



Review article

Significance of solar trees: Configuration, operation, types and technology commercialization

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ABSTRACT

Developing energy efficiencies solutions from sunlight to electricity is a crucial solution for the world's energy shortage and reducing greenhouse gas emissions. However, the typical photovoltaic (PV) flat module has a poor sunlight energy collection capability without a solar tracking system. Despite its advantages, solar PV technology has difficulties with land demand, capturing effectiveness and public image, especially in metropolitan areas due to the lack of pleasant aesthetics. This article presents an overview about the recently modified solar tree technology that can address these challenges efficiently. The main technology configurations, operational aspects and types are deeply presented and discussed. Many innovations and technologies of solar trees are analyzed and several commercial prototypes are discussed. Moreover, the main challenges and limitations that restrict the technology commercialization also highlighted in comparison with the traditional PV systems along with some remarks for future incomers. Analyzed studies show that solar tree technology is a good energy conversion method as it need only 1% land compared with traditional PV systems to produce power as more as 10%. Besides, this technology could efficiently collect off-peak sunshine and reflect light, and thus, create greater solar fraction.

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Nomenclature

Abbreviations

DNI	Direct normal irradiance (W/m ²)
DNI _h	Direct irradiance on horizontal (W/m ²)
DHI	Diffuse horizontal Irradiance (W/m ²)
GHI	Global horizontal irradiance (W/m ²)
MBSS	Multi-branch single stem
FPST	Fibonacci pattern solar tree
SPST	Spiraling phyllotaxy solar tree
HDST	Hemispherical dome solar tree
TDGD	Three-dimensional geometric design
RLST	Ross Lovegrove solar tree
TPVD	Three photovoltaic design
MPPT	Maximum power point tracking
PV	Photovoltaic
PSO	Particle swarm optimization

Greek letters

$E(\beta, \gamma)$	Annual incident energy on tilt surface (kWh/m ²)
I_b	Hourly beam irradiance on horizontal surface (W/m ²)
$I(\beta, \gamma)$	Hourly global irradiance on tilted surface (W/m ²)
A_h	Area of panel shadowed at time h
η_e	Electrical efficiency of solar panel
θ_i	Angle of incidence
θ_z	Zenith angle
γ	Surface azimuth angle
β	Surface tilt angle

1. Introduction

The quest for sustainable and clean energy sources has become one of the greatest challenges recently because of the rapid loss of conventional fossil fuels, climate change, global warming, and the ever-rising energy demand (Hyder et al., 2018b; Almadhhachi and Seres, 2020). Renewable energy is relatively cheaper, more affordable, and more environmentally friendly than fossil fuel oil (Almadhhachi et al., 2020). Renewable energy is commonly defined

as energy from sunshine, wind, rain, oceans, waves, and geothermal heat, continuously replenished on a human time scale (Awdic et al., 2013; Kim and Kim, 2015). Renewable energy markets have been grown worldwide steadily due to strengthened international legislation, as recommended in the Convention on Climate Change (Bantikatlal et al., 2019). Moreover, countries have been invested massively in renewable energy field. This phenomenon is attributed to two significant factors (Nwaigwe et al., 2019; Al-Rousan et al., 2021). First, initial attempts to establish renewable energy sources have concentrated on global environmental issues; however, in the last few years, each countries have attempted to enhance their energy stability and achieve sustainable economic development through renewable energy (Kim and Kim, 2015). Second, to reduce greenhouse gas emissions and global warming, which leads to temperature rising, seawater rising level, and risks of heatwave (Al-Yasiri and Géczi, 2021; Al-Yasiri et al., 2022). The energy intercepted by the earth from the sun is approximately 1.8×10^{11} MW, which is several times higher than the actual energy consumption rate (Solar, 2018). There are two main types of technology to accumulate solar energy: First, solar thermal is a viable option for generating energy, processing chemicals, providing space heating and cooling for buildings, Food, non-metallic, textile, chemical, and even business-related industries can all benefit from it. Second, photovoltaics (PV) are widely used to power lights, pumps, engines, fans, refrigerators, and water heaters in the telecommunications, agricultural, water desalination, and construction industries (Awdic et al., 2013; Mekhilef et al., 2011). One of the easiest ways to harvest solar power is employing PV technology (Parida et al., 2011; Ishaq and Ibrahim, 2013). Photovoltaic (PV) systems, which convert the sun's useful power from DC to AC, drive this transformation (Nwaigwe et al., 2019; Lingayat et al., 2020). Fig. 1 shows the rapid development and growth of solar PV technology worldwide, which gives researchers a motivation to make a greater effort to overcome obstacles, study challenges and find solutions to obtain the largest possible amount of energy and with a relatively higher efficiency.

PV modules can be manufactured in many different technologies, and also the varied PV modules types have different spectrum reactions, temperature coefficients, voltage, and current values, as well as different reactions to environmental elements such as radiation, temperature, wind speed, and different efficiencies between 11%–21% (Elibol et al., 2017; Jordehi, 2016). the temperature effect on the solar PV module efficiency inversely after 25 °C (Alshawaf et al., 2020). It is possible that an efficient Solar PV plant with a high number of small-sized polycrystalline modules might be more energy efficient than a plant with larger-sized glass modules (Dhaundiyal and Atsu, 2021). a parabolic

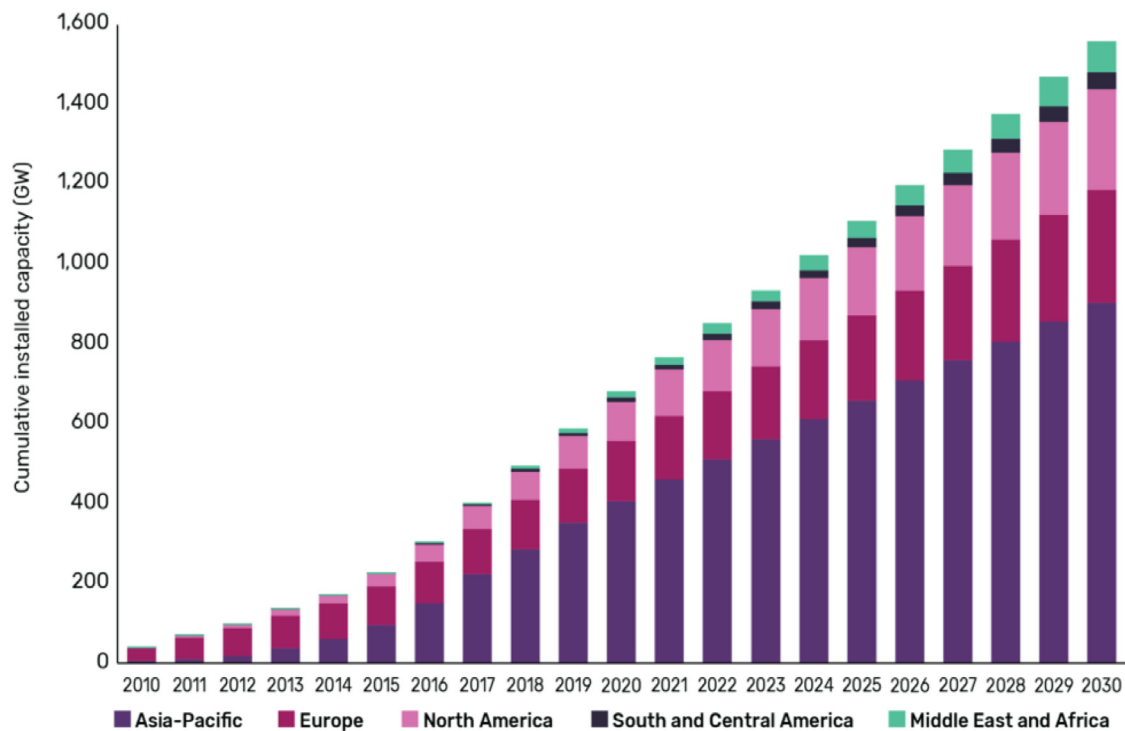


Fig. 1. Global solar photovoltaic capacity expected (2010–2030) (Ldata, 2019).

