R$ 15,500.00	R$ 20,925.00
BA	Salvador	1.45	R$ 14,500.00	R$ 19,575.00
CE	Fortaleza	1.42	R$ 14,200.00	R$ 19,170.00
DF	Brasília	1.52	R$ 15,200.00	R$ 20,520.00
ES	Vitoria	1.56	R$ 15,600.00	R$ 21,060.00
GO	Goiânia	1.52	R$ 15,200.00	R$ 20,520.00
MA	São Luiz	1.61	R$ 15,295.00	R$ 19,320.00
MG	Belo Horizonte	1.74	R$ 16,530.00	R$ 20,880.00
MS	Campo Grande	1.55	R$ 15,500.00	R$ 20,925.00
MT	Cuiabá	1.52	R$ 15,200.00	R$ 20,520.00
PA	Belém	1.57	R$ 15,700.00	R$ 21,195.00
PB	João Pessoa	1.44	R$ 14,400.00	R$ 19,440,00
PE	Recife	1.39	R$ 13,900.00	R$ 18,765.00
PI	Teresina	1.44	R$ 14,400.00	R$ 19,440.00
PR	Curitiba	2.05	R$ 19,475.00	R$ 24,600.00
RJ	Rio De Janeiro	1.63	R$ 15,485.00	R$ 19,560.00
RN	Natal	1.4	R$ 14,000.00	R$ 18,900.00
RO	Boa Vista	1.61	R$ 15,295.00	R$ 19,320.00
RR	Porto Velho	1.72	R$ 16,340.00	R$ 20,640.00
RS	Porto Alegre	1.68	R$ 15,960.00	R$ 20,160.00
SC	Florianópolis	1.77	R$ 16,815.00	R$ 21,240.00
SE	Aracaju	1.44	R$ 14,400.00	R$ 19,440.00
SP	São Paulo	1.91	R$ 18,145.00	R$ 22,920.00
TO	Porto Nacional	1.55	R$ 15,500.00	R$ 20,925.00

4. Use of solar potential

In addition to the weather conditions, the availability of solar radiation, depends on the local latitude and position in time. This is due to rotation, the slope of the imaginary axis around which the Earth rotates daily, and translational motion, elliptical path that the Earth describes around the sun. Thus, the period of visibility of the sun or lightness varies in some regions and periods of the year where the variations are more intense in the polar regions and periods solstice.

Most of the Brazilian territory is located relatively close to the equator, so that it is not observed wide variations in the solar duration of the day. Thus, in order to maximize the use of solar radiation, the position of the collector or solar panel can be adjusted according to the local latitude and time of year in which it is required more energy. In the Southern Hemisphere, for example, a fixed solar collector system should be oriented to the north with tilt angle similar to the local latitude. Fig. 6 shows the annual average daily insolation in Brazil.

Although only part of the solar radiation reaches the earth's surface due to reflection and absorption of sunlight by the atmosphere, it is estimated that the solar energy incident on the Earth's surface is of the order of 10,000 times the world's energy consumption [62].

In 2006, the Brazilian Atlas of Solar Energy presented a survey on the availability of solar energy in Brazil, using a radioactive transfer model powered by climatological data and 10 years of information extracted from geostationary satellite images and validated by data collected from surface stations. The mapping of solar energy potential presented in this document has been one of the products generated by SWERA Project (Solar and Wind Energy Resource Assessment), funded by the United Nations Environment Program (UNEP) and co-funded by the Global Environment Facility (GEF).

The project, started in 2001 under the coordination of the Division of Climate and Environment of the Weather Forecasting and Climate Studies Center of the National Institute for Space Research (DMA/CPTEC/INPE), had the main focus to gather information from a reliable and high quality database aiming to assist in the planning and development of public policy to encourage national projects of solar and wind energy and in addition to attract capital investments from the private sector to the area of renewable energy.

The database reached is compatible with geographic information systems (GIS) and thus can be easily used in economic feasibility studies in the development projects.

