HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

Solar PV tree based on spherical configuration

PhD Thesis

by

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1. INTRODUCTION, OBJECTIVES

Solar energy, a prominent form of renewable energy, can be efficiently harnessed through photovoltaic (PV) technology, which has witnessed significant advancements over the past two decades. Solar tree technology has emerged as a solution to several technical challenges associated with PV systems, including land footprint concerns, aesthetic integration, and efficiency optimisation. Solar trees combine an integrative process between technical effort and modern technology to create an advanced form that produces electricity from solar energy, and the amount of shade provided by trees can have a considerable impact on human thermal comfort.

This study introduces an innovative integration of solar tree technology, which endeavours to mitigate various limitations while concurrently altering the external morphology of solar modules, adopting spherical and hemispherical configurations. This design innovation seeks to address and alleviate specific challenges inherent in solar cell systems through straightforward yet effective solutions. This study explores new ways to apply thin solar cells on spherical surfaces, examining their unique attributes and performance in electricity generation throughout the day. The analysis includes voltage-current diagrams to understand the behaviour of these shapes, considering their interconnections and the impact of external temperature variations. This thermal impact, in turn, imparts consequential effects on the overall energy conversion efficiency. Additionally, the interaction dynamics between multiple interconnected spheres were examined, offering insights into their potential amalgamation for creating aesthetically pleasing constructs such as solar arboreal formations or artistic embellishments on architectural facades.

The main objectives of the present work are to investigate the following:

- Examining the use of spherical shapes in solar modules to reduce the ecological footprint of solar energy installations.
- Examining hemispherical solar module configurations as an alternative to costly solar tracking systems, aiming to address the challenge of the sun's changing position throughout the day.
- Introducing a novel solar tree design, drawing inspiration from natural trees, with the intention of enhancing aesthetic elements within urban landscapes.
- Constructing a model of the most efficacious existing solar tree designs for the purpose of juxtaposing and evaluating the novel tree configuration, aiming to discern the distinctive strengths and attributes inherent in the innovative shape.
- Investigate the impact of shadows on the land created by solar tree structures and propose suitable applications for this phenomenon.

2. MATERIALS AND METHODS

This chapter thoroughly overviews the materials, techniques, equipment used, and the scientific methodologies employed in the experimental measurements to accomplish the research goals.

2.1. Materials and PV configuration types

Many PV configurations were made and tested in Gödöllő city at the Hungarian University of Agriculture and Life Sciences, Solar Energy Laboratory. Moreover, Throughout the experimental phase, various measuring instruments and different types of PV modules were utilised to gauge a range of operational parameters and characteristics inherent to PV systems. Table 1. Shows the specifications for every solar module used in the research work.

Table 1. Specifications of the solar module as provided by the manufacturer

Parameter	Monocrystalline, first type	Monocrystalline, second type	polycrystalline	Thin film, leaf	Thin film, rectangular
Maximum power (W)	1.8	1.1	3.3	1.56	0.13
Rated power (W)	1.3	0.9	3	1.3	0.1
Maximum voltage (V_{max}) (V)	2	2	12	2	1.5
Maximum current (Imax) (I)	0.9	0.55	0.25	0.65	0.07
Open-circuit voltage (V_{oc}) (V)	2.36	2.36	13.2	2.2	1.65
Short-circuit current (I_{sc}) (I)	0.99	0.605	0.26	0.71	0.09
Dimension (L×W×T) (mm)	180×60×3	130×40×3	480×370×4	173×38×1	110×30×2
Cell efficiency (%)	22	22	16	17	11

Conventional photovoltaic systems typically exhibit a flat configuration, with most installations characterised by a minimalist black appearance. However, in recent years, the emergence of solar trees has challenged this conventional design, offering an aesthetically pleasing and environmentally friendly alternative to conventional solar panels. These structures not only harness solar energy but also contribute to urban beautification, fostering a greater public acceptance of renewable energy sources. The external design of the solar PV modules was changed to study the effect of shape on electrical energy production.

2.1.1. Flat PV module

Flat configurations of photovoltaic (PV) systems are ubiquitously adopted across diverse scales, ranging from large-scale industrial installations to smaller, decentralised systems, for the purpose of electrical energy generation. A flat PV module is an assembly of eighteen monocrystalline modules, as shown in Fig. 1. This modular architecture is consistent with industry practice, demonstrating the ubiquitous use of planar geometries in the manufacture of PV systems. Another flat PV module is composed of twelve thin film leaf PV modules, as shown in Fig. 2, to study the characteristics of the solar PV module and compare it with other spherical and hemispherical shapes.

Fig. 1. Monocrystalline PV module

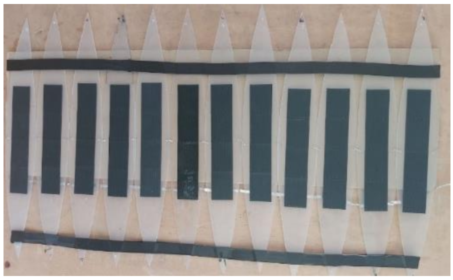

Fig. 2. Thin film, leaf shape PV module

2.1.2. Solar tracker hemispherical PV module

In the context of this research, a meticulously crafted hemispherical structure with a diameter of 0.25 meters has been devised, as shown in Fig. 3. This structure integrates six leaf-shaped segments within a robust metal framework, facilitating the installation of thin-film solar modules, each strategically inclined at an optimal angle of 45 degrees to further enhance energy absorption efficiency. The amalgamation of these design features underscores a holistic approach toward addressing the technical and economic considerations associated with solar energy harvesting systems.

2.1.3. Hemispherical PV module

Hemispherical configurations have been covered by adaptable solar cells that adhere to rectangular forms, albeit with certain surface areas remaining uncovered. The quantification of these exposed regions is amenable to calculation. 30 flexible PV modules covered 70% of the hemispherical PV surface area with a diameter of 0.3 m, as shown in Fig. 4.

Fig. 3. Solar tracker hemispherical shape

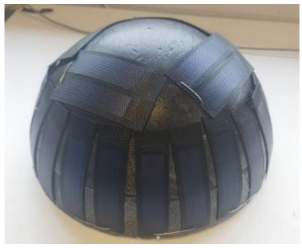

Fig. 4. Hemispherical PV module

2.1.4. Spherical PV module

The amalgamation of two hemispherical photovoltaic modules results in a cohesive spherical shape, constituting a distinctive configuration in solar module design. Notably, in the pursuit of an efficient and non-overlapping arrangement, the application of 60 flexible PV modules emerges as the optimal threshold, as shown in Fig. 5. This maximum limit is defined by the requirement to avert any overlap between modules, ensuring a seamless and unobstructed coverage across the surface area.