bifacial photovoltaic one of the method to reduce the temperature and keep the efficiency of the solar cells (El Majid et al., 2019). The direction of the PV module plays a vital role in PV technology efficiency. To gather the most power, the solar module should be perpendicular to the direct incident sunlight (Abdollahpour et al., 2018). Several techniques have been adopted to reach this goal. Among others, the solar tracking system has been applied to improve the overall system efficiency tracking the sun ray using special controlled mechanism (El Hammoumi et al., 2018). It has been reported that up to 84% enhancement in the PV system could be achieved with solar tracking system (Alktrane et al., 2020). Due to the presence of spinning components, PV systems integrated tracking method have more complicated control and design mechanisms (Awasthi et al., 2020).

PV technology lacks aesthetic due to the black or blue color of PV module; on the other hand, needs a large flat area to install the solar system (Pemula, 2017). Solar trees combine an integrative process between technical effort and modern technology to create an advanced form that produces electricity from solar energy, and the amount of shade provided by trees can have a considerable impact on human thermal comfort (de Abreu-Harbach et al., 2015). Researchers and inventors have been racing to create new artistic forms for several years to achieve utility from solar cell technology (Cao et al., 2014; Torgal, 2016). Due to its direct conversion of sunlight into electricity, ease of use, and clean energy generation, solar tree systems are seen as a viable source of energy (Hyder et al., 2018a; Kumar et al., 2021). When compared to flat solar PV, solar tree structures employ 1% of the land surface and boost efficiency by 10% to 15% by providing variable height and unique design (Gangwar et al., 2021b; Gupta, 2021). Solar tree designs are unique, and they are made to help people in a variety of urban and natural settings, it can be produce more than 10% electrical power compared with traditional PV system (Baci et al., 2020; Rajae and Jalali, 2021).

This article consists of several sections dealing with solar tree technology's main aspects. Section 1 gives a general overview of the technology and its historical progress from the PV technologies with the main benefits and drawbacks. Section 2 presents the

concept and main components of solar trees. Section 3 deals with the popular solar tree configurations that universally exist. Section 4 presents the main operating parameters and cost aspects that influence the technology's performance. Section 5 shows the importance of the solar tree compared with the traditional PV systems in terms of several operational and economic considerations necessary for technology commercialization. Section 6 sheds light on some limitations and recommendations for future incomers proposed along with several conclusions derived from the reviewed studies included in the last section.

2. Overview of solar tree technology

Solar trees are a decorative (or antiquated) means for producing renewable electricity; most often, solar trees embody a steel structure (Berny et al., 2015). The modules are arranged in layers or in symmetrical or random shapes to absorb the enormous amount of solar PV energy to generate electricity. Given that PV modules are set at different angles, a solar PV tree can capture sunlight throughout the day regardless of the sun's position. One of the most important components of solar tree is to enhance the total surface area of sunlight absorption through a three-dimensional (3D) structure compared with the traditional PV units of solar cells (Bernardi et al., 2012).

2.1. Concept of solar tree

The concept of “solar PV tree” is an advanced blend of modern technology and art to form a solar PV sculpture (Hyder et al., 2018c; Renugadevi, 2017). This idea uses solar energy and adds aesthetics to cities with an environmentally friendly technological nature (Jain and Verma, 2021). Sheds under solar trees can be used as public seats in gardens and parks or as good areas to benefit from agriculture. Many types of solar tree are designed based on optimal energy feasibility. Tree stands for tree generating renewable energy and electricity (Avdic et al., 2013; Shanmukhi et al., 2019).

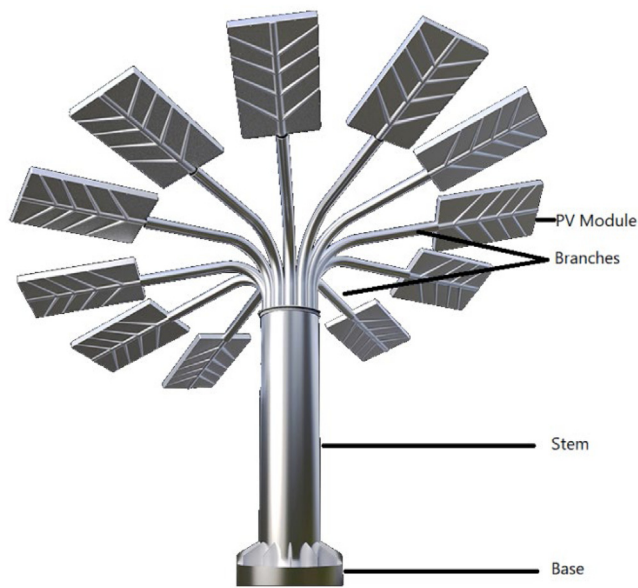


Fig. 2. Layout of hybrid solar tree.

The final initiation of the idea of solar trees boosts the public understanding of solar PV technology by making it aesthetically appealing. The goals of the concept of a solar tree are:

1. Increase the awareness of civilians in the use of renewable energy and solar energy;
2. Increase the number of trees in residential cities, which affects civilians' comfort;
3. Increase the efficiency of solar modules as possible;
4. Add aesthetics to municipalities to build environmentally friendly forms; and
5. Create a new structure for the surrounding fences for service and entertainment projects, such as parks and gardens.

2.2. Components of a solar tree

Fig. 2 depicts the components and overall arrangement of a solar tree. Solar trees are solar-powered structures that mimic the appearance of a real tree (Balaji et al., 2020). The state-of-the-art consists of a steel frame with solar modules installed on top to capture sunlight and turn it into usable electricity. Solar trees are used to charge cell phones, computers, small appliances, and street lights attached or built into the structure (et al., 2018). They are intended to solve the large land requirements of solar modules, raise public consciousness about green and clean energies, and improve the performance of solar modules in urban areas.

2.2.1. PV modules

Solar modules are an essential part of solar trees because they convert solar energy into electric current energy. PV cells are energy-harvesting technologies that transform solar power through PV effects into convenient energy (Awan et al., 2020). These solar cells consist of two distinct types of semiconductors, as shown in Fig. 3.

