Renew. Energy Environ. Sustain. 7, 26 (2022)

https://doi.org/10.1051/rees/2022014

Renewable Energy and Environmental Sustainability

Available online at:
www.rees-journal.org

Review Article — Open Access

Solar photovoltaic tree multi aspects analysis – a review

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Received: 21 July 2022 / Received in final form: 16 September 2022 / Accepted: 17 September 2022

Abstract. The generation of photovoltaic solar energy worldwide has increased significantly in recent years. This is mainly due to the growing demand of society for electricity, the need to reduce environmental impacts, and costs of such technology. The installation of a photovoltaic system with horizontally fixed panels requires a significant unshaded area, which has become increasingly scarce, especially in urban centers. The photovoltaic solar tree is a strategy used to increase the efficiency of photovoltaic systems by reducing the occupied area and optimizing the orientation angles of the panels. The originality of this work was that, through a literature review in different researches, seven relevant parameters related to solar photovoltaic trees were analyzed: (i) modeling and simulation, (ii) tree topology, (iii) orientation of the panels, (iv) constructive characteristics, (v) solar tracking, (vi) occupied area and (vii) site multiple uses. It was found that the photovoltaic solar tree is an interesting alternative to generate renewable energy for places without large enough areas, which can be used for other purposes, such as crop production and parking. Finally, it was concluded that, to date, there are no studies available in the literature on the optimization of photovoltaic generation per area for different topologies of known solar trees.

Keywords: Spatial arrangement of photovoltaic panels / phyllotaxy / Fibonacci sequence.

1 Introduction

The use of fossil fuels as an energy source has seriously damaged the environment due to greenhouse gas (GHG) emission, which is related to global warming, climate change, air pollution, acid rain and other problems [1,2]. In contrast, the use of renewable sources to generate energy is essential to mitigate environmental problems and help meet the increasing world energy demand, since non-renewable resources are finite [1,3].

According to data from the International Energy Agency (2020) [4], electricity consumption has grown in recent years. The annual worldwide electricity consumption rose from 13,181.7 TWh in 1998 to 24,738.9 TWh in 2018, which is an increase of about 3.2% per year in the period (Fig. 1). Also in this period, $CO2_{eq}$ emissions increased 2.3% per year, due to electricity generation and heat production. Thus, it is essential to recognize the relevance of using renewable resources and efficient energy use to help meet the demand for primary energy and reduce environmental impacts in the coming years.

Solar energy, through photovoltaic cells, is considered one of the most promising renewable energy sources [1,5,6]. The recurrent studies related to solar energy are associated with efficiency of photovoltaic cells [7–9] and the electronic components used in photovoltaic systems [10,11]. Furthermore, several researches focus on the effective use of photovoltaic panels by employing methods for solar tracking and optimizing the orientation [6].

Some photovoltaic systems are designed to track the trajectory of the sun during the day, by keeping the panels at a right angle to the sun rays to capture most solar radiation and, consequently, increasing electricity generation. Uniaxial trackers have only one degree of freedom. These systems can generate about 30% more energy than a fixed horizontal one [5].

On the other hand, biaxial trackers have two degrees of freedom, which work as rotation axes perpendicular to each other, but require a more complex control. Biaxial tracker systems can be up to 17% more efficient than a single axis system [12]. However, systems with trackers are significantly more expensive and require additional maintenance [13].

The photovoltaic solar tree is an alternative to increase the efficiency of photovoltaic systems by optimizing inclination angles and reducing the occupied area. A solar tree design usually aims to maximize the electrical energy

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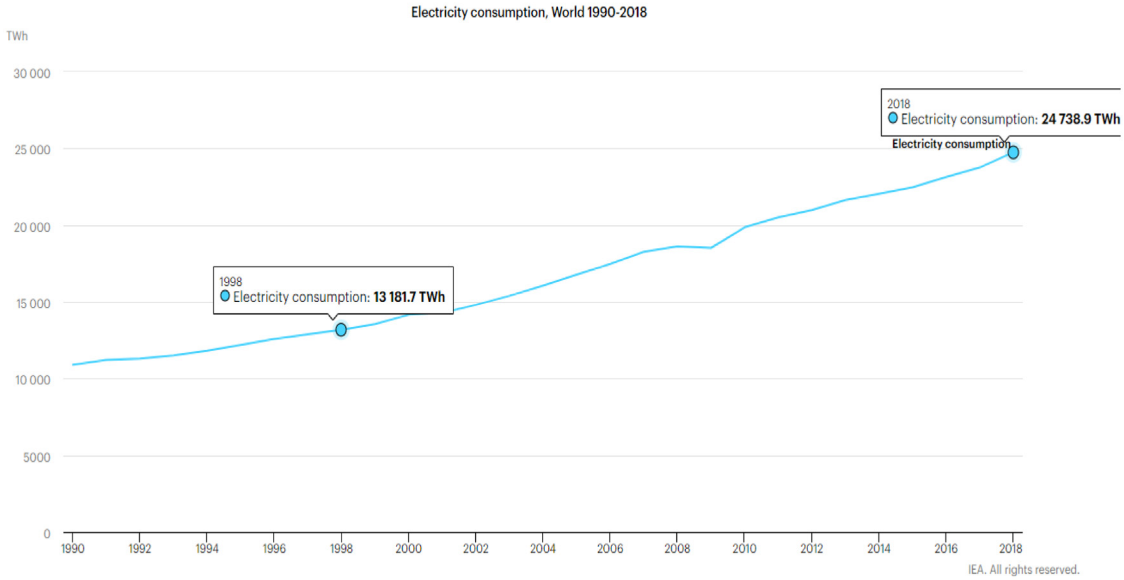

Fig. 1. Electricity consumption in the world between the years 1990-2018. Source: [4].

generation in a given area whereas the traditional solar photovoltaic system aims to minimize the energy cost generated. In a solar tree, the word TREE forms the acrostic "T = Tree generating; R = Renewable; E = Energy; and E = Electricity" [14].

The photovoltaic solar tree is composed of a support structure with photovoltaic panels conveniently connected and a control unit. The structure is associated with the trunks and branches of a tree, and the panels, which are arranged on the branches, are the leaves. It is an analogy to natural trees with photovoltaic panels instead of leaves [15].

