# Energy Efficiency in Urban Spaces: a comparative analysis between traditional photovoltaic systems and solar trees

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## Abstract

This study compares traditional horizontal and verticalized photovoltaic (PV) systems, such as Solar Trees, to evaluate their performance in space-constrained urban areas. Employing digital modeling and simulations, the case study considered a public park in Vila Velha (Brazil), where parameters such as monthly energy production, energy density, and shading losses were analyzed. The results indicate that the horizontal system generates 49,3% more energy in absolute terms; however, the vertical system exhibits an energy density almost three times higher, optimizing space utilization. Despite the higher shading losses in the vertical system, its configuration allows for the integration of additional functionalities and aesthetic value, making it advantageous in locations with limited space. Thus, Solar Trees constitute a promising alternative for maximizing urban energy efficiency.

*Keywords: Photovoltaic Systems, Solar Tree, Energy Efficiency, Urban Areas, Space Optimization.*

## 1. Introduction

The efforts of public managers and researchers to comply with international agreements aimed at neutralizing carbon emissions also encompass electrical energy consumption in large urban centers. The growing demands for energy generation from renewable and sustainable sources have led experts to re-evaluate the traditional configurations of photovoltaic (PV) systems, which, although they have advanced significantly in terms of cost and technology, still face challenges for their implementation in certain urban contexts.

High population density, the intense deposition of particulate matter resulting from atmospheric pollution, and the high cost of land in cities constitute the main challenges for the implementation of conventional photovoltaic systems in cities (Gabrovska-Evstatieva et al., 2025). In this regard, building elements such as roofs, facades, and windows have begun to perform an additional function: energy generation, through integration with photovoltaic cells, in the concept known as BIPV (Building-Integrated Photovoltaics) (Martín-Chivelet et al., 2022).

Another alternative for a photovoltaic system adapted to space-constrained locations is the Solar Tree. A Solar Tree is a three-dimensional photovoltaic system distinguished by its vertical, generally metallic, structure, on which photovoltaic modules are distributed in a manner resembling the branches and leaves of a natural tree (Hyder et al., 2018) (Strauss et al., 2020). This arrangement aims to minimize the effects of shading among the panels, increasing the efficiency of solar energy capture and optimizing electrical energy generation. Solar Trees, when compared to traditional systems, can occupy less ground area and, consequently, increase the electrical energy production density (Dey et al., 2018).

Solar trees emerged as a solution to several technical challenges associated with photovoltaic systems, including concerns about occupied area, aesthetics, and efficiency optimization. In certain configurations, they can generate 16% to 23% more energy than equivalent flat systems, operate at temperatures up to 10 °C lower, and occupy up to 85% less area (Almadhhachi et al., 2024). On the other hand, this type of system can present a high initial cost when compared to traditional flat systems commercialized on a large scale. The solar tree


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model proposed by Chowdhury et al. (2024) presented an implementation cost approximately five times higher than that of an equivalent flat system. However, it was capable of generating 128% more electrical energy and promoting a 129% greater reduction in carbon emissions.

Currently, there are several models of Solar Trees developed with the objective of maximizing energy efficiency while simultaneously addressing the space constraints imposed by the urban environment. Each model offers advantages regarding the reduction of ground occupation but also has specific limitations related to its structural design.

Vyas et al. (2022) compared the efficiency of four distinct Solar Tree configurations: Tulip, Sunflower, Marigold, and Daisy. The Tulip model features a central trunk with two main branches that support 12 photovoltaic modules, resulting in a structure with low ground occupation and high installed capacity. The Sunflower configuration was inspired by the shape of the natural flower and supports 10 photovoltaic modules. The Marigold, in turn, stands out for its greater number of branches, which allows for a higher installed capacity, totaling 15 modules. Finally, the Daisy model presents the smallest foundation area per kWp and a simplified arrangement of modules in a landscape orientation.