Solar cell has many types, and each type has its advantages, efficiency, cost, and applications. The overall performance of silicon solar cells for domestic and industrial use is 92% for total worldwide silicon solar modules (Kim et al., 2021). The efficiency of flexible modules can reach 24% (Asaduzzaman et al., 2016; Zomer et al., 2020).

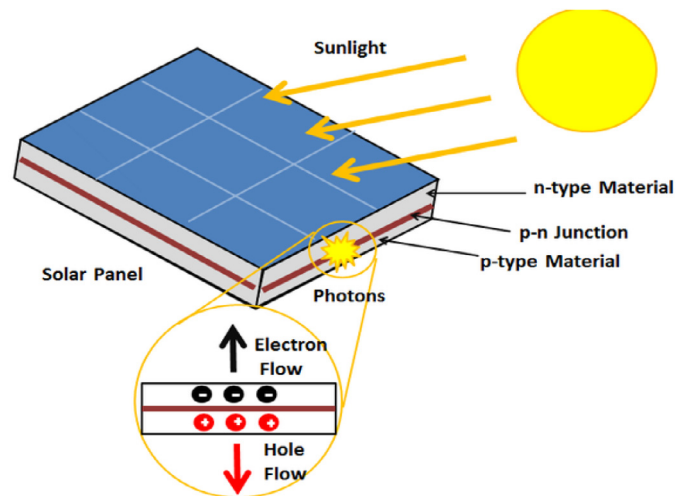


Fig. 3. Work mechanism of PVs.

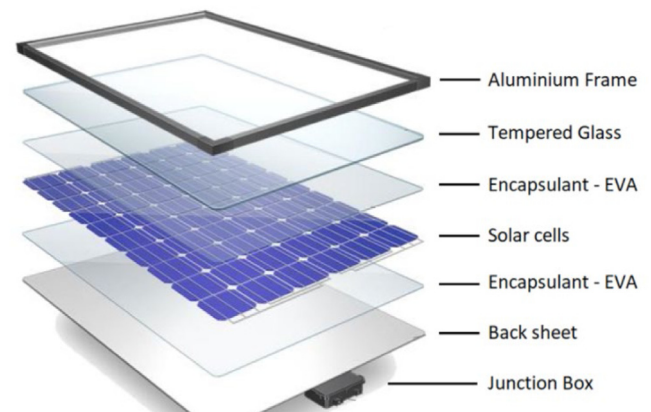


Fig. 4. Main components of a solar module (Svarc, 2020).

“Vertically integrated”, solar panel producers are well known; it implies that one business supplies and manufactures all the essential elements, including silicone ingots, and wafers for solar cells. However, numerous panel makers assemble solar panels, including cells, polymer back sheets, and EVA enclosures, by utilizing external sources. These producers can choose the components but cannot always control product quality. Thus, they should make sure that they choose the best possible suppliers (Of and Bond, 2015). Fig. 4 shows the six primary components of a solar module.

2.2.2. Batteries

Batteries are one of the most costly elements (Hassan et al., 2021), and an essential part of solar energy systems. They are among the oldest technologies that have accompanied the discovery of electricity and continue to develop in terms of materials used in their manufacture, shape, design, and amount of energy capable of storing it. Deep-cycle batteries have been used for green and clean energy applications worldwide for decades. The back-to-the-box acid, lithium-ion battery, lithium polymer battery, and nickel-cadmium batteries are some of the most commonly used batteries in PV applications. Lithium-ion batteries are comparable with energy storage costs (Zubi et al., 2020; Prakash et al., 2020).

2.2.3. Inverters

Smart inverters are power electronic instruments with advanced features in external software that control the inverter's behavior as connected to the grid (Rangarajan et al., 2019). Inverters aim to convert the DC voltage produced by the solar modules into the AC voltage's grid frequency. The most critical aspect of an inverter is its conversion quality. Current devices can run via an inverter with a performance of about 98% (Hyder et al., 2018c). Other essential activities of the inverter are power optimization (i.e., maximum power point tracking (MPPT)), control of the PV plant's energy yield, and protection of the plant by disconnecting it from the grid in the event of faults. Each panel receives a different irradiance in a solar tree to have different I-V and PV curves. Thus, the voltage fixed by the inverter will result in significant conversion losses. A battery can store energy and provide constant power to an inverter to prevent this problem.

2.2.4. Cables and connections

Atmospheric conditions such as precipitation, snow formation, solar irradiation, and high temperatures are subject to PV modules. Cables of outstanding mechanical strength are necessary to provide stable connections between the modules for use in environments with high mechanical stress, dry and wet weather, elevated temperature conditions, and high solar insolation. Losses due to connections and cables in small solar PV systems can be represented by 1% (Ekici and Kopru, 2017).

2.2.5. Frame structure

The metal structure is subject to the innovator, how it can branch or what height it reaches, and the trees' dimensions. All these details are subject to the innovator of the solar tree. Solar trees differ from one design to another and according to the applications. The external structure must be strong enough to preserve the tree at different weather conditions such as the case of wind load, which plays a vital role in the design calculations of the tree structure. In this regard, solar trees may overturn in high winds due to great strength on the tree, not to mention that the aesthetics of the external structure should not be ignored (Oluwafemi et al., 2019). The type of metal structure is one of the costly parts. Studies have used reinforced plastic to reduce the costs of constructing the solar tree structure (Shanmukhi et al., 2019). The design is optimized to minimize the weight and maximize the power generation on different components of the solar tree (i.e., trunk, base plates, middle flats, stalks, and gussets) (Srisai and Harnsoongnoen, 2019). The body weight significantly lowers by 40% by applying tree structure optimization. By leveraging genetic algorithms, a 20% structural mass reduction is achieved in a confined space (Dey and Pesala, 2020).

3. Configuration of solar trees

The types of designed trees are displayed spiraling phyllotaxy solar tree (SPST), Fibonacci pattern solar tree (FPST), single trunk with branches, and three-axis symmetric design. Modules on a natural tree are typical shapes, structures, and patterns of solar trees.

Researchers and designers have struggled to obtain beautiful engineering art forms since 1997, and the technology is promising (Tooby and Cosmides, 2001; Liu et al., 2015). Some companies produce various types of solar tree, which prove that solar trees have a commercial market in various parts of the world. Most of the trees mentioned in the research and markets are included in this study.

3.1. Multi-branch single stem (MBSS)

Fig. 5 shows a simple structure consisting of a long column; this column looks like a tree stem and branches emerging at different heights, carrying solar modules at different surface angles and orientations according to the areas in which these trees are applied (Dey and Pesala, 2020). MBSS is characterized by the design simplicity that is easy to develop, but it is considered one of the least efficient designs in capturing solar radiation throughout the daytime due to the orientation of the solar module with different lengths of tree branches (Hyder et al., 2018c).