2.1.5. Sunflower PV module

One of the more efficient solar trees is the simple tree, which is inspired by nature and has high power productivity. The proposed solar tree has been made as a sunflower with a total diameter of 660 mm facing the sun with a southern orientation on a wooden structure to reduce costs and weight. It consists of a stem of 1800 mm in height and a flat wooden sheet cut into 15 branches holding the PV modules to create the sunflower shape, as shown in Fig. 6.

Fig. 5. Spherical PV module

Fig. 6. Sunflower PV tree

2.2. Experimental procedure

The main objective of this work is to find new designs for the PV system to harvest solar power efficiently, with less land footprint and more aesthetic shapes. The efficiency of the PV modules has been measured and compared to each other, and many new designs have been fabricated and tested.

The solar daytime in Hungary in the summertime lasts for about 15 hours. The average sunrise is at 5:25 a.m., and the average sunset is at 8:10 p.m. The highest solar irradiance occurred mid-day, between 12:00 a.m. and 02:00 p.m. The investigation into the attributes of solar modules involves the correlation of specific loads or variable resistances, each falling within a known range, to ascertain the supplied power during intervals characterised by predetermined weather conditions and solar radiation levels. Rheostat was utilised as a load cell to identify the solar PV module’s maximum power point to get the maximum possible power output. During the experiment, the rheostat was attached to the modules. The investigation started by varying the rheostat’s pointer while monitoring the current and voltage coming from the PV modules. Finally, the pointer’s position is kept when the maximum current is seen at the maximum voltage, and the entire solar PV module’s dataset is extracted.

The examination of solar modules was conducted comprehensively and variedly, focusing on five distinct shapes. These shapes were meticulously scrutinised and can be categorised based on both the type of solar cells employed and the methodology of their formation, delineated into three distinct cases.

2.2.1. Testing the solar tracker hemispherical PV module

The experimental work to study the solar tracker hemispherical shape was conducted from 2:00 p.m. to 7:10 p.m. In other words, the experimental work considered half of the solar irradiance curve since the curve starts from zero at sunrise to the maximum value of the solar irradiance at mid-day to zero at sunset. Therefore, this work considered the recorded data and measurements for the second half of the curve. The work has been done by comparing a flat PV module with a solar tracker hemispherical PV module in two different positions to study the effect of inclination angle on the power generating and compare the results with a flat PV module of the same thin-film solar modules. The study examines a single hemisphere constructed from six flexible PV modules, with a comparative analysis against a flat plate comprising six rigid modules arranged linearly. The objective is to follow the power generation curve throughout the day and gain insights into the performance of the hemispherical configuration. To further comprehend the behaviour of the hemispheres and the corresponding power production curve, two hemispheres were interconnected in a linear arrangement with a separation of 25 cm, equivalent to the diameter of each hemisphere. This setup is compared with a flat panel containing twelve flexible PV modules arranged linearly for comparative evaluation of results. Two positions have been studied horizontally and with a 45-degree inclination for both six and twelve PV modules.

2.2.2. Testing the spherical and hemispherical PV module

Spherical solar modules represent a unique and innovative approach to harnessing solar energy. Different shapes and configurations were studied to understand their characteristics, including single sphere, three spherical shapes, single hemispherical shape, and multiple hemispherical shapes. The aim was to explore how these configurations affect the solar PV module efficiency and overall performance, considering their arrangement, connections, and distances.

2.2.3. Testing the Sunflower PV module

The characteristics of the solar tree and the power generation should be compared with the results with solar modules with dimensions of (1100 × 200) mm flat of the same type of PV module. The cells were connected in the same way to avoid any additional energy losses. The solar tree and the flat module were connected and formed with the same electric circuit, which has six rings connected in parallel, and each ring contains three modules connected in series; thus, the total number of cells was eighteen solar modules, as shown in Fig. 7.

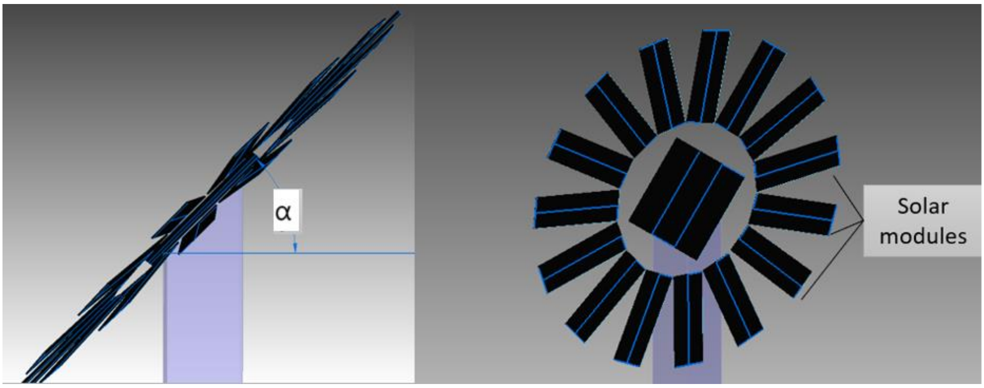

Fig. 7. Sunflower PV tree

The sun's thermal effect on the solar PV modules will also be calculated to measure the temperature of the solar module and calculate the temperature of the shaded surface through the solar modules, in addition to measuring the ambient temperature. A flat PV system (land-based fixed-angle) with the same power capacity is compared to the solar PV tree's output. Three different tilt angles have been tested and measured to find the best tilt angle: case 1: tilt angle (α=45°); case 2: tilt angle (α=30°); case 3: tilt angle (α=20°).

