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Solar Photovoltaic Tree: Urban PV power plants to increase power to land occupancy ratio

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A B S T R A C T

With the day-by-day modernization, increasing electricity demand, and the restriction of climate change, more pressure is to search the renewable energy sources (Solar, Wind, etc.) and draw maximum power from them as it increases the need to develop Smart Cities, which have heavy electricity demand. For renewable energy power plant installations, one of the major difficulties is availability of land, as power plants like Solar photovoltaics have higher demand of open land, which is scarce in urban landscapes. In context of the problem statement of generating same electric power using less land, new models of Solar Photovoltaic Trees have been proposed, which can be used instead of conventional Solar PV plants. Simulations have been done on different SPV Tree models, concluding that very less land area is required to generate the same amount of electric power in comparison to conventional SPV plants, for example if a conventional ground − mounted model requires 300 m^2 area, but one of our proposed models; Daisy SPV Tree requires only about 13 m^2 area for generating the same electric power. Out of the total land area, other available space can be utilized for various purposes, which can be a solution for switching to renewables and can become very useful in urban landscapes. The possible designs are studied to get optimum "Power-to-Land occupancy Ratio" and "Land Coverage Ratio" with no additional power loss as compared to conventional ground-mounted Solar PV power plant and generate same amount of power using very marginal amount of land.

1. Introduction

The use of renewable energy (RE) sources to generate clean electricity is among the most urgent demand of the present day to protect the change in climate. These renewable energy sources include solar, wind, geothermal heat, bio energy, chemical and many other sources [1–3]. These sources require bigger land area for their installation; and till now solar photovoltaic (SPV) power plants have been installed on waste land, which is now unavailable in sufficient quantity in urban areas to generate electricity for sudden surge in power demand. Often the scarcity of available land is faced due to rapid urbanization, for which a different solution is needed to generate maximum power by utilizing minimum space. In such cases, for optimized output by utilizing most of the available land space for installation, a sustainable model (with combination of SPV Tree and SPV Artefact/tower structure along with energy storage) can be very beneficial. Despite its merits, SPV technology has issues of high land requirement and public perception (due to the absence of pleasing structural aesthetics). Therefore, SPV Tree structures may be one good option, to ensure access to reliable, sustainable and modern energy sources, providing a powerful aspiration for improving our world through sustainable development (as SDG7). As a solution for generation of more power from the minimum available land area in urban cities, authors have tried to provide a sustainable solution in the form of SPV Trees by proposing four different models of SPV Trees. The advantages of SPV Tree models over conventional ground mounted plants are discussed, providing a base for further research in RE integrated Smart City and sustainability applications along with a benchmark for selection of different renewable and alternative energy models.

SPV Tree is a compact system designed to produce electricity, essentially making use of a single or multiple number of PV modules, a charge controller, may be a battery bank for storage and an inverter circuitry to supply electrical loads, in case of off-grid system [4,5]. In case of a grid-connected system, the charge controller

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Abbreviations

GW	Giga Watt
kWp	kilowatt peak
LCOE	Levelized Cost of Energy
LCR	Land Coverage Ratio
MW	Mega Watt
PLR	Power-to-Land occupancy ratio
PV	Photovoltaic
RE	Renewable Energy
SPV	Solar Photovoltaic
STC	Standard Test Conditions
Wp:	Watt-peak

and battery bank are replaced by an on-grid inverter, which converts the DC power from PV modules to AC power and exports it to the grid. Depending on the electrical load demand and area of application, SPV Tree can provide single-phase or three-phase AC output. SPV Tree is an elegant and uniquely designed superstructure with PV modules installed to generate power for lighting, remote power, and feeding-tariff applications [6]. SPV Trees are setup where space availability is a major constraint and are constructed to maximize capture of sunlight in less space. As an example, Figure – 1 shows that instead of using car-parking area to install conventional car-parking SPV plant, SPV Trees with customized structure can be installed for generating electricity from the same parking area.

SPV Tree concept is rapidly gaining attention for achieving higher energy generation per unit ground footprint area but high shading losses and increased structural material requirements are major bottlenecks resulting in lower public acceptance [7]. Moreover, there is no standard structure for the solar trees; it can be creatively designed in order to make it's look pleasing to the public eye and consume less area while avoiding shading effect on leaves/panels [8]. SPV Tree structures are designed with various aims like aesthetics, latest technology demonstration, generation of renewable energy with minimum land occupancy, etc. Cao et al. [5] have discussed on the viability of assembling a “solar palm tree” based on organic solar cells on flexible polyethylene terephthalate (PET) substrates. Herein the main focus was to fabricate a flexible solar cell with leaf – like shape. Dey et al. [9] have proposed location/application specific tuning of solar power generation curve by appropriately orienting PV modules in a SPV Tree. Thus, the main aim is to optimize the irradiance available on the PV modules using different optical simulations. Further, Dey et al. [10] proposes a location specific design framework for maximizing electrical output with minimized structural material. The energy generation optimization is obtained after minimizing the shadow losses by optimizing the structural dimensions of SPV Tree, keeping all PV modules at different tilt angles.

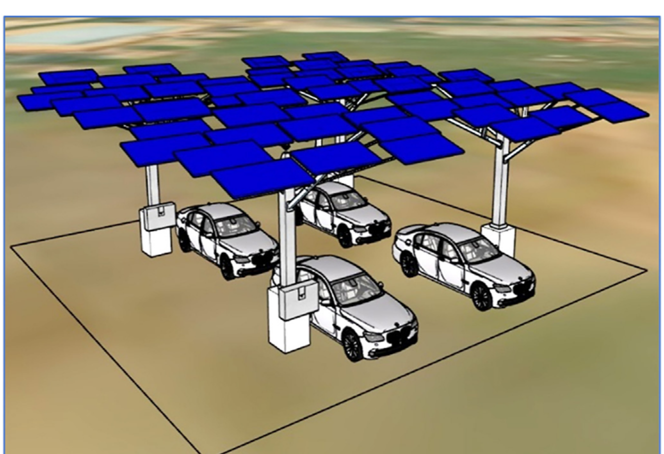


Figure-1. Graphical design layout for usage of car parking space for installation of Solar Tree models.

However, to best of our knowledge, not much research has been carried out to assess the design and other parameters of SPV Trees to provide smart solutions for constructing smart cities with high rise buildings [11–16]. Therefore, in current research article different types of possible designs are simulated, analyzed, and studied. Various parameters based on the proposed designs are compared with conventional ground-mounted PV structures. This provides advantages like high “Power-to-Land occupancy ratio” (PLR) and low “Land Coverage Ratio” (LCR) of the different proposed and optimized models of the SPV Trees saving a lot of land area, which can be utilized for other requirements. Hence, this research study focusses on designing techno-commercially feasible SPV Tree models in comparison to conventional ground-mounted SPV plants for maximum power generation using minimum land area. Considering same research and analysis work, the procedure and simulation studies and designing of suggested SPVT models are presented in section 2. Further the analysis, findings, and comparison in respected to various parameters, such as specifications, PLR, LCR, & Land Cost Comparison, are discussed in Section 3. Later, the outcomes and conclusions drawn from the present research work are provided in Section 4.

