Applications of solar PV tree systems with different design aspects and performance assessment

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Abstract

Solar energy is deemed as the most abundant, reliable, eco-friendly and totally free resource of energy. There is a wide range of techniques to harness solar energy for different purposes. Among all the available methods, direct conversion of sunlight into electricity through photovoltaic (PV) phenomenon is the most mature and popular process. Progress of PV technology in market is perspicuous; however, it has still some drawbacks such as notable land requirement in cities, energy conversion efficiencies that already reached the theoretical limits and social acceptance issues due to aesthetic details. To overcome the aforesaid challenges, solar PV tree concept has been recently developed, and the simplicity, compact structure and elegance of this novel technology have been in the focus of researchers. Within the scope of this review, the concept of solar PV tree has been extensively investigated in terms of various design aspects and potential applications. Current performance characteristics of solar PV tree systems and power management strategies in real applications have been discussed. Challenges involved with the solar PV tree technology have also been addressed as well as suggestions on the direction of further works.

Keywords: land footprint; performance assessment; efficiency; design aspect; Keywords: solar PV tree

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1 SOLAR PV TREES

Solar photovoltaic (PV) tree (SPVT) is a natural tree-shaped metallic structure that has PV modules at the top as alternative branches of natural tree in different shapes and orientation angles. SPVT can be defined as a decorative means of generating renewable electricity [1]. In a typical SPVT, PV modules are arranged as leaves of the branches as shown in Figure 1 [2]. The term 'TREE' also refers to T, tree generating; R, renewable; E, energy; and E, electricity.

The design of SPVT permits the batteries to charge on throughout the sunshine period, and as the solar radiation level reaches to its lower limit (after the sunset), the LED lights are switched on automatically by SPVT. SPVT has an outstanding flexibility for rotating to face the sun and generate maximum energy by using a system which is called 'spiralling phyllataxy' [3, 4]. The said system allows even the smallest PV module to collect plenty sunlight needed for electricity generation. The design of SPVT is variable due to diverse factors. For instance, in India, SPVT contributes to fulfil the energy demand of the people by saving land use [5].

SPVT technology ensures uninterrupted supply of power in the areas where enough electricity supply is not available and benefits those who are unable to access the grid anyhow. Solar

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Figure 1. *SPVT of 35 PV panels with a capacity of 11.55 kW (Open-source image: PIB, Govt. of India) [2].*

energy is renewable and clean source of energy, and it is an improved alternative over some other techniques of electricity generation [6]. SPVT systems are very appropriate for using in off-the-grid isolated locations where point-sourced light is utilised such as car parking zone, religious places, streets and parks etc. Moreover, with a gird connectivity or battery bank, SPVT systems can generate electricity wherever required [7].

SPVTs are pole-mounted structures so they occupy very less space on the ground compared to conventional PV systems. In other words, this saved land area can be used for different purposes. Owing to their design and aesthetic details, SPVT systems draw attention year after year. SPVTs beautify the location where they are installed with their numerous design characteristics and colour configurations [8]. SPVT systems are usually designed for different applications in real life for maximum power generation through sunlight. In this respect, they are flexible for mounting on the roofs or in long terraces of the buildings as a clean energy source owing to the feature of less space consuming. The concept of SPVT is a good option to generate electricity for people from different communities and households [9].

Besides the power generation capacity of SPVT systems with a negligible land use, it can be easily asserted that these systems have various opportunities and advantages in terms of creating new employment areas. SPVT-based clean energy generation is also of vital importance in terms of mitigating greenhouse gas emissions and improving environmental consciousness. It contributes to people being educated about solar power and the great benefits of solar products installation to them and the environment [10]. SPVT systems have more multifunctional features than conventional PVs. Besides consuming less land space on the ground, a typical SPVT offers artificial light (through LEDs) in the evening and night that is installed underneath the panel; moreover, one can also charge his/her low power-consuming electronic gadgets from the built-in benches besides sitting on it round the clock [11].

2 OBJECTIVES OF THE SPVTS

An SPVT is an aesthetic design of solar electricity in which PV modules are configured as the leaves of a tree by inspiring the nature. SPVT systems aim to provide electricity to people as an on-grid or off-grid unit, and currently these systems are usually preferred for lighting purpose with energy-efficient LED integrations [12]. Besides lighting, these systems are used to meet various energy demands in both urban and rural areas. For instance, one can recharge cell phones, laptops, electronics notebooks and other low potential electronic gadgets through SPVTs. A typical tree is specialised to harness solar energy throughout the day, and the design of SVPT follows the same principle [13]. The system can be asserted as a natural solar tracking structure that captures the sunlight as much as possible.

Main objectives of an SPVT concept are as follows:

a) To make all citizens aware about sustainability through renewable energy.
b) To develop the community perception about PV technology through building it aesthetically attractive.
c) To improve the overall efficiency of PV systems by using 3D structure imitating a natural tree.
d) To decrease the land or space required to harness solar energy.
e) To provide the electricity wherever grid supply is not available or wherever people cannot access it.
f) To utilise solar energy maximum to fulfil the electricity demand of public round the globe.
g) To make every city into a smart green city.

3 APPLICATIONS OF SPVT

Applications of SPVT are in places where small-scale electricity is required. If the electricity is required on a large scale then the numbers of SPVT can be increased according to the load requirement. Table 1 shows some outstanding applications of SPVT technology.

Figure 2 shows the various applications of SPVT where it does not only provide the electricity or light but also make also such the location attractive by enriching its beauty of appearance.