2.3. Power calculations

The following equation can calculate the maximum electrical power generated by the solar PV module:

$$\eta_{PV} = \frac{Output\ Power}{Input\ Solar\ Power} = \frac{V_{max}\ I_{max}}{G\ A}. \quad (1)$$

Where η_{PV} is the efficiency of the PV module, V_{max} is the maximum working voltage (V), I_{max} is the maximum working current (A), G is the solar irradiance (W/m^2), and A is the PV module surface area (m^2). This equation finds application within conventional planar photovoltaic modules. In assessing the computation methodology for electrical energy yield derived from configurations possessing curvature or sphericity, due consideration must be accorded to solar incidence geometry. This imperative arises due to the Earth's perpetual and uninterrupted rotational motion, engendering alterations in the incident angle of solar radiation upon solar cell surfaces, alongside fluctuations in the effective solar projection area upon the non-planar geometries. The following equation will calculate the power for the spherical configuration:

$$P_m = \eta_{PV}\ A_c\ G - \eta_{PV}\ 3\ A_c\ G_d. \quad (2)$$

Where Pm is the maximum power (W), A_c is the projection circle area (m^2), and G_d is the diffused solar irradiance (W/m^2). The outer surface area of any spherical shape = $4\ \pi\ r^2$ = 4 circle area, the sunlight will fall on the circular projection area of the spherical shape, and the rest of the outer surface continues harvesting the diffused solar irradiance.

A hemispherical PV module presents an interesting case for modelling power output because it combines aspects of both flat and spherical modules. Like the spherical module, the hemispherical shape means that different parts of the module will receive different amounts of sunlight depending on their orientation relative to the sun. To estimate the power output of a hemispherical PV module, an equation similar to the one suggested for the spherical module could be used with more complexity but modified to account for the fact that only half of a sphere is being dealt with:

$$Pm = \eta_{PV} \int G(\alpha,\gamma)\ \cos(\alpha)\, dA. \quad (3)$$

where: $G(\alpha,\gamma)$ is the solar irradiance (W/m^2) at a given point on the hemisphere as a function of the polar (α) and azimuthal (γ) angles. Cos (α) accounts for the angle of incidence of the sunlight. dA is the differential area element on the hemisphere. Integration over the surface of the hemisphere would be performed to account for the varying irradiance across the module. The $\cos(\alpha)\cos(\gamma)$ term would ensure that areas of the module that are not directly facing the sun contribute less to the total power output, consistent with how photovoltaic cells behave.

3. RESULTS

This chapter presents the most important results obtained from the experimentation and their discussions.

3.1. Solar tracker hemispherical PV module

Inclined solar modules can capture solar irradiance more efficiently, capturing more perpendicular light than inclined light. Fig. 8 compares the power produced by twelve flat flexible solar modules with two hemispherical modules with the same number of PV modules at the same inclination angle. The results demonstrate a convergence in the electricity production quantities. Moreover, the shape of the output power line for the hemispherical module was like the behaviour of the solar tracking system.

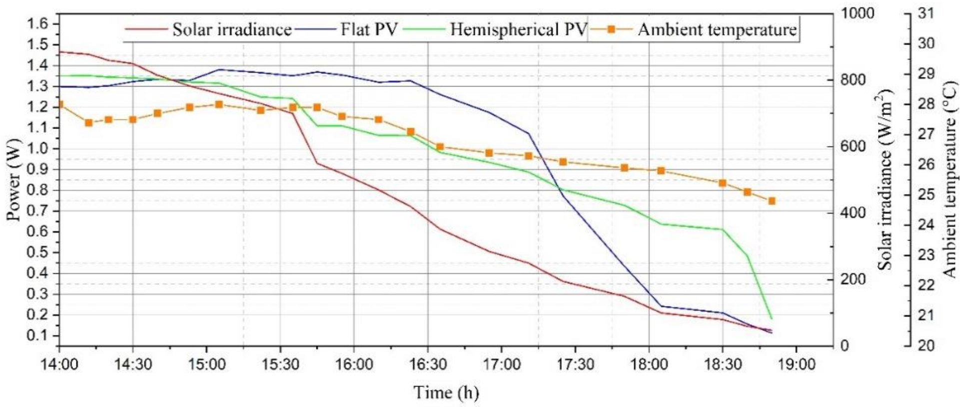

Fig. 8. Power generation from twelve PV modules titled 45°

The hemispherical-shaped module continued to produce electricity at the solar irradiance below 250 W/m2.

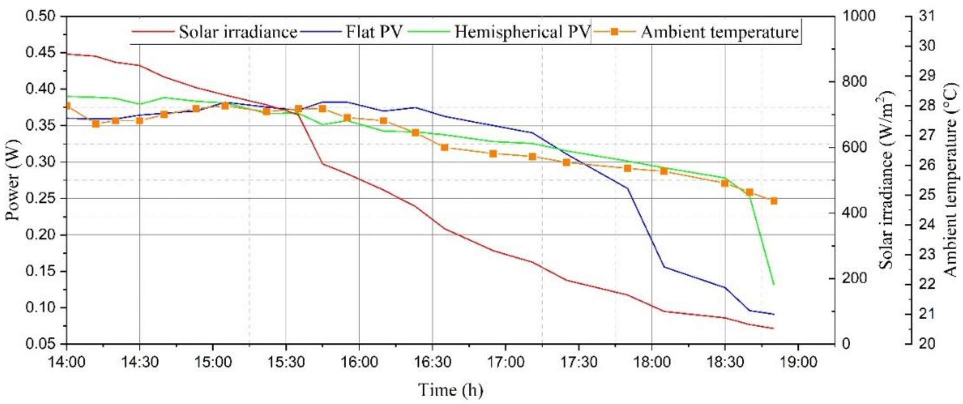

Fig. 9. Power generation from six PV modules titled 45°

The single hemispherical shape with six thin-film solar modules showed greater electrical energy production than the flat PV module because there is enough perpendicular PV area along the solar path. Fig. 9 shows the output electrical power during the afternoon in which the hemispherical shape PV system produced more power than the flat PV shape system by 6.7 % during the experiment.

The hemispherical module showed less power generation than the flat PV system. The flat system contained twelve PV modules, producing more than the two hemispherical PV modules by 6.95 W and 23% during the experiment. The PV system is affected by the incidence angle of sunlight. This is the main reason describing the lower power generated from the horizontal PV system. In addition, the shadow caused by the horizontal hemispherical PV system (another side of the hemisphere shape) has decreased the generated electricity more than the flat PV system.

3.2. Spherical and hemispherical PV module

The spherical PV configurations commence the process of solar energy harvesting from the early morning until late afternoon, as they are not reliant on the peak hours typically associated with generating electrical energy between 10:00 a.m. and 4:00 p.m.

3.2.1. Single spherical PV module

Spherical configurations persist in collecting solar energy and the subsequent generation of electrical power, commencing in the early morning and extending throughout the day.