All these models avoid shading among the modules, as they are installed on the same plane. Although this configuration minimizes shading losses, it also limits the capture of solar radiation from different angles. This characteristic demands a more robust and, consequently, more costly structure. Nevertheless, when compared to conventional ground-mounted photovoltaic systems, the verticalized models present significant advantages, such as lower area occupation and reduced thermal losses.

Beyond the initial cost, the challenge related to shading losses, resulting from the vertical arrangement of photovoltaic modules in some Solar Tree configurations, can be mitigated by incorporating growth patterns observed in natural plants into the design of these vertical structures. In nature, various species develop specific leaf arrangements as a strategy to maximize sunlight capture and reduce shading among leaves. A notable example is the Fibonacci Sequence, widely observed in plant species, which provides an optimized distribution of leaves around the stem, favoring the incidence of solar radiation on their surfaces (Strauss et al., 2020).

Experts suggest that adopting natural patterns, such as the Fibonacci Sequence, can be an efficient strategy to maximize the utilization of sunlight from all directions. Gangwar et al. (2021) analyzed the performance of solar trees inspired by the spiral leaf growth pattern, known as Fibonacci phyllotaxis. In this study, the researchers designed two solar tree models, with 2/5 and 3/8 phyllotaxis patterns, and compared them with a conventional flat solar panel. The results indicated that the 3/8 phyllotaxis model showed a gain of 18.85% in energy generation and an efficiency 54% higher than the traditional system. Similarly, Deep et al. (2020) conducted a comparison between a flat solar panel and a solar tree designed according to the Fibonacci Series. The authors observed that the verticalized system produced approximately 50% more energy than the conventional flat system.

Despite these advantages, Solar Trees inspired by the Fibonacci Sequence may not be ideal for large-scale applications, as they demand more complex structures, detailed geometric calculations, and higher manufacturing and installation costs (Hyder et al., 2018). Furthermore, factors such as shading among modules, the predominant direction of solar radiation, and the available area for implementation must be carefully considered to ensure the system's best performance. Thus, it is incumbent upon the responsible designer to evaluate the specific conditions of the installation site and weigh energy efficiency, cost-effectiveness, and technical feasibility to define the most suitable verticalized model.

In this context, the main objective of this study is to promote the use of photovoltaic systems in space-constrained environments, such as densely occupied urban areas or locations with limited roof space, through a comparative analysis between two distinct configurations: the traditional photovoltaic system, installed horizontally, and the verticalized system, inspired by natural patterns of solar capture. This comparison seeks to highlight the potentialities and limitations of each model, contributing to the advancement of new solutions in the field of solar energy.

## 2. Methodology

To achieve the proposed objective, this study considered two types of photovoltaic systems: a verticalized model, in the form of a Solar Tree, and another in the traditional flat configuration. The activities were structured into four main methodological stages: (i) development of digital models, (ii) execution of simulations, (iii) data collection and processing, and (iv) comparative analysis of the obtained results, as presented in Figure 1.

The first stage, developing the digital models, involved the application of geometric principles derived from the Fibonacci Sequence to reproduce the leaf distribution pattern observed in natural plants. The mathematical formulation adopted considered variables such as the number of modules, divergence angle, leaf radius, tilt angle, and vertical spacing between modules.

The second stage consisted of computational simulations, performed on the SolarEdge Designer platform, based on real meteorological data. The two system configurations, the vertical (Solar Tree) and the flat, were simulated using the same 170 Wp modules from Solar Born, SolarEdge SE3680H inverters, and P370 optimizers, ensuring equivalent conditions for the comparison.

In the third stage, data collection and processing from the simulations were carried out. Parameters such as generated energy (kWh), energy density (kWh/m²), and system losses (%) were extracted. This data was organized into tables and graphs to allow for quantitative analysis and the identification of behavioral patterns between the evaluated configurations in the fourth stage.

