

## Solar PV Tree: Shade-Free Design and Cost Analysis Considering Indian Scenario

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### Abstract

In this paper, the performance and the cost-effectiveness of a solar PV tree for supplying the energy demand of a flood lighting system at a basketball court in the School of Engineering and Technology, Christ (Deemed to be University) at Bangalore, India, are analyzed. Also, the energy demand of a flood lighting system for year 2017 is estimated (16 kWh/day), and the design of 4 individual trees of 1 kWp each is proposed, which saves around 40 sq.m area of land near to the basketball court. The experimental data was collected from June 1<sup>st</sup>, 2018 to May 31<sup>st</sup>, 2019, using a data acquisition system and processed to calculate the monthly cost of energy produced by each tree. In order to reduce the complexity in design and allow it to be shade-free, all the panels of a tree were oriented at the same azimuth angle. Based on technical and economical assessments with respect to rooftop systems, the solar PV tree presented reasonable results and could be a future adoptable technology for high population density areas, as well as for remote applications. Later, the adoptability of the proposed solar PV tree was simulated for 2 kWp, considering the climatic conditions of 2020, for different rural and urban locations of India. From the techno-economic-environmental analysis, it is highlighted that the annual energy yield is more with the solar PV tree model than with a land-mounted SPV system. The cost savings and greenhouse gas (GHG) reduction are also higher with the proposed oak tree-based solar PV tree in urban areas than in rural areas recommending it for practical applications.

**Keywords:** Solar PV system, Rooftop solar PV system, Solar PV tree, Techno-economic analysis

### Introduction

The scenario of global warming and scarcity in convention fuel-based electric power generation have influenced and forced the adoption of alternative and sustainable power generation technologies across the world. Renewable energy (RE) technology is one of the major alternatives for electric power generation and, currently, its share in the Indian power grid is around 21.12 % [1]. In future times, the trend may further increase with the initiatives, incentives, and policies offered by the Indian government [2]. Among all RE technologies, solar photovoltaic (SPV) technology is the one which has been widely adopted across the world, even for small applications, due its simple design and clean operation at an affordable cost. The SPV systems can be designed as either grid-tied or stand-alone modes. As compared with grid-tied, the stand-alone SPV system has advantages, like independence, no blackouts, and no electricity bills. On the other side, it also suffers from some drawbacks, like high initial cost, storage, and high energy efficiency requirement since there is no other alternative source at the site. In order to overcome these disadvantages, stand-alone SPV systems need to be designed precisely and optimally. In the literature, many works can be found on the optimal design of a stand-alone SPV system for minimizing the initial cost and storage requirement, considering meteorological conditions [3-6]. In

Ahsan *et al.* [7], the performance and economic aspects of a 1 kWp stand-alone SPV system installed at Jamia Millia Islamia, New Delhi (28.5616° N, 77.2802° E, and about 293 m above sea level), India, were analyzed. The study revealed that the installation of small-scale SPV systems in rural areas can overcome the lack of power scenario with minimum investment cost. In Chandel *et al.* [8], on-site and off-site options for SPV systems were proposed for meeting the energy requirement of Jaipur (India) and a techno-economic analysis was performed. The study highlighted the scarcity of land in Jaipur city and its impact on system economic performance. In Akinyele and Rayudu [9], the techno-economic-environmental analysis of an off-grid solar PV system considering the Bununu community in Bauchi State, Nigeria, was presented. From the results obtained, the study revealed that off-grid PV systems could be a better option for remote areas around the world. In Chaurey and Kandpal [10], stand-alone solar home systems and micro-grid options for remote areas of India were analyzed considering techno-economic aspects. The study highlighted that micro-grid-based solar PV systems were a better option for remote areas but did not consider the land cost. Similarly, in Bhakta and Mukherjee [11], techno-economic analysis for a stand-alone solar PV system was presented considering isolated Indian islands, the Andaman and Nicobar islands, and their geometric conditions. Similarly, works related to techno-economic analysis can also be found in [12-16], but the majority have not considered the land cost.