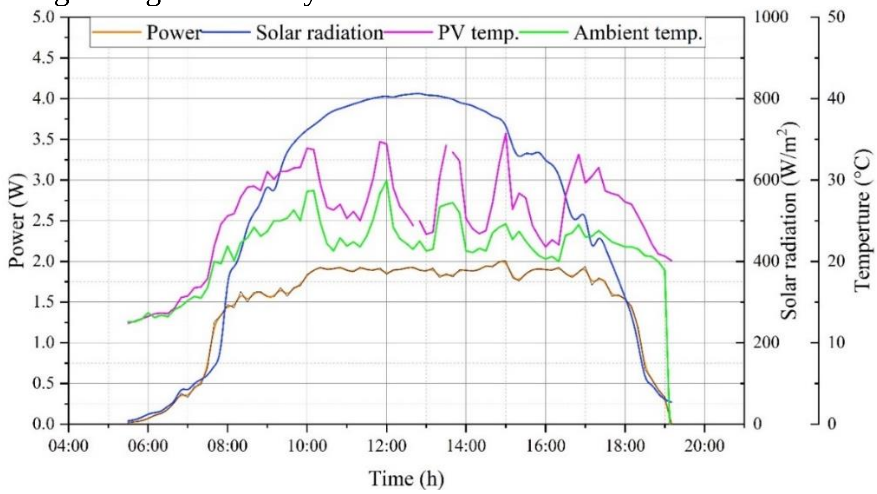

Fig. 10. The power generated from a single spherical shape

Fig. 10 illustrates the electrical power curve associated with solar radiation incident upon a spherical structure enveloped by photovoltaic modules. This curve exhibits a behaviour akin to that of a solar tracking system. This similarity can be attributed to the consistent cross-sectional surface area, which maintains a circular configuration throughout the day for spherical shapes. The difference between the measured maximum power (2.02 W) and the calculated power (2.41 W) is approximately 16%. This difference could be considered acceptable in some contexts, especially given the complexity of measuring and modelling the performance of a spherical PV module.

3.2.2. Three spherical PV modules

The three spherical configurations collectively form a simplified model resembling a solar tree inspired by a grape structure, facilitating the examination of the influence of interconnected spherical shapes on both the environment and energy production. By offering an extensive surface area relative to their land footprint, solar trees effectively contribute to decreasing surface temperatures through enhanced airflow, thereby promoting improved heat dissipation and the sustained efficiency of the solar modules. The output of three spherical configurations yielded a power output of 3.13 W, juxtaposed against a theoretically computed value of 4.09 W, resulting in an appreciable variance of 23%. Fig. 11 presents data illustrating the energy production, temperatures, and solar radiation for three spherical clusters of solar modules.

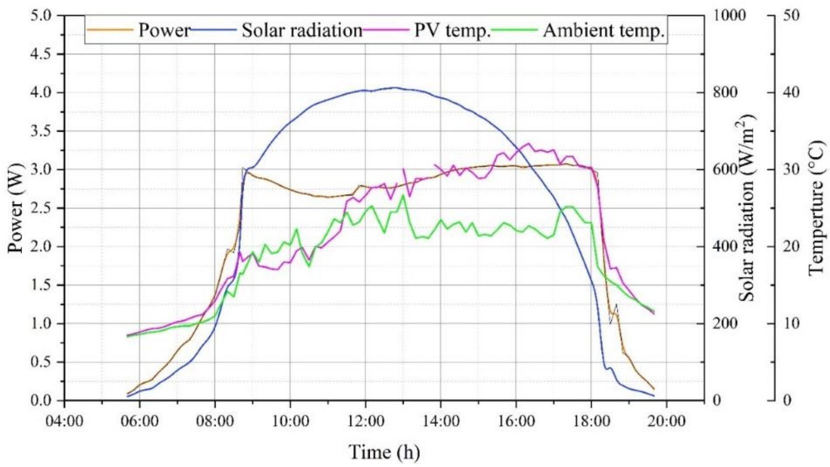

Fig. 11. The power generated from three spherical shapes

3.2.3. Single hemispherical PV module

Hemispherical configurations display a notably reduced land footprint and its implications on electrical power generation, as clarified in Fig. 12; this figure illustrates power generation, solar radiation, air temperature, and the average temperature of the solar PV modules, showcasing a remarkable degree of stability and consistency in power generation. The hemispherical shape recorded an amount of energy higher than the spherical shape by 32%, compared to a similar number of solar modules used in practical experiments, because of losses in the opposite directions of sunlight.

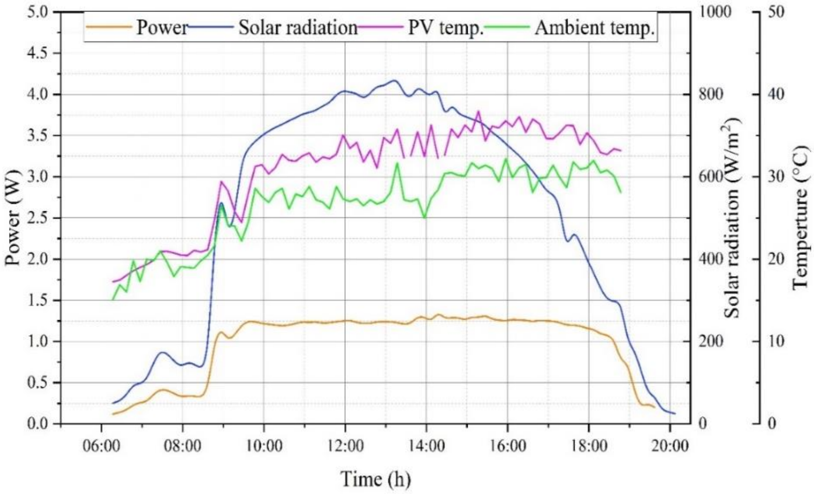

Fig. 12, the power generated from a single hemispherical shape

3.2.4. Multiple hemispherical PV modules

The two hemispherical configurations of solar modules were interconnected along a single axis in parallel; the ensuing results are presented in Fig. 13. These results encapsulate power generation, solar radiation, and temperatures.