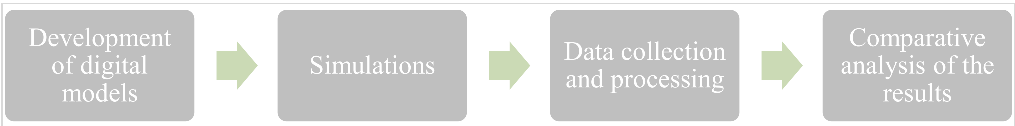



**Figure 1: Methodological stages adopted in the present study.**

## 2.1. Development of digital models

The method adopted in this study for positioning the photovoltaic modules aims to reduce shading losses through the application of the Fibonacci Sequence. Within the context of phyllotaxis, several structural patterns organized in natural plants are observed. Among the most common are the Fibonacci logarithmic spiral and the divergence angle of 137.5°, also known as the Golden Angle (Yonekura and Sugiyama, 2021).

The set of equations presented in Table 1 was used to identify the points in cylindrical coordinates for positioning the photovoltaic modules. This method is based on studies that translate organic patterns into exact scientific formulations. Six initial variables were considered: number of modules (n), divergence angle between modules (α), plastochron ratio (logα), leaf radius (r), leaf tilt angle (θ), and height between modules (k) (Okabe, 2012). From Eqs. (3) and (4), the x and y coordinates are derived, as indicated in Eqs. (6) and (7). Meanwhile, the z coordinate is a function of the internode height (k), represented by Eq. (8), and the number of modules n. Figure 2 illustrates the variables considered in the study.

In the context of multijugate phyllotaxis, a pattern in which more than one leaf emerges simultaneously at each node of the plant, J represents the jugacy of the pattern, which is the number of leaf organs present at each plant node. In a J-jugate pattern, there are J corresponding fundamental spirals, and the organs of the same node are distributed regularly around the plant's axis. On the other hand, j is the jugacy index, an integer ranging from 0 to J-1 that serves to individually identify each organ within a single node.

The number of leaves adopted in the base model was 21, defined considering two main factors: the height limitation imposed by the buildings at the installation site (7 m) and budgetary constraints for the project's execution. The divergence angle between modules (α) was fixed at 137.5°, while the adopted tilt angle (θ) was 20°, a value defined according to the site's latitude. The height between modules was 0.2 m, resulting in a total structure height of 6 m. Each leaf had an area of 1 m², and the radius of the structure was defined as 4 m.

After defining the constructive parameters, the development of the digital models began, using AutoCAD for the technical drawing and SolarEdge Designer for modeling and simulation of the photovoltaic systems. These tools were chosen due to their intuitive interface and the precision of the results they provide.

**Table 1. Set of equations suggested by Okabe (2012).**

| Description | Equation | |
|---|---|---|
| Number of modules | $n$ | |
| Divergence angle (α) Divergence angle (d), in degrees | $\alpha_0=\frac{\tau^{-2}}{J}$ ; $d=2\pi\alpha_0=137{,}5°$ | (1) |
| The Plastochron ratio for the ***n***-th leaf | $\log(\alpha)=\frac{1}{2j(n-1)}\log(n)$ | (2) |
| The radius (r) of the ***n***-th leaf | $r_n=\alpha^{n-1}$ | (3) |
| The tilt angle of the ***n***-th leaf | $\theta_n^j=\theta_n=2\pi(n\alpha_0+\frac{j}{J})$, $j=0,1,2,...,J-1$ | (4) |
| The height between modules (k) | $k=\frac{\log(\alpha)}{2\pi}$ | (5) |
| x coordinate | $x_n=r_n*\cos(\theta_n)$ | (6) |
| y coordinate | $y_n=r_n*\sin(\theta_n)$ | (7) |
| z coordinate | $z_n=n*k$ | (8) |