The main advantage of a photovoltaic solar tree, when compared to photovoltaic systems with single orientation panels, is the possibility of optimizing the orientation of each solar panel. This characteristic may allow the energy generation to be optimized in desired periods. For example, it is possible to increase energy generation during winter, or the whole year [6].

Thus, with better orientation and distribution of these panels over the structure of the tree, it is possible to increase the energy generation and reduce the occupied area when compared to an arrangement of generators in a single plane or parallel to the orientation of the roofs [16]. Reducing the occupied area is pertinent, since large areas are needed to install a photovoltaic plant, which should be unshaded, as far as possible, considering that unshaded areas are usually scarce [17].

In urban areas, the increased number of buildings tends to restrict the availability of unshaded surfaces. The available areas on roofs, where panels are generally installed, may not be enough to implement a solar power plant that meets the energy demand of the building. In rural areas, the installation of these systems reduces the useful space that could be allocated to crop production [6].

Recent studies have addressed the concept of the solar tree project, using different approaches involving: (i) Incident radiation and solar generation [6,16]; (ii) structure [18,19]; (iii) prototypes [13,20–22]. The incident radiation and solar generation are one of the most important aspects to be simulated and tested; Structure: simulation the strength of the behavior of the support structure of trees in the trunk, branches and leaves; Prototypes: construction and testing of prototypes with and without solar tracking, in reduced and real scale.

The solar tree and its surroundings were evaluated in terms of topology, the orientation of panels/leaves, constructive characteristics, use of solar tracking, occupied area, and possible multiple uses of the area.

This research aimed to survey the state-of-the-art review of photovoltaic solar tree development. Thus, design parameters such as: modeling and simulation; topology; orientation of the panels; constructive characteristics; solar tracking; occupied area; and multiple uses, were analyzed to evaluate trends in these lines of research.

2 Methodology

Were reviewed, in the scientific literature, the subject photovoltaic solar trees considering their academic, technological and social relevance, to generate a structured knowledge. This research used search engines, such as Google Scholar and ScienceDirect, to find the most relevant recent scientific publications in essays, dissertations and thesis collections, to obtain reliable results.

Some keywords, such as "solar tree", "PV tree", "solar PV system", "phyllotaxy patterns" and "agrivoltaic systems" were defined to help the research and find relevant bibliographic material about the subject. Also, studies were carried out on the efficiency of the solar tree and/or photovoltaic plant, with crop production located around and below these systems, as well as solar parking and floating PV plants.

The search was limited to studies that are more recent and covered articles from 2016 to 2021. After selecting relevant documents for the study, a set of references was created and classified according to the structure and content covered.

Some important aspects were highlighted in this study regarding solar trees: (i) modeling and simulation, (ii) topology, (iii) orientation of the panels, (iv) constructive characteristics, (v) solar tracking, (vi) occupied area, and (vii) multiple uses.

3 Results and discussion

After researching and filtering the materials found, it was observed that the number of works addressing the subject has increased modestly in the last five years. No more than 30 studies were found, including articles, essays, thesis and dissertations.

Regarding the origin of the articles, 72% of them were developed in India. Other countries, including Germany, Bangladesh, Brazil, Indonesia, Nigeria, Thailand and Colombia, have also published articles on the subject. Except for Germany, all mentioned countries have a portion of its territory within the tropical zone, between the Tropic of Cancer (23°27' N) and the Tropic of Capricorn (23°27' S), where happens the highest solar incidence on the globe. Again, except for Germany, any of mentioned countries have solar photovoltaic energy as one of the main energy sources to supply the respective nation.

3.1 Modeling and simulation

The authors in [16] proposed an orientation of the solar tree panels in order to improve the energy generation. Detailed analytical models combined with multi-objective genetic algorithms were used to optimize the orientation of the solar panels and minimize the shading between them.

Firstly, they determined the incident radiation $I(\beta, \gamma)$ on the inclined surface, Equation (1), described by the tilt angle (β) and azimuth angle (γ), following the Liu-Jordan isotropic model [16]:

$$I(\beta,\gamma) = I_b \frac{\cos\theta_i}{\cos\theta_z} + I_d \frac{1+\cos\beta}{2}, \tag{1}$$

where I_b is the hourly direct solar radiation on a horizontal surface (W/m^2), I_d is the hourly diffuse solar radiation on a horizontal surface (W/m^2), θ_i is the angle of incidence (°), and θ_z is the zenith angle (°) [16].

In the work of [16], β ranged between 0° and 90°; and γ ranged between 0° and 360°, both at 0.01° intervals, until finding the values of β_{opt} and γ_{opt}, which gave the highest indexes of incident radiation on the analyzed surface, which is each solar panel/leaf, Equation (2):

$$(\beta_{opt}, \gamma_{opt}) = (E(\beta,\gamma)); \beta \in [0, 90°], \gamma \in [0, 360°], \tag{2}$$

where $E(\beta, \gamma)$ is the 365-day sum of the daily values of incident energy results in the annual incident energy for a surface with orientation (β, γ).

The global incident radiation accounted for every hour between 7 am and 5 pm, as presented in equation (3) [16]:

$$E(\beta,\gamma) = \sum_{\text{day}=1}^{365} \sum_{7\text{am}}^{5\text{pm}} I_{(\text{h,day})}(\beta,\gamma). \tag{3}$$

It is important to point out that, in different regions and seasons there is sunshine before 7 am and after 5 pm, so to not consider the solar radiation in all periods that it is available could lead to avoidable errors.

The energy loss by shading, E_l, was given by equation (4):

$$E_l = \sum_{h=7\text{am}}^{5\text{pm}} I_b(\beta,\gamma)\eta_e A_h, \tag{4}$$

where η_e refers to the efficiency of the photovoltaic panel (%) and A_h is the shaded area of the panel (m^2).

The authors did not mention whether they considered the annual degradation of the photovoltaic panel. However, according to [23], photovoltaic modules degrade on average around 0.7% per year. A_h was determined by projecting the area of one panel onto another, considering the solar radiation direction vector. Thus, their goal was to position the desired number of panels so that the shadow from one panel did not significantly reduce the energy generation from the others [16]. It was noted that the only shade researched was the shade of a panel in other(s) and note the shade from branches or the trunk on panels.

Finally, with the orientation of the panels already determined, the model was validated through a comparison with a simulation of the optical ray, using ZEMAX® (optical design software system). The panels had their surfaces subdivided into parts of 1 mm^2 so that the light intensity could be verified over their entire surface. The simulations were carried out on one day of each month, for three different times: 9 am, 12 pm and 3 pm [16]. However, simulating more times of the day would increase the reliability of the results, since major changes may occur in the incident radiation values between the periods analyzed.