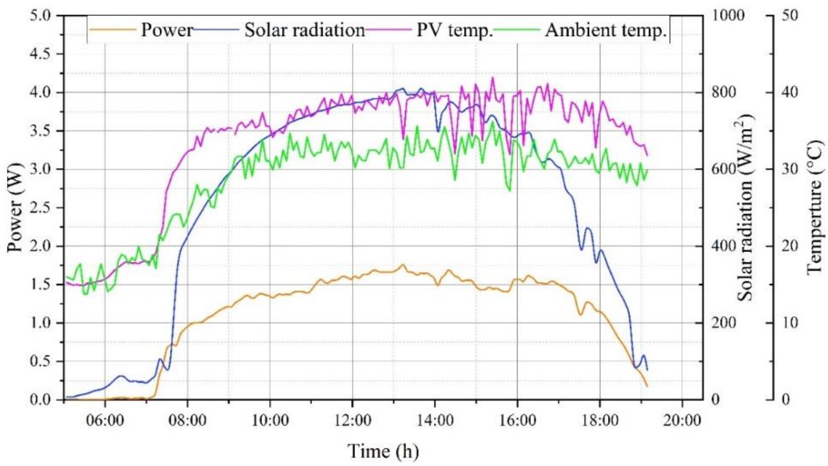

Fig. 13. The power generated from two hemispherical shapes

The three-dimensional PV system shows behaviour similar to the two hemispherical PV modules, as illustrated in Fig. 14, the power generation curve, solar radiation levels, and temperature. The power generation remains uniform throughout the day, reflecting exceptional stability and efficiency.

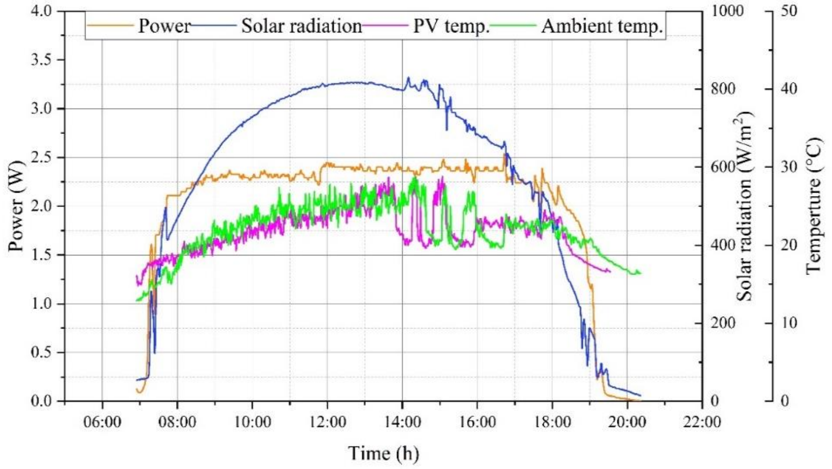

Fig. 14. The power generated from three hemispherical shapes

The capability to generate an average power of 2.4 W at an incident solar irradiance of 600 W/m^2 is noteworthy. This accomplishment distinguishes these hemispherical configurations by their ability to generate significant electrical energy without heavily relying on high-intensity direct solar radiation.

3.3. Solar tree mode

3.3.1. The temperature of PV modules

The interval from 10:00 to 15:00 constitutes the prime window for effective solar energy harvesting. During this period, solar irradiance levels were meticulously documented to facilitate a comparative analysis of the temperatures across disparate photovoltaic (PV) module configurations, thereby elucidating the thermal disparities between them.

The central area of the sunflower configuration simultaneously recorded a maximum temperature of 38.05 °C. The temperature fluctuations depicted in Fig. 15 can be attributed to considerable variations in wind speed, ranging from 12 to 30 km/h, while the flat PV module registered a peak temperature of 49.8 °C at 11:50. The mean temperature disparities between the flat PV module, the sunflower, and the ambient air are quantified at 25.2 °C and 12.1 °C, respectively. The temperature of the conventional system exhibited a 23.5% increase compared to that of the solar tree.

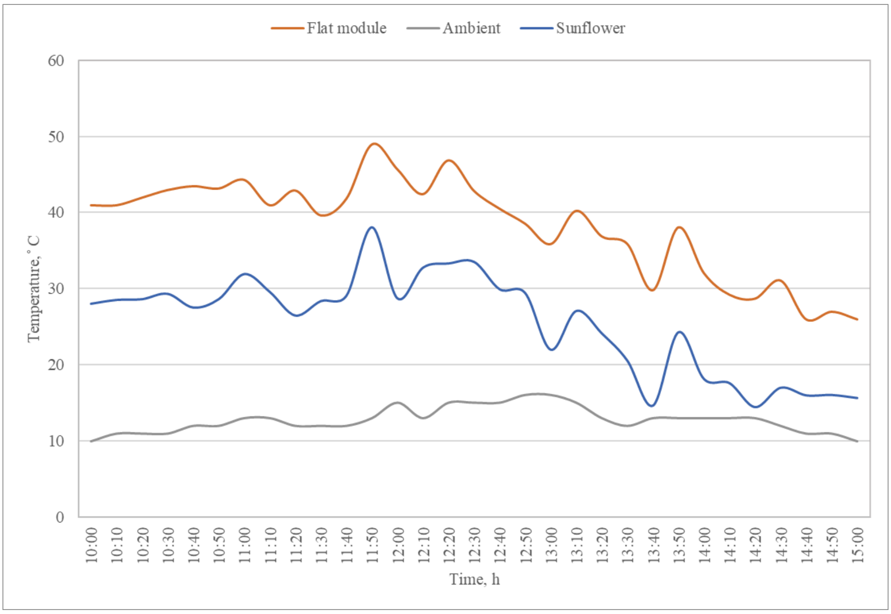

Fig. 15. PV systems temperature measurement (α=45°)

The photovoltaic (PV) systems have reduced ground temperature by casting shadows upon it. The average temperature difference between the ground and the shadow created by the sunflower configuration is 1.8 °C. In contrast, the average temperature differential between the ground and the shadow of the flat PV module is 6.7 °C. Fig. 16, illustrates the comparative analysis of ground temperature relative to the shaded areas produced by the PV systems.