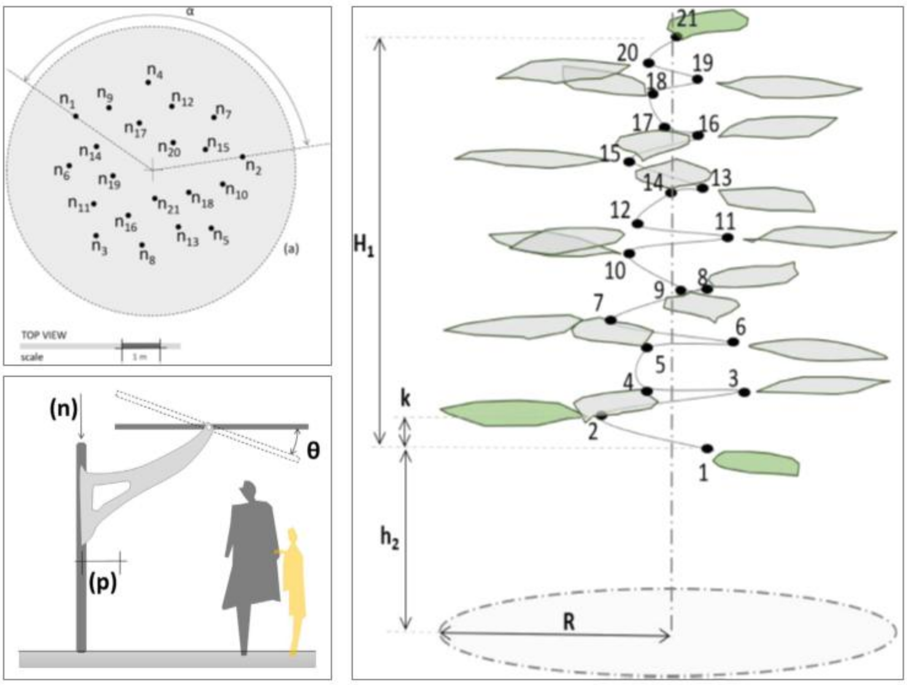



**Figure 2: Schematic representation of the variables used to calculate the positioning of the photovoltaic modules**

SolarEdge Designer is an online platform developed for the planning and validation of photovoltaic systems. The tool allows for modeling and simulating projects, providing estimates of energy generation, system costs, and return on investment projections. Compared to other solutions, such as PVGIS, it presents energy production results that are quite close, and can even exceed the estimates provided by PVGIS by up to 5% (Stott et al., 2021).

The first model developed was the verticalized photovoltaic system, denominated Solar Tree, in which the specific positioning of each photovoltaic module was considered (Palaoro et al., 2026), in order to respect the distances and heights previously defined based on the Fibonacci logarithmic spirals. To enable the creation of a faithful digital model of the Solar Tree, a .dxf format file, created in AutoCAD, containing the position and numbering of each module, was used as a reference. Subsequently, this file was imported into the modeling area of SolarEdge Designer. The platform allows extensive customization of photovoltaic modules in different parameters, with the exception of geometry, which is restricted to commercially available models. The dimensions and technical details of the selected photovoltaic module are described in Table 2.

**Table 2: Parameters of the custom photovoltaic module adopted in SolarEdge Designer.**

| Module Datasheet | | | | |
|---|---|---|---|---|
| **Manufacturer** | Solar Born | | | |
| **Power** | 170Wp | | | |
| **Dimensions** | 1 x 1 m | | | |
| **Electrical Data** | **STC** | **Max Achieved** | **Mechanical data** | |
| **Peak Power (Pmax)** | 170 W | 170 W | Cell type | Poly-SI |
| **Voc** | 23.68 V | 24.58 V | Connector | MC4 |
| **Isc** | 9.55 A | | Nº of cells | 60 |
| **Vmpp** | 18.98 V | | Nº of substrings | 3 |
| **Impp** | 9.08 A | | Length | 1.105 mm |

Similarly, the traditional flat photovoltaic system model was developed from the arrangement of 21 photovoltaic modules, identical to those used in the Solar Tree model, organized on a flat surface, totaling an installed capacity of 3.6 kW. In this model, the modules were positioned without any inclination. In both cases, the same SolarEdge inverters (model SE3680H) and the same optimizers (model P370) were used. Chart 1 presents the configuration of the two systems in the SolarEdge Designer environment.