Only direct radiation was used for these simulations, since diffuse radiation was not found to significantly contribute to shading losses. The solar radiation values simulated in the panels, by ZEMAX®, presented an excellent correlation with the results of a software system written in MATLAB® [16].

Also using Liu-Jordan's isotropic model was also used to determine the values of direct and diffuse incident solar radiation on inclined surfaces, the authors in [6] designed solar tree models for seven locations around the globe. However, they stated that this design methodology is generic and can be, as long as some adaptations are made, applied to other places.

The authors aimed to tune the power generation curve "*as per the need*". For such, they simulated the incident solar radiation by varying the angles β and γ to increase energy in the desired period of the year without losing much energy in the remaining period. Thus, they were able to determine the orientation of each photovoltaic panel. Finally, the incident energy in the desired months and the average annual incident energy were calculated [6].

Aiming to maximize the energy generated and reduce the structural cost of a solar tree, the authors in [19] not only simulated the orientation of the panels similarly to the work from [16], but also simulated the physical structure of the solar tree. To reduce the mass of the structure of the tree without compromising its integrity at high wind

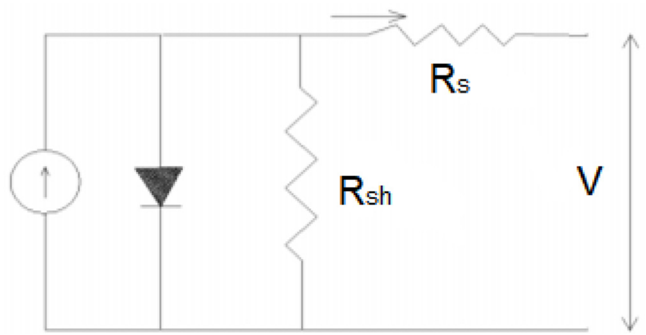

Fig. 2. Photovoltaic cell equivalent circuit model. Source: [15].

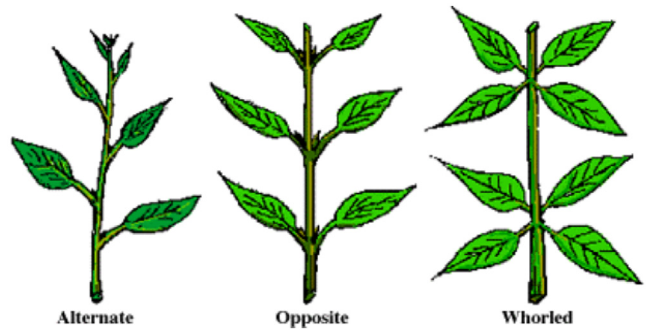

Fig. 3. Basic phyllotaxies: alternate or spiral, opposite and whorled. Source: [20].

speeds, the authors carried out a finite element model to analyze the tensions acting on the structure. The dimensions and masses of the trunk and branches of the solar tree were individually optimized.

Also regarding the solar tree structure, the researchers in [19] designed different tree models, using the Creo Parametric 2.0 software. The authors used the ANSYS 16.2 software system to carry out the static analysis of the structure by calculating deformation, von Mises tension, shear tension and others.

Kishore et al. [24] simulated the placement of five panels in their trees, using the method employed by [16], and implemented an IoT (Internet of Things) system to monitor the energy generated by the solar tree.

A different approach was employed by [15], who initially used the MATLAB®/Simulink software system to model and simulate a photovoltaic cell used in the solar tree. For such, they represented the cell as an equivalent circuit of one diode model, as shown in Figure 2, and calculated the electric current and voltage values to raise the P–V and I–V characteristic curves. The tree output power values were estimated using the PVgis® and PVsyst® photovoltaic system simulation software.

The works in [25,26] developed similar research. They started by calculating the daily energy consumption at their facilities. Then, it was possible to specify the necessary components to implement a photovoltaic system in a tree-like arrangement, such as battery bank, quantity, physical arrangement, power of the photovoltaic panels, charge controllers and inverters. Following these specifications, [26] designed the photovoltaic solar tree using Solid Edge ST9®, SOLIDWORKS®, Luxion Keyshot 6®, CorelDRAW X8®, and the Microsoft Visio® software. However, none of the works simulated incident radiation on the panels or optimized their orientation.

Although simulation is a partial clipping of a real situation, it is a relevant resource that helps describe the current and future behavior of a system, elaborate hypotheses and propose adjustments. Thus, the modeling and simulation of solar radiation, as well as the equivalent electrical circuit of a photovoltaic system, are believed to significantly contribute to the optimization of models and prototype performance.

According to the studies mentioned above, there are different simulation approaches, from incident radiation on photovoltaic panels to the structural analysis of trunks and branches. However, so far, no research was found in the scientific literature on the influence of the trunk and branches as objects that cause shadows, thus reducing the efficiency of the photovoltaic system.

We believe that a more rigorous evaluation of shading from panels, trunk and branches in other panels must be systematically done in order to better appraise the solar tree performance. Such evaluation must cover all panels of a given tree, all days of the year, all hours of each day, as well as any location, technology used, orientation of each panel, age of the equipment and possible dust on the panels.

It was also verified the lack of specific software systems that design photovoltaic solar trees and simulate the study on shading in photovoltaic panels. Thus, it was observed that the software system used by each author was chosen and/or developed and adapted to meet the specific goals of each work. However, it seems that none of them were comprehensive enough to carry out all the designing steps, namely: a. number of leaves needed; b. structural calculations; c. simulation of incident radiation and possible shading sources; d. operation evaluation with and without Maximum Power Point Trackers (MPPT).

It would be interesting to develop a software system that can simulate different structures of photovoltaic systems, including loss of efficiency due to shading, estimation of incident radiation on surfaces with different orientations, electrical energy generation and the configuration of the sets of photovoltaic panels connected to a single or multiple MPPT.

3.2 Topology

Topology, which is the arrangement of the leaves and branches of the tree, is a fundamental parameter to achieve better performance during the generation. It is necessary to carefully analyze the best tree format to be reproduced and understand how the patterns of the leaves on the stem arrangements are formed. This arrangement is called phyllotaxy.

According to [20], the three basic phyllotaxies found in plants are: alternate or spiral, opposite and whorled, as illustrated in Figure 3.