Due to the lack of land and/or rooftop space, the adoption rate of SPV technology is still less in urban areas as compared with rural areas. In addition, the land cost is also considerably high in all high-density areas. On the other side, electrification in rural areas becomes difficult due to the lack of near grid connectivity and, hence, stand-alone PV systems become the best option, as highlighted in the aforementioned review. To overcome this situation, it is vital to identify new methods for designing SPV systems with space/land as a major constraint and their techno-economic analysis. One such attractive concept is a solar PV tree, by which land constraint can be overcome successfully. Conceptually, a solar PV tree is a replica of a natural tree consisting of 1 supporting structure, like a stem, and solar panels as branches. Based on the artistic features, different types of solar PV tree concepts have been identified across the world. In Gupta [17], a single tall pole (stem)-based solar PV tree with tracking was designed for a residential home in Kolhapur, Maharashtra. The PV panels (the leaves of the tree) were arranged in a 'Phyllotaxy' pattern. In Duque *et al.* [18], a public mobile charging facility was proposed via a solar PV tree concept considering the metrological conditions of urban areas of Medellin city in Colombia. As per the techno-economic-environmental and physical-chemical properties, *Guadua angustifolia* was considered when designing the PV tree model. In Rawat and Singh [19], the advantages of a 3-D arrangement of a solar PV tree over a 2-D one were discussed. Finally, an oak tree with a Fibonacci pattern of 2/5 was considered as an advanced solar PV tree configuration due to its optimum position of PV panels to receive solar energy throughout the day without a shade effect on each other. In Hyder *et al.* [20], the comparison between land-mounted SPV systems and 6 different dome-type solar PV tree configurations were presented considering the metrological conditions of Kuala Lumpur, Bhopal, and Barcelona. The study highlighted the technical benefits of solar PV trees over land-mounted systems in terms of energy yield. In addition to a brief history on solar PV tree technology in Rawat and Singh [19], the reader can find an exhaustive literature survey on different types of solar PV tree concepts and models presented in Hyder *et al.* [21]. Considerable factors in solar PV tree concepts are initial cost, the mechanical strength of the supporting structure, and shading effect.

In our proposed model, a high mast light tower is used as a stem as it has long durability and sustainability without considering the cost factor, but it is economical as compared to the land cost in the work place, i.e., Bangalore. The possibility of free access to the land-mounted solar PV system and the lack of any rooftop area near to the ground means the solar panels are proposed to be placed on each lighting tower. The proposed tree model is simple, shade-free, attractive, and serves the required electrical energy at the spot successfully. Also, the adoptability of the solar PV tree concept for various rural and urban places is analyzed and compared with a land-mounted SPV system. The proposed solar PV tree model uses an oak tree due to its feasibility to permit solar ray on all leaves equally throughout the day. In a comparative study, the techno-economic-environmental benefits of the proposed solar PV tree over a land-mounted SPV system are highlighted.

### **Design of solar PV tree**

The project of the solar PV tree was initiated in the Faculty of Engineering, Christ (Deemed to be University), at a basketball court in 2016, to supply the energy required by the floodlight system. The design of the solar PV tree majorly consists of a stem, branches, a battery, and a converter. In this section, each part is explained briefly.

#### ***Design of stem***

In simple terms, the supporting structure for housing the solar panels in a solar PV tree concept can be considered as being similar to the stem of a natural tree. In order to have long durability and sustainability, the project considered a high mast light tower as the stem without considering the cost factor. In this project, we have used a 16 m high mast tower, which can sustain a symmetric/asymmetric loading of up to 8 luminaries for wind speed of 180 km/h [22].

#### ***Design of branches***

In comparison with other type of lighting poles, the luminaries' carriage ring is attached to a 2HP 1Ø integral motor using 3 stainless steel wire ropes of the high mast tower and can easily be brought down or lifted up for any maintenance purposes. Hence, the luminaries' carriage ring is altered for placing the solar panels. In order to provide symmetric loading on the high mast tower, 4 panels (250 Wp, VMPP = 30.2 V, IMPP = 8.3 A at Pmax [23]) are arranged on the luminaries' carriage ring similar to the spotlight solar PV tree (industry model) [24]. In this model, the panels can be arranged similar to a rooftop PV system by which the shading effect of the solar PV tree can be overcome. The implementation of the proposed tree is given in **Figure 1**.

#### ***Battery, inverter and lighting system design***

On each tree, 10 floodlights (warm white color LED, 100 W, 230 V AC with ip65 waterproof) are arranged on the luminaries' carriage ring. On average, with a working period of 4 h/day (05:00 - 9:00 pm), each tree needs to produce 4 kWh energy/day, i.e., 4 units/day. Considering an average of 5 peak sunlight h/day at the site, 1 kWp system is proposed. At the ground level of each tower, an ip65 outdoor sheet metal waterproof electric panel box is used to house 1 lithium ion battery (200 Ah, 24 V, 10 C), 1 inverter (2 kVA, 1Ø, 50 Hz, 230 V pure sine wave), and a controlling unit with a data logger unit. We have used Polycab 1 sq.mm 4 core PVC insulated copper flexible cable (black) and trenched through the stem. In the cable, 2 wires are used for connecting the solar panels (connected all in parallel) and the battery and remaining 2 wires are used to supply the floodlights through the inverter.