## 2.2 Simulation

After the development of the digital models, the process advanced to the simulation stage, which was also conducted using the SolarEdge Designer platform. This stage aimed to generate the necessary data to analyze the energy production behavior of the studied systems, based on metrics such as: produced energy (kWh), produced energy density (kWh/m²), and system losses (%).

To ensure simulation accuracy, some parameters were configured in SolarEdge Designer, such as the location and the analysis period. The selected location for the installation of both systems was a public park in the municipality of Vila Velha (20.19° South, 40.16° West), in Espírito Santo (Brazil). The analysis period covered one year, from January to December. Furthermore, the software uses irradiation data from the nearest meteorological station, which, in this case, is the 83649 automatic weather station, located in the city of Vitória (Brazil).

It is important to mention that, in both models, each of the 21 photovoltaic modules was equipped with an optimizer (model P370), and all were connected in series to form a single string linked to the single input channel of the selected inverter (model SE3680H). On the direct current side, the inverter has a maximum input power of 7,360 W, a maximum voltage of 480 V, and a maximum current of 10.5 A. On the alternating current side, it provides a maximum output power of 3,680 VA, with a nominal output voltage of 220 V AC and a maximum output current of 16 A.

**Chart 1 – Vertical Photovoltaic System vs. Flat Photovoltaic System**

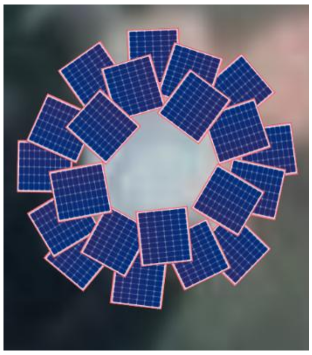
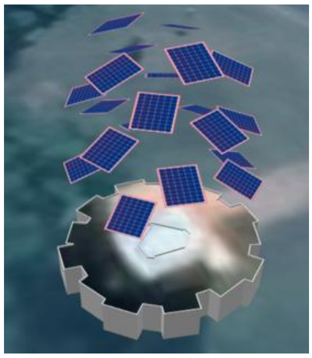
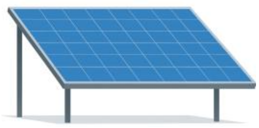
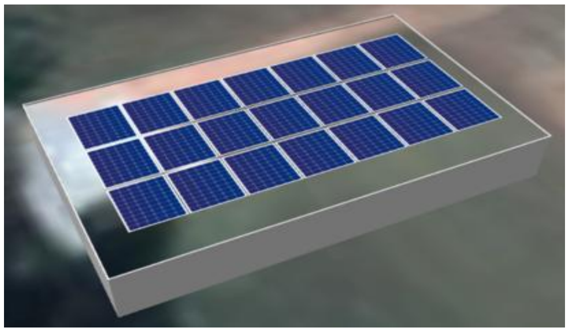
| Type of PVsystem | System Configuration |
| --- | --- |
| Vertical Photovoltaic System (Solar Tree)  |   |
| Horizontal Photovoltaic System  |  |

