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Innovative PV Sunflower Solar System Design and Performance Assessment for Sustainable Urban Energy Solutions

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ABSTRACT

In order to address the pressing issue of enhancing solar photovoltaic (PV) efficiency in both rural and urban settings, this research aims to maximize the system's output of solar electric power and investigate its thermal behavior. With the use of extensive calculations and empirical validation, the Smart Sunflower system's thermal performance in relation to conventional panels is investigated. The insightful results highlight how crucial efficient heat management is to PV system efficiency and resilience optimization. Key findings reveal that a 25% increase in solar radiation results in a notable 26% rise in output power. Conversely, a mere 10°C temperature rise can lead to a 1% decrease in panel output, highlighting the significance of meticulous environmental considerations. Results are more credible when validated against simulations and real-world data. Furthermore, this study shows that routine panel cleaning can increase efficiency by as much as 4.5%, which would provide significant benefits for urban solar energy systems. In summary, the work that has been described helps to tackle the pressing problem of maximizing solar energy generation in agricultural and urban environments using cutting-edge innovations like the Smart Sunflower system.

1. INTRODUCTION

The global energy sector faces significant challenges in meeting the increasing demand driven by population growth and technological advancements. Conventional energy sources, such as oil, natural gas, and coal, are major contributors to climate-related issues [1]. Consequently, the global community is actively exploring renewable alternatives to meet the escalating demand for energy. In recent decades, renewable energy sources, particularly solar power, have gained prominence due to their abundance and environmental advantages [2]. Solar energy, with its clean and sustainable attributes, has become a favored global possibility for electricity generation [3]. Scientific reports from the World Research Energy Centre highlight the substantial growth in photovoltaic (PV) system installations, underscoring the increasing importance of solar energy [1]. The global emphasis on photovoltaic solar energy, especially in our region, aims to combat environmental degradation and challenges linked to fossil fuel usage. As a result, photovoltaic power competes favorably with conventional power plants [4], leading to governments promoting the integration of photovoltaic systems in the built environment [5]. While solar energy holds the potential to significantly contribute to global electricity demand, its widespread implementation requires substantial land resources [6].

Concerns arise about the potential displacement of other essential land uses due to the expansion of renewable energy facilities. Therefore, it becomes imperative to conduct studies on the strategic placement of future solar energy plants to maximize energy output and perfect the use of Earth's limited resources [7].

The innovative Sunflower solar system is designed to ensure efficient land use, resulting in reduced installation costs and area requirements.

The global efficacy of solar photovoltaic (PV) systems is reported by Adeh et al. [8], utilizing data on solar radiation, air temperature, wind speed, humidity, and wind direction. Important details on the amount of solar energy resources are provided by PV efficiency. The PV panel's generated solar energy to incident solar irradiance ratio is its definition.

Previous studies aiming to identify regions with the most potential for solar electricity included Western America, Southern Africa, and the Middle East [9]. This outcome is consistent with prior assessments that included a range of factors, such as the business's profitability and the accessibility of the infrastructure [10]. NASA's Moderate Resolution Imaging Spectrometer (MODIS) data is used to indicate the solar power potential of various land cover types. Based on the median values, an extensive computation was provided.

NASA's Moderate Resolution Imaging Spectrometer (MODIS) data assessed solar energy availability over different land cover types, revealing croplands, grasslands, and wetlands as the three classes with the greatest potential [11]. Surprisingly, barren terrains, typically considered ideal for solar PV systems, ranked fifth, challenging conventional notions and emphasizing the importance of diverse land cover types for optimal solar power generation [8]. The assessment shows that croplands, grasslands, and wetlands show the highest ability for solar energy generation [12]. Remarkably, these conditions align with optimal agricultural productivity, suggesting potential synergies between solar energy infrastructure and agricultural land use [13]. Recent research highlights integrating solar PV systems into existing croplands, grasslands, and wetlands for dual-purpose energy generation and agriculture, optimizing land use, and fostering synergies [13]. This approach addresses land scarcity challenges, enhances climate resilience, and aligns with sustainable development goals. Future studies should prioritize evaluating the technical, economic, and environmental aspects to enhance viability [9].

Urban areas, responsible for 80% of the world's GDP and over 70% of carbon dioxide emissions, are crucial for global sustainability. Cities in the EU and North America are adopting ambitious renewable energy goals, contributing to low-carbon urban environments [14]. Municipal-level actions, including regulations, incentives, and financial engagement, play a pivotal role in guiding private developers toward sustainable strategies [15]. National efforts have propelled solar PV and thermal technologies, with PVs projected to cover one-third of new electrical energy demand by 2030 [16].