2. Simulation studies

In this simulation study authors have worked on a comparative study of different designs of SPV Tree v/s Conventional Ground-mounted Solar plant. The simulation study is done with the objectives of designing four different SPV Tree models and creating a comparative analysis of four SPV Tree models with conventional ground-mounted plant. Based on the comparative studies, we can conclude the best SPV Tree model based on “Power-to-Land occupancy ratio” (PLR) and “Land Coverage Ratio” (LCR). The simulation study is carried out to answer the problem statement of rapid urbanization in cities, leading to scarcity of available land along with increasing electricity demand. The aim is to also cater the problem of using land for installation of Solar plant but also keep it useable for other purposes by proposing a SPV plant model with increased PLR and lower LCR.

The simulation studies are carried out for Amity University Uttar Pradesh in Noida campus, India. GHI for the location considered in studies is 1737.4 kWh/m^2/year. Global Horizontal Irradiance (GHI), i.e., solar radiation received from Sun, is the addition of Direct Normal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI). DNI is the amount of irradiance received on a surface perpendicular to the rays of sunlight, whereas DHI is the irradiance received by that surface due to scattering of sunlight in the atmosphere. GHI can be represented by following equation (eq. (1)):

$$GHI = DNI\ x\ \cos(\theta_z)\ +\ DHI \tag{1}$$

where, θ_z is the zenith angle (angle between the normal to observer surface and a line joining the Sun and observer) [17]. Solargis software has been used to obtain the GHI data for this location. The GHI pattern over entire year can be seen in Figure – 2. It can be observed that the GHI decreases during the Winter months and is highest during the months of April and May.

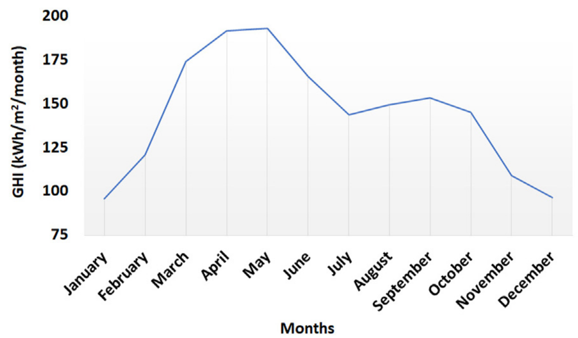


Figure-2. Monthly Global Horizontal Irradiance (GHI) pattern for Amity University Noida Campus.

2.1. Simulation study methodology

A comparative study has been designed to study about the difference between conventional ground mounted SPV plant and proposed SPV Tree designs. Location of reference for the simulation study is Amity University Uttar Pradesh in Noida campus, India (28°32′37.66"N, 77°19′59.43"E). Four different types of Solar Tree models and a conventional ground mounted SPV plant have been designed using Sketchup Pro software. Energy yield analysis of the proposed Solar Tree models has been performed in PVSyst software (version 7). A system with AC power rating of 20 kW (at normal test conditions) is considered and designed for all four Tree models and conventional ground-mounted plant. The power generated is assumed to be exported to Grid with unlimited load, and the comparison of electrical parameters has been carried out. The performance of SPV projects depends on the local climate and atmospheric conditions of the location of installation and the availability of solar radiation at the site [18]. As the angle of incidence of sunlight varies throughout the day, the PV modules need to be installed at an optimum tilt angle of 20° and 0° azimuth (for the selected location) to gain maximum energy [18].

SPV Tree comprises of a main metal support structure, on which PV modules are mounted on sub-structures/branches, just like the branches of a tree in real life. Just like a conventional ground mounted SPV plant, a SPV Tree has all the components i.e., PV modules, inverters, DC cables, AC cables, etc., but the main difference is the structural design. SPV Tree has multiple number of PV modules mounted on a structure which is supported by a single pole-like structure, whereas in ground mounted SPV plant the PV modules are mounted on a structure with two or three PV modules arranged in portrait orientation. As shown in Figure – 3, the total land area occupied by SPV Tree is the area occupied only by the Base/foundation of its structure [8]. The land area considered in simulation analysis is the effective land area occupied by the base foundation of the structure (which cannot be used for any other purpose) and not the available land area at the project location. The structural simulation analysis for base foundation has been performed using STAAD Pro software. In the current simulation studies, the four best possible SPV Tree models are proposed and named as, Tulip Tree, Sunflower Tree, Marigold Tree, and Daisy Tree. The comparative design of SPV Tree v/s ground mounted plant can be seen in Figure – 4, to have a clear understanding on the overview of their layout.

2.2. Designing of SPV tree models

The four different types of possible designs for SPV Trees are proposed and simulated using Sketchup and PVSyst simulation software, to provide a sustainable solution for the RE integrated smart cities. The models are analyzed and optimized considering electrical, structural and land acquisition parameters. The design and structure layout of consider four models are discussed in the following section. Each SPV Tree model is provided with a particular name, due to its analogy to flower like design.

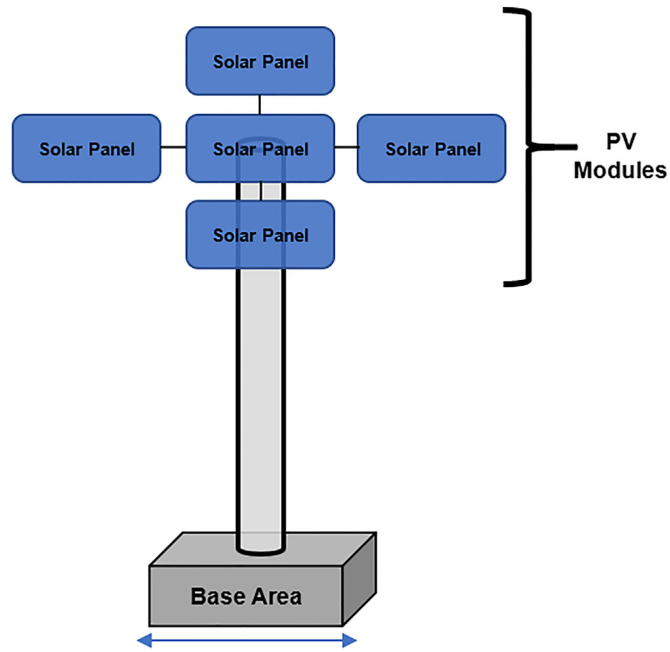


Figure-3. Schematic layout for land area ratio of SPV tree.

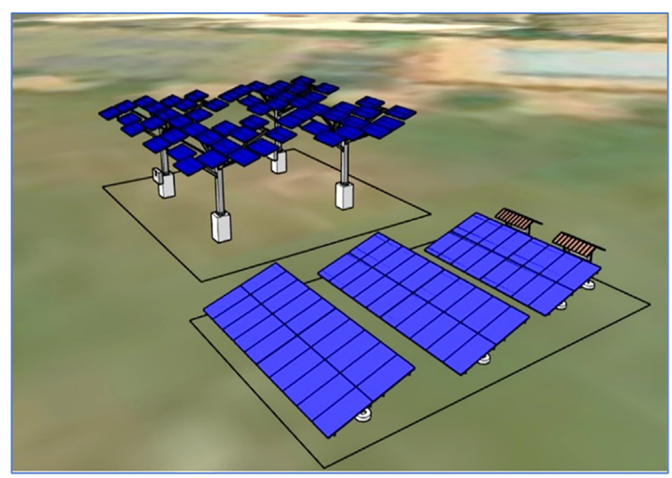


Figure-4. Graphical representation for Solar Tree v/s Ground-mounted plant.