In the alternate or spiral pattern, the leaves are connected in different nodes and can be oriented in different directions. In the opposite phyllotaxy, two leaves, arranged in opposite directions, are connected in the same node of the stem. In whorled phyllotaxy, several leaves arise from the same node and are arranged in different directions [21].

More than 80% of the plant species found in nature have alternate or spiral phyllotaxy [20]. This arrangement was also widely used in the design of photovoltaic solar trees. The Fibonacci pattern to determine the angular distance between subsequent leaves is incorporated into the spiral phyllotaxy. This angle allows the panels to receive solar energy from more different directions, that is a greater solar radiation on the leaves throughout the day.

According to [14], the Fibonacci pattern is derived from a sequence discovered by the Italian mathematician Leonardo Fibonacci, in the year 1202. In this sequence, each number in the sequence is the sum of the two preceding ones. The Fibonacci sequence, F, is described from equations (5)–(7):

$$F = \{F_0, F_1, F_2, \dots\}, \tag{5}$$

which,

$$F_0 = 0, F_1 = 1, \tag{6}$$

$$F_k = F_{k-1} + F_{k-2}, \tag{7}$$

for $k = 2, 3, 4, 5 \dots \infty$.

Thus, we have the Fibonacci sequence, $F = \{0,1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, \dots\}$.

To determine the angular distance (d_{ang}) between subsequent leaves, equation (8), it is necessary to identify the number of turns needed (n_t) until the next leaf overlaps the first and the number of leaves (n_l) per period. Several studies have demonstrated that, in nature, the most frequent values of n_t and n_l are numbers present in the Fibonacci sequence [27]

$$d_{ang} = \frac{n_t}{n_l} 360. \tag{8}$$

Figure 4 shows an arrangement with spiral leaves using the 5/8 Fibonacci pattern. It can be observed that 5 full turns are required for the ninth leave to overlap the first leave. In this pattern, the angular spacing between subsequent leaves is 225°.

There are several n_t/n_l phyllotaxy patterns, including 1/3, 2/5 and 3/8. The authors from [29] designed a solar tree inspired by the 2/5 pattern spiral phyllotaxy found in oak trees. The five branches were evenly distributed in two revolutions around the trunk, forming a vertical spacing and an angular distance between subsequent branches of 5 cm and 144°, respectively. Two photovoltaic panels were placed in each branch. Although the branches respected a sequence of placement, the panels attached to them did not have a determined orientation based on a specific pattern.

The study of the optimal orientation of the panels is considered important for further research.

The length of the branches also followed the Fibonacci sequence. The upper branch was designed with a length L, the second and below, with a length 2L, the third with 3L, the fourth with 5L, and the last branch, at the bottom of the tree, with a length of 8L [29]. This branch design can create a solar tree similar to conifer trees.

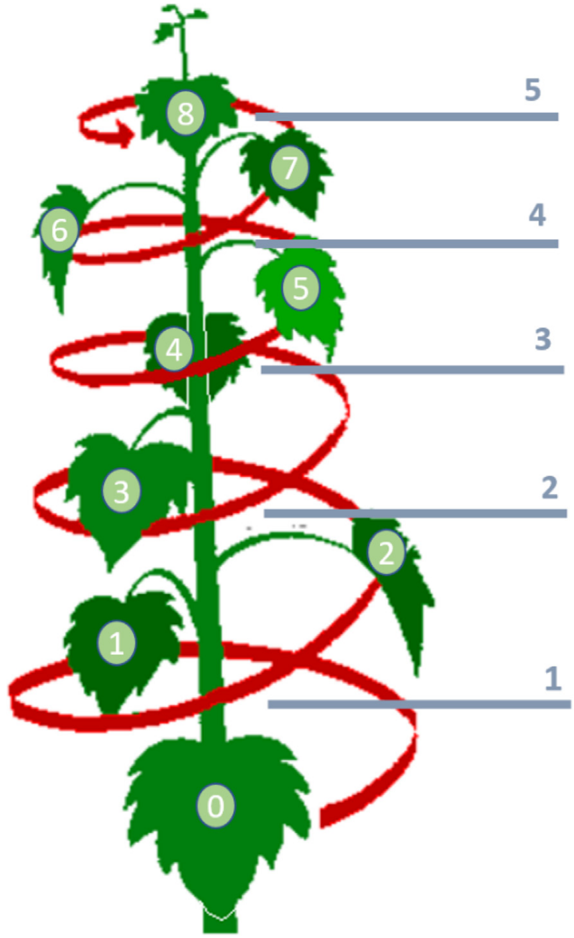

Fig. 4. Example of 5/8 Fibonacci pattern in a spiral phyllotaxy. Source: [28], adapted.

Similarly, [20] also developed their solar tree based on the 2/5 pattern identified in oak trees. The branches had different lengths to minimize the upper panels from shadowing the lower ones. The upper panel was defined as the reference, and the other four panels were offset 144° from each other, counterclockwise.

In addition to designing a solar tree with a 2/5 pattern, the authors in [21] developed one with a 3/8 pattern, which formed an angle between the branches of 135°. They concluded that the solar tree built with the 3/8 pattern generated more energy than that with the 2/5 pattern and the conventional photovoltaic plant with a single orientation, under the same solar radiation conditions.

The researchers from [30] built a solar tree using an angle of 137.5° (golden angle) between branches and between trunk and branches. The authors did not specify in detail the n_t/n_l pattern to determine this angular distance. Furthermore, for comparison purposes, they installed the same number of cells with a fixed inclination. They verified that the tree generated more energy during the day than the cells with a fixed inclination.

In the studies from [22,26], trees with shapes similar to a palm tree with whorled phyllotaxy were adopted. Arrangements of three or more photovoltaic panels were attached to the same node of the tree trunk.

Other topologies of photovoltaic solar trees were also studied. The studies from [6,16,18] did not adhere to a pre-established pattern of tree topology. With the simulations and algorithms developed, they determined the arrangement and placement of each panel for maximum efficiency.

Many researchers used the Fibonacci pattern with alternate phyllotaxy to develop solar trees. The most common patterns were 2/5 and 3/8, with an angular spacing between subsequent leaves of 144° and 135°, respectively. Whorled phyllotaxy was noted in palm-like topology. Finally, the opposite phyllotaxy was not applied to any project. It is believed that, in the latter case, the arrangement of photovoltaic panels would cause much loss due to shading compared to other phyllotaxy.