**Chart 2 – Photovoltaic system losses considered by SolarEdge.**

| Loss Type | Description |
| --- | --- |
| Global horizontal irradiance | Total solar radiation received on a horizontal surface |
| Global irradiance | Total solar radiation adjusted for the actual tilt and orientation of the photovoltaic modules |
| Irradiance loss due to shading | Amount of solar irradiation that does not reach the photovoltaic module due to shading. |
| Energy after PV conversion | Energy that can be produced by the photovoltaic modules considering their efficiency. |
| Irradiance level losses | Energy loss caused by the reduction in photovoltaic module efficiency due to the actual irradiation conditions at the site. |
| Temperature losses | Energy loss caused by a reduction in photovoltaic cell efficiency (relative to STC) due to high module temperature. |
| Electrical shading losses | Energy loss caused by partial shading of the photovoltaic modules. Shaded cells in a photovoltaic module can impact the production of unshaded cells in the same module. |
| Optimizer efficiency loss | Energy loss caused by the optimizer's operation. This value depends on the optimizer's efficiency |
| Module quality loss | Possible loss or gain due to differences between the actual performance of the photovoltaic module and the manufacturer's specifications. This value is calculated based on the power tolerance reported by the manufacturer. |
| Ohmic losses in DC cabling | Energy loss caused by the electrical resistance of the cabling. |
| Energy after DC losses | The total amount of energy that is available to the inverter |
| Inverter efficiency loss | Energy loss caused by the inverter's operation. This value depends on the inverter's efficiency. |
| Exportable energy | Part of the total system production that can be exported, according to the export limitation. |

## 2.3 Data Collection and Processing

As a result of the simulation, SolarEdge Designer provides a report with an overview of the studied systems.

This report includes an estimate of monthly energy generation (kWh) over one year, in addition to information on $CO_2$ emissions (kg), tree equivalent (units), system performance (%), and the system yield index (kWh/kWp). The report also provides a simplified diagram of system losses, as presented in Chart 2.

### 2.4 Comparative Analysis

The comparative analysis aimed to identify the potentialities and limitations of each photovoltaic configuration, vertical and horizontal, in terms of energy performance and efficiency in space utilization. The comparison metrics included total energy generated (kWh), energy density (kWh/m²), and the system loss rate (%), allowing for an integrated assessment of productivity and physical land occupation. The tables and graphs produced during the study assisted in substantiating these analyses.

## 3. Results

The results obtained from the simulations of the two photovoltaic systems, carried out over one year, are presented in Tables 03 and 04. Three main metrics were considered: generated energy (kWh), energy density (kWh/m²), and system losses (%). According to the data in Table 03, the horizontal system showed superior performance to the vertical system in all analyzed months, with higher monthly energy production. On average, the conventional horizontal system generated 486.5 kWh per month, a value approximately 1.5 times higher than the monthly average recorded by the vertical system. This performance difference is mainly associated with the shading effects between the photovoltaic modules. Figure 3 shows the variation of this metric for both systems over one year.

Regarding energy density, the capacity for energy generation per square meter of occupied ground area was evaluated. According to the data presented in Table 3, the vertical system showed significantly superior performance to the horizontal system in all months of the year. The average monthly energy density of the vertical system was 65.08 kWh/m², a value approximately three times higher than the average recorded by the horizontal system, 22 kWh/m². These results highlight the effectiveness of the verticalized design in optimizing solar energy production relative to the occupied area. Figure 4 shows the variation of this metric for both systems over one year.

After the photovoltaic conversion of energy, losses associated with the irradiance level are also observed, which are naturally higher in the Solar Tree (0.95%) due to the actual irradiation conditions at the site, compared to the horizontal system (0.51%). Furthermore, electrical losses due to shading stand out, occurring exclusively in the verticalized configuration, representing 18.71% of the energy after photovoltaic conversion. This significant fraction results directly from the inter-module shading inherent in the vertical arrangement.