2.2.1. Tulip SPV Tree model

Tulip Tree model is a conceptual SPV Tree model, named after Tulip flower. It has a main support pole structure, which distributes into two branches, which can accommodate 6 PV modules in each branch. In this design, the PV modules selected are monocrystalline type (with 72 cells) and of 380 Wp power rating (at STC), and total 12 PV modules can be accommodated in one SPV Tree, which results into 4.56 kWp DC capacity at STC. The land area occupied by the foundation of this model is 5 m^2, hence the land area requirement per kWp of power generated, for this model is

1.096 m^2/kWp. The ground clearance (from lowest edge of SPV module) is approximately 4 m. The specific yield of this Solar Tree model is 1554 kWh/kWp/year (as simulated using PVSyst version – 7 software). In our simulation study, Tulip SPV Tree is installed at 0° azimuth and the tilt angle of SPV modules is 20° (which is usually considered for Delhi NCR location). The conceptual graphical layout of Tulip SPV Tree can be seen in Figure – 5. A graphical representation of an average human with 1.67 m height is shown alongside the Tulip SPV Tree structure for scale.

A group of 5 Tulip SPV Trees can be combined to form a system of 22.8 kWp (at STC). One 20 kW inverter is taken to form a system with AC capacity of 20 kW. The inverter can be mounted on the base of the Tree or can be placed on a separate inverter stand. The DC cables can be routed using flexible cable conduits, clamped along the branches of the tree structure. The SPV Tree can be arranged according to the desired azimuth and PV modules at a specific tilt angle to get maximum energy generation as per the location of installation. Figure – 6 shows the experimental setup for a system of 20 kW (AC), as a part of our simulation study.

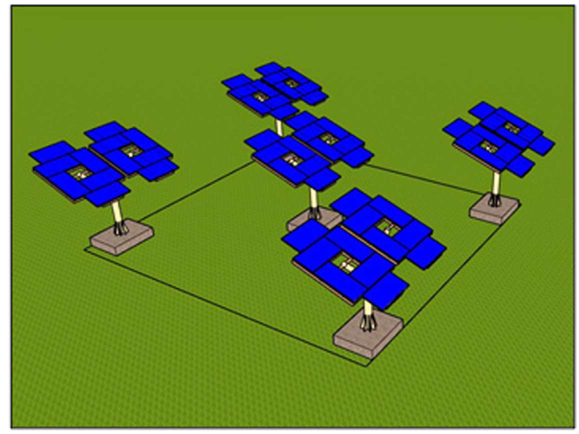


Figure-6. Layout of Tulip SPV Trees for a 20 kW system.

2.2.2. Sunflower SPV Tree model

Sunflower SPV Tree model is named after Sunflower, as the PV modules are arranged like the flower petals of a sunflower plant. A main support structure is there, which is bent at required angle at the top portion to achieve required tilt angle for PV modules, as per the location of installation. As compared to Tulip SPV Tree where the branches are tilted, here the main support structure itself is tilted as there is only one branch. In this design, the PV modules selected are mono-crystalline type (with 72 cells) and of 380 Wp power rating (at STC), and total 10 PV modules can be accommodated in one SPV Tree, which results into 3.8 kWp DC capacity at STC. The land area occupied by the foundation of this model is 4 m^2, hence the land area requirement per kWp of power generated, for this model is 1.052 m^2/kWp. The ground clearance (from lowest edge of SPV module) is approximately 4 m.

The specific yield of this Solar Tree model is 1560 kWh/kWp/year (as simulated using PVSyst version – 7 software). In our simulation study, this SPV Tree is installed at 0° azimuth and the tilt angle of PV modules is 20° (same as Tulip SPV Tree). The conceptual graphical layout of this SPV Tree can be seen in Figure – 7. A graphical representation of an average human with 1.67 m height is shown alongside the Sunflower SPV Tree structure for scale. As shown in Figure – 8, a group of 6 Sunflower SPV Trees can be combined to form a system of 22.8 kWp (at STC). One 20 kW inverter is taken to form a system with AC capacity of 20 kW. The inverter can be mounted on the base of the Tree or can be placed on a separate inverter stand and the DC cables can be routed using flexible cable conduits, clamped along the branches of the tree structure.

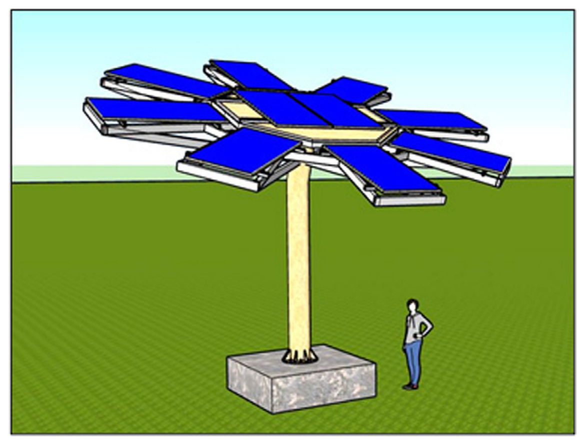


Figure-7. Graphical layout design of Sunflower SPV Tree Model.

The main advantage of this design is that the model looks like a Sunflower. Due to this, this model can be utilized in public recreational areas in cities like parks, playgrounds, stadiums, and car

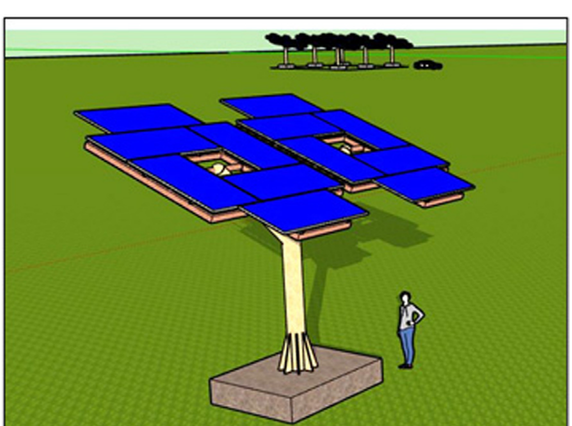


Figure-5. Graphical layout design of Tulip SPV Tree model.

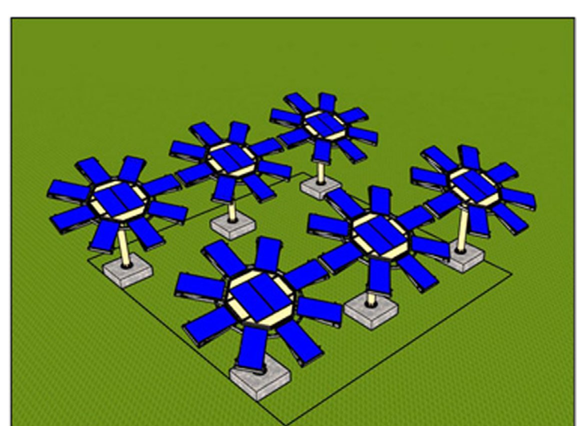


Figure-8. Layout of Sunflower SPV Trees for a 20 kW system.

parking. In parks, playgrounds, or car-parking area, Sunflower SPV Tree can also be fitted with streetlights. On traffic signals, a small cabin can be built around the main support structure and fans and lights can be fitted, so that the policemen can sit in the cabin. This design has a single support structure, which can also be fitted with a dual axis tracker system, so that the tree always faces the Sun and follows its path, to further optimize energy generation.

2.2.3. Marigold SPV Tree model

Marigold SPV Tree model is named after Marigold flower, as the structure branches in the tree model are arranged like the petals of Marigold flower. A main support structure (vertical pole type arrangement) is there, which supports the branches on which PV modules are installed. The branches are inspired from the branches of real-life trees.