Distributed rooftop arrangements, like building-integrated photovoltaics (BIPV) and solar thermal (BIST) technologies, offer advantages in energy generation, reducing losses, and providing flexibility in extreme weather [17, 18]. Implementation of vertical urban structures needs to address complex phenomena, including solar reflections and shadowing effects. Consideration of energy, climate, fire hazards, and sociocultural impacts is vital [19].

Emerging alternatives like floating and agrivoltaic solar systems show rapid growth, minimizing land footprint and offering benefits such as enhanced crop yield and defense against severe weather conditions [20]. Thoughtful consideration of these alternatives is essential for sustainable urban energy solutions.

The prevailing trend in solar energy integration within buildings, urban areas, and agriculture highlights the growing importance of harnessing solar power. Nevertheless, this transition faces technical and practical challenges. Constraints like limited solar radiation due to shading effects, sun tracking difficulties, and roof usage constraints for service and agricultural facilities are significant hurdles. Cooling solar cells in closed spaces further complicates effective operation, and architectural incongruity hampers societal acceptance of renewable energy technologies [21].

To overcome these challenges, a promising solution has emerged in urban planning, known as the Smart Sunflower. This innovative system addresses the limitations of conventional building-integrated solar and urban PV energy systems. The Smart Sunflower features a compact, foldable array of solar cells within a base structure, facilitating efficient deployment and sun tracking. Its unique shape, resembling sunflower petals, distinguishes it from traditional PV panels.

Critical to accurate PV system characteristics, photovoltaic cell modeling aims at enhancing energy conversion efficiency. Various parametric models, such as the single-diode and two-diode models, have been proposed. The single-diode model, preferred for solar array performance matching [22], is crucial for studying, analyzing, and improving the energy conversion performance of PV systems.

Saleh et al. [23] overviewed cooling methods for solar PV systems, emphasizing water, air, and other techniques. Jadallah et al. [24] highlighted a novel glass-to-glass PV module with significant improvements. Omer et al. [25] explored optimal PV panel connections for variable speed loads, revealing the 2p2p configuration's high exergy efficiency. Al-shammari et al. [26] studied standalone PV systems in Baghdad for component optimization. Chaichan et al. [27] addressed the impact of dust on PV systems, stressing dust management's importance. Farghali et al. [28] scrutinized the social, environmental, and economic consequences of renewable energy integration. Kadia et al. [29] analyzed a-Si and CIGS PV modules, offering valuable data for Baghdad's climate. Kassem et al. [30] assessed solar PV feasibility in Baghdad, recommending CdTe technology and Two-axis sun-tracking. AL-Agele et al. [31] provided insights into Agrivoltaics' Systems, calling for further research on broader implications. Trommsdorff et al. [32] evaluated APV systems, noting gaps in long-term impacts, economic viability, and scalability. Agostini et al. [33] assessed Agrivoltaics' systems' environmental and economic aspects. Ghosh [34] reviewed the nexus between agriculture and photovoltaics, identifying gaps in large-scale agrivoltaics system research. In summary, the literature highlights cooling methods, novel module designs, optimal panel configurations, standalone system design, dust management, societal consequences of renewables, module performance, feasibility studies, Agrivoltaics Systems' impact, and APV system evaluation. While promising, research gaps include scalability, practical challenges, and broader environmental impacts, suggesting avenues for further exploration.

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This paper aims to design, fabricate, and experimentally analyze a PV panel integrated into a Smart Sunflower system under diverse atmospheric conditions. SIMULINK within the MATLAB package is effectively used to comprehensively understand the PV panel's performance and assist in the design guide. The study contributes to advancing knowledge in solar energy systems, particularly in assessing the performance of PV panels integrated into innovative systems like the Smart Sunflower.

2. MATHEMATICAL MODELLING

The modeling of PV array systems is crucial for determining the efficiency of PV systems. This involves analyzing efficiency curves and the non-linear current-voltage (I-V) and power-voltage (P-V) characteristics of PV cells. A common approach, as outlined in [35], is to use a basic equivalent model consisting of a current source in parallel with a diode, depicted in Figure 1. Environmental conditions have a significant impact on the characteristics and efficiency of PV modules, as highlighted in previous research [36].

According to the works of literature, single, double, and three-diode models are employed for PV cell modeling. These models incorporate parameters such as photoelectric current (I_{ph}), diode current (I_d), shunt resistance (R_{sh}), and series resistance (R_{se}), to calculate the PV current and voltage (I_{pv} and V_{pv}), respectively.