It was found that the Fibonacci sequence was used both in the angle between the branches and the trunk and in the length of the branches, which affects the dimension of the solar tree as a whole. Actually, the optimization must also consider other geometric parameters, such as tree height, the vertical distance between branches and leaf dimensions.

3.3 Panel orientation

The angle of solar incidence changes according to the time, day of the year and geographic location. According to [6], although Chennai (13.08° N) and Bangalore (12.96° N) are Indian cities with almost the same latitude, the solar radiation patterns in both cities are significantly different. Variables such as local altitude and clearness index are also influential parameters. This means that designing a photovoltaic system with fixed orientation panels based just on local latitude may not always be the best option.

It is attractive to design a photovoltaic system based on a tree topology. Natural trees are effective in absorbing sunlight due to the diversified orientation of their leaves, which optimizes solar radiation absorption. Consequently, not all leaves will have optimal incidence angles at the same time [14].

Thus, the orientation of the panels must be determined according to the purpose of the system. This purpose may require, for example, greater energy conversion in a specific season, such as winter, or even to maximize the energy conversion over the whole year.

Some authors, such as [6,18,24] determined the angles β and γ of each panel through simulations. The optimal angles found were unique for each panel and were not necessarily close to the latitude where the experiment was carried out, since the goal is to maximize the radiation at the solar tree for a given period of time.

The authors in [20,21], who designed solar trees in India, inclined only the panels facing south, with an angle equal to the local latitude. The other panels of their solar tree had different orientation values, not specified by the authors. A second solar tree was also built by [21]. The solar panels facing east and west were placed horizontally, while those facing south, southeast and southwest had an inclination of 30° (the latitude where the experiment was carried out was 29.02° N). The panels facing north, northeast and northwest were oriented at −30°. These authors did not explain the reasons of such orientation for the leaves on each side of the solar tree studied.

Optimizing the inclination angles of solar panels is regarded as a promising alternative to increase the efficiency of photovoltaic systems. Factors such as the location and direction of each panel must be considered to estimate the best inclination. However, this is not an easy task since specific software and radiation data must be available.

It was also noted the tendency to orient the solar panels to the north when located in the southern hemisphere and to the south when located in the northern hemisphere, in addition to orienting the photovoltaic panels with an angle equal to the local latitude. However, the exact values of the panel orientation angles should be calculated by simulation based on solar tree topology, location and period of the year.

Furthermore, simulation studies are not the only tool to be used. It is also recommended to validate the simulation through practical experiments and prove the optimal orientation (tilt and azimuth angle) of the photovoltaic panels that maximizes the radiation in the solar tree.

3.4 Constructive characteristics

During the research, it was observed that some authors decided to design full-size solar trees while others built prototypes on a small scale.

Deep, Mishra and Agarwal [15] built a full-size tree in New Delhi, India (latitude 28° N). They used a metal frame and five 1 kWp crystalline silicon panels, totaling 5 kWp. Each panel was 1.65×1.00 m.

Shanmukhi et al. [19] and Dey and Pesala [18] simulated real-scale solar trees with a power of 3 kWp and heights ranging from 4 to 5 meters.

The solar tree developed by [26], in Medellín, Colombia (latitude 6.217° N), was 3.5 m high, with four acrylic leaves that supported the four photovoltaic panels, as shown in Figure 5. Each panel was 54×83.2 cm and 50 Wp. The tree trunk was made of bamboo and the tree base, an octagonal bench of steel and wood, was built to support the structure.

Kishore et al. [24] installed two full-size solar trees (Fig. 6) with five panels each, at the Central Electronics Engineering Research Institute (CEERI) in Pilani, India (latitude 28.37° N). They were designed to maximize average energy generation over the year. They made it possible to power the local server, the LED lighting at the entrance of the institution and the sensors connected to the solar tree that monitor the energy generation and air quality.

Rodrigues et al. [22] projected a 1.5 kWp solar tree (Fig. 7a) in the state of São Paulo, Brazil (latitude 23.5° S) and built a prototype (Fig. 7b) named G.I.N.O® (Interactive Oriented Navigation Branch) in a 1:10 scale. During the experiment, on rainy days, the authors observed increased instability of the G.I.N.O® to capture energy, when compared to a plane photovoltaic system. However, the authors noticed that, even so, the generation efficiency of the G.I.N.O® was higher.

