Design of Tree-Mimicking Solar Photovoltaic System Achieving Both Power Generation and Acceptability

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ABSTRACT

The design of solar photovoltaic (PV) systems is a crucial challenge for sustainable urban development. Conventional systems are composed of flat-mounted systems, which maximize the power generation per unit cell. However, they require vast lands with sufficient sunlight and have been limited to installations in mountainous areas or on building rooftops. Solar PV tree has been proposed as a solution to this problem. It retains solar PV modules three-dimensionally in a structure similar to a natural tree. It has the potential to effectively utilize small scattered urban spaces by reducing the ground contact area compared to conventional systems. In solar PV tree systems, there is a demand for a design that harmonizes spatially with the urban environment, in addition to pursuing the conventional goal of ensuring power generation. In this paper, we parametrically describe tree-like shapes, evaluate their electrical performance and acceptability in the urban environment through simulations and demonstrate the effectiveness of utilizing small urban spaces.

CCS CONCEPTS

• **Computing methodologies** → **Modeling methodologies**; **Model verification and validation**.

KEYWORDS

Urban Design, Landscape, Renewable energy, Urban Solar Photovoltaics, Solar Photovoltaic Tree

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1 INTRODUCTION

The adoption of renewable energy has recently increased. Among them, solar PV systems have gained popularity due to its abundant energy source and fewer production costs. Conventional systems are typically installed flat, maximizing the power generation per unit cell. These systems require vast amounts of land, limiting their installation to rooftops or house roofs in urban areas. As a result, installations have been concentrated in mountainous regions, leading to environmental degradation. Moreover, the long-distance transmission of power poses additional challenges in terms of losses [4].

To seek new solutions harmonizing with urban areas and buildings, solar PV trees in which solar PV modules are arranged three-dimensionally have been proposed [2]. Previous research focused on phyllotaxis [11], the regular arrangement of leaves around a plant stem. However, this approach did not adequately address the balance between functionality and acceptability in architectural design. Additionally, the efficiency of solar PV trees compared to conventional systems in small urban spaces remains unclear.

We propose a novel solar PV tree in urban streets, which constitute 30–45% of urban areas and have great potential for solar power generation. The main contributions of this paper are as follows: first, we propose a parametric description method that allows for a high expressive modeling of various natural tree forms. Second, we conducted simulations under different lighting conditions to determine suitable shapes. The simulations demonstrate the high efficiency of the proposed solar PV trees in small urban spaces, providing a solution for energy production in spatially constrained urban environments.

2 DESIGN REQUIREMENTS FOR CITYSCAPE

In conventional systems, a large number of solar PV modules are often installed flat in areas inaccessible to humans. This is a reasonable choice considering electrical and economic efficiency, but it can be seen as a method of enabling power supply at the expense of mountainous regions and landscapes.

Recently, there is a demand for designs that are functional and considerate of the landscape, creating more enriching and sustainable solutions. For example, in the design of architectural structures such as bridges, both mechanical performance and the comfort for people are equally valued, resulting in the creation of new landscapes that receive praise. Therefore, when constructing solar PV systems in urban areas, it is necessary to design them not only with electrical functionality but also to be loved and used by people for a long time.

The concept of solar PV trees is to make a solar PV system considerate of the landscape by mimicking natural trees, which have been planted in urban areas for over 1,000 years and become familiar presence to humans. However, previous research adopting phyllotaxis [8] [2] [9] have not been able to achieve a solar PV tree design with tree-like shapes. This is because the determination of

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tree shape involves the branching of the trunk and branches, which cannot be fully described by phyllotaxis.

In most architectural design, considering usability and comfort is important from initial stages, as people not only view them from a distance but also enter into the surrounding space and engage in various activities. Additionally, statistical analysis based on questionnaire surveys suggests that people prefer trees with broad canopies that give shade along the roadsides [7].

Therefore, we set the following goals of usability and comfort in the design of solar PV trees: replicating tree-like appearances, considering passageways dimensions, and achieving shade formation.

3 DESIGN PROCESS

3.1 Parametric Tree Description

Natural trees exhibit complex shapes, and faithfully reproducing every detail becomes challenging for analysis and implementation. Therefore, we describe tree shapes using four parameters.

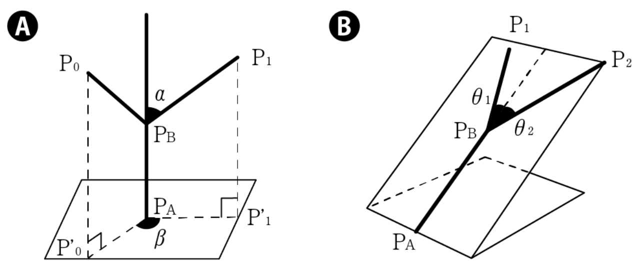

Figure 1: Branching Diagram. (A) shows branching from trunk, and (B) shows branching from branch.