3.2. Fibonacci pattern solar tree (FPST)

Fig. 6 shows the most popular solar tree nowadays, which captures sunlight with relatively high efficiency. This pattern helps direct the tree's leaves toward the sun to ensure that the most energy is absorbed (Singh et al., 2019). One of this tree's essential features is that it is borrowed from nature, as some likened it to an oak tree. It is considered a source of energy with a relatively constant amount (Aiden, 2011). One of this tree's determinants is the expensive seat structure that cannot be invested in large energy projects (Hyder et al., 2018c). FPST produces more energy compared with traditional PV modules (Gawad, 2021). In comparison to traditional solar panels, the 3/8 phyllotaxy-based solar tree provides 54% (approximate) more efficiency and 43% (approximate) more efficiency than the 2/5 phyllotaxy-based solar tree (Gangwar et al., 2021a).

3.3. Spiraling phyllotaxy solar tree (SPST)

Innovative from natural plants is the most widespread and forms a large complex umbrella, which helps them capture sunlight in an extensive and highly efficient manner (Gangwar et al., 2019b). The productivity of these solar trees is high and closely mimics nature (Kumar et al., 2019). As shown in Fig. 7, (SPST) is one of the trees that consumes considerable space for its leaves, is extremely expensive due to its iron structure, and is challenging to manufacture (Gangwar et al., 2019a; Deep et al., 2020).

3.4. Hemispherical dome solar tree (HDST)

One distinctive design covers daylight hour to capture the sun's rays with the best efficiency. It consists of modules that form a semi-spherical dome, as shown in Fig. 8. It is directed toward the sun to cover the sun path from morning to evening (Verma and Mazumder, 2014).

3.5. Three-dimensional geometric design (TDGD)

The type of design consists of a leg, as shown in Fig. 9. At the top of the summit, a solar panel is directed at a certain angle. Solar modules are distributed on the branches symmetrically and on both sides within specific inclination angles to enhance the capture of sunlight. It consists of three axes to form a 3D body, hence its name. It also takes less space for its papers. Its cost is relatively lower due to the ergonomic and minimalist design inside (Kumar et al., 2020).



Fig. 5. MBSS used for powering fuel station (Budapest, Hungary).



(a)



(b)

Fig. 6. FPST for low-scale electricity generation, (a) in India (Singh et al., 2019), (b) in USA (Aiden, 2011).

3.6. Ross Lovegrove solar tree (RLST)

RLST comprises beautiful architectural designs or industrial art consisting of PV with curves in circular groups, which capture sunlight and have a height of 5.5 m, 40-mm grass stems, 1 LED with approximately 1 W and protected by a diffuser screen, and 10 poles (76 mm in diameter) that support the body heads Fig. 10. The 10 headers, which include the PV cells at the top and support poles with a diameter of 76 mm (Fairs, 2007). RLST also has 20 energy LED lights powered by 500 mA and have a neutral white temperature, and at the bottom of the 4 of them is an aluminum spoiler (Bingham, 2012).

3.7. Simple solar tree

This type of solar tree is one of the most widespread types. It is similar to solar module surface systems, except that these modules are installed on steel structures and at an appropriate

height and a suitable slope to capture sunlight more efficiently, as shown in Fig. 11.

It is considered one of the most effortless engineering designs. It is always inhomogeneous, symmetrical, and perpendicular to sunlight to ensure that an enormous amount of energy is absorbed (Javaid, 2020).

The world's largest solar tree is shown in Fig. 12. It was built in India and produces roughly 11,500 W of electricity and developed by the Central Mechanical Engineering Research Institute in 2020; it has 35 solar PV modules with 330 W for each module (Nair, 2020)

3.8. Super trees

The gardening project in Gardens by the Bay looks like something out of science fiction or an image of future cities. Nevertheless, it is an actual Singapore landscaping project, with tree heights ranging from 25 m to 50 m, as shown in Fig. 13. The value of this sophisticated horticultural project is approximately US \$1



Fig. 7. SPST in Millennium square (Bristol, England) (Hjålm, 2015).

billion (Sheppard, 2013). Engineers have created ultra-modern designs that mimic actual tree structures and ecological functions through their environmentally friendly features. PV technology has been incorporated into its illusions to capture sunlight to produce electrical energy while illuminating at night (Prize et al., 2014). This project includes 18 gigantic trees that serve as vertical gardens, 11 of which have been integrated with PV cells to generate electrical energy; thus, it forms an industrial mechanical forest that represents a distinct tourist destination that displays natural plants in addition to environmentally friendly industrial plants (Perry, 2019). The tree consists of a steel trunk fixed with reinforced concrete on the ground. The planting modules are installed along the trunk for planting plants, and vertical gardens are formed; the end of the trunk is in the form of an upside downslope, which is 50 m high (Solaripedia, 2014).

3.9. Smart palm tree

The new city-sponsored convenience for visitors and beachgoers is a 6-m-tall solar-powered towers shaped like a palm tree. It will be a unique structure made with 3D printing technology Fig. 14, and it will be the largest of its type outdoors. Smart palms are powered by monocrystalline solar modules that provide up to 21% efficiency and generate sufficient power for daytime and nighttime functionality (O'Keefe, 2015). Smart palms are designed to serve as a functional public art that complements Dubai's iconic architecture and scenic beaches.

3.10. Three PV design (TPVD)

Fig. 15 shows that 3D shapes have proven higher efficiency than the average modules in harvesting sunlight and generating electricity significantly during the summer. These ratios may be higher in the winter season. This type provides large land areas, which is a valuable feature in cities (Bernardi et al., 2012).

4. Parameters influencing solar tree performance

The essential parameters that identify or distinguish solar trees according to previous studies are presented in this section.

4.1. Footprint

One of the main disadvantages of the solar PV system is that it occupies large areas of land (Deepak and Patil, 2018). In comparison, the improved MBSS requires only 1% of the land for the same energy produced from sunlight compared with surface PV systems (Prasad et al., 2018). FPST is one of the best facilities that reduce the utilized land area compared with the modules because it covers only 1% of land area for the same productive capacity (Singh et al., 2019). TDGD is becoming more common because it minimizes land use and provides various complimentary services to cover maintenance costs (Kumar et al., 2020). Fig. 16 shows the relationship between land areas needed for the PV systems and the power generated, in which the solar tree produces more power for the same area.

4.2. Solar tree design

Solar trees are designed in different shapes and dimensions, including regular geometric shapes (Nair, 2020; O'Keefe, 2015; Hirani, 2020), symmetric (Prasad et al., 2018; Chitra et al., 2019), and random (Svarc, 2020), as well as those run by mathematical functions under similar, irradiated conditions (Singh et al., 2019). A solar tree model based on a 3/8 phyllotaxy pattern produces more power than a solar tree model based on a 2/5 phyllotaxy pattern and a conventionally mounted solar panel (Gangwar et al., 2019b). Therefore, the direct normal irradiance (DNI) and diffused horizontal irradiance (DHI) (Svarc, 2020) must be calculated to find the solar tree's optimum design.

$$GHI = DHI + DNI \cos(\theta_z) \quad (1)$$

In TPVD, three shapes are modeled and simulated, and the features of each design have been studied. The amount of increase in the total energy of a cube, a tall cube, and a tower is 1.3–1.8, 3.5–5, and 2–20, respectively, compared with flat PV (Bernardi et al., 2012). Some investigators have improved the study of the structure with the simulation in MATLAB program, and the weight reduction is 40% of the original weight while preserving the tree's production (Shanmukhi et al., 2019).

