Sunflower Inspired Solar Tree Design for Urban Energy Optimization in Space-Constrained Environments: A Case Study from Sudan

Asmaa Ammar Hamid Suliman

Email: *asmaammar29[at]gmail.com*
0000-0002-7633-6630

Abstract: ***Solar radiation is one of the most important alternative energy sources, that can be used in the form of electric power with the help of photovoltaic modules placed under the sun. Sudan is a country with very limited natural resources and the energy costs are high, Solar energy offers a promising solution that could solve many of the country's problems if well utilized especially since the majority of days in Sudan are sunny. Optimal conversion of the energy from the solar modules can be achieved through the use of Maximum Power Point Tracking (MPPT), which continuously adjusts the angle of the modules to the change in the angle of solar irradiance. The solar tree is one of the best techniques for having Maximum conversion of energy in each direction, this method is very efficient in saving a land requirement in major cities in Sudan. This paper presents a sunflower-inspired solar tree designed for maximizing photovoltaic (PV) power output within constrained urban spaces, particularly in Sudan. Leveraging a multilayered radial configuration, the design optimizes solar exposure while minimizing land use. The system's performance was experimentally evaluated under varying sunlight conditions and orientations. Results indicate a 65% efficiency gain over conventional flat-panel systems within the same footprint. The findings suggest that such biomimetic solar structures offer a scalable, land-efficient solution for urban and semi-urban renewable energy deployment in developing regions.***

Keywords: solar tree, photovoltaic system, sunflower design, land optimization, renewable energy Sudan

1. Introduction

Energy consumption recently recognized as an indicator of economic development and is directly proportional to its Gross Domestic Product (GDP). In many developing regions, such as Sudan, the high cost of energy places a substantial burden on economic resources. However, Sudan's abundant solar irradiation and predominantly sunny climate which present a significant opportunity for harnessing solar energy. Photovoltaic (PV) systems face challenges, particularly the large land area they require an issue that is especially critical in densely populated urban settings.

Solar energy, particularly through photovoltaic conversion, has emerged as one of the most promising and environmentally sustainable solutions to address global energy demands. This energy can be harnessed either directly through photovoltaics (PV) or indirectly through concentrated solar power (CSP) systems, which use lenses or mirrors and tracking systems to focus sunlight. Among these, PV systems are more widely adopted due to their simplicity and scalability. Their efficiency is often maximized using techniques like Maximum Power Point Tracking (MPPT), which optimally aligns panels with the changing angle of solar incidence throughout the day.

To scale solar adoption in areas where space is limited, innovative structural designs have become increasingly necessary. One such solution is the solar tree, a vertical, tree-like arrangement of solar modules designed to optimize energy output per unit area. These systems are inspired by natural forms, often utilizing Fibonacci phyllotaxis, a spiral leaf pattern that mimics the efficient sunlight capture strategy of plants. The term "TREE" itself fittingly stands for Tree Renewable Energy Electricity, highlighting its structural and functional resemblance to natural trees. Solar trees typically occupy just 1% of the ground space required by traditional flat PV systems, making them ideal for urban environments.

The design features multiple PV layers arranged radially and vertically at varying heights. This configuration not only mitigates shading but also enhances power density and improves resilience against environmental conditions such as wind. Unlike traditional flat-panel systems, the proposed solar tree captures sunlight from various angles throughout the day, increasing its overall efficiency.

This study aims to design, prototype, and evaluate a novel, multilayered solar tree system inspired by sunflower phyllotaxis, intended to optimize energy output per unit area for urban applications in Sudan.

The main contributions of this work are as follows: (1) Introducing a sunflower-inspired solar tree design with a multilayer PV arrangement optimized for urban deployment in Sudan, (2)Experimentally evaluating voltage outputs under various sunlight angles and placement orientations, (3)Analyzing the effects of shading, layer positioning, and angle of incidence on power generation, (4) Comparing the performance of the proposed structure with flat-mounted PV systems occupying the same area footprint.

These findings advance the research on compact solar architectures and open new avenues for the development of land-efficient, renewable energy systems, particularly in developing nations where space and resources are limited.

2. Literature Review

1) Overview of the Solar Tree technology

Solar energy—the sun's radiant light and heat—is harnessed using a number of emerging technologies, including solar heating, photovoltaics (PV), solar thermal systems, solar architecture, and artificial photosynthesis. The solar tree is one of the most inventive and space-efficient approaches.