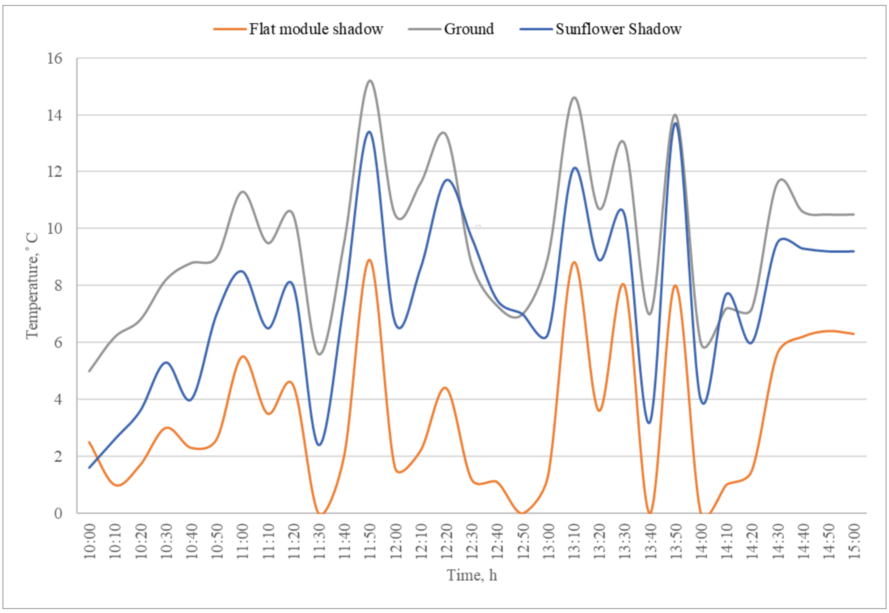

Fig. 16. The shaded and unshaded ground temperatures (α=45°)

As depicted in Fig. 15, the ambient air temperature was observed to be lower than that of the flat PV module and the sunflower configuration by an average of 7 °C and 15 °C, respectively. This phenomenon can be attributed to the incidence of brisk winds, which facilitate the cooling of the PV modules despite the presence of intense solar radiation and an atmosphere devoid of dust and particulate obstructions. A notable temperature gradient is observed across the sunflower-configured modules, with the highest thermal readings centralised within the core of the solar tree, while the peripheries register cooler temperatures, owing to the air currents traversing the interstices among the solar tree's limbs. The shaded ground beneath the flat module experienced a greater temperature reduction than that overshadowed by the solar tree, given an equivalent surface area of photovoltaic (PV) modules. The sunflower configuration casts a shadow upon the terrain, mimicking the silhouette of a solar tree, with its influence tracing an arc-like trajectory from dawn to dusk.
Fig. 16 illustrates that the ground temperature exceeds the projected area of the flat and sunflower module configurations by an average of 7 °C and 2 °C, respectively. This disparity substantiates the efficacy of flat photovoltaic (PV) modules in facilitating ground cooling. Such a temperature modulation is consequential for the cooling load of buildings when these modules are installed atop roofs. The resultant decrease in ceiling surface temperatures may confer a positive economic impact by mitigating energy consumption required for interior climate control.

3.3.2. The power generation

The primary role of solar PV modules is converting solar irradiance into electrical energy.

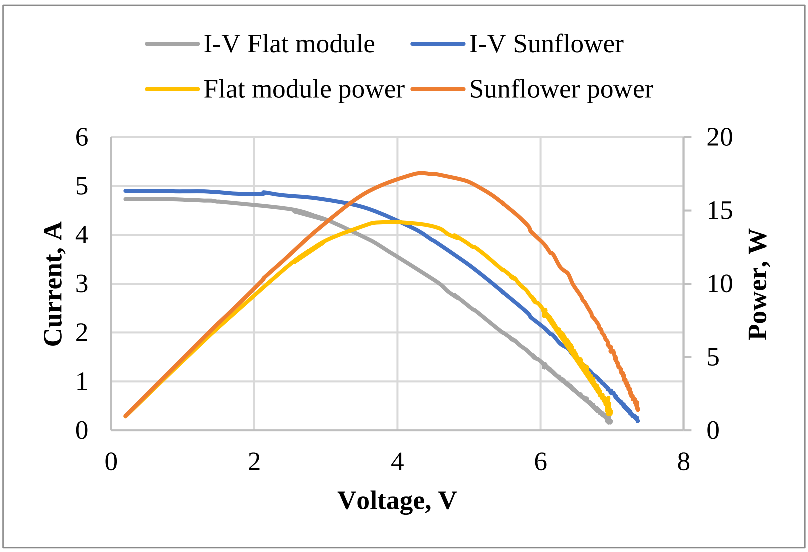

Fig. 17. I-V curve for PV module

Fig. 17, elucidates the current-voltage (I-V) characteristic curves for the sunflower-configured and flat PV modules. While both modules exhibit comparable operational characteristics, the sunflower module demonstrates a superior power output. The open-circuit voltage (V_{oc}) is more effective at high temperatures than the short-circuit current (I_{sc}). To find the Maximum Power Point (MPP), the optimum resistance must be loaded to the circuit by changing the variable resistance value, recording and analysing the results, and drawing the (I-V) curve. (MPP) The sunflower and flat PV systems are observed at 4.5 V and 4 V, respectively.

At an inclination angle of α=45, the sunflower configuration yielded a maximum power output of 14.54 W, while the flat PV module produced 11.8 W. As indicated in the initial segment of Fig. 18, the flat PV module's performance was detrimentally impacted by rising temperatures, a factor that only marginally influenced the sunflower module. Nonetheless, the sunflower module remained within its operational temperature range.

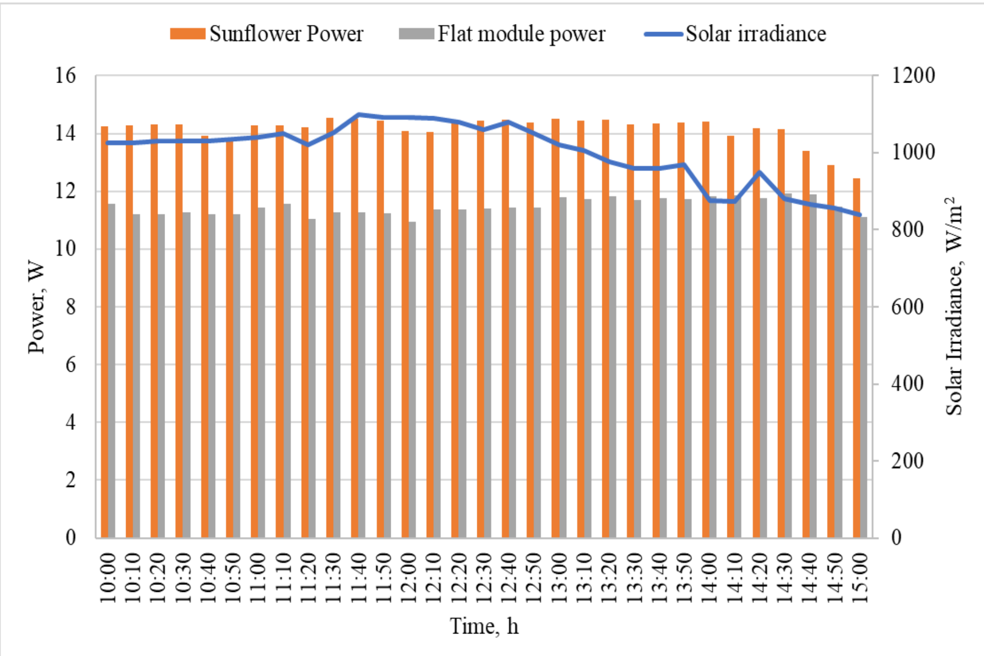

Fig. 18. Power generation from the sunflower and the flat PV module (α=45°)

The efficiency of solar cells is measured under Standard Test Conditions (STC), which stipulate a temperature of 25 °C for the solar PV module. Thus, it is the reference for measurement and assessment. Each solar PV module has its temperature effect factor, which affects the efficiency of the solar module when the temperature rises or falls below 25 °C. The temperature reduces efficiency due to the temperature effect factor of a flat module, which is 23.5% more than that of sunflowers.