In Table 2 it is showed the technical potential of photovoltaic generation in residential roofs per Brazilian region (the potential installed capacity and the potential annual generation of energy for each Region). In Fig. 7 we show the country map with details about such data.

5. Photovoltaic solar energy in Brazil: historical perspective and actual situation of brazilian programs

During the 1970s and 1980s, a considerable number of development assistance agencies attempted to sponsor renewable energy technologies in developing countries. Small-scale rural enterprises such as biogas biodigesters, cooking stoves, wind turbines, and solar heaters were the main products of such financial support. Reports from the United Nations Development Program (UNDP) and World Bank Energy Sector Management Assistance Program indicates that a considerable number of donor renewable energy programs experienced a range of technical obstacles by the end of the 1980s [64,65]. As result, many donors had become disenchanted, and aid recipients had come to view renewables as second-class technologies that industrialized countries were unwilling to adopt themselves [66–68]. Nevertheless, from 1980 to 2000, official development assistance for renewable energy totaled about $3 billion [69,70]. Nowadays, worldwide, at least 170 countries have policy targets for renewable energy, where many of them have been introduced by developing countries, including Brazil,

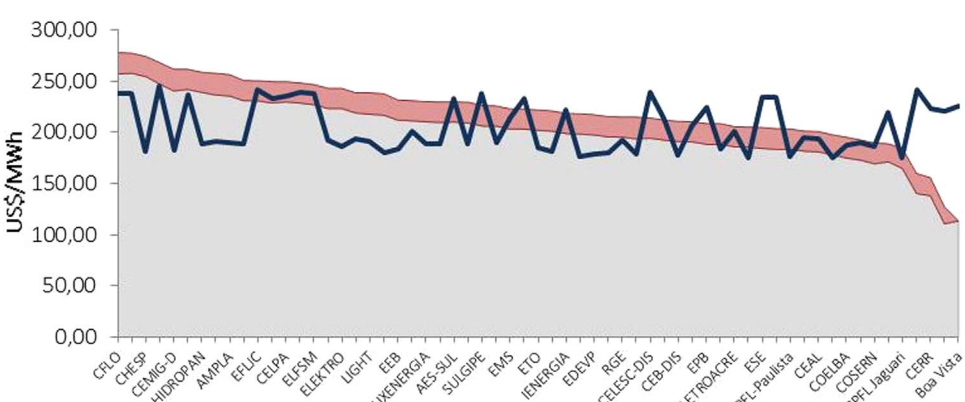

Fig. 5. Power electricity tariff versus cost of distributed photovoltaic generation at October 2015 in Brazil for 31 power distribution companies. The upper band corresponds to the final cost including the 'red flag' tariff (when it is added thermoelectric power generation costs). The line corresponds to the distributed generation level cost. From [57].