A solar tree is a vertical, metal structure that resembles a natural tree, with solar panels installed at the tips of the branches. These PV modules capture solar radiation and transform it into electricity using the photovoltaic effect, which generates electrons within the solar cells. The generated direct current (DC) is then transformed to alternating current (AC) by an inverter, making the electricity useable for a variety of purposes, including battery charging. The stored energy can then be used for illumination, small appliances, or grid support, depending on the system's capability and integration.

The key advantage of solar trees lies in their vertical, biomimetic architecture, which allows stacking of PV panels in a compact footprint—ideal for space-constrained environments such as dense urban areas. By mimicking the phyllotaxis pattern found in nature—particularly the Fibonacci sequence (golden angle of 137.5°)—these structures maximize solar exposure while minimizing shading between modules.

Several studies have demonstrated that phyllotactic solar tree designs outperform other designs. Studies have shown that solar trees, particularly those inspired by natural leaf patterns, can significantly outperform traditional flat-panel systems in energy efficiency. In [1], Fibonacci-based configurations demonstrated superior daily energy generation, especially in regions with variable solar angles. Furthermore, [2] revealed that optimizing the angular arrangement of photovoltaic (PV) modules based on phyllotaxis patterns can enhance annual energy yield by over 30%, highlighting the effectiveness of solar trees as a high-performance, space-efficient renewable energy solution.

To design a functional solar tree system, several key components are required:

a) Solar modules – to collect and convert sunlight into electricity
b) Steel support structure – to provide mechanical stability and elevation
c) Batteries – for storing the harvested energy
d) Cabling – for electrical connectivity
e) Inverter – to convert DC to AC for standard electrical use

Solar trees are a combination of engineering and natural design, providing a sustainable and scalable solution for clean energy generation in both urban and rural areas.

2) *Advantage of the Solar Tree*

- Optimization of land area: compared with traditional PV systems, Solar Tree requires less land. Therefore, a system generates maximum. Energy with minimum land consumption.
- Efficient energy production: Solar trees can produce energy very efficiently.
- Protection from wind: Solar trees with flexible trunks that turn in any direction and shake themselves can also generate energy from the wind, just like a natural tree.
- Solar tree panels can charge batteries during the day.
- No air-polluting energy source.
- Improved design.
- Small size.

a) Disadvantage of the Solar Tree

- The cost is high.
- Impact on the environment.
- Selection of potential sites

b) Regional Considerations-Focus on Sudan

In countries like Sudan, solar tree deployment offers distinct opportunities and constraints:

- High solar irradiance: The region's abundance of sunlight makes it perfect for solar energy installations.
- Environmental stressors such as seasonal dust storms, high ambient temperatures, and strong winds necessitate long-lasting construction designs.
- Optimal Design Response: This paper proposes a sunflower-inspired, radial solar tree model that overcomes many of these environmental challenges:
  - A concentric, multi-layer PV configuration that balances shading and power density.
  - A stable mechanical construction capable of sustaining regional wind stresses,
  - Enhanced energy capture during periods of bright sunlight with limited land use.

c) Site Selection Criteria

For effective deployment, careful site selection is essential. The following factors should be considered:

- Solar Orientation and Angle of Incidence
- Annual Solar Radiation and Temperature Profiles.
- Obstructions (buildings, trees, terrain)
- Accessibility and maintenance feasibility

3) *Comparative Performance and Efficiency*

Solar trees generate much more energy per unit area than standard flat-panel photovoltaic (PV) systems, making them an attractive option for space-constrained locations. According to [3], a well-optimized solar tree structure can provide up to 300% more energy per square meter than traditional PV arrays. These efficiency gains are the result of a combination of multilayer panel stacking, multi-angle sun exposure, and improved natural cooling owing to vertical architecture.

Solar trees are becoming increasingly popular because to their small land footprint, which can be as little as 1% of the ground area when compared to standard flat PV installations [3]. This makes them ideal for urban settings and land-scarce places where increasing energy output in a limited space is crucial.

In [2], a comprehensive review was conducted and identified the following important benefits:

- Superior land-use efficiency, enabling renewable energy deployment in densely populated areas,
- Reduced shading losses by optimizing angular panel spacing,
- Aesthetic appeal allows for incorporation into urban infrastructure such as parks, streetscapes, and public buildings.

However, implementing a solar tree system does bring some engineering hurdles. Because of their towering vertical structure and the weight of several PV panels, solar trees require a strong foundation, similar to how a true tree supports its branches and leaves. Although the surface area occupied above ground is tiny, a significant percentage of the foundation work is performed underneath, assuring mechanical stability and wind resistance.