In this design, the PV modules selected are mono-crystalline type (with 72 cells) and of 380 Wp power rating (at STC), and total 15 PV modules can be accommodated in one SPV Tree, which results into 5.7 kWp DC capacity at STC. Each branch of the Marigold Tree holds 3 PV Modules, which are arranged at a specific tilt angle, according to location of installation. The land area occupied by the foundation of this model is 5.76 m^2, hence the land area requirement per kWp of power generated, for this model is 1.01 m^2/kWp. The ground clearance (from lowest edge of SPV module) is approximately 4 m. The specific yield of this Solar Tree model is 1561 kWh/kWp/year (as simulated using PVSyst software).

In our simulation study, this SPV Tree is installed at 0° azimuth and the tilt angle of PV modules is 20° (same as previous two SPV Trees). The conceptual graphical layout of this SPV Tree can be seen in Figure – 9. A graphical representation of an average human with 1.67 m height is shown alongside the Marigold SPV Tree structure for scale. As shown in Figure – 10, a group of 4 Marigold SPV Trees can be combined to form a system of 22.8 kWp (at STC). One 20 kW inverter is taken to form a system with AC capacity of 20 kW. The inverter can be mounted on the base of the Tree or can be placed on a separate inverter stand and the DC cables can be routed using flexible cable conduits, clamped along the branches of the tree structure.

2.2.4. Daisy SPV Tree model

Daisy Tree model is the fourth proposed design, as a part of this simulation study. The PV modules are arranged in landscape orientation, to optimize DC cable quantity. This Tree has a single support structure, which supports all the PV modules. In this design, the PV modules selected are mono-crystalline type (with

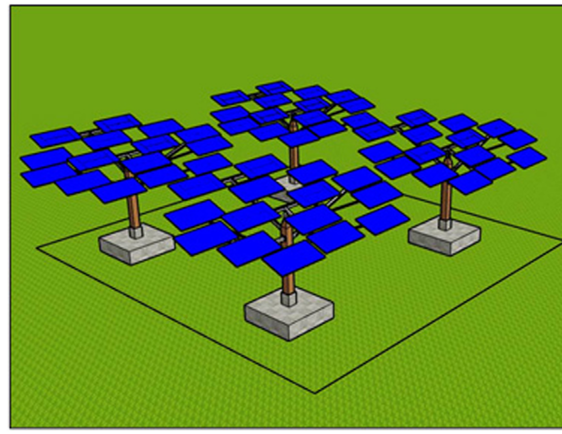


Figure-10. Layout of Marigold SPV Trees for a 20 kW system.

72 cells) and of 380 Wp power rating (at STC), and total 15 PV modules can be accommodated in one SPV Tree, which results into 5.7 kWp DC capacity at STC. The land area occupied by the foundation of this model is 3.33 m^2, hence the land area requirement per kWp of power generated, for this model is 0.58 m^2/kWp.

Here, the area occupied by the foundation is lesser than all the three SPV Tree models described in previous sections, because the foundation is installed deeper inside the ground in comparison, hence there is less part of the foundation above ground. The ground clearance (from lowest edge of SPV module) is approximately 4 m. The specific yield of this Solar Tree model is 1561 kWh/kWp/year (as simulated using PVSyst version – 7 software). In current simulation study, this SPV Tree is installed at 0° azimuth and the tilt angle of PV modules is 20° (same as previous two SPV Trees). The conceptual graphical layout of this SPV Tree can be seen in Figure – 11. A graphical representation of an average human with 1.67 m height is shown alongside the Daisy SPV Tree structure for scale.

As shown in Figure – 12, a group of 4 Daisy SPV Trees can be combined to form a system of 22.8 kWp (at STC). One 20 kW inverter is taken to form a system with AC capacity of 20 kW. The inverter can be mounted on the base of the Tree or can be placed on a separate inverter stand and the DC cables can be routed using flexible cable conduits, clamped along the branches of the tree structure. One major advantage of this Tree design is that we can easily integrate double axis tracker system in the structure, to further increase the energy generation, if required. The PV Modules

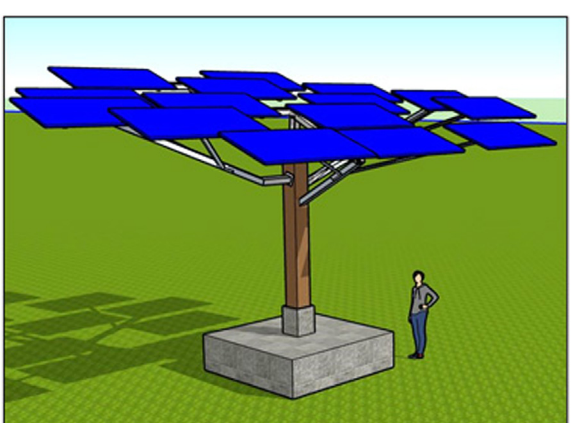


Figure-9. Graphical layout design of Marigold SPV Tree Model.

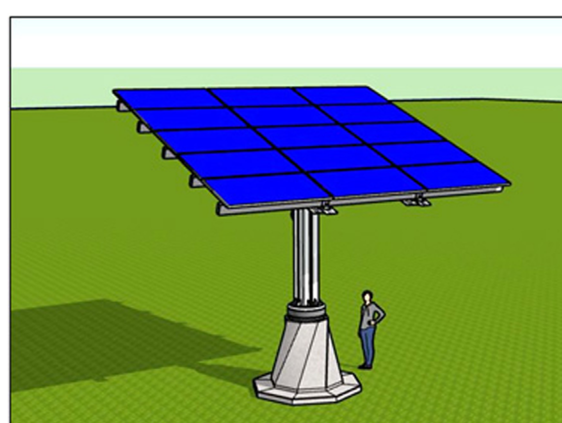


Figure-11. Graphical layout design of Daisy SPV Tree Model.

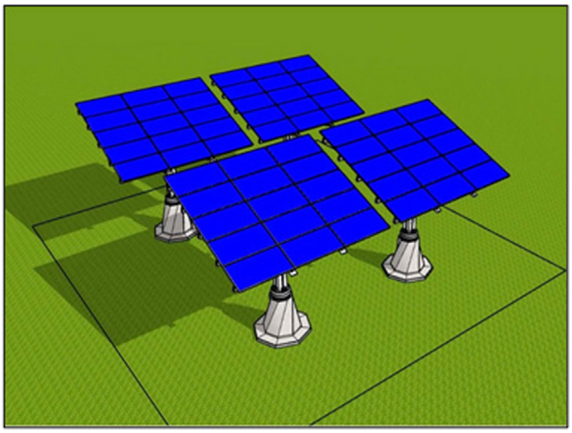


Figure-12. Layout of Daisy SPV Trees for a 20 kW system.

are mounted on one single frame; hence the integration of tracker mechanism can be done very easily.

2.2.5. *Conventional ground-mounted solar PV plant*

A conventional ground-mounted SPV plant has also been designed as a part of this simulation study, to do a comparative analysis with the proposed models of SPV Tree. Herein, the PV modules are arranged in 2P5 pattern on ground, with 0.5 m ground clearance. The structure is supported on ground using pile foundations. Each structure uses two pile foundations on ground. The inverters are usually mounted on the structure at the backside of PV modules or on a separate inverter-stand near the PV modules. Conventional ground-mounted structure has PV modules very near to ground, hence there is less air ventilation around the PV modules as compared to the Solar Tree arrangement. Figure – 13 and 14 show the conventional ground mounted solar power plant structure.