4 COMPARISON OF SPVT AND CONVENTIONAL PV SYSTEMS IN TERMS OF EFFICIENT LAND MANAGEMENT

Solar PV power plant of different sizes for power production is a land-consuming system. As an example, a typical 2 MW PV power plant needs the land about 10 acres [16]. After the lack of potable water [17], scarceness of land is an utmost crisis on the earth. From this point of view, SPVT is a better solution

Table 1. *Various applications of SPVT systems [4, 14].*

Applications	Remarks
Urban area	To meet a daily demand of electricity a household, less land is required, which is much supportive as land in urban regions is constrained. SPVT is supportive for this.
Remote islands and mountains	To fulfil the electricity demands in remote areas and mountainous households (off-grid locations). A SPVT can be installed on the planes and sloppy hilly territory disparate land based SPV.
Rural area and agriculture	Many households are still not connected to the main grid to fulfil their daily demand of electricity. An SPVT can also be installed simply to supply electricity to those houses and to power the farming tools, e-tractors, e-power tillers and water pumps.
Resorts and golf courses	To supply electricity to the golf buggies, fountains, small size grass cutter etc. Well-designed SPVT can also enrich the beauty appearance of the entire resort.
Streetlights (highway and localities)	Many accidents take place on the highways and nearby localities due to digs on the roads that cannot be seen in beam lights of vehicles. Therefore, SPVT is the best option to avoid accidents by providing street lighting on the dividers on the middle of highways and nearby localities, unless government of different nations has to be paid a lot of money on the grid electricity for the same.
Public parks and gardens	To provide the electricity in the public parks and gardens to avoid the danger of reptiles, muddy surface, other accidents etc. Sometime, due to poor maintenance, electricity current from the grid is present for a high voltage in the poles of parks light, which cause unnecessary deaths. Meanwhile, there is no high risk with SPVT.
Airports	To supply the electricity vital at airports, as the airports already consume massive pieces of land for their running tracks. An SPVT offers electricity by consuming little less land.
Worship places	To provide the electricity in the religious places as the worship of the god is done even in the night at many religious places. These places also have their own small parks for the people. So, SPVT is also a good option for likely places in the world.
Vehicle’s parking units	It is also a good option to provide the electricity to lights of parking places. Here, the electricity can also be utilised to charge the hybrid vehicles and the torch lights of the security guards.
Universities and institutions	Many students in hostel keep on playing, walking and sitting in the fields of the campus. SPVT is the best option to be used as a green tree in the campus and to provide the electricity to parking places, indoor games hall, open auditorium, parks etc.
Charging electric vehicles and gadgets	Electric or hybrid vehicles and electronic gadgets can be charged by the electricity provided by SPVT. Thus, encouraging a clean and green environment and transportation.
Information board	To provide electricity wherever advertisement, digital display boards and water coolers are powered by electricity such as railways and bus stations, markets, malls etc.
Sea shore and bank of the rivers	To provide the light at the sea shore and bank of the rivers for a clear visibility of water, muddy space and water species.
Smart cities and localities	Well-designed SPVT provides the light to environment and enrich the beauty appearance of the entire city and its localities. Everybody will feel safe in the night in such environment.

to overcome because it takes only ∼1% of land in comparison with a PV system. For an example, SPVT needs only 0.4-m^2 land area to generate the electricity ∼2.2 kWh in a day, while a traditional PV array requires a land area of 40 m^2 for the said power production [18].

An SPVT needs a strong foundation to hold a tall pole with heavy weight of panels. In order to install an SPVT, a high-strength metallic pole of 40∼80 feet in height is founded on an area of 4 m^2, which holds the weight of all the PV panels on its structure like a natural tree. In other words, a small size of surface land is required, but it needs to be noted that noticeably most of the foundation work is underneath the ground surface [19]. Thus, an SPVT (which is more ergonomic as shown in Figure 3) can be easily installed for solar power production on the roads and sides of the highways, on the islands, in the parks etc.

The SPVT systems can be installed in a specific place without any procurement of wide land. A single SPVT can be installed easily on the road sides by consuming a land area of ∼0.4 m^2. Moreover, roads of the villages and the large frontier walls of paddy lands provide enough space to install SPVT to supply sufficient electricity for electrification of rural community and their irrigation deeds. All the highways are big sources for SPVT installation.

A recent calculation demonstrates that if the 300-km national highway from Kolkata to Asansol (in India) is used for installation of solar trees with an equal space of 15 m, then it would produce ∼110 MW. Meanwhile, for the same amount of power production through conventional PV systems, it would actually need ∼660 acres of land space, which also needs a high maintenance. Apart from this, Central Mechanical Engineering Research Institute, Durgapur (CMERI, India) has designed an SPVT of 3 kW capacity that takes only ∼0.4 m^2, and it is enough for 4–5 small-sized households in India. On the other hand, a conventional PV system occupies at least 40 m^2 of land space to generate the same output. Moreover, each SPVT has potential to save 10∼12 tons of CO_2 emissions according to CMERI, India [2, 20].

The vertical type of solar plants also has the possibility to harness 10% more energy than traditional PV systems [26] if installed towards northern pole. SPVT can also be used to enhance the power supply availability to a specific location if connected to the