To summarize, solar trees offer great energy efficiency, compact design, and visual harmony with urban landscapes, but they require careful structural planning to reach their full potential as a scalable renewable energy source.

3. System Design and Methodology

1) Conceptual Framework

The suggested solar energy system is based on a vertically organized solar tree design inspired by the radial petal arrangement of sunflowers. Unlike typical phyllotactic or Fibonacci-based arrangements, this approach uses a concentric, multi-layered circular layout to maximize solar capture while minimizing land use. This design is tailored to urban and resource-constrained locations such as Sudan, and it solves the important demand for land-use efficiency in highly populated places.

The area ratio is an important consideration in the development of solar PV trees because it measures how efficiently solar panel systems can amplify electricity output per unit area. To achieve this, the solar tree has four stacked layers of photovoltaic (PV) panels, each placed radially to mimic the disk of a sunflower. This multilayered design maximizes sunshine exposure by catching rays at various angles throughout the day, including some that would otherwise be lost in flat-panel systems.

Each layer of the solar tree operates semi-independently and is electrically tuned to maximize voltage and current output. In addition, the design improves solar absorption by carefully regulating the zenith angle—the angle between the sun and the panel surface—and orienting each layer appropriately. This intentional stacking and angular optimization greatly improve the overall energy yield per unit footprint, making the system excellent for use in places with limited space but high solar potential.

2) Design Parameters of the PV Panels

Each PV cell used in the solar tree is a miniaturized monocrystalline module suitable for lightweight and compact installations, shown in fig.1 & Table I.

Table 1: Technical parameters of the monocrystalline photovoltaic panels used in the solar tree.

Parameter	Value
Panel dimensions	39 mm × 19 mm (1.53” × 0.75”)
Maximum Power	0.12 W
Average Voltage (V)	0.5 V
Average Current (I)	0.24 A
Efficiency	~17%
Panel Type	Monocrystalline Silicon
Mounting Orientation	Circular/Layered (sunflower)

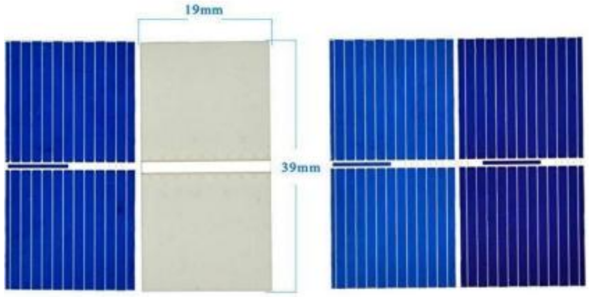

Figure 1: Schematic diagram of a monocrystalline photovoltaic panel used in the solar tree.

3) Structural Layout and Layering

The solar tree consists of four vertically stacked tiers, each with a distinct number of solar cells. To attain higher voltage levels, the number of panels and wire layouts (series/parallel) change by layer. This design also distributes shade more evenly and prevents hotspots shown in fig 2,3.

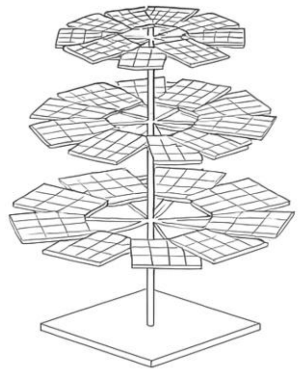

Figure 2: 3D model of the sunflower-inspired solar tree structure showing radial multilayer arrangement.

Figure 3: Photograph of the constructed solar tree prototype with a 64 cm × 64 cm base

4) Electrical Configuration of Layers

Each layer contains multiple series-connected modules, while layers are wired in parallel to improve total current output. The detailed configuration is shown in Table II:

Table 2: Electricalconfiguration of the solar tree layers and output characteristics

Layers	Series 1	Series 2	Series 3	Total in parallel
1	10panels (5V,0.24A)	10 panels (5V,0.24A)	10 panels (5V,0.24A)	5V,0.72A
2	24panels (12V,0.24A)	28panels (14V, 0.24A)	-	14V,0.48A
3	32panels (16V,0.24A)	35panels (17V,0.24A)	-	17V,0.48A
4	43panels (21.5V,0.24A)	48panels (24V,0.24A)	-	24V,0.48A

5) Orientation and Optimization Strategy

To investigate the impact of sun angle and placement, the system was tested in two configurations:

a) Vertical orientation: The tree is positioned upright to imitate real-world deployment.
b) Horizontal orientation: The tree is put flat to mimic flat-panel installations in the same footprint.