4.3. Shadow loss

The solar tree has multiple solar module layers, which leads to shading of solar irradiation to another layer and loss efficiency. Many designers and researchers have been looking for a new structure to construct the branches and solar modules to prevent or decrease the shading of each other. The FPST pattern helps the tree leaves avoid misleading the production from each other and being resistant to difficult weather conditions, such as snow (Rawat et al., 2017). The tree is designed to have the most significant capture of sunlight, and the shaded area is the minimum in solar trees. Thus, it can be installed in agricultural farms to replace diesel with running pumps and electronic tractors (Javaid, 2020). Genetic algorithms have been used to improve the position of the solar modules of the MBSS to reduce the shade losses and the expected ground area. The branch's length is less in the solar tree, which reduces the structure's cost and obtains the optimal balance. It only has 0.17% annual decay loss and 1.67 natural footprint area (Dey and Pesala, 2020). The energy lost due to the shadow effect can be calculated by Eq. (2) (Dey et al., 2018).

$$E_l = \sum_{h=7 \text{ a.m.}}^{5 \text{ p.m.}} I_b(\beta, \gamma) * \eta_e * A_h \quad (2)$$

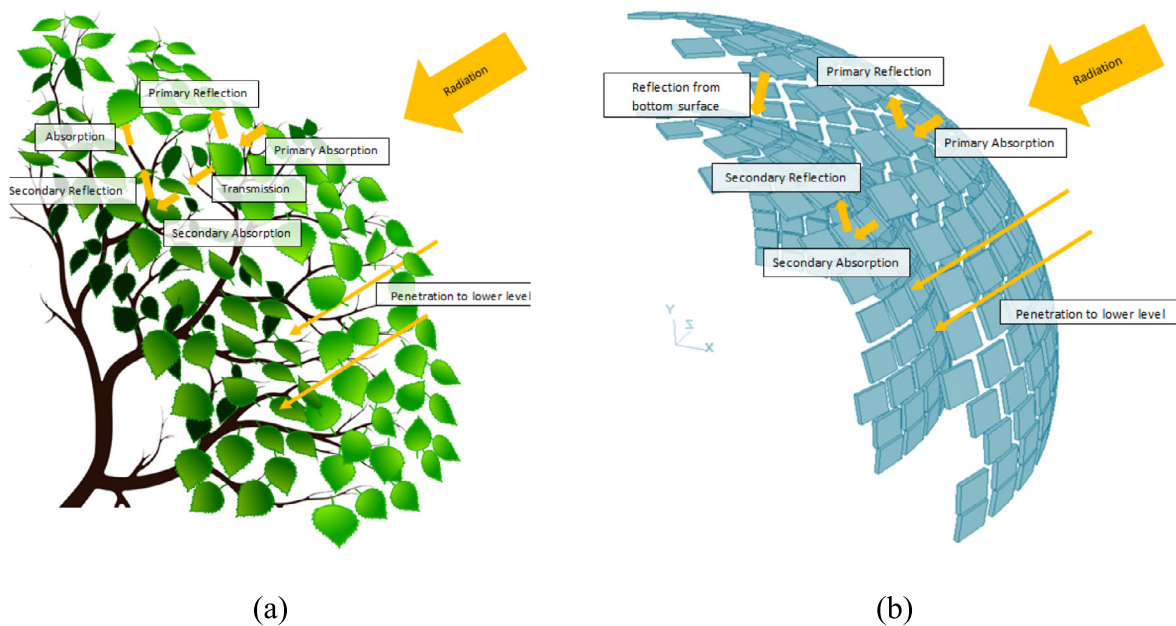


Fig. 8. HDST configuration (Verma and Mazumder, 2014), (a) Tree shape, (b) Simulated shape.



Fig. 9. Photo of TDGD.

4.4. Solar tree structure

Architects have been racing in creativity, especially concerning sustainable energy issues. Innovations have no limits. Solar modules need strong bases to bear the weight of the modules and resist the elements of nature. Most trees contain stems, branches, and leaves; and steel is used as the primary material due to its high mechanical characteristics (Muminovic et al., 2013a). Instead of steel, topped with nine leaf-shaped PV modules, the current smart palm tree is made of fiber-reinforced plastic, making it lighter and sturdier than previous prototypes. In addition, UV and humidity protection have been added to minimize maintenance (O'Keefe, 2015).

4.5. Efficiency

The efficiency of solar trees depends on many factors, such as the quality of the modules used, the incidence angle of solar irradiation, and the ratio of shadows on the panels to each other. Researchers have not mentioned the efficiency of solar trees due to the factors mentioned. According to technical analysis, a simple solar tree design is more efficient than others, as a single layer of PV modules faces the sun.

4.6. Maximum power tracking

One of the main differences between the traditional PV system and solar PV tree technology is receiving a different amount of

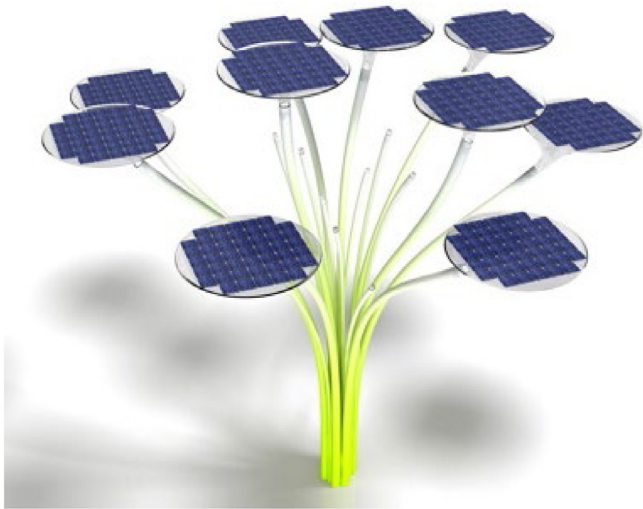


Fig. 10. Photo of RLST (Milan) (Fairs, 2007).



Fig. 11. Simple solar tree (Aurangabad, India) (IndiaMART, 2019).

irradiance for each module. Given that solar irradiance is inconstant, (MPPT) is essential for solar tree systems to produce maximum power at all time. A tree can be constructed in two ways; first is to build the solar tree depending on direct solar irradiance, and second depends on the intelligent optimization of each solar module location in the solar tree (Hyder et al., 2018b). The flowchart of the main steps for the design and simulation for each module and the sum of the results to calculate the annual energy produced by the solar tree is shown in Fig. 17.