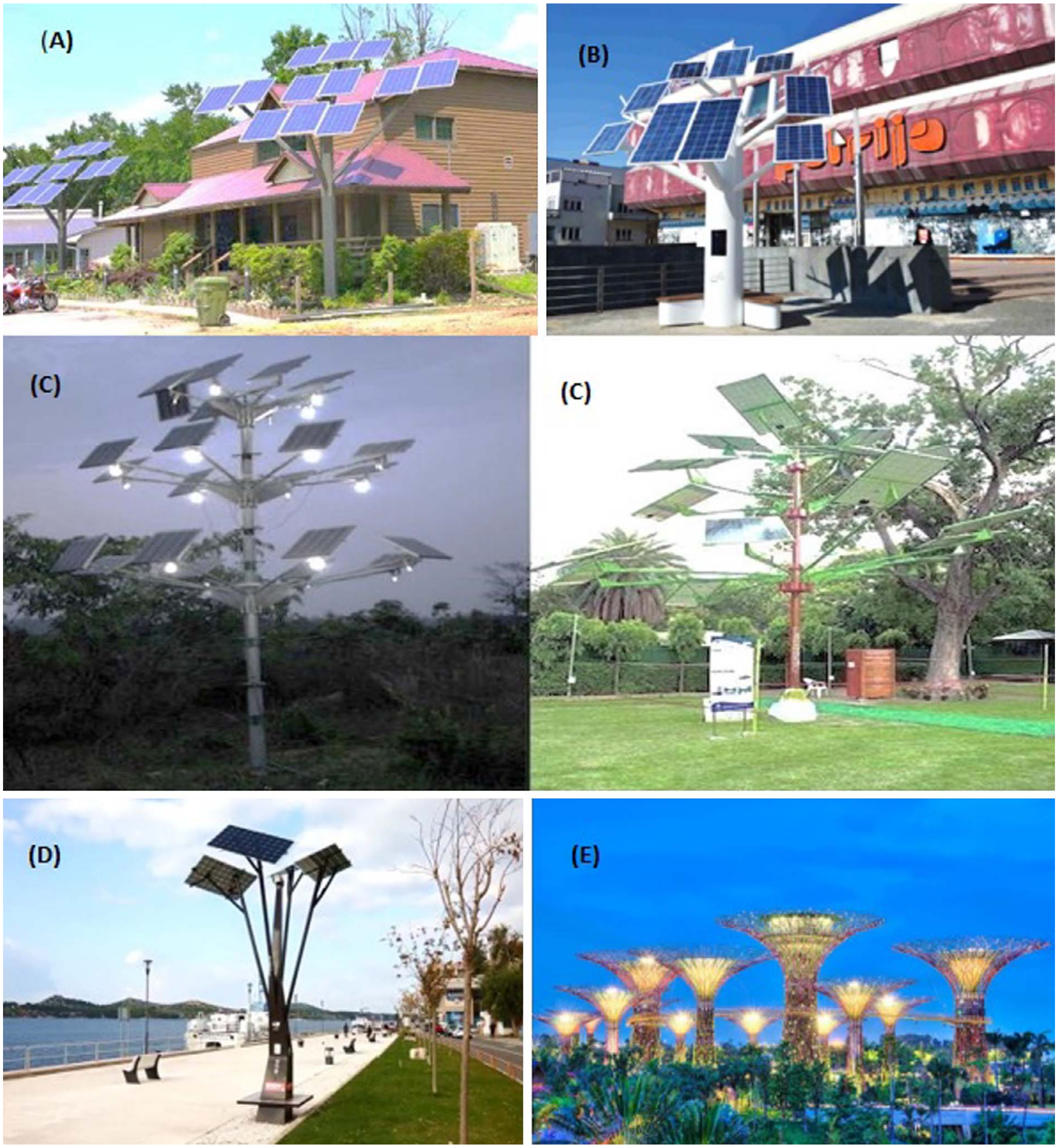

Figure 2. *Various applications and locations of SPVT [15] (a): solar tree at public mall (b), solar tree at public park (c), Solar tree at sea link load (d) and solar trees inside (e).*

grid system. Table 2 summarises the main components of a SPVT to connect the grid system.

5 END-OF-LIFE MANAGEMENT FOR SPVT

End-of-life (EOL) management is a process that describes how to evaluate the final stages of a product's existence, taking in consideration the production process and all operating conditions. All technological products come to the EOL stage and degrade due to environmental factors like corrosion and temperature, the parameters related to the physical and chemical structure of the material (the internal structure of the material), operating conditions and the inability to properly manage the quality control process in production. After all, every product turns into a waste. The 3R rule, which is defined as reduction, reuse and recycling in sustainable waste management, is a key proposition in environmental policies. In this terminology, recycling is a good preference for products that cannot be reused or repaired, before diverging to the disposal option [22].

Figure 3. *A classic PV rooftop power plant of 20 kW capacity installed in a large land area (A) and a SPVT of 20 kW installed in a small land area (B).*

Table 2. *Components for SPVT to connect with gird [21]*

No.	Items	Units
1	Solar PV modules (multi crystalline)	Required in numbers
2	Individual module power	W_p
3	Mild steel galvanised module mounting structure (for making solar array in a form of a natural green tree)	Required in numbers
4	Suitable copper DC cable as per the module current (specify cable type and cross section area)	Metres
5	Suitable AC cable (specify cable type and specify cable type and cross section area)	Metres
6	SMA inverter (STP 10000 TL) with compatible data logger for remote monitoring	Required in numbers
7	Sensor to measure module temperature	Required sets
8	CAT6 cable for providing interface along with RJ45/RJ11 sockets	Required sets
9	AC distribution board	Required in numbers
10	Energy metre	Required in numbers
11	Array junction box/combiner box	Required in numbers
12	Earthing kit	Required Sets
13	GI strip 25 mm × 3 mm LS	Lumpsum
14	Any other hardware/accessories to complete I&C	Lumpsum

SPVTs are systems that consist of PV modules in different configurations, structurally similar to real trees, and can be located on roadsides, service roads and parks and gardens without creating aesthetic concerns. Basic components of SPVTs are PV modules, cables for connecting units, inverter, batteries, steel structures and charging points/LEDs [13]. Besides the use of steel material in the main structure of SPVTs, different construction materials such as galvanised, PVC and wooden are used [3, 4]. The components that comprise the SPVT need to be evaluated in terms of EOL management. However, it is required to be noted that the EOL management of PV panels is dominant and should be emphasised.

Steel structures can last for many years with the protection processes applied to the surface. According to the American Iron and Steel Institute, steel is the most recyclable material on the planet. Steel products are 100% recyclable at the end of their life, and every steel produced in the USA contains recycled material. Other components of SPVT can be qualified as electronic waste (e-waste) or waste from electrical and electronic equipment (WEEE) at the EOL [23, 24].