Measurements were taken over three different time frames to capture diurnal performance Table III:

Table 3: Measurement intervals and corresponding solar angles during testing.

Time Interval	Solar Angle Characteristics
6:00 AM – 10:00 AM	Low-Angle Morning Sun
10:00 AM – 2:00 PM	Peak irradiance (zenith angle ~90°)
2:00 PM – 5:00 PM	Afternoon irradiance with more shadows

4. Result

The proposed solar tree was evaluated under real-world conditions to measure its electrical performance and assess the impact of orientation, shading, and time of day on power output.

1) Voltage Output Across Time Intervals

The solar tree was tested in real-world conditions at various times of day to determine the voltage output of each photovoltaic layer. To emulate practical deployment scenarios, the system was tested in two configurations:

- Vertical orientation, mimicking the genuine installation.
- Horizontal orientation, where the entire construction was laid flat with the same surface area for comparison.

Measurements were taken at three important time periods to capture the impact of shifting sun angles:

- 6:00 to 10:00 a.m. (low-angle morning sun)
- 10:00 AM–2:00 PM (peak irradiance period)
- 2:00–5:00 PM (afternoon sunlight with increasing shadow presence)

Table IV presents the voltage data recorded across these intervals, highlighting performance differences between the vertical and horizontal orientations throughout the day.

Table 4: Layer-wise voltage output of the solar tree in vertical orientation across time intervals.

Layers	6 am – 10 am	10 am – 2 pm	2 pm – 5 pm
1	V1=5.54, V2=5.54 V3=5.54	V1=5, V2=5 V3=5	V1=4.5, V2=4.31 V3=4.03
2	V1=12.31, V2=15.17	V1=6.5, V2=8	V1=10.46 V2=10.8
3	V1=16.2 V2=16.64	V1=10 V2=12.7	V1=14.8 V2=14.7
4	V1=19.1 V2=23.5	V1=16.4 V2=18	V1=20.4 V2=20

When measuring the voltage output of the tree, it was discovered that some of the solar panels (the last three layers) were being shaded by other panels.

In the case of a flat position using the same tree space (64/64) cm, we observe that the output is significantly smaller relative to the tree structure, yet having multiple layers can provide as much power as desired.

2) Power Output Estimation

Using the measured voltages and an average panel current of (0.24 A), the estimated power outputs for each layer were computed using the following formula:

$$P = V \times I$$

Where:

- P is the electrical power output (W).
- V is the measured voltage (V).
- I is the current (A).

Table 5: Estimated power output of each layer during peak midday conditions.

Layer	Avg. Voltage	Current	Power Output
Layer 1	5 V	0.72 A	3.60 W
Layer 2	7.25 V	0.48 A	3.48 W
Layer 3	11.35 V	0.48 A	5.45 W
Layer 4	17.20 V	0.48 A	8.26 W
Total	-	-	~20.79 W

During midday, the tree's peak power reached 20.79 W, which was much higher than that of a flat setup with the same footprint, which achieved a maximum output reached 12.5 W.

3) Shading and Positional Effects

A key observation was the impact of internal shading, which occurs when top layers cast shadows on lower layers. The voltage dropped significantly in the early morning (6-10 AM) and late afternoon (2-5 PM) hours, particularly in lower layers that received partial blockage. This shows the need for:

- Optimizing layer spacing.
- Adjusting panel angles.
- Consider using tracking systems for high-yield designs.

***4)* Comparison to Flat Panel System**

A controlled test involved arranging the identical PV panels flat within a 64 x 64 centimeter rectangle. The output was recorded as:

- Maximum output (10-2 PM): around 12.5 W.
- Tree design provides an average efficiency boost of approximately 65%.

This performance gain is the result of improved exposure at different angles and stacking, demonstrating the solar tree model's usefulness in small-area situations.

5) Design Implications for Sudan

Sudan's high irradiance, urban land scarcity, and limited electrification in rural regions make tiny renewable installations extremely valuable. The suggested tree:

- Reduces land consumption by over 90% compared to flat systems.
- It performs well even with non-optimal alignment.
- Can be scaled for urban rooftops, community centers, or rural microgrids.

5. Conclusion

This study presented the design, building, and evaluation of a new, tree-shaped solar energy system designed to maximize power generation within a small footprint, particularly in urban and semi-urban locations such as Sudan. The structure used a tiered, radial shape inspired by natural phyllotaxis patterns, with many photovoltaic (PV) panels deliberately positioned to maximize solar exposure throughout the day while using substantially less land.