**Figure 1** Installed solar PV trees at the basketball court.

## Results and discussion

### Analysis of proposed solar PV tree performance

The performance of the installed solar PV trees is monitored over a period of 1 year and compared with a rooftop system. The rooftop system performance is assessed through simulation using a PVWatts® calculator [25]. The monthly average energy of 4 solar PV trees in kWh and the simulation results of the 4 kW rooftop system are given in **Table 1**.

**Table 1** Comparison of solar PV tree and rooftop performance.

Month	Tree-1	Tree-2	Tree-3	Tree-4	Total Energy (kWh)	Cost (Rs)	PVWatts® calculator	
	$A_0 = 0^\circ$	$A_0 = 90^\circ$	$A_0 = 180^\circ$	$A_0 = 270^\circ$			Energy (kWh)	Cost (Rs)
06/18	133.13	125.00	120.56	129.78	508.47	4,067.76	666.26	5,330.04
07/18	124.04	118.68	115.62	124.18	482.52	3,860.16	624.96	4,999.67
08/18	115.69	112.87	113.67	125.22	467.45	3,739.60	676.18	5,409.42
09/18	119.74	122.04	126.09	125.35	493.22	3,945.76	601.52	4,812.19
10/18	106.69	114.23	122.98	116.16	460.06	3,680.48	562.30	4,498.41
11/18	97.78	111.06	127.28	109.38	445.50	3,564.00	481.94	3,855.56
12/18	95.95	111.97	130.98	117.50	456.40	3,651.20	463.00	3,703.97
01/19	106.61	122.99	145.21	132.34	507.15	4,057.20	469.45	3,755.60
02/19	110.92	122.36	137.72	129.15	500.15	4,001.20	535.03	4,280.24
03/19	136.04	139.32	149.61	149.88	574.85	4,598.80	540.12	4,320.92
04/19	138.61	135.58	137.80	142.89	554.88	4,439.04	568.61	4,548.88
05/19	145.46	137.02	135.07	147.02	564.57	4,516.56	588.94	4,711.49
Total	1,430.65	1,472.93	1,562.58	1,548.86	6,015.02	48,120.16	6,778.30	54,226.40

The panels on each tree are oriented at different azimuth angles by considering a common tilt angle nearly equal to Bangalore's latitude angle, i.e.,  $12.97^\circ$ . The energy cost is calculated with a tariff @ 8 Rs/kWh (for top slab of residential consumers in Bangalore). By observing the results, Tree-3, which has panels oriented at  $180^\circ$  azimuth angle, produced maximum energy among all other trees. In addition, the rooftop system performance is also observed, which is nearly equal to Tree-3 performance.

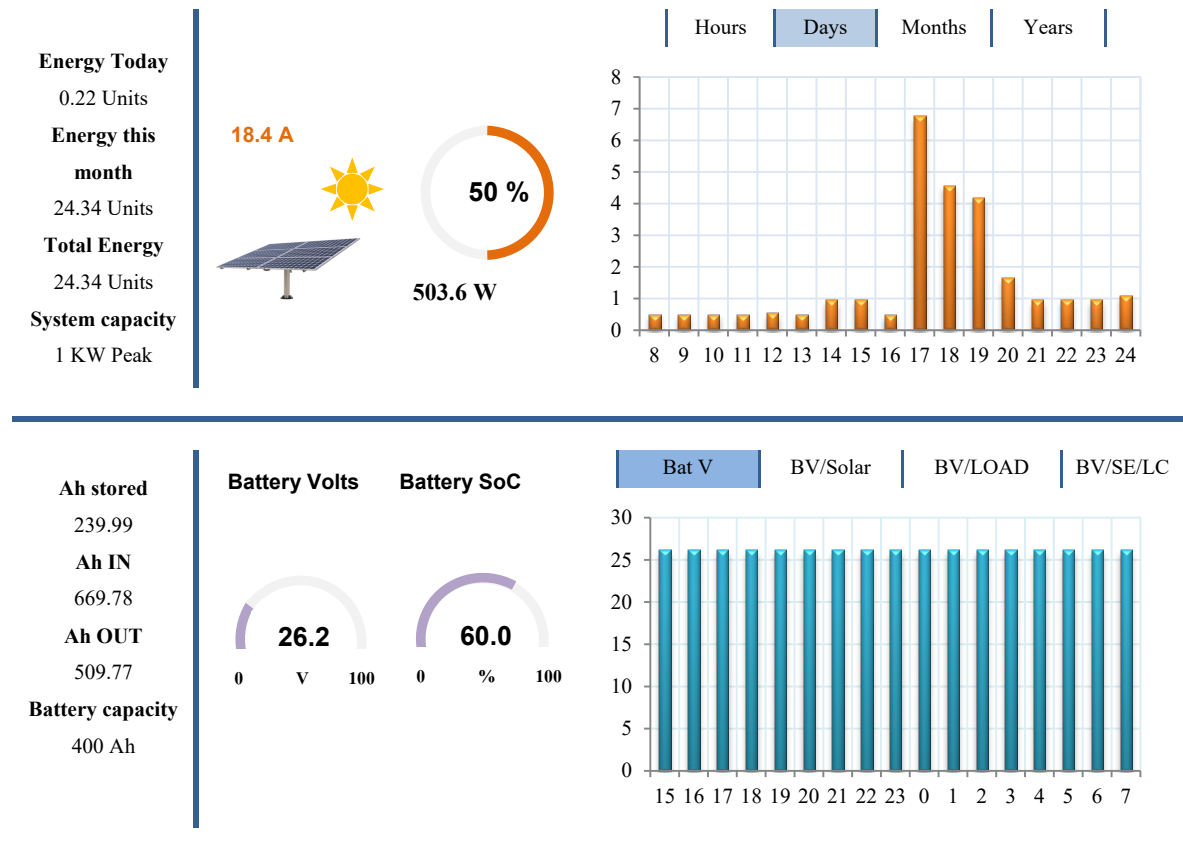
As computed using SPIN, the Ministry of New and Renewable Energy (MNRE) [26], the CO<sub>2</sub> reduction by each tree over a lifetime of 25 years is 31 tons, which is equivalent to planting 49 teak trees over a lifetime. By considering 4 trees, it is equivalent to 124 tons CO<sub>2</sub> reduction, and nearly 196 teak trees, with this project implementation.