With the increase in global energy production based on renewable energy sources, the PV market is rapidly expanding. According to the report prepared by IRENA in collaboration with IEA-PVPS Task 12 [23], considering the average panel lifetime of 30 years, a large amount of PV panels are expected to decommission in the near future. PV panel wastes can create a new value besides its environmental challenges. The PV value chain shown in Figure 4 refers to all the different processes required to build a PV system. Decommissioning and EOL management can be an important part of the PV value chain [25].

In general, there are six alternative options associated with the product life cycle (can be thought of as the solar PV value chain in PV systems) in the EOL management of a product as depicted in Figure 5 [26]. The primary and the most preferred option in waste management is to reduce waste. Less waste can be generated at the EOL by significantly reducing raw material inputs with research and development and technological developments. The second option is the reuse opportunity, which occurs with the repair of early failures in a product. However, when considering in terms of PV panels, the effects of repair processes on efficiency need to be taken into account. The third and the least preferred option is to recycle, which enables the recovery of the main components that make up the product [23]. Incineration (or energy recovery) is a less preferred option than recycling because of the potential loss of material and environmental problems with the release of toxic gases. However, with the technological developments in the incineration process, harmful gas emissions are significantly reduced.

Figure 4. *Solar PV value chain [25].*

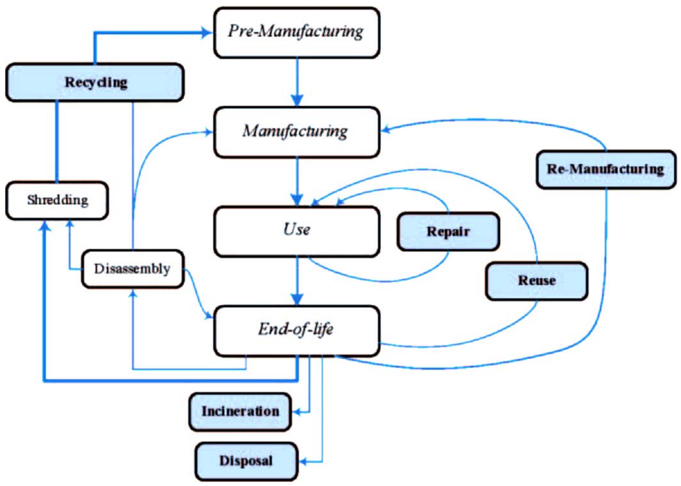

Figure 5. *Alternative options for EOL management in the product life cycle [26].*

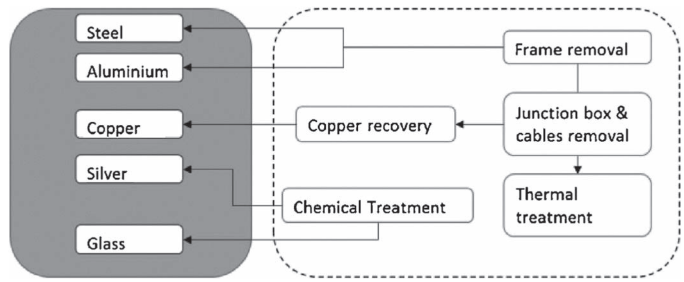

Figure 6. *EOL method based on thermal and chemical treatment [34].*

Disposal of waste in landfills is the last and the worst form of management [26]. An economic and environmental assessment is necessitated to determine the best waste management for a product at the EOL.

International organisations including United Nations Environment Programme, International Solid Waste Association and International Telecommunication Union around the world have introduced particular rules, standards and policies for waste management. Moreover, there is an open-ended partnership called Global Partnership on Waste Management for international organisations, governments, environmentally sensitive businesses and non-governmental organisations.

In PV industry, c-Si panels, which are the oldest technology, dominate the market with a share of 92% [23]. Therefore, the most widely used panels in SPVTs are c-Si. Duflou *et al.* [27] conduct a comparative evaluation to determine the most appropriate treatment for EOL management for c-Si panels. These treatments are destructive separation, thermal and chemical treatment and delamination (selective mechanical separation).

Gangwar *et al.* [20] use the EOL model based on thermal and chemical treatments scenario to estimate the material recovery potential from 24 W SPVT developed based on the phyllotaxy pattern. In this method, after PV modules are dismantled and materials such as aluminium, steel and copper are recovered, thermal and chemical treatments shown in Figure 6 are applied to the PV module, as described in detail in the literature [10, 12]. The material composition of c-Si PVs is estimated based on data given by Duflou *et al.* [27]. In addition, the recovery amounts of each material constituting the PV module are calculated by using the recovery percentages given in literature.

6 DESIGN PARAMETERS

In literature, there are several models developed according to the geometry of the trees, their branching shapes, the arrangement of the leaves and their tendency towards orientation [3, 13–15]. The results obtained in these studies reveal the parameters that are effective in the design and their degree of influence.

One of the most important parameters in the design of solar PV trees is the area ratio. Solar panels are arranged in a tree-like structure, and the output power capacity per unit area is increased with a large number of panel configurations as shown in Figure 7. Some researchers increase the area ratio by placing the panels in two or more stages in a phyllotaxy pattern [13]. Verma and Mazumder [7], in order to capture sunlight effectively, increase the area ratio by increasing the number of layers of panels/leaves in their simulation through configuring solar PV trees as hemispherical as given in Figure 8. In this way, the solar radiation passing through the spaces between the first layers is caught in the second layer. Another parameter that is effective in the design is to increase the sunlight capture capacity by optimising the angle of the solar radiation with the normal of the surface (zenith angle), together with the orientation of the panels. In order to capture sunlight,