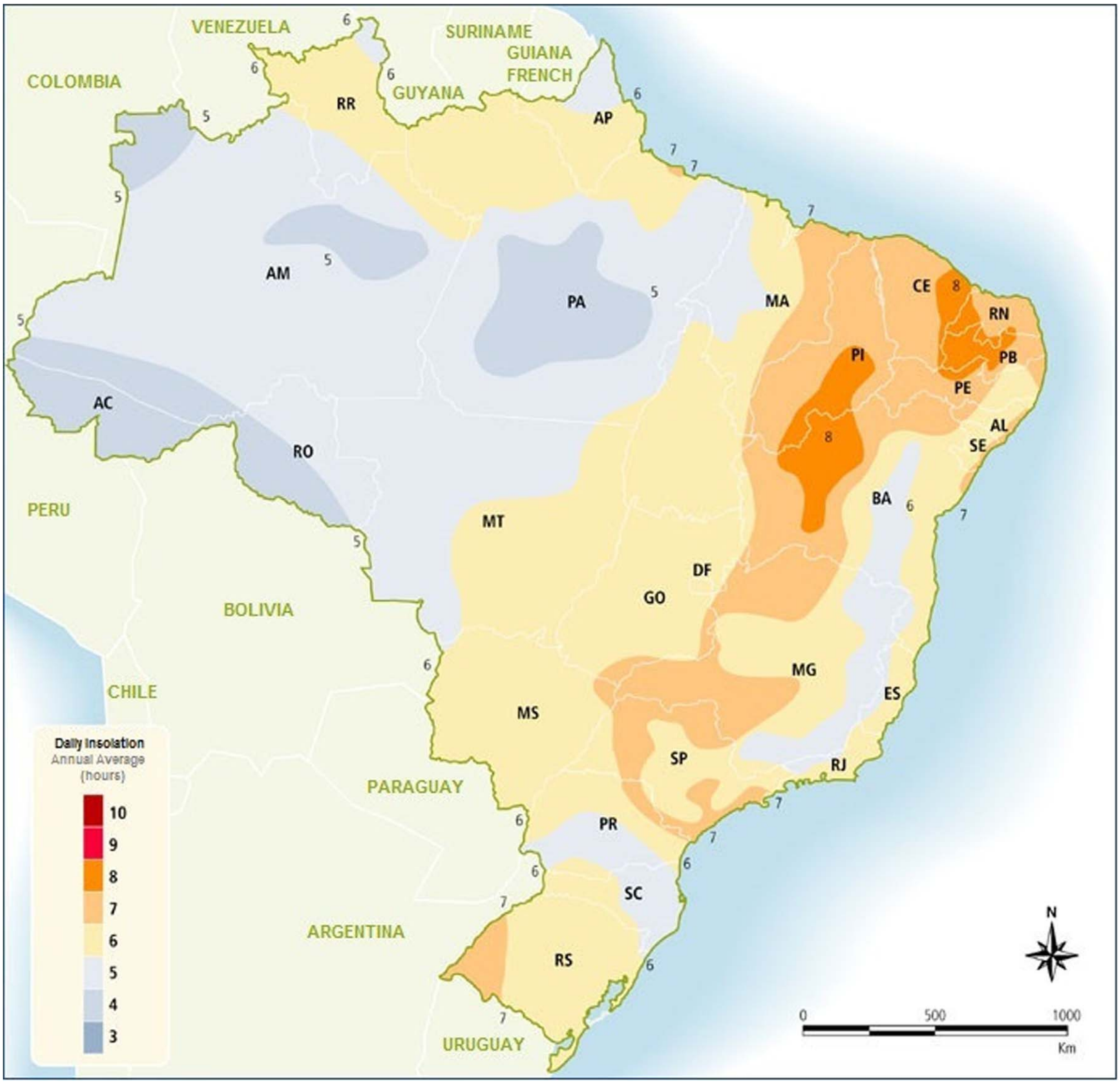

Fig. 6. Annual average daily insolation in Brazil (hours). Source: ATLAS Solarimetric of Brazil, 2000 (adapted) [61].

Table 2
Residential photovoltaic technical potential per Brazilian Region. Adapted from [63].

Brazilian region	Residential photovoltaic potential capacity (MW)	Residential photovoltaic technical potential (energy generation in MW h/year)
North	2215	19,403
Northeast	8840	77,440
Center-West	2705	23,696
Southeast	14,055	123,122
South	5005	43,844

China, Dominican Republic, Egypt, India, Korea, Malaysia, Mali, South Africa, and Thailand [71].

Brazil has a strong hydraulic base in its electrical matrix. However, the stimulus to other "modern" sources of renewable energy is still very incipient compared to the world average, despite the efforts made by the federal government through the Incentive Program for Alternative Sources of Electricity (Proinfa). In the last thirty years, the increase in primary energy production in Brazil has been closely tracking GDP growth, but electricity consumption has increased more rapidly, due to the country's increasing electrification and the installation of electro-intensive industries, such as aluminum [72].