Using the d/Data logger, the parameters of all the components in the solar PV tree are continuously measured and processed for energy yield/month calculation. For a particular instant/login time, the system performance is illustrated in **Figure 2** for daytime. The total energy generated from the solar array can be visualized in an h/days/month/year timespan. We are also able to easily understand the percentage of power generated at a particular instant. It is actually calculated as the ratio of power generated at that instant to total installed plant capacity.

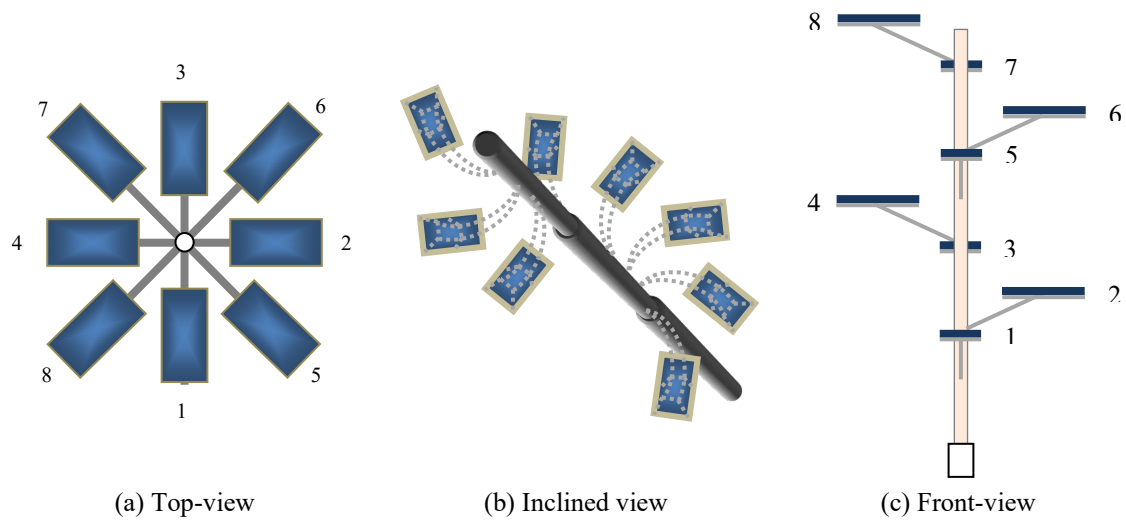
### Simulation and analysis of solar PV tree performance for different climatic conditions

In order to verify the feasibility of solar PV tree technology, the simulations are extended for climatic conditions of various metropolitan cities and rural areas of India. The performance of the land-mounted flat SPV system and the proposed oak tree-based solar PV tree model are determined for the year 2020 using the PVWatts® calculator. The top view, inclined view, and front view of the proposed

solar PV tree of 2 kWp capacity are given in **Figure 3**. The panel specifications are taken to be the same as in the proposed practical model. The panel locations on the stem as ground clearance and its corresponding orientation in terms of azimuth angles are given in **Table 2**.