**Table 3: Monthly generation estimate of the systems analyzed**

| | **Vertical System** | | | **Horizontal System** | | |
|---|---|---|---|---|---|---|
| Month | Energy (kWh) | Occupation area (m²) | Energy density (kWh/m²) | Energy (kWh) | Occupation area (m²) | Energy density (kWh/m²) |
| January | 341 | 4.84 | 70.45 | 513 | 21 | 24.43 |
| February | 323 | 4.84 | 66.74 | 511 | 21 | 24.33 |
| March | 341 | 4.84 | 70.45 | 538 | 21 | 25.62 |
| April | 293 | 4.84 | 60.54 | 419 | 21 | 19.95 |
| May | 274 | 4.84 | 56.61 | 382 | 21 | 18.19 |
| June | 271 | 4.84 | 55.99 | 388 | 21 | 18.48 |
| July | 258 | 4.84 | 53.31 | 363 | 21 | 17.29 |
| August | 279 | 4.84 | 57.64 | 398 | 21 | 18.95 |
| September | 307 | 4.84 | 63.43 | 462 | 21 | 22.00 |
| October | 349 | 4.84 | 72.11 | 533 | 21 | 25.38 |
| November | 364 | 4.84 | 75.21 | 558 | 21 | 26.57 |
| December | 379 | 4.84 | 78.31 | 577 | 21 | 27.48 |
| TOTAL | 3779 | - | 780.79 | 5642 | - | 268.67 |
| Average | 315 | - | 65.08 | 486.5 | - | 22.00 |