Solar energy research in Brazil dates back to the 1950s [73]. From a strategic point of view, Brazil has a number of favorable natural characteristics, such as high levels of solar irradiation and large reserves of quality quartz, which can generate an important competitive advantage for the production of high purity silicon, cells and solar modules, potentiating the attraction of investors and the development of an internal market, allowing an important role to be seen in the electric matrix for this type of technology. Because of this, during the 1970s, some German universities and research institutes became interested to begin scientific collaborations in the area. It was realized that countries such as Brazil and India with a high level of insolation would be ideal places for harnessing solar energy. For example, during the 1970s, research and development of first generation thin-film solar cells of Cu_2S/CdS was carried out at the Instituto Militar de Engenharia (IME), Rio de Janeiro, in collaboration with the Institut für Physikalische Elektronik (IPE) at Stuttgart University. In this way, a considerable number of other groups in Brazil also began their activities both in scientific research and in technological advancement of solar cells and solar cell materials. Development of solar energy research in Brazil evolved through establishment of well-equipped laboratories, spread of post-graduate education and basic research during 1958-72, intense applied research on solar thermal collectors, refrigeration, furnaces, cookers, driers, and distillation; and photo-

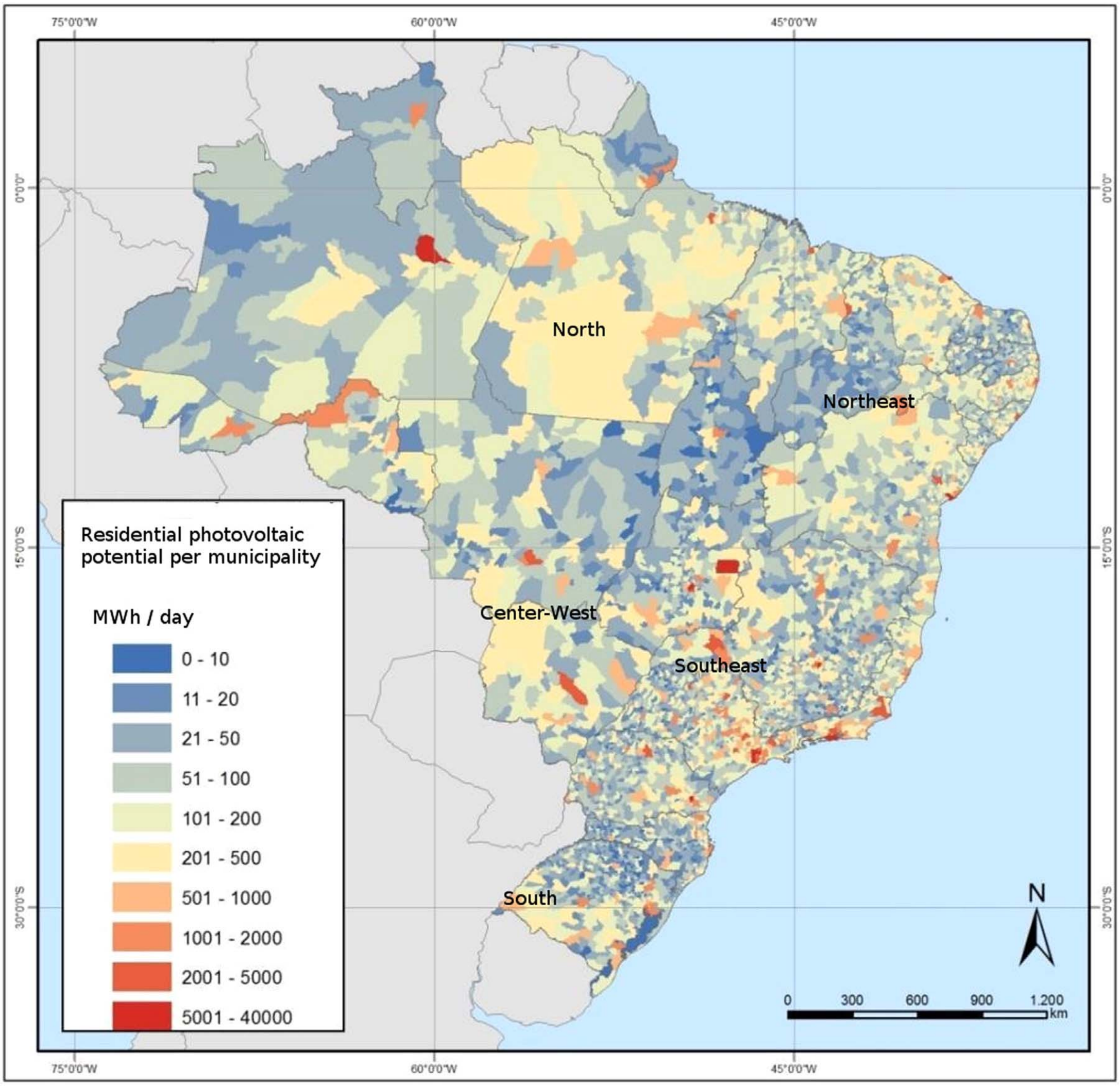

Fig. 7. Technical potential of photovoltaic generation in residential roofs per municipality (MW h/day). Data from [63].

voltaics silicon and module manufacturing during 1973-83 and again after 1994 with higher emphasis on field-deployment of photovoltaic (PV) systems during the 2000s [73,74].

The main research groups on PV systems during this period were the Materials and Interfaces Laboratory, Federal University of Rio de Janeiro (from 1970), the Solar Cells and Microelectronics Laboratory, Military Institute of Engineering, Rio de Janeiro (from 1971), the Microelectronics Laboratory, University of Sao Paulo (from 1974), the Sensors and Materials Laboratory, Institute of Space Research, Sao Jose dos Campos (from