The single diode model, also known as the five-parameter model [37], includes series-parallel connected resistance and a diode, as depicted in Figure 1. In this study, the single-diode model is specifically employed due to its helpful features [38]. Notably, its computational efficiency, stemming from the simplicity of the Shockley diode equation, aligns perfectly with our study's scope and objectives. Additionally, the model's ease of implementation, coupled with its broad applicability and straightforward parameter identification, makes it ideal for the comprehensive coverage we aim to achieve [39].

The PV module current, I_{pv} could be calculated using Kirchhoff's Current Law (KCL), expressed as:

$$I_{ph} - I_d - I_{sh} - I_{pv} = 0 \quad (1)$$

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (2)$$

$$I_{psh} = (V_{pv} + I_{pv} * R_{se})/(R_{sh}) \quad (3)$$

$$I_{rs} = (I_{sh})/(\exp((q * V_{oc})/(n_s * N_s * K * T)) - 1) \quad (4)$$

$$I_o = I_{rs} * (\frac{T}{T_n})^3 * \exp\left[\frac{q * E_{go} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}{n_s * K}\right] \quad (5)$$

$$V_t = (k * \eta * T)/q \quad (6)$$

$$I_{ph} = (I_{sc} + (\sigma * (T - 298)))/1000 \quad (7)$$

Utilising Eqs. (2) through (7), I_{pv} could be calculated as:

$$I_d = I_o * \left[exp\left(\frac{V_{pv} + I_{pv}R_{se}}{\mathrm{N_s} * V_t}\right) - 1\right] \quad (8)$$

$$I_{pv} = I_{ph} - \left[I_o * \left[exp\left(\frac{V_{pv} + I_{pv}R_{se}}{N_s * V_t}\right) - 1\right] * I_{sh}\right] \quad (9)$$

where, $\mathrm{I_{sh}}$ represents the shunt current (the current through a shunt resistor), σ denotes Boltzmann's constant (1.38×10^{-23} J/K), q stands for the electron charge (1.602×10^{-19} C), T represents temperature in Kelvin, I_{pv} signifies the module output current, V_{pv} indicates the module output voltage, V_{oc} represents open circuit voltage, $\mathrm{I_{ph}}$ denotes the photocurrent generated by PV cells under illumination, I_o is the saturation current of the diode, I_{rs} stands for the reverse saturation current, I_{sc} represents the short circuit current, N_s denotes the number of cells, and V_t represents the junction's thermal voltage. The resistance R_{se} is connected to account for voltage drops and internal losses while R_{sh} is connected to account for the leakage current.

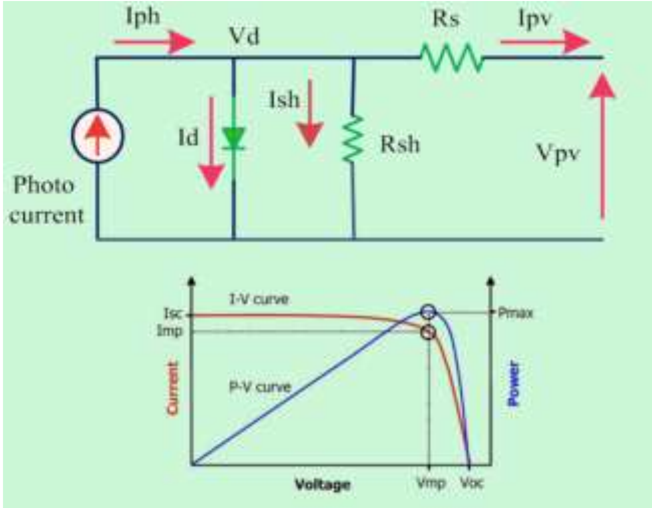

Figure 1. The single-diode model and standard I-V and PV characteristics of a PV module

3. DESIGN AND FEATURES OF THE SUNFLOWER

Designed with SOLIDWORKS software, the sunflower incorporates key elements like the photovoltaic panel petal, a two-axis rotating mechanism, and a base structure. This innovative sunflower autonomously opens and closes its petals 360 degrees, adjusts vertically, and precisely tracks the sun's movement. As illustrated in Figure 2, the sunflower uniquely combines design innovation, aesthetic appeal, and efficient energy production. Its tree-like structure minimizes land usage, providing public shade, and streamlined components simplify installation, reducing overall product components compared to traditional PV systems.

Figure 2. The designed Smart Sunflower by SOLDWORKS

4. SIMULINK MODEL FOR PV SYSTEM

Featuring a flexible external control block for parameter adjustments, this model consists of forty-two interconnected PV cells forming a unit. Module voltage is figured out by multiplying cell voltage by cell count, maintaining a constant total module current. The paragraph discusses the construction and analysis of a PV array with six interconnected modules (Figure 3).