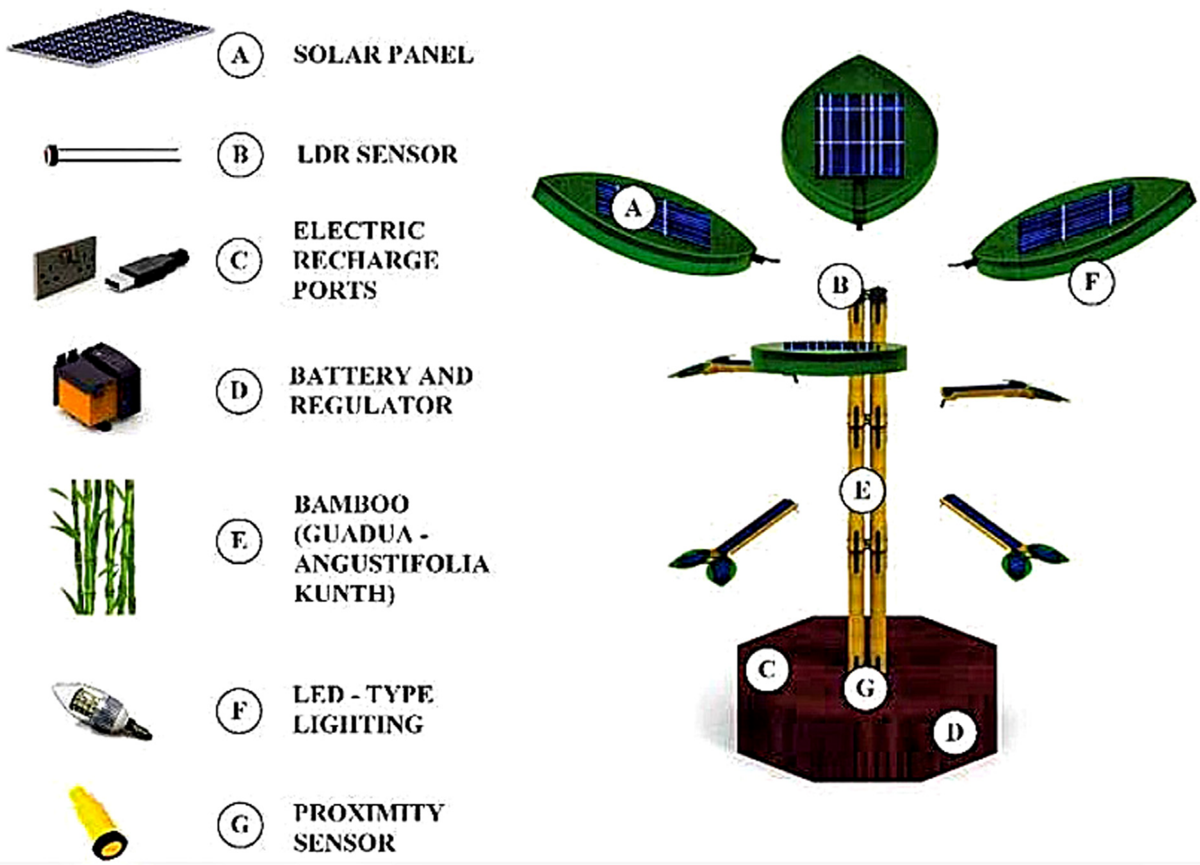

Fig. 5. Solar tree design with a bamboo trunk. Source: [26].

Patil and Madiwal [13] built a prototype (Fig. 8) in Kolhapur, India (latitude 16.76° N). The lower part of the trunk was fixed, while the upper part was mobile, which allowed its position to be regulated. The photovoltaic panels, of 50Wp each, were placed on supports fixed to the upper section of the trunk. With this system, the panels could be manually oriented to an angle equal to the local latitude or any other necessary (winter and summer correction) to obtain the maximum solar radiation for a given period.

Gangwar et al. [21] made two distinct solar trees with 3 Wp photovoltaic panels and dimensions of 185 × 185 mm, in Pantnagar, India (latitude 29.02°N). The first had a 1.84 m high PVC trunk, with eight photovoltaic panels attached to it through aluminum branches (Fig. 9a). The second tree also had a PVC trunk, but it was 1.37 m high and had only six photovoltaic panels (Fig. 9b).

Also in Pantnagar, India, Singh, Rawat and Srivastava [20] built a prototype with a 1.52 m high PVC trunk and six 3 Wp photovoltaic panels with dimensions of 200 × 200 mm each, very similar to the second tree by [21], as shown in Figure 10.

In the last two works cited, a system with fixed panels was built for comparison. This conventional system consisted of six panels equal to those used in those solar trees. These panels were fixed at an inclination equal to the local latitude and oriented to the south (Fig. 10).

Both studies concluded that, when compared to the conventional system, the solar trees obtained higher values

Fig. 6. Solar trees in CEERI, India. Source: [24].

(a) (b)

Fig. 7. (a) Projected G.I.N.O® model, (b) Prototype built. Source: [22].

Fig. 8. Solar tree prototype. Source: [13].

of average energy generated per panel. It should be noted that installing PV generators with an inclination equal to latitude is not always ideal. In addition, this tilt angle equal to latitude can be ideal considering an annual optimization. In these studies, measurements were carried out on just a few days of the year, so they have limitations of data to allow general conclusions.

Dey, Lakshmanan and Pesala [16] developed a 12×12 cm small-scale solar tree model (Fig. 11) for the city of Paris (latitude 48.82° N). Five 15 cm^2 solar cells were used. The cells were made of monocrystalline silicon and had an efficiency of 12%, positioned according to the optimized orientations through the multi-objective simulation mentioned above. A 3D printer was used to manufacture the tree structure.

Karmakar, Mallipeddi and Protiq [31] designed a solar tree using a 1.22 m aluminum pipe as the trunk. The project consisted of three photovoltaic panels measuring 12.5×9.8 cm each. One panel was fixed horizontally above the others. The other two mobile panels were placed on the opposite sides, with the help of two rods (branches) of approximately 30 cm each, thus forming an axis of symmetry in the solar tree (Fig. 12).

Finally, Oluwafemi, Laseinde and Salau [32] designed their project with a solar tree. However, they built only one 100 Wp monocrystalline silicon panel supported by a metallic structure (Fig. 13). The panel was arranged to move freely and follow the movement of the sun, like a sunflower.

The analyzed works used different materials to build the structures of the solar trees. For full-size constructions, metallic material was predominant, except for one model, which used bamboo, due to its economic, environmental and physicochemical characteristics.

Regarding the installed power, 18 Wp to 5 kWp trees were built ranging from 1 to 12 photovoltaic cells/panels. Since all the studied solar trees in the literature did not have more than 12 leaves, may represent an indication that those trees presented were not optimized regarding the generation of electrical energy per total area used. It was observed that the greater the number of panels, the greater the degrees of freedom and, therefore, the greater the

Fig. 9. Solar tree (a) with 8 solar panels; (b) with 6 solar panels. Source: [21].

Fig. 10. Solar tree and traditional system with fixed inclination, both with 6 solar panels. Source: [20].

flexibility to adjust the energy generation curve. However, it must be pointed out that the greater the number of panels, the greater the chances of shading losses.

Nevertheless, it was difficult to directly compare the works analyzed, due to the lack of data in the description of the construction of solar trees, such as height, distance among panels, quantity, power of the photovoltaic panels, location and test conditions. In addition, not all works specified the constructive/technological characteristics of the panels nor their efficiencies under different operation conditions.

Fig. 11. Small-scale solar tree. Source: [16].

It is advisable for future prototypes of photovoltaic solar trees to use trunk and branches diameters as smaller as possible, to generate less shading, and trunk and branches surfaces with high reflectivity. It is also suggested

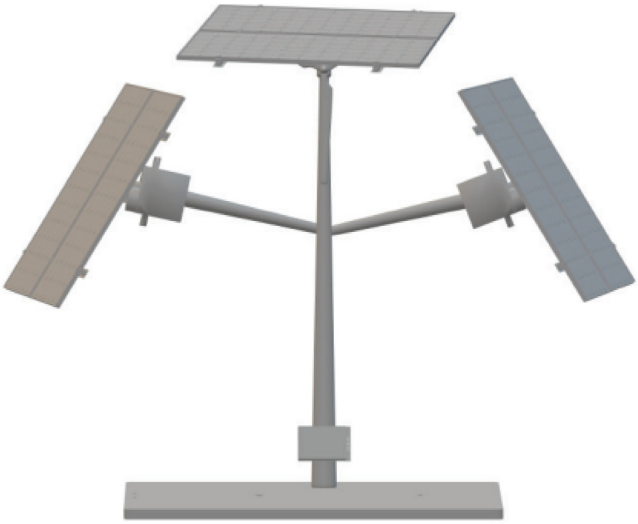

Fig. 12. Solar tree prototype. Source: [31].