The algorithm used in Dey et al. (2018) was applied in MATLAB to obtain the optimum position points (x , y , z) in the scheme space generated arbitrarily shown in Fig. 18(a). The number of solar modules to be positioned (n) and the orientations of (n) solar modules (β_n , γ_n) are presented. The MPPT procedure for the solar tree capturing the maximum sunlight by the solar module and decreasing the shading from each other for a long time is also discussed. Computer software can be used to find the perfect number and location for the solar module in the solar tree. According to the simulation, the proposed hybrid electromechanical MPPT improves energy gain by 203.5 W h/day, equating to a 27.7% rise in harvested energy. Notably, this benefit percentage is dependent on the operating context (Abdelsalam et al., 2017).

The flowchart was modified in Dey and Pesala (2020). The optimum design processes focus on the shading percentage to obtain higher energy from the solar tree shown in Fig. 18(b).

4.7. Cost

The cost of a 5-kW solar-powered MBSS is \$7500. This project was developed by the Central Mechanical Engineering Research Institute (CSIR), a constituent laboratory of the Council of Scientific and Industrial Research, India (Vardhan, 2016). FPST is more expensive due to its complex structure (Hyder et al., 2018c). A 120-W FPST costs \$680 (Chitra et al., 2019). HDST is expensive due to the large number of modules that the tree comprises to obtain more energy (Hirani, 2020). The largest solar tree in the world was developed at an estimated cost of \$9560 (Bandyopadhyay, 2020). However, solar tree modules cost twice as much as traditional PV solar modules. The cost of these trees according to the energy produced may be \$1300/kW. This division decreases by increasing the total power of one tree (IndiaMART, 2019). The steel structures and beautiful designs are one of the reasons for the high cost of solar trees. Within these reasons, the complex and innovative designs have a high price. The payback period up to 12 years for small application (Gupta, 2017). A 7.5-kW smart palm tree costs more than \$25,000, because of its high quality and modern tech structure (EnergySage, 2016). Fig. 19 shows a comparison of prices for different types of solar tree with traditional PV systems.

Notably, some solar trees do not contain batteries, which are the most expensive part of solar systems, thereby leading to a significant reduction in cost. FPST is expensive due to its structural formation, affinity, and similarity cost for the other types.

5. Solar tree commercialization

Trees are one of nature's most fundamental features, and their forms and colors differentiate them. Manufacturing companies have engineers who can design on demand the quantities, sizes, and shapes that meet the needs of customers, research centers, institutions, companies, and governments. Thus, solar trees have a wide application. A straightforward comparison has been presented of the existing trees from a commercial point of view, comparing this modern technology with the technology of solar cells on the ground.

5.1. Traditional PV and solar tree technologies

Differences exist between traditional PV systems and solar trees, such as the land needed for installation and system cost. The comparison below (Table 1.) clarifies the primary differences between the two types to familiarize the readers with the requirements for each type and the type of application that can be used more.

5.2. Comparison among commercial solar trees

Manufacturing companies compete to attract customers and meet their desires according to the requirements of institutions or individuals who want to obtain solar trees. The comparison below (Table 2) shows most of the differences among solar tree types to determine the type of solar tree in advance with the manufacturer. Particularly, four solar trees are the most widely used.



Fig. 12. Largest solar tree installed in the world (India) (Nair, 2020).



Fig. 13. Super tree (Singapore).

Table 1

Comparison between traditional PV and solar tree systems.

Parameter	Traditional PV	Solar tree
Power produced	Diversification of the productive capacity from small to large stations up to 2 MW	Less power per tree up to 11.5 kW
PV system cost	Simple structure design and relatively low cost	Generally, more costly but it depends on the complex 3D design and the application
Land footprint	Large land footprint in general, and it depends on PV system size, the footprint factor is up to 700 W/m ²	Less footprint, due to the tree containing many layers of PV modules on a single stem, the footprint factor is up to 11500 W/m ²
Shading	Less shading effect	More shading effect because of many PV layers and random orientation of modules
Amount of sunlight captured per square meter of soil area	Less due to its extensive array design consuming more area	More as modules are arranged on many layers, which takes less area
Applications	Mainly for generating electricity	Many applications, such as integrating art with technology
Suitable angles of incidence	More efficient than the tree at low angles of incidence (0°–20°)	More efficient at higher angles of incidence (40°–80°)
Capture during peak sunshine hours	High as modules are oriented to face the sun directly during peak sunshine hours	Modules are angled in different directions, and not all modules face the sun directly during peak sunlight hours; thus, the energy generated is relatively low
Art and appearance	Lack of art and aesthetics	Pleasing aesthetic appearance

Table 2
Comparison of popular solar tree types.

Parameter	MBSS	RLST	Simple solar tree	Smart palm tree
Power	Generate electric power on demand.	Limited electric power generation.	Generating electricity on demand. Building the largest solar tree in the world.	Limited electric power generation.
Structural design	The tree structure consists of a single stem with multiple branches and many layers, and shapes can also be placed (FPST).	Consists of a sinuous tree constructed of steel pipes, measuring 5.5 m, supporting a light bubble, in which there exists 38 solar PV panels.	The tree structure consists of a single stem with solar panels distributed on a single layer, directed toward the sun.	A sophisticated structure of a single stem mixed with plastic and solar panels circulated on a single layer directed toward the sun.
Efficiency	Lower efficiency due to the shadow of the panels on each other.	Lower efficiency due to vertical panel installation.	High efficiency because the panels face the sun.	High efficiency because the panels face the sun.
Appearance	Unpleasant solar tree.	Remarkably beautiful solar tree.	It is considered a shade solar tree.	Remarkably beautiful solar tree.
Pros	Less expensive than other designs.	Designs that are influenced by nature.	The best tree to electricity-generating.	Can be used for tourism area.
Cons	All panels are oriented in the same direction; thus, light collection is less efficient.	Limited power generation.	Large scale and needs a strong structure to meet the weather conditions.	Extremely expensive.
Cost/watt	\$1.5/W, which is an acceptable cost compared with the traditional system.	High cost and custom-made.	\$0.84/W, which is the cheapest one.	\$3.5/W, which is the expensive one.



Fig. 14. Layout of smart palm tree (Dubai, UAE) (O'Keefe, 2015).

6. Limitations and recommendations for future work

Modern technologies are subject to many studies and experiments in order to prove the variables and advantages of this technology and are tested reliably. One of the modern technologies is the technology of solar trees to generate electrical energy by solar cells. It is known that solar cells have become widespread, with some determinants addressed, some of them are in the technique of solar trees.

Solar trees, like any other technology have some limitations that could be summarized as below:

- the relatively high cost is the most important indicator in solar tree technology advancement. This high cost attributes to several reasons including the external structure design of the tree, the quality of materials used in the construction, the cost of solar cells and the periodic maintenance and dust cleaning.