mid 1970s), the Photovoltaic Conversion Laboratory, University of Campinas (from 1980). The financial support came mainly from the collaboration between Brazilian and international funding agencies as the Bank of National Development (BNDES), the National Fund for the Development of Science and Technology (FNDCT), the National Fund for Technical Development (FUNTEC/BNDES), the Financing Agency for Studies and Projects (FINEP), the National Research Council (CNPq), the Bank of Brazil, the Research Foundation of Sao Paulo State (FAPESP), the Electrical Utility Company of Sao Paulo State (CESP) and the Organization of American States (OAS) [59,73–75].

From mid 1980s the industrial manufacturing of solar panels in Brazil was inaugurated with the solar cell module assemblage employing imported solar cells. Later, such experience enabled the encouragement of cell production. The first Brazilian company to make this was Heliodinamica, that started the production of 100 mm diameter single-crystal silicon ingots and solar cells. The process, developed locally, consists of the growth of p-type silicon single-crystal ingots, crystal cutting and wafer polishing, p-n junction formation by diffusion of phosphorus using POC13, and formation of an n-p-p+ structure with diffusion from an aluminum paste for generating the back surface field [74].

The period after 1994 was marked by significantly larger expansion of research development and deployment activities. The substantial new funding from the Federal and State Governmental programs for alternative energy led to the creation of new programs, as for example the Program for Energy Development of States and Municipalities (PRODEEM), established in 1994 and managed by the Brazilian Ministry of Energy (MME). It has supplied electric power to rural communities located in remote regions, where the energy consumption was low [59]. During the 2000s, MME have already carried out six International Biddings for the acquisition of modern equipment. The installed systems are scattered throughout all the 26 Brazilian Federal States, with higher concentration in the Northeast and North regions of the country. After 2002, due to the problems faced in the sustenance of PRODEEM, MME decided to promote a huge re-organization in this Program, with the aim of reviving all the systems that were installed