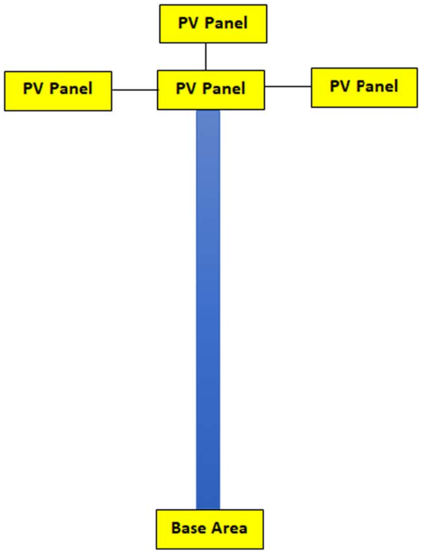

Figure 7. *Schematic illustration of area ratio for SPVTs [13].*

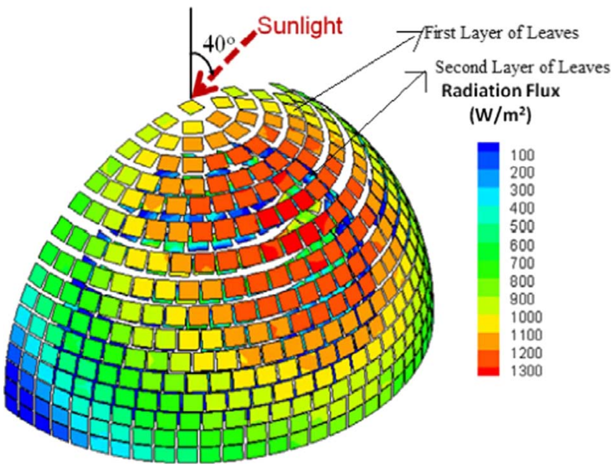

Figure 8. *Illustration of first and second layers in SPVTs [2, 15].*

Figure 9. *Nano leaves [28].*

Table 3. *Design parameters of SPVTs*

Design parameters
Area ratio
Orientation and tilt angle of panel/leaf
Leaf shape
Panel/leaf wattage
Tree structure

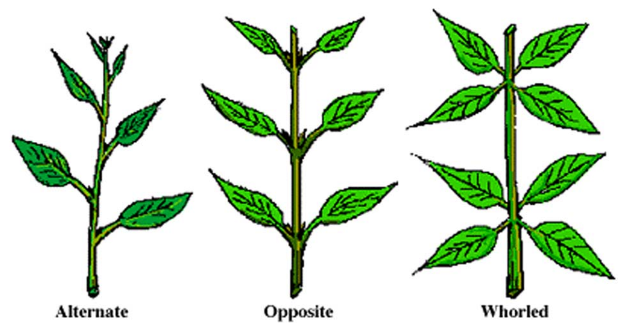

Figure 10. *Phyllotaxy patterns adopted in the design of SPVTs.*

Gangwar *et al.* [21] orient the panels in phyllotaxy pattern and configure the tilt angles of the panels with the PVsyst software.

With the development of nanotechnology in SPVTs, leaf-like cells illustrated in Figure 9 will be produced and it will be possible to capture sunlight with the most appropriate orientation and angle. In structures called solar botanic trees, it will be possible to generate electricity from the sun and wind in the near future [28]. In addition, organic solar cells, which have great potential in recent years, have come to the fore due to their low cost, ease of production and lack of harmful emissions [5]. In this context, leaf shape can also be added to the design parameters.

Hyder *et al.* [13] state that the leaf/panel wattage is one of the parameters that are effective in the design. The leaves that make up SPVTs can be of the same or different wattage. Considering a multi-layer design, the first and the second layer can comprise a leaf of different powers. However, in this case, because panels with different powers increase inverter losses, they are not suitable for systems connected to large power grid. It is reported that these would be suitable in systems that use batteries to store energy. There are designs with different stem and branching shapes in the literature. Although sometimes aesthetic concerns come to the fore, designs are made in a structure that will make optimum use of sunlight in general. The parameters that affect the design of SPVTs are summarised in Table 3.

7 DIFFERENT DESIGN SOLUTIONS OF SOLAR PV TREES

Solar electricity is still being dominated by PV industry in market because of their well-documented features, potentials and satisfactory performance figures. PV modules are traditionally mounted on roofs, terraces, building facades or flatland surfaces for different purposes. Especially in recent years, as a consequence

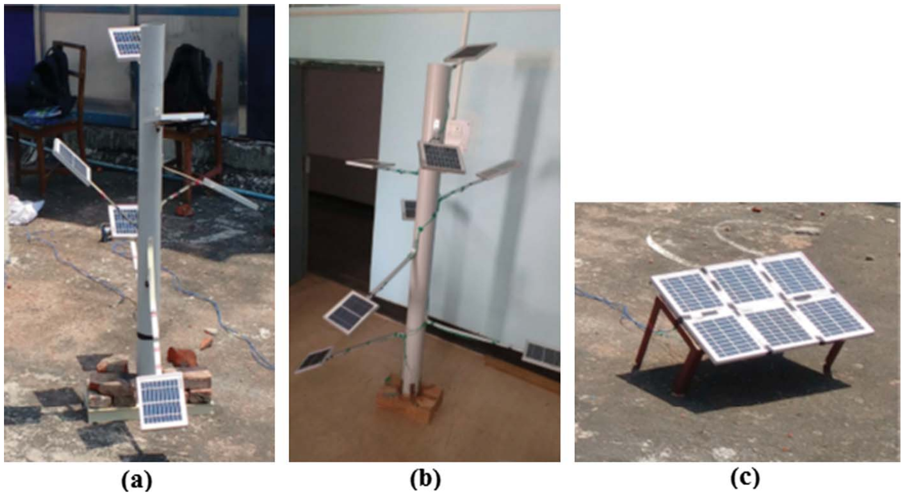

Figure 11. *SPVTs based on (a) 2/5 phyllotaxy pattern, (b) 3/8 phyllotaxy pattern and (c) conventional model [21].*