One of the significant advances in this design was the ability to supply unique voltage levels across each layer, which increased overall system flexibility. While the system did not initially achieve the intended power levels, performance can be enhanced using the following enhancements:

- Adding additional panel layers
- Adjusting the radial layout to optimize space usage
- Incorporating a mobility circuit for dynamic alignment with the sun

The key findings include:

- The solar tree produced up to 65% more electricity than a standard flat PV array with the same surface area.
- Maximum power generation was roughly 20.79 W during peak sun hours, with sustained efficiency over longer periods because to optimal panel angles and placement.
- Voltage outputs varied per layer, impacted by direction and shadowing, particularly at lower layers in the early morning and late afternoon.
- The charging circumstances were found to be ideal between 3:00 and 6:00 PM, since shadow effects were minimized and the solar angle supported improved light collection.
- The system proved high structural robustness, and its modular design allows for scalability in residential, commercial, and rural off-grid applications.

A comparison investigation revealed that the solar tree regularly outperformed flat-mounted PV systems with the same geographical footprint, highlighting the advantages of vertical, biomimetic PV structures.

Future work should center on:

- Improving panel angles and spacing to reduce internal shadowing
- Integrating Solar tracking systems to enhance exposure.
- Investigating the application of bifacial or flexible PV materials
- Integrating energy storage and IoT-based monitoring systems.

To summarize, the proposed sunflower-inspired solar tree represents a potential, land-efficient, and sustainable solution to solar energy generation, especially in areas with high solar irradiation and limited available space.

The study addresses critical challenges faced by rapidly urbanizing and resource-constrained nations, offering a replicable model for sustainable energy systems that minimize land consumption while maximizing power generation efficiency."

References

[1] H. Khan and P. Gaur, Design of solar tree with photovoltaic panels using Fibonacci pattern, Adv. Res. Electr. Electron. Eng. **2**, 67–71 (2015).

[2] P. Gangwar, R. P. Tripathi, and A. K. Singh, "Design of Fibonacci sequence-based solar tree and analysis of performance parameters of different phyllotaxy pattern-based solar trees: An experimental approach, in *Proceedings of the 62nd International Scientific Conference on Information Technology and Management Science* (Riga Technical University, Riga, Latvia, 2021), pp. 1–6.

[3] P. M. Cuce, A. Saxena, E. Cuce, and S. Riffat, Applications of solar PV tree systems with different design aspects and performance assessment, Int. J. Low-Carbon Technol. **17**, 266–278 (2022).

[4] Kavaz, S. Hodžić, T. Hubana, S. Ćurevac, N. Đozić, H. Merzić, and B. Šestan, Solar Tree Project, Green Design Conf. 8–12 (2014).

[5] Avdić, A. Muminović, N. Pervan, P. Tasić, and S. Zečević, Implementation of the project'Solar Tree in Sarajevo, in Proceedings of the Green Design Conference, Sarajevo, Bosnia and Herzegovina (2013), pp. 8–12.

[6] M. Boxwell, *Solar Electricity Handbook: A Simple, Practical Guide to Solar Energy – How to Design and Install Photovoltaic Solar Electric Systems*, (Greenstream Publishing, 2012).

[7] *Advances in Solar Energy: An Annual Review of Research and Development, Vol. 8 (American Solar Energy Society, 2007).*

[8] V. Avdić, S. Zečević, N. Pervan, P. Tasić, and A. J. Muminović, Different design solutions of solar trees in urban environment Faculty of Mechanical Engineering, University of Sarajevo, Bosnia and Herzegovina, (2013).

[9] G. Kaur and M. Singh, Performance analysis of solar tree,Guru 494 Kashi University, Talwandi Sabo, India. 495

[10] F. Hyder, K. Sudhakar, and R. Mamat, Solar PV tree design: A 496 review Renew. Sustain. Energy Rev. 82, 1079–1096 (2018). 497

[11] Y. Siregar and Y. Hutahuruk, Optimization design and simulating 498 solar PV system using PVSyst software, in Proc. 4th Int. Conf. Electr. 499 Telecommun. Comput. Eng. (ELTICOM), Medan, Indonesia (IEEE, 500 2020), pp. 219–223. 501

[12] N. N. Wadaskar, M. S. Pal, and S. S. Markad, Designing and 502 fabrication of solar tree, Int. J. Eng. Sci. 10, 27304–27307 (2020).
[13] S. Gupta and M. Gupta, The benefits and applications of solar trees with the natural beauty of trees, Swami Devi Dyal Institute of Engineering and Technology, Haryana, and University Institute of Engineering and Technology, Kurukshetra, India, (2015).