3.1.1 *Branching from Trunk.*

Given Figure 1A, we denote the parent branch as P_AP_B and the child branches as P_BP_0 and P_BP_1. The child branches diverge from the parent branch at a branch angle α. Additionally, P'_0 and P'_1 are the projected points of P_0 and P_1 onto the plane that is parallel to the XY plane and contains P_A, and $\angle P'_0P_AP'_1 = \beta$. With the coordinates of P_A and P_B as (x_A, y_A, z_A) and (x_B, y_B, z_B), the coordinates (x_1, y_1, z_1) of the endpoint P_1 of the child branch P_BP_1 is described as follows:

$$\begin{aligned} x_1 &= x_B + \{u \cos\beta + (vcos\alpha + wsin\alpha)\sin\beta\} \\ y_1 &= y_B + \{-u\sin\beta + (v\cos\alpha + w\sin\alpha)\cos\beta\} \\ z_1 &= z_B + (-v\sin\alpha + w\cos\alpha) \end{aligned} \tag{1}$$

Here, $u = x_B - x_A$, $v = y_B - y_A$ and $w = z_B - z_A$.

3.1.2 *Branching from Branch.*

As shown in Figure 1B, we define the parent branch P_AP_B generating two child branches P_BP_1 and P_BP_2 in a branching. The child branches diverge from the parent branch at branching angles θ_1 and θ_2 within the plane $P_AP_1P_2P_B$. In this case, with the coordinates of P_A and P_B as (x_A, y_A, z_A) and (x_B, y_B, z_B), the coordinates (x_1, y_1, z_1) of the endpoint P_1 of the child branch P_BP_1 is described as follows:

$$\begin{aligned} x_1 &= x_B + \left(u\cos\theta_1 - \frac{L_2}{L_1}v\sin\theta_1\right) \\ y_1 &= y_B + \left(v\cos\theta_1 + \frac{L_2}{L_1}u\sin\theta_1\right) \\ z_1 &= z_B + w\cos\theta_1 \end{aligned} \tag{2}$$

Here, $u = x_B - x_A$, $v = y_B - y_A$, $w = z_B - z_A$, $L_1 = \sqrt{u^2 + v^2}$, and $L_2 = \sqrt{u^2 + v^2 + w^2}$. The coordinates (x_2, y_2, z_2) of the endpoint P_2 of the child branch P_BP_2 can be described similarly.

3.2 Tree Form Modeling

In agriculture and landscape designs, the appearances of trees is systematized as tree form [10]. In this paper, we modeled three representative tree forms: columnar, fan, and conical, using the aforementioned parameters. The results are shown in Figure 2. The values for each parameter are showed in Table 1. The phyllotaxis type in previous research are classified to the columnar type. Furthermore, it is possible to describe fan-shaped and conical tree forms by varying the parameter α from Table 1. Therefore, we set the range $0^\circ < \alpha \leq 45^\circ$ for the fan type, and $45^\circ < \alpha \leq 90^\circ$ for the conical type in this paper.

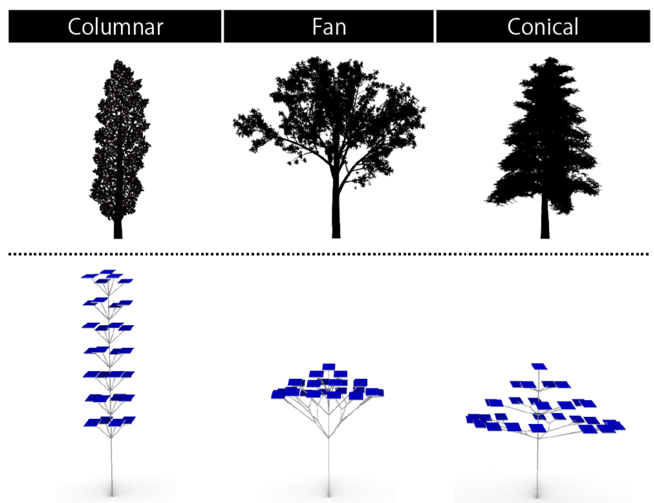

Figure 2: Results of tree form modeling. Each column shows three typical tree forms based on natural tree appearances. Each row shows examples of natural trees and the results of reproducing tree forms using four parameters.

Table 1: Values of parameters in Figure 2.