Fig. 13. Solar Tree with a single panel. Source: [32].

the optimization of the number of PV cells/panels to study the relationship between generation and/or total efficiency based on the number of panels.

It is important to point out that some of the solar tree models used solar panels as leaves oriented as the conventional system, that is with inclination as the local latitude and toward the south (when located in the north hemisphere). So, the developers of those solar trees did not optimize the set of leaves for a given period, but rather treated the whole set of leaves as an individual leaf that will be positioned to optimize the solar radiation.

Thus, in many of those models of solar trees the leaves were positioned in different heights but with inclination and azimuth of the conventional solar system is usually installed. In those cases, the position of the leaves could be useful in cases with abundance of area, and the need to multiple use of the solar tree as for example: Energy generation and Parking space. It seems then that optimization of the inclination and azimuth of leaves should be further studied.

3.5 Solar tracking

In the studies from [22–32], solar tracking systems were used to position the photovoltaic panels and ensure that they were exposed to maximum solar radiation.

For solar tracking, [32] used two Light Dependent Resistor (LDR) light sensors, one at each end of the panel, which sent the measured signals to an Arduino microprocessor. Through a tracking algorithm, it determined the maximum solar radiation and corrected the position of the modules. The solar panels were moved by a motor controlled by an actuator, which represented one degree of freedom (Fig. 13).

Rodrigues et al. [22] built their prototype as shown in Figure 6 and assigned a reorientation system to each set of three photovoltaic cells. The solar tracking movement was performed through three servomotors connected to each cell, which positioned the cell according to the LDR sensor readings. These sensors were placed at the extreme positions of each photovoltaic cell. With this prototype, [22] obtained significant gains, namely, around 21% more efficiency in capturing energy than plane system prototypes, for a location with 23.5°S latitude.

Karmakar, Mallipeddi and Protiq [31] also used LDR sensors for solar tracking. Two LDR's were used for each mobile panel arranged on the sides of the solar tree (Fig. 12). The microcontroller processed the data received by the sensors and generated signals to drive the two servomotors, each arranged on one branch. The authors concluded that the solar tree with solar tracking was 15% more efficient than the same tree without solar tracking and fixed panels.

The studies above did not mention the energy consumed by the servomotors to move the axes, nor did they report the need for periodic maintenance in the tracking system. However, it is known that part of the energy generated is necessary to power the equipment used in this type of system and that more frequent maintenance becomes essential. Thus, an improved assessment is suggested to verify whether the implementation of a solar tracking system on a solar tree is technically and economically feasible. Therefore, maintenance is considered to be a major issue in the tracking system.

3.6 Occupied area

Several works aim to use solar trees to reduce the occupied area to obtain an equivalent or greater amount of energy generation than a photovoltaic system with horizontally arranged panels.

According to [33], traditional photovoltaic system plants require a large unshaded open space. However, the scarcity of these lands can be a serious problem in big cities. Renugadevi [34] emphasizes that land has become a very expensive asset for society due to high population growth.

Hyder, Sudhakar and Mamat [14] noted that, although installing these systems on roofs has become an attractive option, roofs may have limited space to allocate the modules. Thus, Renugadevi [34] observed that the solar tree is an attractive alternative for energy generation since it generally requires less space than the traditional photovoltaic system.

Some authors consider that the space required for the installation of a photovoltaic solar tree is only the area for a trunk base, without considering the area of the solar panels [14]. This is explained by the fact that, despite occupying a projected area larger than the base alone, in some cases, the land below the solar tree panels can have an alternative use. The discussion about the multiple use of the area of the solar tree is presented in the next section.

Thus, [14,34] reported that, to generate the same amount of energy as a traditional photovoltaic system, a considerably smaller area (about 1%) is needed to install a solar tree.

Also considering the trunk's base area as an occupied area of the solar tree, Rodrigues et al. [22] concluded that the solar tree proposed in their research reduced the occupied area by 86.9%. Deep, Mishra and Agarwal [15] stated that the total area occupied by the traditional photovoltaic system was 99.14% greater than the area required for the solar tree.

Other authors, including [16], considered not only the base area. Instead, they determined the projected area of the entire solar tree, including the panels. They concluded that the area occupied by the tree was about 2.7 times greater than the area occupied by panels with an inclination equal to the latitude. This was observed because the paper goal was not to optimize the number of "leaves/panels" in the solar tree. However, the authors emphasized that the ground space was not fully occupied and could be used for other purposes.

It is believed that, if optimized, photovoltaic trees could generate more than a plane photovoltaic system with the same projected area. However, the cost of a solar tree can be higher due to the greater number of panels and the structure employed.

Also, although the area below the panels can be used for other purposes, considering only the area at the base of the trunk to specify the area occupied by the solar tree can be a mistake. For example, it would be complex to install two trees next to each other, considering only the area at the base of the trunk, without causing the conflict in the use of space of leaves/panels. It is recommended to use the projected area of the panels on the ground or even use the length of the largest branch as the radius of a circle and calculate the area needed to install the tree. In addition, the ideal distance between trees should be studied to minimize the chances of the shading of one tree over another.

3.7 Multiple uses

Finally, the multiple uses of the space under the solar trees were reviewed, considering the photovoltaic energy generation and other goals. The space under the solar tree panels can be used for various purposes, such as crop production, leisure and shaded parking lots. It is also possible to install panels in lakes and reservoirs, as a floating plant, which helps to decrease evaporation and allows for multiple uses of the site.

Combining crop production and electricity generation through photovoltaic technology is called an agrivoltaic system [35]. These systems may consist of photovoltaic panels positioned at a certain height above the ground and arranged at specific intervals. The distance between panels is designed to allow sunlight to reach the crop, which is essential for photosynthesis. At the same time, the crop will help cool down the panel temperature, thus improving the energy conversion efficiency [36].