3.3.3. Positioning of PV modules for optimal solar tree design

The photovoltaic (PV) modules configured in the sunflower design engender an aesthetically pleasing form and facilitate air passage between the modules, thereby enhancing heat dissipation through convection. Empirical results indicate that the flat PV module's temperature exceeds the solar tree's by over 10 °C, owing to the less efficient convective heat transfer. Additionally, the temperatures of the ground shaded by the solar tree are reduced by 3 to 7 °C compared to the unshaded ground. This temperature reduction is even more pronounced in the context of the flat PV module.

The uniform southern orientation and identical tilt angles of the flat PV module and the solar tree ensure the comparability of the results. This study reveals that the proposed sunflower design yields an average increase in electrical energy production of 16 to 20% over the flat PV module under the same operational capacity and conditions. This enhancement is primarily attributed to the lower operational temperatures and improved ventilation of the PV modules within the solar tree, contributing to elevated energy output.

3.3.4. The land footprint of solar PV tree vs. flat PV module

Photovoltaic (PV) technology converts sunlight into electrical power, necessitating extensive areas for deploying large-scale systems. In urban contexts, where land costs are substantial, land footprint becomes critical in applying PV cell technology. This research analyses the land area necessary for installing a solar tree equipped with a specified number of solar modules compared to a conventional flat PV system.

A conventional flat system incorporating eighteen solar modules requires a land area of 0.3125 m^2. This measurement accounts for the land directly under the solar modules, the surrounding clearance space on all four sides, and the inter-group spacing within a large-scale PV array. In comparison, the suggested sunflower structure, which can accommodate an equivalent of 18 solar modules, takes up just 0.01 m^2, or 3.2% of the land surface required by the flat PV system. As a result, 96% of the land in the footprint for solar technology implementations is saved.

4. NEW SCIENTIFIC RESULTS

This section presents the new scientific findings from the research as follows: work as follows:

1. The inclined hemispherical PV module power

Based on the experimental work, I have demonstrated a 6% increase in energy yield of the hemispherical shape compared to conventional PV systems with the same inclination angle. I have found that the hemispherical shapes, designed for solar energy harvesting, operate seamlessly from sunrise to sunset, emulating the functionality of solar tracking systems without any requirement for moving parts.
I have proven the arrangement of six PV modules on the outer surface of the hemispherical shape with a 45-degree inclination angle generates more power than the inclined conventional PV system.
I have pointed out that the inclination angle of the hemispherical PV module range is proportional to the solar incident angle to the observed pattern in the daily power generation curve, which aligns closely with the characteristic curve of solar tracking systems.
I have found the horizontal hemispherical PV module generates less power than the conventional PV module due to being affected by shadow on the opposite side of the incident solar light.

2. Comparison of hemispherical and spherical PV modules

The spherical configuration experiences limitations in direct sunlight exposure across its entire surface area, leading to energy losses. I have proved the hemispherical shapes present a favourable alternative. This unique placement empowers hemispherical modules to harness energy from direct sunlight and reflected and scattered sunlight. I have discovered that a hemispherical shape containing 30 modules can generate 1.4 W, while a spherical shape containing 60 modules can generate 2.04 W.
After changing the outer design of the PV module to get a new shape by adding aesthetic and power generation enhancement, I have found that the hemispherical PV module can generate more power than the spherical PV module by 32%. However, I have found both the spherical and hemispherical can play a role in aesthetic terms and the same behaviour of the power generation curve as a square function.
Comparing the spherical PV module with the horizontal hemispherical PV module has been done in performance for solar radiation range of 200 $W.m^{-2}$ to 950 $W.m^{-2}$ and the same weather conditions.

3. Modification of sunflower PV tree

Sunflowers are a unique combination of solar PV modules organised in a pattern that resembles the structure of a sunflower. This innovative design has a purposeful tilt of the solar modules, which aligns them with the path of sunlight throughout the day.

I have enhanced the thermal conditions of the system by enlarging the spaces between the PV modules. I experienced the result; it was a stunning temperature drop of 10 °C and 16 °C relative to the centre part and the edge of the sunflower, respectively. I have discovered it can generate more power than the conventional PV system by 20% because of the thermal enhancement of the PV system.

Furthermore, this thermoregulatory system is critical to ensure the maximum performance and lifetime of the PV modules since excessive heat can reduce efficiency and durability. The sunflower-inspired solar setup exemplifies a comprehensive approach to optimising thermal and energy performance, indicating a possible route for improving solar harvesting efficiency in various weather circumstances.

4. Reduction of the land footprint by sunflower PV

Based on practical experiences, I found the sunflower PV tree structures function as distinctive architectural additions to the urban landscape and are characterized by a solid vertical column with a 0.01 m^2 area firmly anchored to the ground. This column is the primary support for the elevated 18 solar PV modules strategically configured to bear artistic and visually appealing shapes with a 0.313 m^2 equivalent area relative to a conventional system. I have justified a significant 96% reduction in land footprint by implementing a sunflower PV tree.

Furthermore, adopting sunflower PV trees in urban areas embodies a forward-looking approach, offering a harmonious coexistence of renewable energy solutions and architectural ingenuity because the sunflower PV tree is inspired by nature. Integrating solar tree technology is a testament to the potential of merging eco-friendly initiatives with creative urban planning, fostering a more sustainable and aesthetically pleasing future.

5. Effect of solar tree for cooling down the shaded area

The solar tree prevents sunlight from reaching the ground. I have found the shaded ground area by the solar tree was affected by decreasing the temperature by 23-28%, and the shaded ground area by the conventional PV module was affected by decreasing temperature by 35-39%. I have found it contributes to a discernible reduction in ground temperature, amounting to a decrease of 6°C.