Each structure has 10 PV modules, arranged in portrait orientation, at 20° tilt and 0° azimuth. Ten PV Modules in each structure form a DC capacity of 3.8 kWp (at STC). In this simulation study, six structures of 2P5 type are grouped together to form a system of 22.8 kWp DC capacity. A 20 kW inverter is used to convert the DC power generated from PV modules to AC power output.

3. Results and discussion

The concept of Solar Tree is related to renewable energy generation as well as decorative aesthetics; hence the proposed

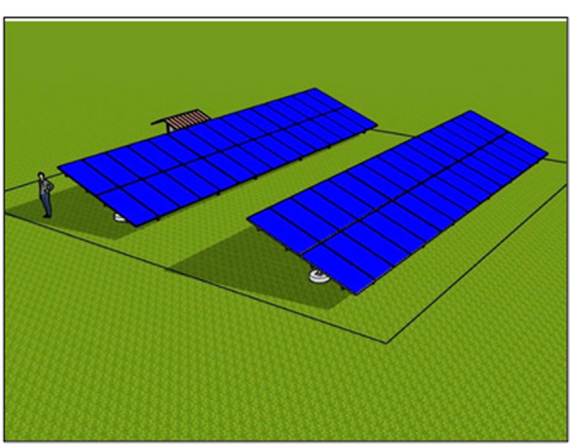


Figure-13. Conventional Ground-mounted Solar plant.

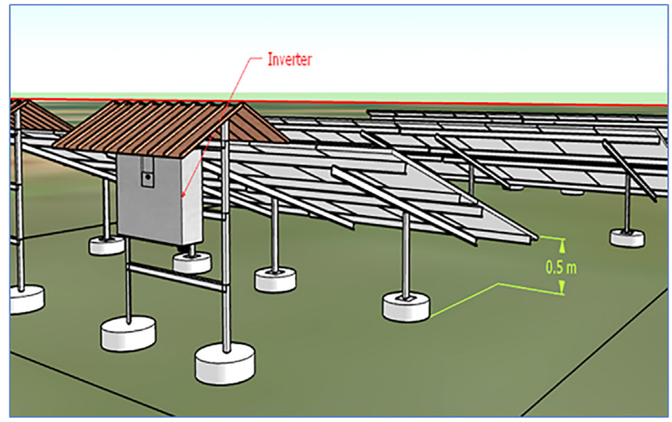


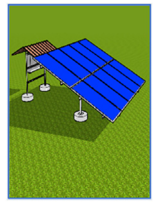
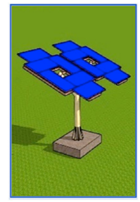
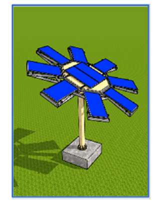
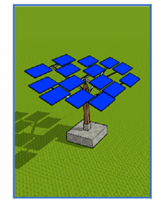
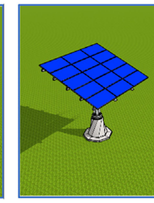
Figure-14. Inverter mounting arrangement in Conventional Ground-mounted Solar plant.

designs of SPV Trees in the present research work will provide a sustainable solution for the RE integrated smart & modern cities. The four SPV Tree designs, i.e., Tulip Tree, Sunflower Tree, Marigold Tree, and Daisy Tree, are designed, simulated, and optimized using simulation softwares Sketchup and PVSyst. Based on the design of all SPV Tree models and conventional ground mounted system discussed in Section-2.2, a basic comparison between the different designs of SPV Tree with conventional ground-mounted SPV plant is carried out as described in Table-1. Through the simulation studies, authors have analyzed the power generation and annual specific yield of each SPV Tree design.

For ease of comparison, the DC and AC capacity of all four SPV Tree systems and conventional ground-mounted system is kept same, i.e. 22.8 kWp and 20 kW, respectively. For this, the number of structures in the system simulated for each SPV Tree model and conventional ground-mounted plant model are different (as indicated in point – 4, Table 1). The tilt angle of PV modules in all models is same, but the mutual shading loss is different in all the models, due to the difference in PV module arrangement and pitch, which leads to difference in energy generation of all the models in simulation. Correlations and elaboration of the parameters discussed in Table-1 are as follows:

1. **Ground clearance:** Ground clearance for each Solar Tree design is kept as 4 m on an average, which is high enough to allow the dual usage of land beneath SPV Trees and not too high to increase the structural cost [19]. However, the ground clearance can be adjusted according to specific operational and/or situational requirements. Conventional ground-mounted type of structure is robust and widely used in the world for installation of SPV plants, due to the cost-effectiveness, but with a major drawback that the land on which it is installed becomes unusable for any other purpose because of low ground clearance. As this simulation study is in a conceptual stage wherein the SPV Tree models are designed using 3D modelling, the base foundation dimensions are calculated based on preliminary structural analysis in STAAD pro software. Further, the higher ground clearance in SPV Trees may give an additional advantage that there shall be higher air flow beneath the PV modules, so should providing enhanced cooling to the PV modules, which could result into lesser temperature losses as compared to conventional ground mounted plants.
2. **Pitch:** While designing each SPV Tree models, the most important parameter is pitch between two structures (adjacent SPV Trees). For each model, the pitch is optimized to keep

Table-1
Electrical comparison of SPV Tree v/s Ground-mounted Solar PV plant.

Sr. No.	Particulars	Ground – Mounted plant	Tulip Tree	Sunflower Tree	Marigold Tree	Daisy Tree
1.	Graphical Representation					
2.	Each PV Panel's rating (Wp)	380	380	380	380	380
3.	Inverter rating (kW)	20	20	20	20	20
4.	Total No. of PV Structures simulation	6	5	6	4	4
5.	Total DC Capacity (kWp)	22.8	22.8	22.8	22.8	22.8
6.	Total AC Capacity (kW)	20	20	20	20	20
7.	GHI (kWh/m^2/year)	1737.4	1737.4	1737.4	1737.4	1737.4
8.	Mutual Shading Loss (%)	0.560	0.669	0.422	0.508	0.419
9.	Annual Energy Output (P50) (kWh)	35536	35424	35570	35595	35597
10.	Specific Yield (P50) (kWh/kWp/year)	1559	1554	1560	1561	1561
11.	Ground Clearance *(height of solar panels from ground)* (m)	0.5	4	4	4	4
12.	Pitch between two structures (m)	8.5	7	10	10	9
13.	Total Land Area required (m^2)	300	25	24	23.04	13.344
14.	Land Area required per kWp (m^2/kWp)	13.16	1.09	1.05	1.01	0.58
15.	Power to Land Ratio	0.07 : 1	0.91 : 1	0.95 : 1	0.99 : 1	1.7 : 1

mutual shading loss at an optimum level. Through shadow analysis in Sketchup Pro software, the optimum pitch has been set to ensure the PV modules remain shadow-free from 9 a.m. to 4 p.m. for entire year. The pitch of conventional ground-mounted system is 8.5 m, and pitch of Daisy SPV Tree, Sunflower SPV Tree, Marigold Tree, and Tulip Tree are 7, 10, 10 and 9 m, respectively (as indicated in point – 12, Table 1).