**Figure 2** Visualization of system performance during a typical daytime.



**Figure 3** Proposed oak tree-based solar PV tree model.

**Table 2** PV panel orientation.

Panel No.	Ground Clearance (feet)	Azimuth Angle	Panel No.	Ground Clearance (feet)	Azimuth Angle
1	6	0°	5	7	0°
2	6.25	90°	6	7.25	90°
3	6.5	180°	7	7.5	180°
4	6.75	270°	8	7.75	270°

**Table 3** Techno-economic analysis considering the climatic conditions of metropolitan cities, India.

Location	Latitude (°N), Longitude (°E)	Land-mount SPV	Solar PV Tree		
		Annual Energy (kWh)	Annual Energy (kWh)	Energy/Cost Savings (%)	Reduction of CO <sub>2</sub> Emission (Metric Tons)
Delhi	28.65, 77.25	2,836	3,349	18.09	0.363
Mumbai	18.95, 72.85	3,071	3,737	21.69	0.471
Kolkata	22.55, 88.35	2,752	3,242	17.81	0.346
Bangalore	12.95, 77.55	3,123	3,813	22.09	0.488
Chennai	13.05, 80.25	3,007	3,646	21.25	0.452
Hyderabad	17.35, 78.45	3,050	3,677	20.56	0.443
Ahmadabad	23.05, 72.55	3,036	3,700	21.87	0.469
Pune	18.55, 73.85	3,080	3,746	21.62	0.471
Surat	21.15, 72.85	3,043	3,701	21.62	0.465
Jaipur	26.95, 75.85	3,083	3,742	21.38	0.466
Average		3,008.1	3,635.3	20.85037	0.443

**Table 4** Techno-economic analysis considering the climatic conditions of rural places, India.

Location	Latitude (°N), Longitude (°E)	Land-mount SPV	Solar PV Tree		
		Annual Energy (kWh)	Annual Energy (kWh)	Energy/Cost Savings (%)	Reduction of CO <sub>2</sub> Emission (Metric Tons)
Mawlynnong	23.05, 72.55	3,036	3,700	21.87	0.469
Dikshit	28.65, 77.15	2,844	3,361	18.18	0.366
Majuli	26.85, 93.75	2,566	3,040	18.47	0.335
Landour	30.45, 78.05	3,002	3,613	20.35	0.432
Mandawa	27.05, 73.85	3,159	3,862	22.25	0.497
Malabar	11.25, 75.85	2,973	3,609	21.39	0.450
Ziro Valley	27.55, 93.85	2,410	2,797	16.06	0.274
Idukki	9.95, 76.95	2,746	3,286	19.66	0.382
Khimsar	28.15, 73.35	3,107	3,759	20.98	0.461
Valparai	11.95, 79.45	3,026	3,696	22.14	0.474
Average		2,886.9	3,472.3	20.27781	0.414

The yearly energy yield for various metropolitan cities and rural places are given in **Tables 3** and **4**, respectively. Also, the energy deference between land-mounted SPV and solar PV tree model is estimated and, correspondingly, the energy/cost savings are determined. In addition, the CO<sub>2</sub> reduction for energy savings with the solar PV tree model is also determined [27]. The results clearly highlight the feasibility of the proposed solar PV tree model for stand-alone and remote applications, irrespective of locations, in terms of energy/cost savings and environmental benefits.

## Conclusions

In the current scenario, the adoption of the solar PV tree concept is essential for providing reliable and independent supply using a very small land footprint, as compared with conventional rooftop or ground-mounted stand-alone solar PV (SPV) systems. In this paper, the performance of 1 kW (4 panels of 250 Wp) solar PV trees, oriented at different azimuth angles (i.e., 0°, 90°, 180°, and 270°) has been presented and compared with a conventional rooftop solar PV system. The tree oriented at an 180° azimuth angle has shown the better performance than the remaining trees and performed nearly equal to the rooftop system, simulated by a PVWatts® calculator. Also, the concept of an oak tree-based solar PV tree model of 2 kWp size is simulated, considering various urban and rural places of India. From the results obtained, the solar PV tree concept is highlighted by its competitiveness with rooftop/land-mounted systems in terms of land footprint, energy yield, economic savings, and GHG reduction, and is a most suitable technology for urban areas. Since the proposed solar PV tree model is mainly designed for stand-alone applications, there is a need to design and compare its techno-economic-environmental benefits for island micro-grid applications [28] with energy storage, considered as future scope for this work.

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