- Solar tree complex design costs a lot and there are many ideas to give simple structure and merge them with the building in urban areas. Among others, is the grape-shaped tree is a good solution to improve this technology as it has a simple structure and the spherical shape of the grape employs as a solar tracker system to harvest the maximum solar irradiance. In addition, the diffusion solar radiation could be absorbed thanks to the rounded cell shape as the which also better than traditional PV shapes considering the dust accumulation.
- The researchers did not deal with the solar tracking system in the solar tree mainly because it is costly and complicated to be applied. Resources and the scientific articles published in the literature are limited and lack to investigate such essential research domain.
- Researchers should find solutions to the straying coefficient resulted due to solar cells over each other and working to reduce the percentage of shadow.
- Long term assessment for solar trees compared with traditional PV system need to be studied to build up a complete feasibility image to provide the investors all needed data to make a decision.
- Finally, researchers are invited to search for a new design to eliminate the shadow generation among the PV modules layers in the trees, it could be by applying algorithms, such as the particle swarm optimization (PSO) and helping by software program like MATLAB.

7. Conclusion

A significant development in the applications of PV cells, their prices, and their efficiency, has been observed in the last 15 years, and materials play an essential role in this scientific development. Trees are one of nature's most fundamental features, and their forms and colors differentiate them. In comparison with traditional PV technology, solar tree technology can absorb solar energy more effectively in any geographic area and season. In comparison with land-based PV systems, solar trees meet today's most pressing social, cultural, and environmental concerns with a considerably smaller land footprint. The solar tree design can become a model of green technology, with a wide variety of research applications in the PV sector. The main interest is in solar cells and tree structures, as the high price of solar trees is due to the design cost. Solar trees have many applications as follows.

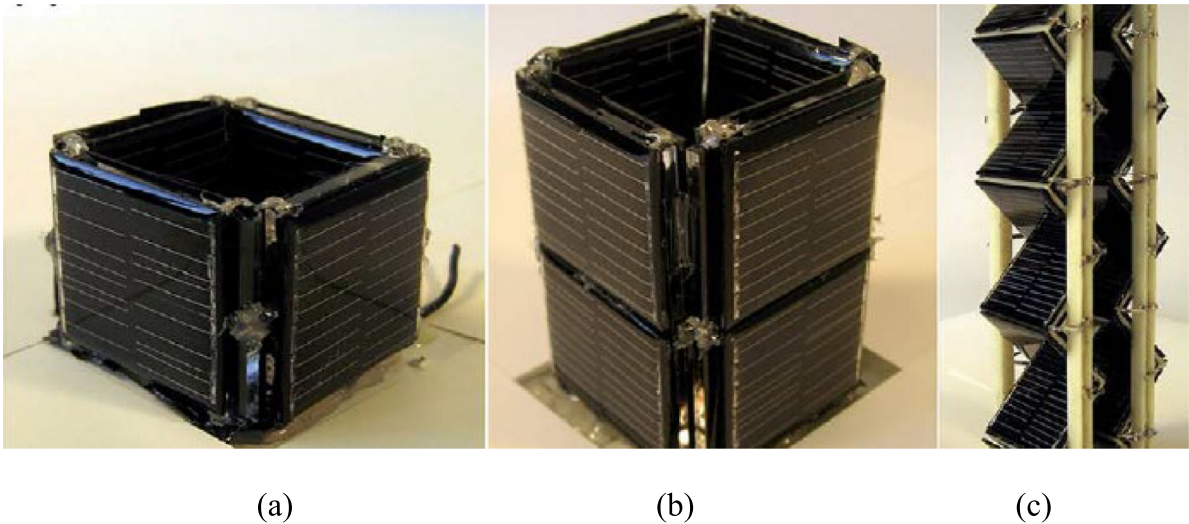


Fig. 15. Three samples of TPVD, (a) Single cube, (b) Double cube, (c) Three-dimensional body.

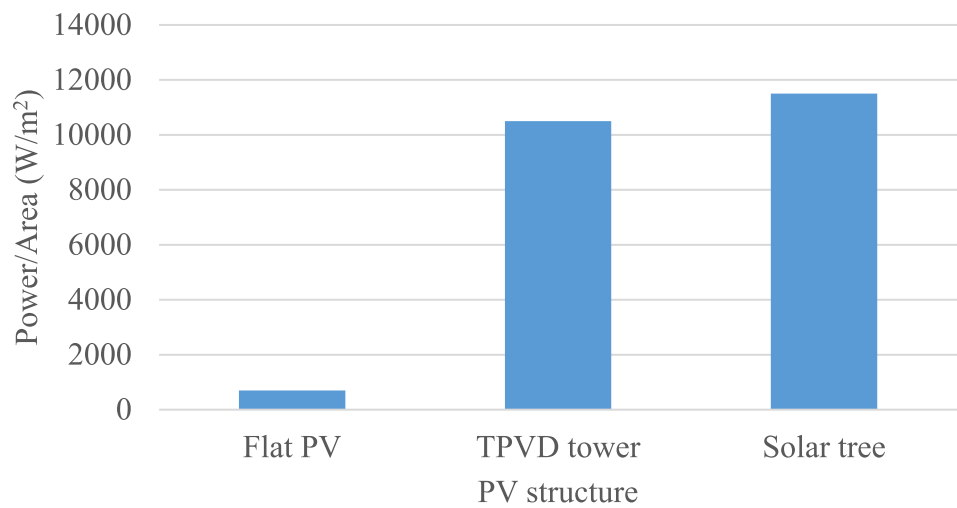


Fig. 16. Relationship between area and production power for PV structures (Bernardi et al., 2012; Javid, 2020).

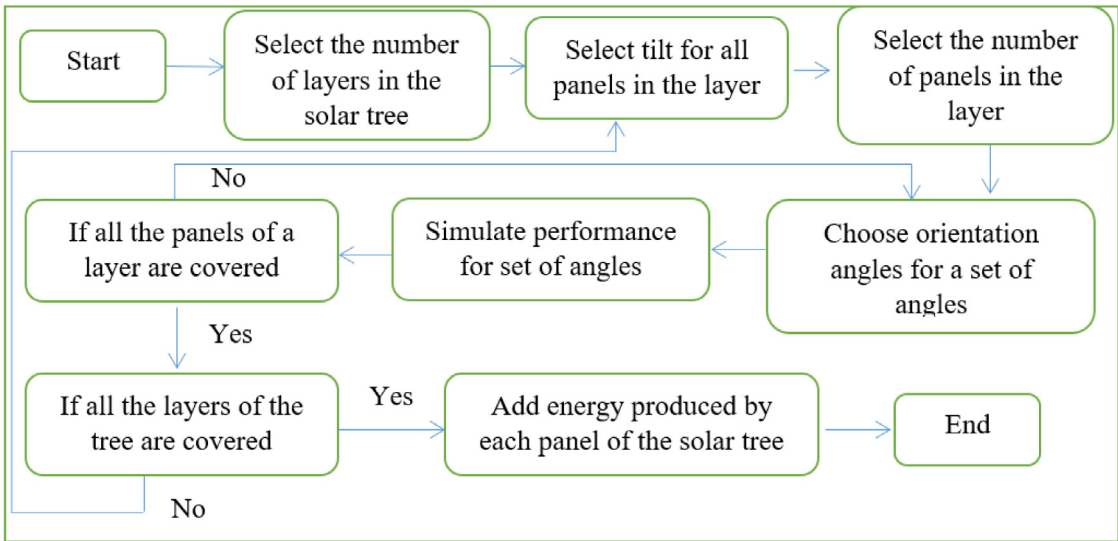


Fig. 17. Flowchart of the optimization procedure for a solar tree (Hyder et al., 2018b).