of notable advancements in thin film PV cells, semi-transparent PV modules are utilised as facade material, fenestration product or roof element, which is highly desirable in modern architecture [29, 30]. But at this point, it is understood that although the aforesaid multifunctional building elements are appropriate for sustainable building and city concept [31], they are still insufficient in terms of thermal resistance when compared to vacuum-based fenestration products or facade materials [32, 33]. Moreover, utilising these products in the built environment is still a costly process that is competitive with thermal superinsulation applications [34]. Therefore, there is an understandable consensus of PVs to consider them primarily for small or large scale electricity production. However, PV power plants still occupy a remarkable land due to their low energy conversion efficiencies; hence, they are not desirable where the land is limited or fertile. Instead of a horizontal plant design, vertical design options are much more preferable for efficient land utilisation. In this context, SPVTs draw attention of researchers and investors. SPVTs are innovative and aesthetic systems that can be placed in many places where solar radiation is sufficient, independent of the land or surface as the requirement of land is less. When they were first introduced in 1998, SPVTs was expressed as a solar artwork. In the following years, the concept has been adopted as solar trees [35]. Generally, SPVTs consist of an array of PV modules on branches that are systematically positioned on a pole or single/multiple trunk. Different design solutions are available for SPVTs. Some researchers do arrangements of stem structures on solar SPVTs to obtain maximum solar power absorption and to utilise the land effectively.

SPVTs are designed in a phyllotaxy pattern, inspired by nature, so that each panel can benefit from solar radiation at the maximum level. Because in this arrangement, each leaf is in perfect harmony so that they do not shade each other. There are three phyllotaxy patterns: opposite, whorled and alternate (also known

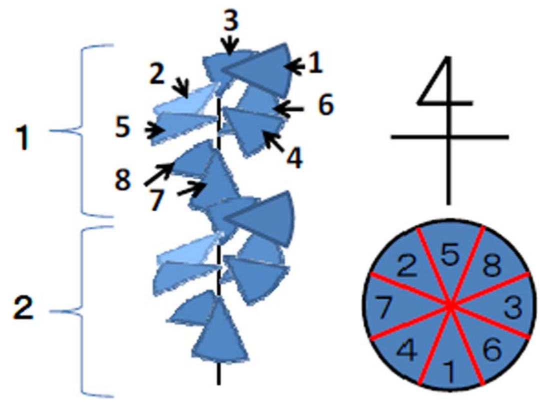

Figure 12. *Two stage FPM (Fibonacci number PV module) [36].*

as spiral), as shown in Figure 10. In an alternate or spiral phyllotaxy, each leaf attaches to a one node on the stem. In this phyllotaxy, the ratio between the number of clockwise tours to encounter another leaf facing the same direction in the leaf arrangement and the number of leaves encountered on the path is unique for each species (for oak, this ratio is 2/5). When turning counterclockwise, the number of tours along the path to encounter another leaf in the same direction represents another number (for oak, 3). The number of tours clockwise/counterclockwise and the number of leaves encountered in the path represent consecutive terms (2,3,5) in the Fibonacci sequence.

Gangwar *et al.* [21] choose an alternate phyllotaxy pattern with only one solar panel at each node. Experimental models given in Figure 11 are prepared creating SPVT designs based on 2/5 and 3/8 phyllotaxy patterns and compared with the conventional model in terms of power and solar intensity variation. PV panels have a particular tilt angle on the branches. Under similar solar radiation conditions, the experimental model based on the 3/8

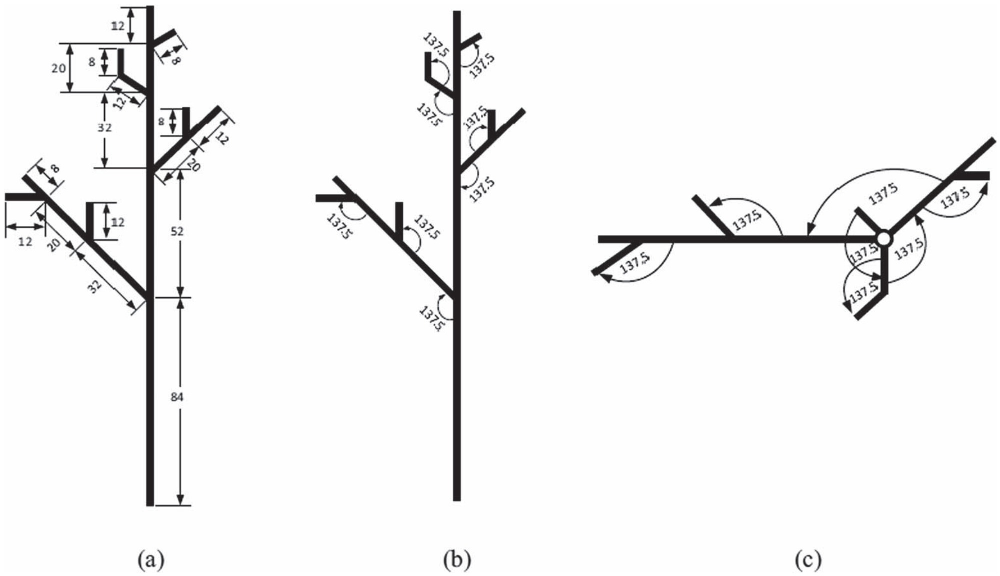

Figure 13. *Structure of SPVT (a) length of side view, (b) angle of side view and (c) angle of the top view [37].*

phyllotaxy pattern produces more power (in per unit) than the others. Also, it is reported that SPVTs with the same output power capacity occupy less land area. In SPVTs, the effect of the solar intensity variation on the output power is less than the conventional panels.

Yuji and Yachi [36] reveal that in the SPVT designed in the phyllotaxy pattern based on the Fibonacci number sequence in their simulation (also, they call this design as Fibonacci number PV module, FPM), as the number of stages increases, the output power increases compared to the planar PV module. More than one stage is created by defining it as a stage inter two modules facing the same direction in their work, schematically as shown in Figure 12.

In other work, Srisai and Harnsoongnoen [37] design the structure of the SPVT based on the golden ratio by using the Fibonacci series (1, 1, 2, 3, 5, 8, 13, 21, ...), as shown in Figure 13.