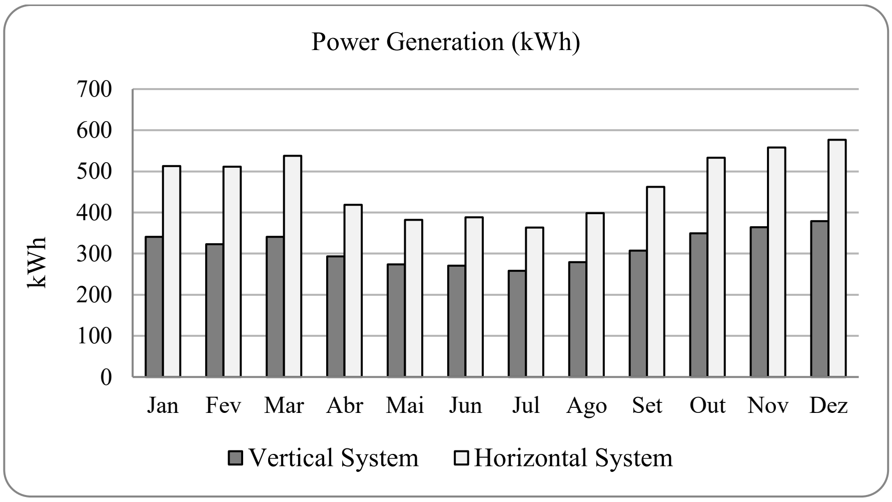



**Figure 3: Absolute energy (kWh) generated per month.**

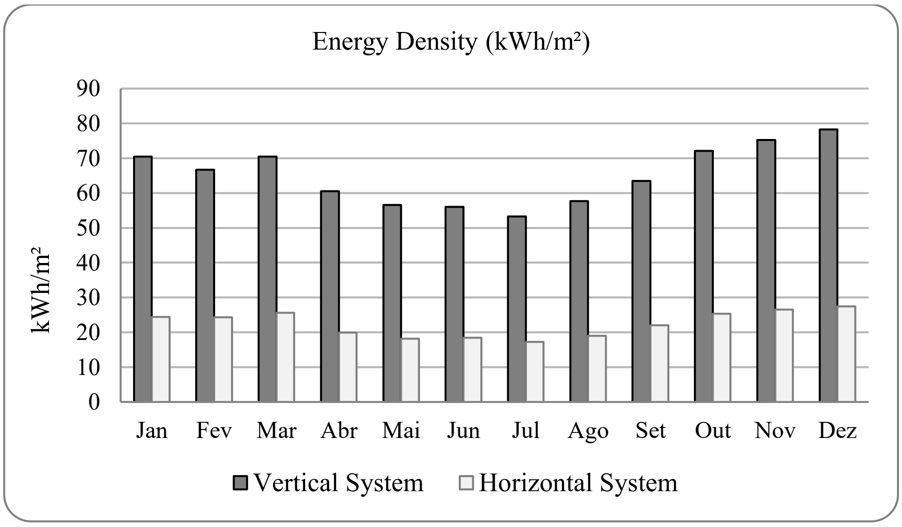



**Figure 4: Energy density (kWh/m²) per month.**

However, shading also contributes to a reduction in temperature losses, as the vertical system features better ventilation between the modules. Thus, the thermal losses of the Solar Tree are 6.63%, lower than those recorded in the traditional horizontal system (10%). Finally, when comparing other loss categories, slightly higher values are observed in the Solar Tree for optimizer and inverter efficiency, while ohmic losses in the direct current (DC) cabling are lower in this system, indicating better electrical utilization in the energy conduction stage.

**Table 4: Global solar irradiance estimates and losses of both systems**

| Parameters | Vertical System | Horizontal System |
|---:|---|---|
| Global horizontal irradiance (MWh/m²) | **1.85** | **1.85** |
| Global irradiance in PV modules | -3.02% | -0.04% |
| Irradiance loss due to shading | -16.16% | 0 |
| Reflection losses | -2.62% | -2.90% |
| Energy after PV conversion (MWh²) | **5.24** | **6.42** |
| Irradiance level losses | -0.95% | -0.51% |
| Temperature losses | -6.63% | -10.00% |
| Electrical losses due to shading | -18.71% | 0 |
| Optimizer efficiency losses | -2.32% | -0.96% |
| Module quality losses | +0.78% | +0.78% |
| Ohmic losses in DC cabling | -0.46% | -0.76% |
| Energy after DC losses (MWh) | **3.86** | **5.70** |
| Inverter efficiency losses | -1.21% | -0.94% |
| Exportable energy (MWh) | **3.78** | **5.64** |

It is worth noting that the portion of irradiance lost due to the effects of snow or dirt accumulation on the modules was not considered in the loss calculations. In addition, light-induced degradation (LID) was also not included in the analyses.

## 4. Conclusions

The results obtained in this study allow for the conclusion that the configuration of photovoltaic systems significantly influences energy performance and the use of available urban space. The horizontal photovoltaic system showed greater absolute energy generation, confirming its efficiency in terms of total productivity. However, the verticalized model, represented by the Solar Tree, demonstrated remarkable performance in terms of energy density, producing almost three times more energy per square meter of occupied area.

Regarding losses, it was found that the horizontal system had lower losses from shading and global irradiance, but higher losses from reflection (2.90%) and temperature (10%), due to its flat arrangement, which increases heat accumulation and the direct incidence of solar radiation on the modules' surface. The Solar Tree, on the other hand, with its modules tilted at 20°, showed slightly lower reflection losses (2.62%) and temperature losses (6.63%), benefiting from better natural ventilation between the modules and more efficient thermal dissipation provided by the three-dimensional structure.

These results indicate that, although Solar Trees exhibit higher losses associated with shading, their configuration offers advantages in urban contexts, where space is limited and the aesthetic and functional integration of energy technologies is desirable. In addition to optimizing land use, the vertical format allows for the reduction of thermal and reflection losses, contributing to greater operational stability and efficiency.

Thus, Solar Trees establish themselves as a technically viable and aesthetically integrated alternative for the expansion of photovoltaic generation in densely occupied urban areas. Their adoption can significantly broaden the potential for clean energy production without compromising land occupation, promoting a more rational and multifunctional use of space. The analysis of the economic viability of these structures also proves promising in certain contexts. According to Palaoro et al. (2026), although the initial investment in Solar Trees based on parametric Fibonacci patterns is higher than that of conventional flat systems, the financial return over time tends to be competitive, mainly due to the high energy density and optimized space utilization. This configuration reduces the need for large installation areas—which are generally costly and scarce in urban centers—and adds architectural and environmental value to the developments. Future studies may further investigate geometric variations based on other natural patterns, in order to further enhance the energy performance and adaptability of these structures to different urban scenarios and climatic conditions.

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