3. **Land requirement:** The land occupancy of all the models in this simulation is different, depending upon their respective structural design. Land occupancy footprint of Tulip Tree is approximately 91.7% lesser than that of the conventional ground-mounted solar plant, as only 1.09 m^2 area is required to generate 1 kWp power. In Sunflower Tree model, the land occupancy footprint is approximately 92% lesser than that of the conventional ground-mounted solar plant, as only 1.05 m^2 area is needed to generate 1 kWp power, in comparison to 13.16 m^2 area required by conventional ground-mounted solar plant. In Marigold Tree model, the land area requirement is 1.01 m^2 per every 1 kWp, which is approximately 92.3% lesser than that of the conventional ground-mounted solar plant. In Daisy Tree model, all PV modules are mounted on a single frame. Daisy Tree model has land requirement of 0.58 m^2, to generate 1 kWp of power.

The 22.8 kWp system for all the SPV Tree models is considered based on group of structures as shown in Figure – 6, 8, 10 and 12. From the simulation study, it has been analyzed that as land is always expensive and the land prices will keep on rising with time and more urbanization. SPV Tree is an effective and sustainable solution for places with scarcity of land availability and high electricity requirements (due to high-rise buildings and densely populated regions), as the proposed designs of SPV Trees have very less land requirement for producing same amount of energy as compared to conventional ground-mounted Solar plant.

3.1. Power-to-land occupancy ratio (PLR) analysis

An important factor of this simulation study is the total land area required for installation of the SPV Trees. To understand the same, the simulation studies were conducted by considering a system with 20 kW (AC) capacity, using all four SPV Tree models. The requirement of land area for our proposed and optimized SPV Tree models are further compared to the standard & industrial layout of the ground-mounted SPV power plants of 20 kW (AC) capacity. Through the analysis, it has been observed that in comparison to the land area for ground-mounted plant, i.e., 300 m^2, the values of SPV Tree models are much lesser, i.e., 25, 24, 23.04 and 13.34 m^2, for Tulip Tree, Sunflower Tree, Marigold Tree, and Daisy Tree, respectively (as shown in Table – 1). Therefore, the land area required per kWp is evaluated as discussed in previous section and is found to be 1.09, 1.05, 1.01 and 0.58 m^2/kWp, for Tulip Tree, Sunflower Tree, Marigold Tree, and Daisy Tree, respectively, as compared to 13.16 m^2/kWp for ground-mounted PV plant (as shown in Figure – 15 and point – 14 in Table – 1). This reflects the huge difference during consideration of land area required for large scale RE power plants to fulfill the requirements of densely populated smart cities.

Most vital factor which represents the significance of implementation SPV Tree in urbanized cities is the “Power-to-Land occupancy Ratio” (PLR). The PLR factor talks about the maximum DC power generation at proposed/target land area (which cannot be utilized for any other applications). PLR is the ratio of DC power generated to the land area occupied by the structure of SPV system

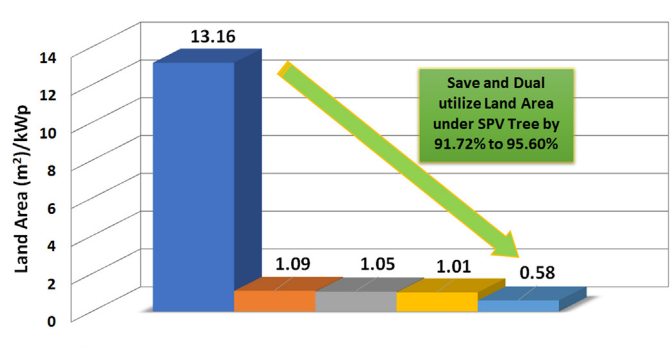


Figure-15. Land Area required per kWp for 20 kW Solar PV system.

installed (which becomes unusable for any other purpose). As seen in Table – 1, PLR obtained is 0.91:1, 0.95:1, 0.99:1 and 1.7:1, for Tulip Tree, Sunflower Tree, Marigold Tree and Daisy Tree, respectively. From simulation studies, it has been clearly seen that for considered ground – mounted SPV Plant, the PLR is significantly low (0.076:1). Thus, as compared to conventional ground-mounted plant, SPV Tree can produce same amount of energy by taking only a small fraction of the land area.

The graph shows how much more power can be generated by each model for every m^2 of land area occupied. Here, Power Generation v/s Land Area requirement graph for all the SPV Tree models increases linearly. As an illustration, when the base foundation of all SPV Trees occupies land area of 100 m^2, the SPV Trees: Tulip, Sunflower, Marigold and Daisy generate power of 91.2 kWp, 95 kWp, 99 kWp and 170 kWp, respectively. Whereas, in 100 m^2 area a conventional ground-mounted plant will generate only 7.6 kWp, which is very less in comparison.

Figure – 16 illustrates that the specific energy yields of all SPV Tree models is almost matching with that of conventional ground-mounted plant. Thus, the same capacity of SPV plant can be installed in different ways, without compromising the energy generation. Therefore, by the PLR analysis, we can conclude that by using SPV Trees, we can get a high PLR using SPV Trees, versus the conventional case.

3.2. Land Coverage Ratio (LCR) analysis

Another important factor like the Power to Land occupancy Ratio (PLR), for the proposed simulation study is “Land Coverage Ratio” (LCR), which is the ratio of land area occupied by the structures (which becomes unusable for any other purpose) to the total land area available at the project site (area occupied by structure/foundation of SPV Tree can be seen in graphical representation in Figure – 3). For LCR analysis, simulation studies were conducted for a scenario of a larger urban landscape of 3.2 Acre (approximately 13,160 m^2) for analyzing higher capacity SPV power plants.

In this case, a system of 1 MW capacity in a land area of 3.2 Acre was designed and simulated using Sketchup Pro software, for all four SPV Tree models and compared with a system of similar rating in the same land area for conventional ground-mounted power plant, whose graphical layout is as shown in Figure – 17. The summarized comparison between the system designed using the four SPV Tree designs with conventional ground-mounted SPV plant is carried out and described in Table-2.

From Table-2 and Figure – 17, among all four SPV Tree models, Daisy Tree has the lowest Land Coverage Ratio (LCR) and the

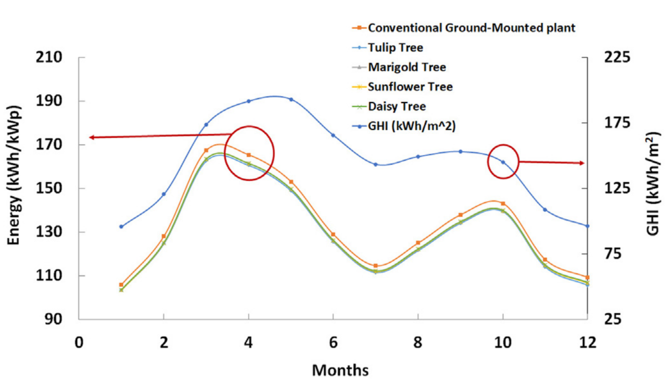


Figure-16. Monthly Energy Yield Comparison of SPV Tree models v/s Conventional ground-mounted plant.

highest Power to Land occupancy Ratio (PLR). Conventional ground-mounted SPV plant has the highest LCR and the lowest PLR. This means, for a conventional ground-mounted plant, the land area covered by the plant entirely becomes unusable for any other purpose. The PLR increases in case of SPV Trees, as the area covered by foundation is only unusable and rest of the land is available for other purposes (refer Figure – 3).