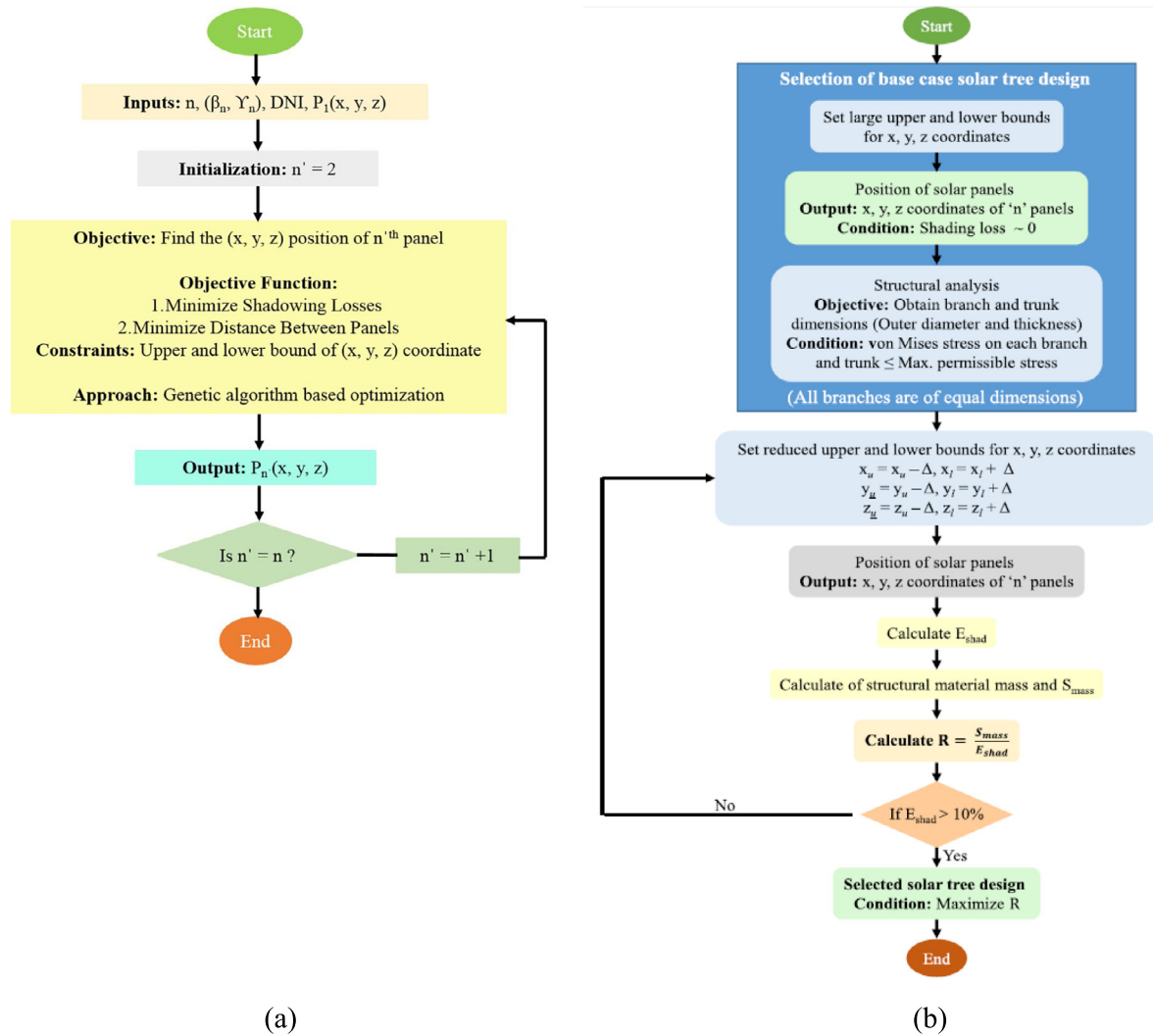


Fig. 18. MPPT for a solar tree, (a) MPPT flowchart (Dey et al., 2018), (b) Modified MPPT flowchart (Dey and Pesala, 2020).

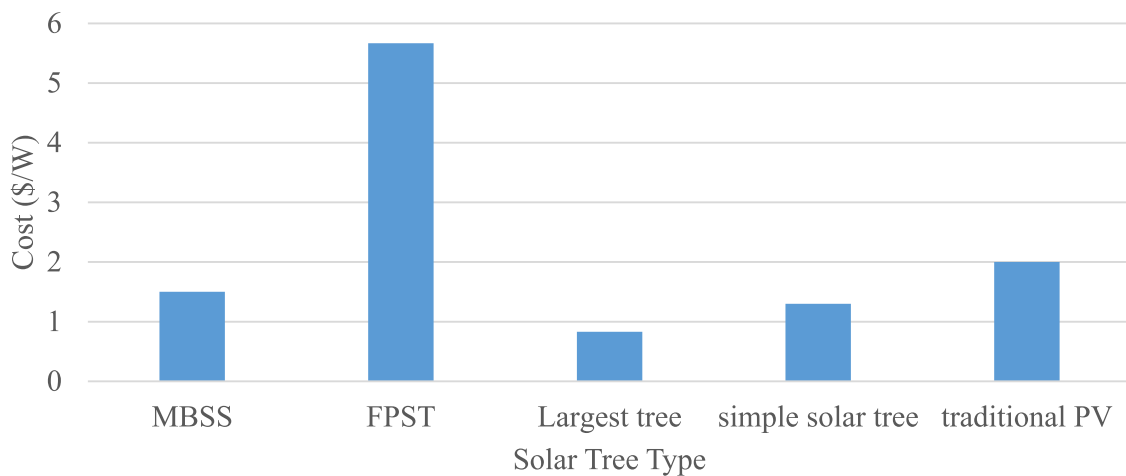


Fig. 19. Cost of commercially available solar trees and traditional PV system.

- (1) Urban areas: To satisfy a house's regular electricity demand while using scant property, which is useful due to the scarcity of land in metropolitan areas.
- (2) Countryside: To operate farm machines and water pumps by providing energy to rural families who are not linked to the grid.
- (3) Street lighting: To provide electricity to highways and urban street lights.
- (4) Garden lighting: To supply power for street lights in gardens and pathways, which will illuminate and beautify the region.
- (5) Office parking lots and manufacturing units: To increment the industry's energy needs while also enhancing the aesthetics of these regions, which are otherwise drab, which can change the working climate.
- (6) Charging purposes: To meet the electricity needs to charge mobiles, laptops, and any electronic devices in airports, city parks, and malls.
- (7) Electric vehicle charging stations: To provide electricity to electric and hybrid car charging stations; as a result, safe and green transportation is encouraged.
- (8) Information centers, billboards, and notice boards: To power isolated information centers and provide electricity for advertising and display boards.
- (9) Vending machines: To supply electricity to vending machines, water coolers, and other related items.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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