As shown in Figure 14, different architectural designs refer to as lift, curve, trestle and industry by customers can be presented in SPVTs [38].

8 ELECTRICAL POWER CONVERSION SYSTEMS FOR SPVT

SPVTs enable free access energy for rechargeable mobile phones, tablets, laptops and other devices driven by DC voltage. By using an inverter, DC voltage can be converted to AC voltage in the electrical system and then can be used in different devices that have an AC voltage. Generally, power conversion system components for SPVTs consist of PV leaf or panel, controller (also known as a charge regulator), battery, inverter and electrical load as shown in Figure 15 [2, 17].

The electrical system of SPVTs can be designed in two ways: on grid and off grid. On-grid SPVTs provide power to the grid by generating electrical power with the help of solar leaf/panel. On the other hand, in off-grid systems, which are often used in SPVT applications, there is no connection to the mains; therefore, the electrical energy is stored in the batteries by selecting the batteries sufficient for the installed power.

In solar panels/leaves, solar radiation varies for different levels instantaneously due to variation of zenith angle, clouding depending on changes in atmospheric conditions and surface contamination, hence different output powers occur. Also, the output power varies depending on the cell temperature. Using Maximum Power Point Tracking (MPPT) methods, The PV array output power is maximised, which is usually dependent on solar radiation and cell temperature [39]. MPPT techniques based on different algorithms are developed for PV arrays and wind turbines where the output power is non-linear. The most used MPPT algorithms for solar PV systems are classified and summarised by many researchers [18, 19]. Gaikwad and Lokhande [40] develop a novel MPPT algorithm based on the maximum power transfer theorem for SPVT applications. This algorithm is capable of maximising the panel output power under variable irradiation and temperature conditions.

9 SOLAR CELL TYPES FOR SPVTS

Solar cells made from silicon are the most widely used type in SPVT applications, as in other PV systems, because of their high efficiency. In addition to efficient silicon solar cell types like monocrystalline, polycrystalline, amorphous silicon and thin film, the newly and efficient solar cell technologies such as organic solar cell, dye-sensitised solar cell and nanowire solar cell are used in SPVT applications [13].

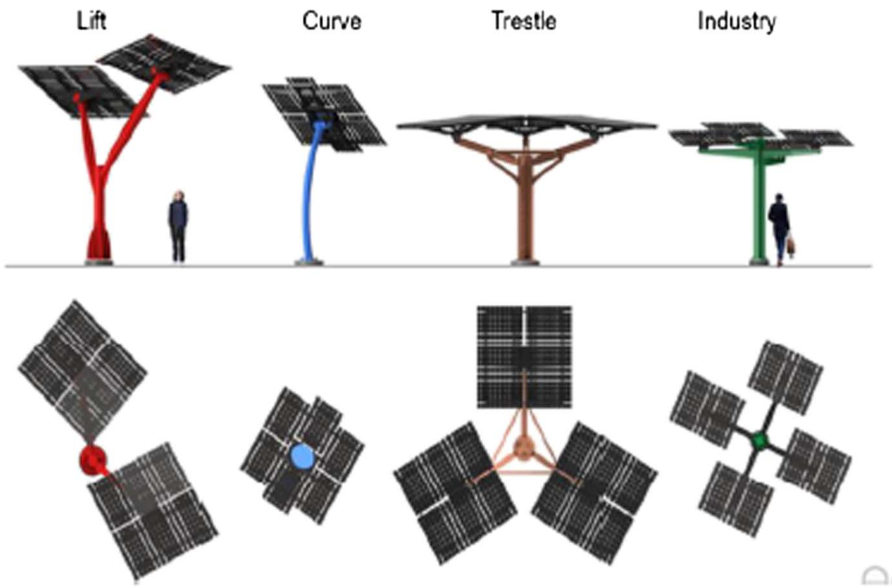

Figure 14. *Different SPVT designs: front view and top of the view [38].*

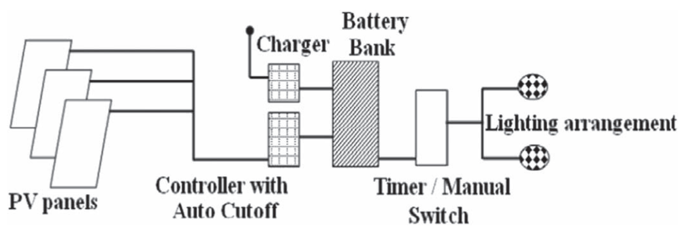

Figure 15. *Schematic illustration of PV power conversion system [1].*

Especially in recent years, organic solar cells draw a great attention because of their environmental and economic benefits like lack of harmful emissions, low-cost materials and ease of production. Thanks to these advantages, organic solar cells gain a significant market share in the commercial field. Because organic semiconductors have high flexibility, light weight and rich colours, they have a wide range of usage areas. For instance, organic solar cells can be integrated into fabrics like jackets or bags [5]. Despite these economic and environmental benefits, the low efficiency and less lifetime period are the most disadvantages of organic solar cells. Nevertheless, organic solar cell efficiency reached ∼10% with newly design and material characteristics [21]. Dye-sensitised solar cells are of the most promising solar cell technologies. Basically, it produces energy through a process like how plant cells produce energy [41]. Dye-sensitised solar cells have a wide range of usage areas from wireless sensor, computer peripherals to wearable technologies and SPVTs thanks to their advantages like ability to fabrication on various substrates, transparency and low cost [38].

Nanotechnology is one of the most growing and promising scientific fields. Nanowires consist of semiconductor materials like InGaAs. They have excellent light absorption values and, thus, have several usage areas from quantum computers to solar cells. SPVTs with nanowire solar cells can ensure higher conversion efficiency thanks to their very small diameter of a nanowire crystal. Longer life, little and easy maintenance, very low pollution problem and high efficiency are the other advantages with respect to the conventional silicon solar cells [42].