From Figure – 18, it can be seen that for a land area of 3.2 Acre, different SPV Trees can be installed in different ways and the height of their structure can be customized as required, so that the land area which is not occupied by the foundation blocks can be utilized for various purposes (for example, EV charging station in a car-parking, as shown in Figure – 1). It can be seen in Table-2 and Figure – 18, that the LCR for the SPV Tree models: Tulip, Sunflower, Marigold and Daisy are 0.083, 0.08, 0.077, and 0.044, respectively.

The main aim behind designing of SPV Trees is to obtain a SPV Tree model with the lowest LCR and the highest PLR. In urban landscapes, a land area which is being used for some other purpose can be taken and only a small part of that land can be used for installing foundation blocks of SPV Trees, while keeping remaining land area available for other purposes, so that the cost of entire land is not included in the capital expenditure of the SPV power plant being installed. As shown in the results of this simulation study, we can thus conclude with a solution to our problem statement of generating more energy using less land by installing SPV Trees. The number of PV modules in a single SPV Tree structure can be further increased as per requirement by increasing the number of branches and further reducing the land area consumption per kWp power generated and increasing the PLR. PV modules can be arranged at a tilt angle and azimuth as per our requirement, as compared to fixed type structure in conventional ground-mounted plants where the tilt angle and azimuth of each individual module cannot be changed separately. All the studies being done on SPV Tree concept are aimed at creating a balance between aesthetics, energy generation, system function, and technology.

3.3. Land Cost Comparison

In addition to the comparison of LCR, the cost analysis and comparison of land occupancy can be carried out for all four proposed SPV Tree models w.r.t. conventional ground-mounted SPV plants. Considering the metropolitan city, Delhi and the region of NCR (National Capital Region) in India, as per the prevalent market rates, the cost of non-agricultural land procurement is, say, approximately $215 per m^2 [20]. As shown in Table-2, the land area occupied by conventional ground-mounted SPV plant is 13,160 m^2. In case of conventional ground-mounted SPV plant, the entire land area is consumed and becomes unusable for any other purpose and the cost of land procurement shall be around $2.82 Million. For example, if in Delhi a 1 MWp SPV plant installation is to be done along with an EV-charging station in a land area of 13,160 m^2, then in case of a conventional ground-mounted SPV plant, the entire 13,160 m^2 land area needs to be purchased for the SPV plant and in addition to that, another say, 13,160 m^2 land needs to be purchased for setting up EV-charging station, resulting in a total land purchase of 26,320 m^2, because the LCR of conventional ground-mounted SPV plant is 1:1. A comparison of the land procurement cost for conventional PV plant with SPV Tree designs can be seen in Table-3, as follows:

In point-2 of Table-3, the land area occupied by the respective SPV installation can be calculated from the PLR as mentioned in Table-2. The additional land area (point – 3, Table-3) that needs to be procured for setting up EV-charging station is constant in all the cases. As the land area occupied by conventional ground-mounted SPV plant becomes unusable for any other purpose, the land area

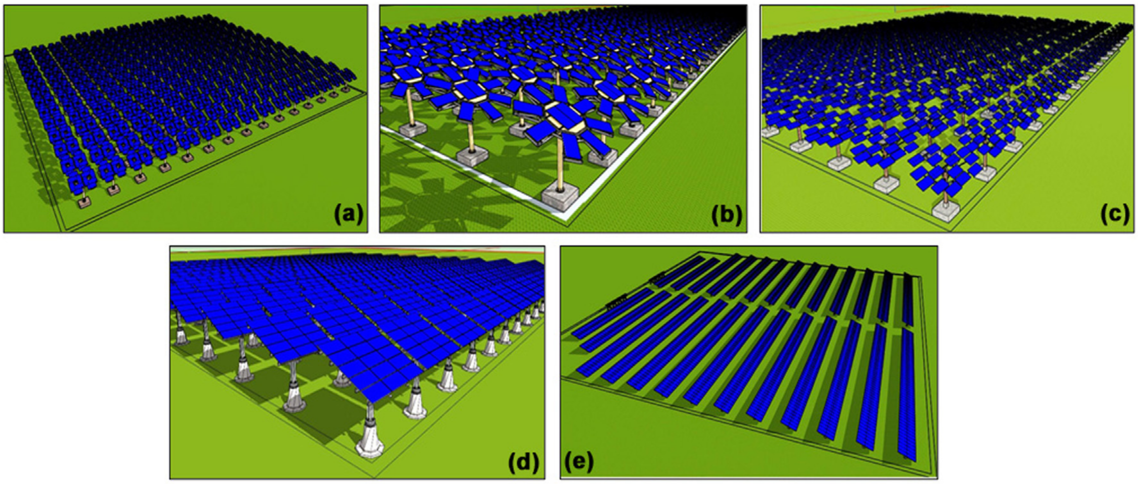
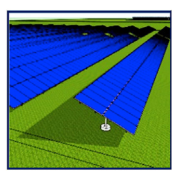
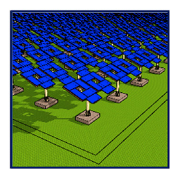
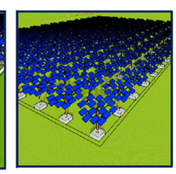
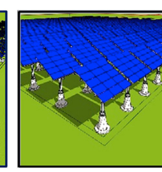


Figure-17. Graphical Layout of SPV Tree models – (a) Tulip Tree, (b) Sunflower Tree, (c) Marigold Tree, (d) Daisy Tree, and (e) conventional ground-mounted power plant, for a system of 1 MW in a land area of 3.2 Acre.

Table-2
Solar Tree v/s Ground-mounted Solar PV plant for a land area of 3.25 Acre.

Sr. No.	Particulars	Ground – Mounted plant	Tulip Tree	Sunflower Tree	Marigold Tree	Daisy Tree
1.	Graphical representation of plant layout					
2.	Land area considered (m^2)	13,160	13,160	13,160	13,160	13,160
3.	Plant Capacity that can be installed in 3.26 Acre area (kWp)	1 MW	1 MW	1 MW	1 MW	1 MW
4.	No. of structures required	264	220	264	176	176
5.	Land area occupied by base of the structures (m^2)	13,160	1100	1056	1013.76	587.13
6.	Land area that is free for use in other purposes (m^2)	0	12,060	12,104	12,146.24	12,572.87
7.	Land Coverage Ratio (LCR) (Land occupied: Land available)	1 : 1	0.083 : 1	0.080 : 1	0.077 : 1	0.044 : 1
8.	Power to Land Ratio (PLR)	0.07 : 1	0.91 : 1	0.95 : 1	0.99 : 1	1.7 : 1

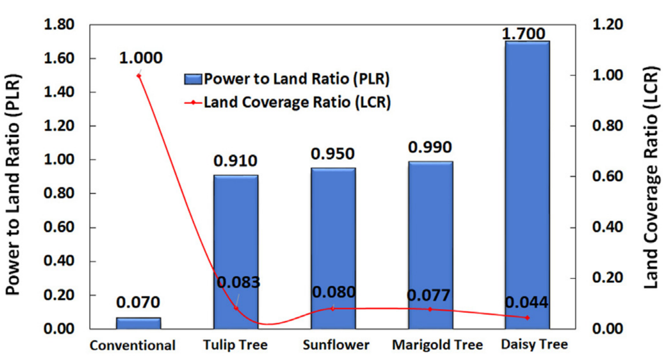


Figure-18. Land coverage ratio (LCR) v/s Power to Land occupancy Ratio (PLR).

requirement becomes double, i.e., 26,320 m^2 for setting up a combination of EV-charging station whereas, in case of SPV Tree models, the land beneath the SPV Tree structures which is not occupied by the base foundation of the structures can be utilized for setting up EV-charging station as the ground-clearance of each SPV Tree is sufficient to allow the electric vehicles to pass through. Hence, separate land needs to be procured only to compensate the area occupied by the base foundations of SPV Tree structures. Thus, it can be concluded that the % saving of land procurement cost in case of Tulip Tree, Sunflower Tree, Marigold Tree and Daisy Tree is 84.57%, 85.14%, 85.70% and 91.46% respectively (refer point-6 in Table-3). The money saved by the reduction in land area procurement can be utilized in the capital investment for procurement of the SPV installation and maintenance, accordingly. Also, as the current simulation study is on a conceptual level, the cost comparison analysis for land procurement can be helpful during the capital cost comparison of installation and also the comparison of operational costs of all four SPV Tree models with that of conventional ground-mounted SPV plant, post working out of a proof-of-concept (POC) in future.