	α	β	θ_1	θ_2
Columnar	45°	90°	-	-
Fan	45°	90°	20°	30°
Conical	75°	90°	20°	30°

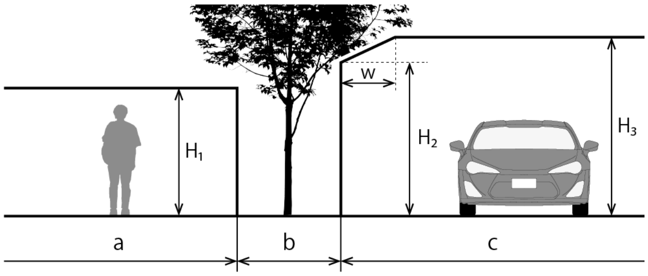

Figure 3: Road dimension. (a)–(c) represents sidewalk, planting strip, and roadway. In a street, w is 0.5 m, H_1 is 2.5 m, H_2 is 3.8 m, and H_3 is 4.5 m [6].

3.3 Dimensions Considering Passageway

In Japan, regulations have been established to ensure safe passageways [6], as shown in Figure 3. According to them, structures must not be placed within a certain area above roadways and sidewalks. Based on the regulations, the upper limit $\alpha_{\text{upper limit}}$ for the branching angle α ($0° < \alpha \leq 90°$) is determined as follows:

$$\alpha_{upperlimit} = 90 - \arctan\left(\frac{H_3 - H_2}{w}\right) \approx 54.45 \tag{3}$$

4 ANALYSIS METHOD

4.1 Solar PV Module Specifications

29 solar PV modules are used in the simulations. Each module consists of 16 cells arranged in 4 substrings. The size of each module is 800 mm × 800 mm × 5 mm (width × depth × height) and each cell is 100 mm × 100 mm × 5 mm. The inclination angle of the solar PV modules is set to 30° facing south, which maximizes the annual power generation in conventional systems. We assume that each solar PV module is equipped with MPPT (Maximum Power Point Tracking) techniques, and calculate the total power generation of the solar PV tree as the sum of the power output of each module. Note that transmission losses are not considered in this simulation.

4.2 Framework of Power Generation Analysis

There are two steps: radiation analysis and power generation calculation. The overall analysis is implemented using Grasshopper. Grasshopper is a visual programming tool that enables modeling and analysis through numerical control.

4.2.1 Radiation Analysis. We use the Radiation Analysis component within the Ladybug Tools, an environmental simulation tool in Grasshopper. This component considers the shading effects caused by surrounding structures while analyzing the radiation on the target surface. In this study, structures except the target are set as obstructions and the radiation is calculated on a per-cell basis.

4.2.2 Power Generation Calculation. Pvlib python [3] is used. Pvlib python is an open-source software that simulates solar PV systems based on PV_LIB MATLAB. The IV curve for each module is constructed by the IV curve of each cell determined by the radiation analysis. Using these results, the maximum power point is captured using the MPPT techniques and the power generation is calculated.

4.3 Meteorological Data

We use EPW (EnergyPlus Weather Data). It is a meteorological data format that follows the EnergyPlus format, which is managed by the National Renewable Energy Laboratory and widely used for simulating energy consumption in building systems. In this study, data measured in Chiyoda-ku, Tokyo in 2005 is used.

5 EVALUATION

5.1 Tree Shape Maximizing Power Generation

We conducted simulations by varying a branching angle α according to equation (3) in the three tree-form types. The simulations are managed in two scenarios: without buildings and with buildings along the roadside. Note that there is interference between the solar PV modules for certain angles ($0° < \alpha < 25°$) and such cases are excluded from the analysis. In the analysis, the angle α_{max} which maximizes the annual power generation is determined and the effect of shading from nearby buildings is evaluated in each tree form.

5.1.1 Planting Location of Street Tree. Street trees are typically planted within planting strips [6]. They are areas for plants and street trees along the roadside that are partitioned by curbs, fences, or similar structures with the aim of creating a favorable road traffic environment and ensuring a pleasant living environment. In Japan, the standard width of a planting strip is typically set at 1.5 m. In this study, we install a solar PV tree within a 1.5-meter-wide planting strip.

5.1.2 Building Environment. We assume the installation of a solar PV tree on a road in Chiyoda-ku, Tokyo. Building data is obtained from PLATEAU [5], a 3D urban modeling and utilization service led by the Ministry of Land, Infrastructure, Transport and Tourism. The buildings are modeled in two city blocks on both sides of the road. The target street has a 3.5-meter-wide sidewalk, which is required to be at least 2.0-meter-wide by law [6]. Therefore, we set the sidewalk width to 2.0 m and the planting strip width to 1.5 m, and install a solar PV tree in the planting strip.