10 PERFORMANCE ANALYSIS OF SPVTS

SPVTs have variety usage areas such as charge of electronics like mobile phone and laptops, light up of LED lamps and energise vending machines because of their environmental and economic advantages [8]. When compared to the ground-mounted PV, SPVTs generate ∼15% more power and covers 99% less land area. For instance, 5-kW power can be obtained from 1-m^2 land area for SPVTs. On the other hand, the same power capacity can be obtained from 30-m^2 shadow-free land area for the ground-mounted PVs [43]. Especially for the past 10 years, scientists have been very interested in this subject and they have been working to increase the performance of SPVTs.

Hyder *et al.* [44] conduct a study to evaluate performance of SPVTs in terms of electric efficiency and land demand. For this purpose, they design six distinct semi-dome shaped SPVT with different orientation and tilt angles. They compare the performance values obtained by simulation for the systems they designed with land-based PV systems of the same capacity for Kuala Lumpur, Bhopal and Barcelona. According to the results, for the constant total capacity, the total produced energy amount increases with the increase of number of panels and layers. Considering the annual energy production values for Kuala Lumpur, Bhopal and Barcelona, it is possible to obtain 17.79%, 41.06% and

20.97% more energy, respectively, by using SPVT instead of land-based PV systems with the same capacity. The results also show that SPVTs ensure ~35% land use efficiency in comparison with land-based PV systems. Balaji *et al.* [45] carry out an analysis study to compare performances of SPVTs for different panel layers and positions. They calculate the yearly performances of SPVTs for five different axis positions, such as fixed axis, 1-axis, 2-axis, azimuthal axis and seasonal tilts, and compare each other. According to the results, 3-layer, 2-axis system shows the best performance with respect to the other layer and axis positions of the systems. In addition to this, all axis and layer positions show better performance than ground-mounted PV system for the constant capacity. Janamala [46] analyses performance and cost effectiveness of SPVTs for a lighting project of basketball court at Bangalore, India. Four different individual tree designs of 1 kWp are developed, saving 40 m^2 land area near the court. Experiments are carried out for 1 year for all panels oriented in the same azimuth angle, and the data are processed to determine the monthly energy amounts. The experimental results suggest that SPVT systems are suitable and efficient technology for both urban and rural areas in terms of economic, environmental and saving land area. Verma and Mazumder [7] conduct a Monte Carlo simulation study to evaluate the accuracy of the information that SPVTs capture more sunlight than conventional PV systems. Simulation data show that SPVTs can capture approximately five times more sunlight. It is also found that, by adding a second layer, the amount of sunlight captured can be increased by 15–30%, depending on the intensity of the first layer. Kumar *et al.* [19] propose a practical solution method supported by the performance prioritisation approach framework for multi-layered SPVTs. They simulate a three-layered SPVT and evaluate CO_2 emissions and energy performance for three different PV-cell technologies named by copper indium gallium selenide, crystalline silicon and cadmium telluride in terms of thermal regulation, power conversion efficiency, degradation rate and lifecycle carbon emissions. The results reveal that for early years, crystalline silicon PV cells are more suitable technology for energy efficiency. However, these PV cells show lower performance as the duration of use increased. On the other hand, cadmium telluride PV cells are found to be the best suitable PV cell technology, thanks to some advantages like low-cost manufacturing, flexible and ultrathin glass structure.

11 POWER MANAGEMENT

Because the efficiency of renewable energy sources such as solar and wind energy is significantly affected by environmental factors such as weather conditions, they can be called intermittent energy sources. Therefore, efficient timing and power management is an important issue for energy production, storage and use of renewable energy sources. SPVT applications are also usually run as off-grid systems. The power management to be applied in these systems not only contributes to the protection and longevity of energy supply equipment but also provides a more comfortable use for consumers. Precisely monitoring the power demands of consumers in certain time intervals and making predictions with the data in these intervals allow the energy amounts needed by the consumers to be met efficiently at the required hours. These processes, which can be provided with various programmes and automation systems such as mixed-integer linear programming model [36, 37], mathematical model [48], logical block diagrams [49] and state machine approach [50], can be called power management.

12 GRID INTEGRATION OF SPVTS

Integration of PV systems into the grid allows the use of excessive electricity from solar energy, which is not used individually, on a national scale. Especially in recent years, with the increasing interest in renewable energy sources around the world, integration of PV systems into the grid provides important benefits such as optimising the building energy balance, reducing operating costs, adding value to the consumer and contributing to the national economy, and is a widely used technology, thanks to these benefits [51]. Grid integration of SPVT systems is also the same as PV systems, but these applications are generally used as off grid, because they are for smaller-scale lighting or laptop and phone charging needs.

13 CONCLUSIONS

Efficient use of land in PV-based clean energy generation is of vital importance more than ever especially in urban areas. On the contrary to the conventional land-based PV power plants, SPVTs draw attention day by day owing to their performance figures, expanding areas of application, aesthetic features and environmental aspects. The goal of this review is to propose a rigorous assessment of SPVT technology with various design aspects, potential applications, challenges and future directions. The following bullet points can be achieved from the present work:

- When the daily solar capture performance is taken into consideration, the concept of SPVT is found more effective than conventional land-based PV power plants.
- SPVTs enable clean energy generation with negligible land use because vertical design is possible with this technology.
- Impacts of solar angles on system performance are less important in SPVTs.
- SPVTs have a great social acceptance in both urban and rural areas owing to their elegance and aesthetic details. They have also a remarkable potential in terms of mitigating greenhouse gas emissions and environmental matters.
- SPVTs are ideal for street lighting in metropolitan cities with area constraints. They require insignificant land footprint.
- SPVTs can be utilised for different purposes such as laptop and cell phone charging, household and industrial supply, street and city lighting and charging of electric vehicles.

They can also be integrated to the grid in case of excessive energy generation.

- SPVT technology is a new research area for PV market.
- Self-cleaning, smart coating and cooling systems may be integrated to the SPVT designs in near future for possible enhancements in energy conversion efficiencies.

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