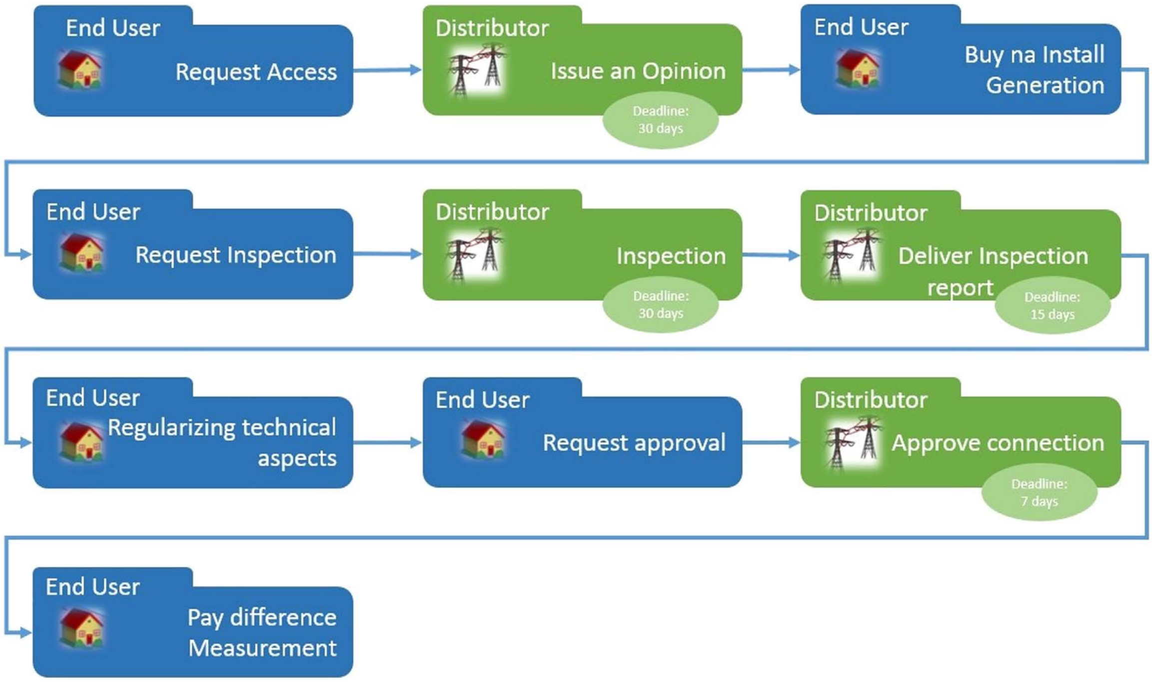

Fig. 8. Procedures and steps for access. Source: ANEEL themed books micro and distributed minigeneration, 2014 [76].

until the end of 2006, then transferring the operation and maintenance tasks to the utility companies all over the country as well as incorporating them in the 'Program Luz para Todos' [59,73]. Regarding centralized generation projects, the first Photovoltaic Plant was inaugurated in 2011, based on a private initiative, with 1 MWp, in the Municipality of Tauá. In 2013, for the first time, photovoltaic generation projects were enabled to participate in an Energy Auction, although no project was contracted due to lack of competitiveness compared to other sources [57,58].

Regarding the development of grid connected systems associated with consumer units, some pilot projects began to be installed in the country in the late 1990s, mainly in universities and research centers. However, only in 2012 this modality of generation was regulated by the National Electric Energy Agency (ANEEL), through Normative Resolution No. 482/2012, which establishes the General conditions for the access of micro and distributed minigeration to the distribution systems of electric power, and the system of compensation of electric energy. At the end of 2015, there were 1675 photovoltaic systems connected under the REN 482 regime, totaling 13.4 MW and at the end of 2016, Brazil had 51.1 MW of installed solar generation capacity, corresponding to 3851 installations [57–59].