The detailed analysis of four proposed SPV Trees is given in Table-1 and Table-2 and some comparative advantages and disadvantages of these models are described in Table-4. Energy yield optimization by designing SPV Tree with PV modules in different orientations and a SPV Tree model with increased number of PV modules, in single structure and optimization of the SPV Tree models using CFD analysis are proposed as a part of future scope to take this simulation study further.

Table-3
Land procurement cost comparison in SPV Tree models v/s conventional ground-mounted SPV plant.

Sr. No.	Particulars	Ground – mounted plant	Tulip Tree	Sunflower Tree	Marigold Tree	Daisy Tree
1.	SPV Plant Capacity to be installed	1 MWp	1 MWp	1 MWp	1 MWp	1 MWp
2.	Land area occupied by the SPV plant installation (m^2)	13,160	1100	1056	1013.76	587.13
3.	Additional land that needs to be procured to set up EV charging station (m^2)	13,160	13,160	13,160	13,160	13,160
4.	Total land area that needs to be procured (m^2)	26,320	14,260	14,216	14,173.76	13,747.13
5.	Total cost of land procurement	\$5.66 Million	\$3.07 Million	\$3.06 Million	\$3.05 Million	\$2.96 Million
6.	% saving of land procurement cost as compared to conventional ground-mounted SPV plant	0%	84.57%	85.14%	85.70%	91.46%

Table-4
Pros and Cons of SPV Tree v/s Ground-mounted Solar PV plant.

S. No.	SPV Tree	Ground – mounted Solar plant
1.	PV Modules are mounted with higher ground clearance	PV Modules are mounted with lower ground clearance
2.	Occupies very less land	Occupies more land area
3.	Land area below the SPV Tree can be used for various uses (car parking, agriculture, EV charging station, park, etc.)	Land cannot be used for any other purpose as it is entirely covered by Solar Plant
4.	More energy generation by using very less space	Comparatively less energy generation per unit area of land occupied
5.	Best suited for urban landscapes with high lack of available space. Can also be used in agricultural land	Best suited for open un-used and non-agricultural ground
6.	Module Mounting Structure weight is higher	Module Mounting Structure weight is comparatively less
7.	Increased DC cable quantity (if inverters are mounted at ground level)	Comparatively less DC cable quantity required
8.	Lower near shading losses as the PV modules are mounted higher	Near shading losses may go high due to nearby shadow casting objects as PV modules are mounted at ground level
9.	Aesthetically pleasing structure	Conventional type structure

Current research studies going on across the world for various possible designs of SPV Trees are for sole aim of providing sustainable solution in urban areas where there is scarcity of land. SPV Trees find applications in various areas as follows [21]:

1. Urban city areas: To meet electricity demand of residential houses in urban areas. All SPV Trees in one housing area can be connected virtually to form a virtual power plant
2. Rural areas: To provide electricity to rural areas where there is no consistent grid
3. Hilly areas: SPV Trees can be set up in hilly areas to provide electricity and avoid transmission lines in difficult land terrain
4. Remote islands: SPV Trees can be set up in remote islands, to generate electricity instead of using Diesel generators
5. EV Charging stations: SPV Trees can be used to set up EV charging stations which are self-sustainable as the energy used for charging EV's can be generated using Solar Trees
6. Car Parking: SPV Trees can also be used in car port structures for a dual purpose of providing a shade for parked vehicles as well as generate energy.
7. Agrivoltaics: SPV Trees can also be used in Agrivoltaics, to use the land below Solar Trees for farming and other agricultural use
8. Ships: SPV Trees can be installed on large ships, to use sunlight for illumination and auxiliary electricity consumption in the ship instead of using generators connected to the engine which runs by burning fossil fuels
9. Industrial buildings (RCC roofs) with less roof space
10. Smart Cities in urban landscapes where land availability is extremely scarce

4. Conclusion

Till now the concept was to use the waste land to install the solar PV plants. Now, due to increase in GHG emission, the pressure is to replace most of the energy sources by the renewable sources. Specially, with an idea of having smart cities, it is very difficult to install the SPV plants in the urban area and occupy too much of land. With this idea of using minimum land and to produce maximum amount of electricity using solar PV plants, the SPV Tree may be the best and optimized solution. SPV Tree design is a blend of combining renewable energy generation (the technology) with nature inspired art (art in the design). The main purpose behind usage of Solar Tree is to provide a sustainable and green energy resource to urban landscapes, where availability of land is scarce, and land costs are skyrocketing, which creates a very heavy impact on the return of investment. Considering same, four best possible SPV Tree models are proposed and named as, Tulip Tree, Sunflower Tree, Marigold Tree, and Daisy Tree. The detailed simulation studies and comparative analysis of SPV Tree models, w.r.t. the conventional-ground mounted PV plant have been carried out. As a result of the simulation studies, the Tulip SPV Tree has LCR of 0.083 and PLR of 0.91, Sunflower Tree has LCR 0.08 and PLR 0.95, Marigold Tree has LCR of 0.077 and PLR of 0.99, Daisy Tree has LCR of 0.04 (lowest among all 4 models) and PLR of 1.7 (highest among all 4 models). However, in comparison to optimized SPV Tree models, the conventional ground-mounted plant has LCR of 1.0 and PLR of 0.076. Further, the % saving of land procurement cost in case of Tulip Tree, Sunflower Tree, Marigold Tree and Daisy Tree are 84.57%, 85.14%, 85.70% and 91.46%, respectively, as compared to land cost in a conventional ground – mounted SPV plant, promoting dual usage of land. Therefore, the money saved by the reduction in land area procurement can be utilized in any other capital investment, like procurement of SPV panels, construction, installation, maintenance, etc, accordingly. With the proposed SPV Tree models, the simulation studies prove that we are able to generate same amount of clean electricity with minimal amount of land usage as compared to conventional ground – mounted PV plants i.e., we can achieve lowest LCR and the highest PLR for our proposed renewable power plant designs. Thus, SPV Trees can prove to be a very effective solution as large capacity of SPV plants can be installed in very less land compared to conventional ground-mounted plants.

CRediT authorship contribution statement

Maharshi Vyas: Methodology, Investigation, simulation, Writing – original draft. **Sumit Chowdhury:** Conceptualization, Methodology, Writing support. **Abhishek Verma:** Conceptualization, Visualization, Writing – review & editing. **V.K. Jain:** Supervision, Writing – review & editing.

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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