I have pointed out that this thermal effect presents an opportunity for leveraging the advantages inherent in this phenomenon across various applications. The potential applications underscore the multifaceted benefits of solar trees' shading effect in diverse urban and communal settings.
The PV system affects the shaded ground area if the ambient temperature is more than 10 °C and the solar radiation is more than 500 $W.m^{-2}$.

5. CONCLUSION AND SUGGESTIONS

In this research, novel spherical shapes were introduced to create hybrid solar trees, imparting an urban aesthetic reminiscent of real trees. Subsequently, an examination of flexible solar modules ensued, aiming to ascertain their efficacy, delineate their characteristics, and juxtapose them against mono and polycrystalline solar modules. The outcomes revealed that flexible modules have the potential to achieve an efficiency of up to 17%.

The solar modules, enveloping hemispherical shapes, underwent testing and analysis across various solar module types. It was determined that hemispherical shapes arranged in an arc-shaped wave towards the sun, close to a tracking system, surpassed other configurations in solar energy harvesting efficiency. This approach exhibited a 6% efficiency gain compared to flat shapes while occupying a land footprint, amounting to 19% of that in flat systems with similar solar modules. Notably, the hemispherical shapes, crafted from cork, were covered by flexible solar PV modules, constituting 70% of the total surface area. This configuration aimed to prevent overlap between adjacent flexible modules. The investigation demonstrated that hemispherical shapes generated 32% more power than spherical shapes, attributable to the presence of flexible modules positioned opposite to direct sunlight. Solar trees exhibited a noteworthy reduction of 96% in the Earth's footprint compared to conventional photovoltaic systems. This characteristic holds the potential for implementing large-scale systems within urban settings to generate electrical energy.

Sunflowers exhibited commendable results in power production, surpassing traditional flat systems by up to 20%. This superiority is attributed to the effective dispersion of solar module heat, facilitated by the presence of empty spaces between modules, ensuring convection-based heat dissipation. Consequently, the ground temperature influenced by solar trees experienced a reduction of 6 °C.

A prospective initiative involves identifying companies interested in enhancing the external design of photovoltaic systems. Subsequently, a comprehensive feasibility study, incorporating detailed cost analysis, will be undertaken to determine the optimal structure for solar trees. This endeavour aims to present a realistic cost assessment for constructing solar trees adorned with sunflowers and black grapes. The overarching goal is to raise awareness among individuals, encouraging them to invest in clean energy sources as a means of mitigating pollution and reducing emissions.

6. SUMMARY

SOLAR PV TREE BASED ON SPHERICAL CONFIGURATION

Photovoltaic technology (PV) has emerged as a prominent environmentally friendly technology, undergoing significant advancements in recent years. However, it faces limitations, including high initial construction costs, extensive land requirements, relatively low efficiency, and aesthetically unappealing outcomes. This research aimed to address these limitations by developing solar tree technology, which offers the potential to enhance urban aesthetics, minimise land footprint and improve PV system efficiency.

Novel spherical shapes were employed to construct hybrid solar trees, deviating from conventional commercial, artistic solar trees and closer to the natural form of trees. The black grape tree, revered for its inverted pyramidal fruit structures, inspired this design initiative. Flexible solar modules were integrated into the spherical structures to evaluate their efficiency, characteristics, and comparative performance against mono- and polycrystalline solar modules. Flexible modules demonstrated the potential to achieve up to 17% efficiency.

Hemispherical shapes covered by solar modules underwent rigorous testing and analysis, incorporating various solar module types and distribution patterns to identify the optimal configuration. The results indicated that hemispherical shapes with an arc-shaped wave orientation towards the sun, resembling a tracking system, exhibited superior energy harvesting capability. This configuration surpassed traditional flat shapes by 6% in efficiency while maintaining a land footprint up to 19% smaller. Because the spherical shapes cannot accommodate rectangular solar modules, customised small-dimension flexible modules were commissioned from a manufacturer. 70% of the flexible solar modules effectively covered polyester hemispherical structures, ensuring minimal overlap. The overall spherical shape, adorned with flexible modules, exhibited a 32% power generation increase compared to hemispherical shapes due to the modules' flexibility away from direct sunlight. Solar trees have demonstrated their potential to occupy a mere 2% of the land footprint compared to traditional PV systems. This feature holds immense promise for large-scale implementation within urban environments, generating electricity sustainably. Sunflower-shaped solar trees showcased remarkable power production, surpassing traditional flat systems by up to 20%. This enhanced performance stemmed from the effective dispersion of solar module temperatures, facilitated by empty spaces between the units, enabling heat dissipation through convection. This resulted in an average temperature difference of over 10 degrees.

7. IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Almadhhachi M.,** Seres I., Farkas I. (2020): Concept of a solar cell operated hybrid tree, Mechanical Engineering Letters, 20, 96–100. https://www.gek.szie.hu/english/sites/default/files/MEL_2020_20.pdf
2. **Almadhhachi M.,** Seres I., Farkas I. (2022): Comparison of the efficiency of polycrystalline and thin-film photovoltaic outdoors, European Journal of Energy Research. 2, 9–12. https://doi.org/10.24018/ejenergy.2022.2.2.43
3. **Almadhhachi M.,** Seres I., Farkas I. (2022): Significance of solar trees: Configuration, operation, types and technology commercialisation, Energy Reports. 8, 6729–6743. https://doi.org/10.1016/j.egyr.2022.05.015 (Scopus: Q1, IF = 5.2)
4. **Almadhhachi M.,** Seres I., Farkas I. (2023): Electrical power harvesting enhancement of PV module by a novel hemispherical configuration, International Journal of Thermofluids. 20,100460 https://doi.org/10.1016/j.ijft.2023.100460 (Scopus: D1)
5. **Almadhhachi M.,** Seres I., Farkas I. (2024): Sunflower solar trees vs. flat PV modules: A comprehensive analysis of performance, efficiency, and land savings in urban solar integration, Results in Engineering, 21. 101742. https://doi.org/10.1016/j.rineng.2023.101742 (Scopus: Q1, IF = 5)
6. **Almadhhachi M.,** Seres I., Farkas I. (2024): Harnessing solar power with aesthetic innovation: An in-depth study on spherical and hemispherical photovoltaic configurations, Energy Science and Engineering, https://doi.org/10.1002/ese3.1717 (Scopus: Q2, IF = 3.8)