Some studies report that these agrivoltaic systems are effective for shade-tolerant crops, such as sweet potatoes, kale and yam [37]. However, Sekiyama and Nagashima [36] concluded that increased crop yield could be achieved even with crops that require much sunlight, such as corn. Therefore, the need for shading depends on many factors, such as climate and culture. Thus, specific studies must be carried out to indicate the amount of shade required.

Solar trees can also be installed in outdoor parking lots. Figueiredo [38] explains that, in addition to providing shading for vehicles by replacing traditional roofs, photovoltaic systems could generate energy to charge bicycles and electric cars, and the excess could be used to power the parking facilities, such as night lighting, among others.

The installation of floating photovoltaic power plants in lakes and reservoirs can also configure multiple uses. A floating photovoltaic plant installed in a hydroelectric dam can complement hydroelectric generation in dry periods, besides improving energy quality [39]. This type of floating installation provides some benefits, such as (i) natural cooling of the panels, which reduces their temperature and, consequently, increases the efficiency of the system; (ii) reduced need of cleaning, since they are installed in an environment with low levels of dust; (iii) reduced evaporation due to panel shading; (iv) exploration of water surface and spared land area that can be used for other purposes [40].

According to Syafriyudin [33], in addition to the area requirements, solar photovoltaic technology faces obstacles related to public perception due to aesthetics. Thus, the solar tree concept would be able to minimize effectively this problem by providing an architectural structure somehow similar to a natural tree.

Thus, studies on positive and negative externalities of solar photovoltaic trees should be carried out, in a context of multiple uses of area, for assessments that integrate aspects such as environment, aesthetics, PV system efficiency and economy, among others.

Finally, it should be noted that some critical points must be studied for a better understanding and application in this field of solar energy. Analyzes for the effect of shading on the performance of the photovoltaic system, as in the works [41,42], add knowledge and help in the development of more efficient systems. In addition, the study of the effects of different weather conditions on the reliability analysis of PV inverters, as in [43] are also relevant.

4 Conclusion

The strategy of arranging solar panels in the shape of a tree has proved to be an interesting alternative for the generation of photovoltaic solar energy when restrictions are mainly due to the scarcity of area rather than the cost of the system. A solar tree allows for the reduction of the area demanded for the installation of solar panels and the maximization of the incident radiation received, consequently increasing the generation of electricity. However, the design parameters must be carefully analyzed to obtain an efficient solar tree.

It was found that several studies have reproduced the topologies of natural trees in solar trees to increase the efficiency of the conversion of solar radiation into electrical energy. The alternate or spiral topology was the tree phyllotaxies most used among the analyzed designs, similarly to that observed in nature. Besides, it was noticed that the Fibonacci sequence pattern, which is very common in nature, was used in most cases reviewed to determine the angular distance between the leaves/solar panels. However, it has not been proven that this is the most efficient pattern to generate electrical energy.

It was observed that optimizing the orientation of solar panels, in respect to the inclination and azimuth angles, is essential to increase the efficiency of photovoltaic systems. This optimization can be achieved through modeling and simulating photovoltaic systems, treating each solar tree as a whole, which means that a given solar panel/leaf should not be optimized separately. Some key design parameters related to location, such as local latitude and altitude, should be considered, as well as those that change throughout the year, such as incidence angle, zenith angle and clearness index.

The analyzed research works developed solar trees with different characteristics, ranging from 1 to 12 solar panels, and installed power ranging between 18 Wp and 5 kWp. It was found that the greater the number of solar panels, the bigger the degrees of freedom and, therefore, the greater the flexibility to adjust the energy generation curve. However, it was highlighted that the chances of losses due to shading can increase as the number of solar panels increase, which reveals the need for the optimization studies.

Although some solar tree designs occupy more space than a conventional installation, most designs manage to reduce the occupied area by rearranging the positioning of the panels. This allows for the maximization of the generation of electricity per area.

It was also noted that there might be multiple uses for the location where the solar tree is installed. It happens when the land below the solar panels is used for other purposes, such as crop production, leisure, floating plants and shaded parking lots.

Finally, it is still necessary to further be investigated: (i) systematic studies encompassing product development modeling, simulation and validation of prototypes; (ii) electricity generation analysis as a function of geometric and electrical parameters of trees, season of the year, control and automation, photovoltaic generation technologies used and solar PV tree location; and (iii) comparison of solar tree topologies.

Implications and influences

Much scientific research on photovoltaic solar trees mainly addresses issues related to the concepts of artistic expression and environmental awareness, and few are focused on design and construction parameters, aiming to maximize the generation of electricity per occupied area. Thus, the contribution of this research is to present, in a revised way, relevant parameters to be analyzed during the development and design of a photovoltaic solar tree, such as: modeling and simulation, topology, orientation of photovoltaic generators, constructive characteristics, tracking, occupied area and multiple use.

List of abbreviations and variables

GHG	Greenhouse gas
LDR	Light dependent resistor
MPPT	Maximum Power Point Trackers
PV	Photovoltaic
d_{ang}	Angular distance between subsequent leaves, °
E	Annual incident energy for a surface with orientation (β,γ), Wh/year
E_l	Energy loss by shading, Wh
F	Fibonacci sequence, dimensionless
I	Hourly incident solar radiation, W/m^2
I_b	Hourly direct solar radiation on a horizontal surface, W/m^2
I_d	Hourly diffuse solar radiation on a horizontal surface, W/m^2
n_t	Number of turns needed until the next leaf overlaps the first, dimensionless
n_l	Number of leaves per turn, dimensionless
β	Tilt angle, °
β_{opt}	Optimal tilt angle, °
γ	Azimuth angle, °
γ_{opt}	Optimal azimuth angle, °
θ_i	angle of incidence, °
$\theta_{z\text{-}}$	zenith angle, °

Acknowledgements. The authors are very grateful to the Department of Agricultural Engineering and its Graduate Program in Agricultural Engineering of the Federal University of Viçosa. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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Cite this article as: Leandro Gonçalves de Bem, Delly Oliveira Filho, Hewlley Maria Acioli Imbuzeiro, João Victor Pereira Oliveira, Sérgio Yoshimitsu Motoike, Vinícius Maciel da Costa, David Lelis Filho, Solar photovoltaic tree multi aspects analysis – a review, Renew. Energy Environ. Sustain. **7**, 26 (2022)