6. Government incentives and regulation in Brazil

The two most important taxes that encourage the use of some photovoltaic systems are, the Tax on Circulation of Goods and Supply of Services – ICMS, of State Jurisdiction, and the Tax on Industrialized products – IPI, Federal Jurisdiction.

In 2008, the government made an agreement granting exemption from ICMS and reduced to zero the IPI for some equipment of photovoltaic power generation, valid until December 31, 2021 [76].

The answer to the question of cost is emerging from the market and the installation of photovoltaic systems falls consistently when compared to other renewable sources [69].

Currently, Brazil does not have photovoltaic systems manufacturers, however in 2004, the Ministry of Science and Technology signed a technical-scientific agreement with the Solar Energy Technology Center of the Pontifical Catholic University of Rio Grande do Sul, for the implementation of the Brazilian Center for Photovoltaic Solar Energy Development (CB - SOLAR). The laboratory has been considered the most modern in the field of manufacturing of photovoltaic modules in Latin America [77].

In January of 2015 the National Bank for Economic and Social Development (BNDES) approved financing of the first plant of photovoltaic panels in Brazil, with an initial investment of 26 million for the Pure Energy company in the municipality of Marechal Deodoro, State of Alagoas. Since 2011, Brazil has shown signs that photovoltaic energy can be established in the national territory as another option of complementary energy to the energy matrix. In May of 2011, the first power plant in commercial scale was connected to the network in the Country, of 1 MW in Tauá, Ceará, MPX. In addition, in the second half of the same year, Coelba, in partnership with the government of Bahia, began the installation of power plant of 400 kW in Pituaçu, in Salvador Municipality. With the power plant, the arena will be the first in Latin America to be powered by solar energy [59–63].

An independent survey carried out by the Photovoltaic System Laboratory of the University of São Paulo (USP) and revised in May 2010 by the Solar Energy Laboratory of the Federal University of Santa Catarina (UFSC) indicates that 38 solar power plants are connected to the network, installed in universities, research institutes and utilities. These projects have a total power of 174 kW, of which only 128 kW are in operation today [57–59].

In order to reach the demand for regulation of distributed photovoltaic power generation, the National Electric Energy Agency - ANEEL, promoted the Public Consultation No. 15/2010 (from September 10th to November 9th, 2010) and the Public Hearing No. 42/2011 (from August 11th to October 14th, 2011), which were introduced in order to discuss the legal provisions dealing with small distributed generation connection in the distribution network. these consultations have been introduced in order to discuss the legal provisions that deal with connection of small distributed generation in the distribution network. As a result of this consultation process and public participation in the regulation of the electricity sector, Normative Resolution No. 482, of April 17th, 2012, established the general conditions for the access of micro and mini generation distributed to power distribution systems, and created the corresponding power compensation system [78].

Thus, it is possible to characterize the mini and micro distributed in the production of electricity from small power plants based on hydraulic, solar, wind, biomass or qualified cogeneration, connected to the distribution network through consumer units facilities. In Brazil, to enable access to distributed generation consumers should follow the procedure as shown in Fig. 8.

The electrical measurement system should be bidirectional (measurement of consumption and generation) and can be made also by two unidirectional meters, one to measure consumption and other power generation where the adequation costs are in account of the accessing party. After installation, the cost of maintenance is the responsibility of accessed party. The initiative of installing micro and mini generation system is from the user and for analysis cost-benefit it should be taken into consideration a number of circumstances, such as generating equipment technology, location of installation, the rate which is subject, project payment terms, existence of other consumer units that can take advantage of possible generation surplus credits [78,79].

The following taxes are imposed on distributed generation: the Tax on Circulation of Goods and Supply of Services- ICMS, Social Integration Program (PIS) and Contribution to Social Security Financing (COFINS).

According to ANEEL recommendation, taxation, instead of what happens, should focus only on the difference, if positive, between the final values of consumption and excess energy injected, however, the power to amend the tax burden on the individual distributed generation is in charge of the government, ICMS state government and PIS and COFINS federal government.