5.2 Comparison with Conventional Systems

The annual power generation of the conventional systems is calculated when they are installed within the planting strip covered by the solar PV tree that has the highest annual power generation. The specifications and the number of solar PV modules in conventional systems are equal in the solar PV tree.

5.3 Shade Given by Solar PV Tree

We evaluate shade given by the solar PV trees with tree cover [12]. This metric represents the proportion of the tree crown's projected area to the ground. Increasing tree cover is actively pursued in Western cities to mitigate the effects of urban heat island. In this paper, 40 % is set as the target, which corresponds to the value pursued in Melbourne, where efforts to increase tree cover have been implemented as a leading initiative globally [1]. We calculate the tree cover p for each tree form based on the α_{max} values as follows:

$$p = \frac{S2}{S1} \times 100 \tag{4}$$

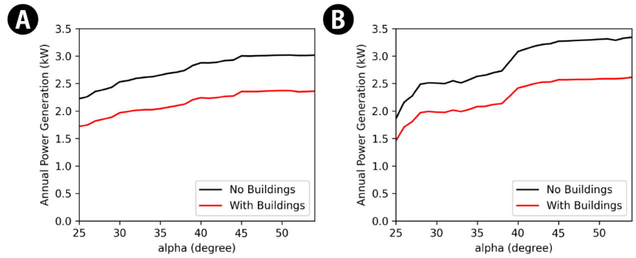

Figure 4: Correlation between α and annual power generation. (A) is the result of the columnar type and (B) is the result of the fan type ($25^\circ \leq \alpha < 45^\circ$) and the conical type ($45^\circ \leq \alpha < 55^\circ$). The black line represents the results in an environment without buildings, and the red line shows the results in an environment with buildings along the roadside.

Table 2: Evaluation Results

	Conventional	Solar PV Tree		
		Columnar	Fan	Conical
Without bldgs (kW)	1.66	3.02	3.27	**3.34**
With bldgs (kW)	1.03	2.37	2.57	**2.61**
Tree cover (%)	-	18.13	34.88	**40.60**

Here, $S1$ is the area of the rectangle formed by the centerline, the boundary line of the street, and two sides that intersect with the tree canopy projection area at a single point. $S2$ is the canopy projection area of solar PV Tree.

6 RESULTS AND DISCUSSION

Figure 4 shows the annual power generation of the solar PV tree plotted against the branch angle α, considering with or without buildings along the roadside. From Figure 4, it can be observed that the annual power generation monotonically increases with α. The α_{max} for each tree form is 50° (columnar), 45° (fan), and 54° (conical). Furthermore, due to the shading caused by nearby buildings, the annual power generation decreased by 20.53–24.73% (columnar), 19.89–25.03% (fan), and 21.36–21.97% (conical) compared to the environment without buildings.

Next, Table 2 compares the annual power generation and tree cover between the conventional systems and the solar PV trees with the angle α_{max}. Regarding the annual power generation, the solar PV tree achieved 2.30-2.53 times higher power generation compared to the conventional systems, in which the same number of panels are installed on the ground and set to 30° facing south, even in the environment with buildings along the roadside. In cramped areas, the conventional systems have smaller installation spaces, making it more susceptible to the shading effects during the lower sun altitude period in autumn and winter. On the other hand, the solar PV tree, with its solar PV modules installed at a higher position above the ground, allows for wider spacing between modules. Therefore, this result demonstrates the effectiveness of the solar PV tree in small areas like streets. Additionally, the reduction rate of annual power generation due to shading from nearby buildings is 37.9 % (the conventional systems), 21.39 % (columnar), 21.41 % (fan), and 21.78 % (conical). These results also show that the solar PV tree is more suitable than the conventional systems in mitigating the effect of shading caused by buildings, which is a common issue in urban environments.

Furthermore, when comparing different tree forms, the conical form achieved the highest results in terms of both annual power generation and tree cover. Particularly, the tree cover of the conical form exceeded the target value of 40 %, indicating that this form is suitable not only in terms of electrical functionality but also for giving shade, which is an important aspect of street trees.

7 CONCLUSION AND FUTURE WORK

In this study, we proposed a design process for solar PV trees that balances functionality and acceptability, and compared them with conventional systems for street tree installation. The results demonstrate that solar PV trees can meet the dimensional criteria required in urban spaces without obstructing pedestrian and vehicular traffic. Furthermore, they show promising electrical functionality for small scattered urban spaces. For future work, we aim to develop and verify material placement methods that ensure both the structural strength and cost-effectiveness. Additionally, we plan to evaluate the power generation and durability of multiple solar PV trees in street with other 3d spatial arrangements. These will contribute to the implementation of solar PV trees in real-world streets.

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