Germany for example is considered the country with the most successful incentive mechanism for renewable energy sources. The price system introduced with the Electricity Feed Act (1991) – and subsequently updated by the Renewable Energy Sources Act (2000) and by the amendment of the Renewable Energy Sources Act (2004) – is the key to the success of renewables in Germany.

Only in 2004, an increase of approximately 100% in photo power installed in Germany, which at the end of 2005 was approximately 1.5 GWp connected to the public network [80]. Such examples could server as the basis for the structure of incentives in Brazil.

The German mechanism is based on the compulsory purchase by the network operator, of all the electricity generated by renewable sources, paying the independent power producer (PI) a tariff premium per kWh generated. This premium rate is relatively higher than the price of conventional kW h and it is distinct for each technology [81–84].

The funds for the payment of premium rates are raised through a small increase in the standard rate for all consumers and are deposited in a fund used to reimburse the PIs.

In this case, the incentive is paid gradually over the time of the program period (20 years for Germany), allowing PIs recover their investments over a period of 10–12 years [85].

7. Concluding remarks

Photovoltaic solar energy has become, in recent years, a reality in some countries, although the development in all cases has been made through the most diverse incentives (see, for example, [78,82,86–93] to understand the vast scenario across the globe in the last 10 years). Although much smaller than in the past, the costs of solar generation is still higher than some of the main renewable energy sources used in electricity power generation. However, the learning curve of industry in the world is in evolution and associated costs had significant decreases. It is considered by some authors that this trend will be maintained over the next few years, which may mean that the source becomes competitive without incentives in the future [94–98].

Specifically for the case of the present review, it has been possible to observe that the generation of photovoltaic energy is an alternative to the diversification of the Brazilian energy matrix. However it is also noted that although the country come trying over the years to encourage the photovoltaic source, as a renewable source, this incentive is still very modest to increase its share in the national energy matrix. The projects installed through government actions use autonomous systems and focus on isolated houses, far from the distribution networks [78,79].

It is understood that to enable a more significant reduction of production costs within the photovoltaic chain in the country it is necessary to stimulate further development of the market for solar energy. This would also allow the country to participate in some stage in the chain of a high value-added industry worldwide. Brazil has quality raw materials and industries that can be adapted for the production of components for photovoltaic systems and indeed heliothermic plants. To promote the development of the local industry is an alternative that can reduce costs and boost participation of this energy source in the national electric matrix, bringing several developments, such as technological, economic and social development [72]. Nevertheless, the international market for such technological components is extremely competitive. In the case of the photovoltaic industry, what has been seen in recent years is the price dumping leading unfortunately several manufacturers into bankruptcy [96–99].

The initial chain of silicon purification and cell production is very expensive and requires large volume production to become competitive. In the case of heliothermic, the production of higher value-added components requires high technological know-how. Therefore, the development of a competitive and sustainable Brazilian local industry is a challenge for planning. The development of specific lines of credit for solar electricity generation is vital for an expressive entry of this source into the Brazilian electricity matrix. However, the distributed grid generation still lacks funding lines with attractive rates that are available across the country. One of the reasons for the few alternatives offered is the lack of knowledge about technology by the financial sector, which causes uncertainties and difficulties in understanding and correctly measuring the risks of these assets. In this case, not only direct financing solutions can be developed, but also financing mechanisms such as the securitization of distributed generation assets, which would more easily facilitate different business models, such as leasing [78,79,86–93,100–108].

In the case of distributed generation, because its competitiveness level is defined from the energy distribution tariffs to the final consumer, the comparison of values already allows us to say that it is close to the condition of economic viability at the Brazilian electric grid [61,70,78]. The same does not occur with centralized generation, of larger size, whose prices are not competitive with those of other renewable sources in the present [78]. To solve the problem, probably it should be considered the contracting of centralized photovoltaic generation, of larger size, by specific auctions, restricted to this specific case, repeating the successful energy policies experimented by other countries [108].

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