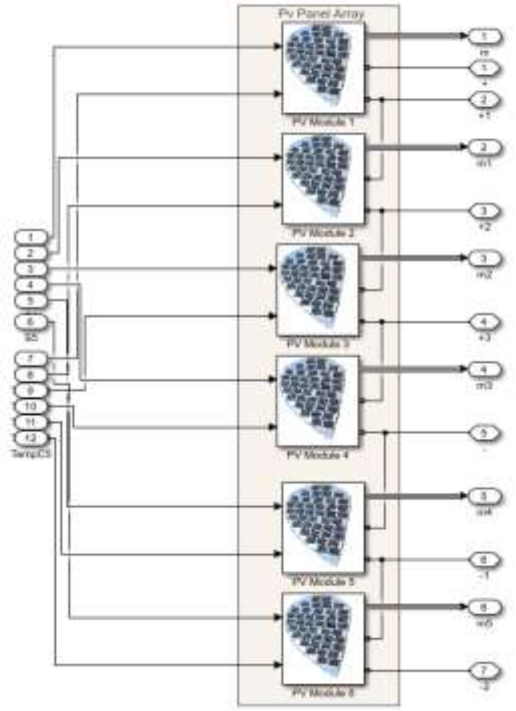

Figure 3. Interconnection of the six PV modules

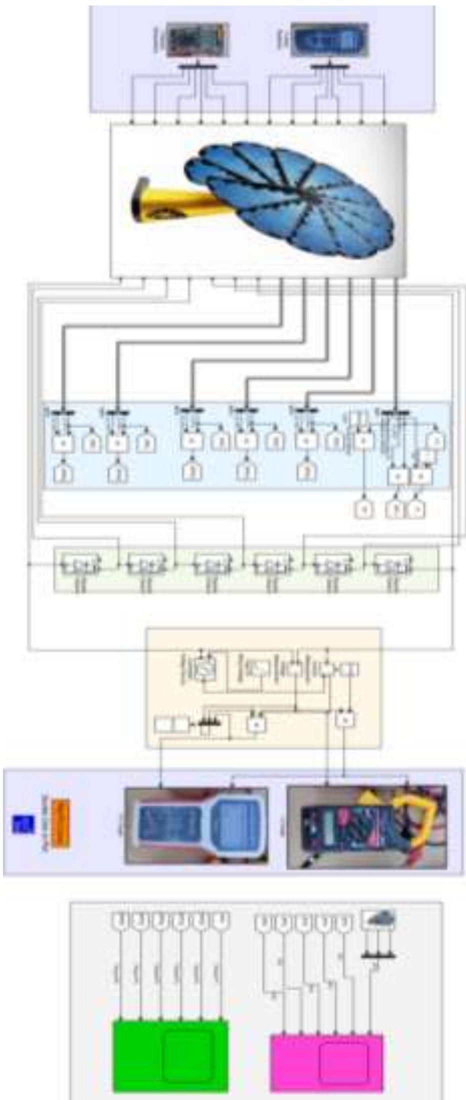

Figure 4. Simulink model for Smart Sunflower PV array

Assembled and connected in parallel for optimal solar energy use, this configuration enhances current collection. Integration with a control block allows performance monitoring. Using the PV module method, a simulation model for the PV array, presented in Figure 4, allows a comprehensive examination of its performance under different conditions. Simulation outcomes offer insights into guiding decision-making, optimizing system performance, and advancing PV array technologies for a wide range of renewable energy applications.

5. EXPERIMENTAL SETTING

Using locally sourced materials for cost-effectiveness, the solar panel includes forty-two solar cells mounted on a 0.5 mm thin aluminum layer, forming sunflower-petal-like structures (Figure 5). The six solar panels in the Smart Sunflower PV system array are affixed to a specially crafted base for stability and motion mechanism support.

Tests were conducted on a Baghdad residential rooftop (elevation: 10 m, coordinates: 44° 25' 16" E, 33° 19' 34" N). Varied conditions were explored, collecting data with electrical, atmospheric, and irradiance devices. Irradiance levels ranged from 100 to 1000 W/m^2, calibrated under standard testing conditions. Figure 6 illustrates the sunflower system test, with measurements using a thermocouple for temperature, a voltmeter for voltage, and an ammeter for current.

The experimental procedure for gathering data is shown in the flow chart, Figure 7, which offers a methodical framework to guarantee precise and effective measurements for the Smart Sunflower system's operational analysis. The figure illustrates the methodical approach taken to track important performance metrics, including system efficiency, energy output, and environmental conditions. This procedure is essential for assessing how well the system performs in various operating settings and finding possible areas for improvement.

Figure 5. The manufacturing stages of sunflower solar panel

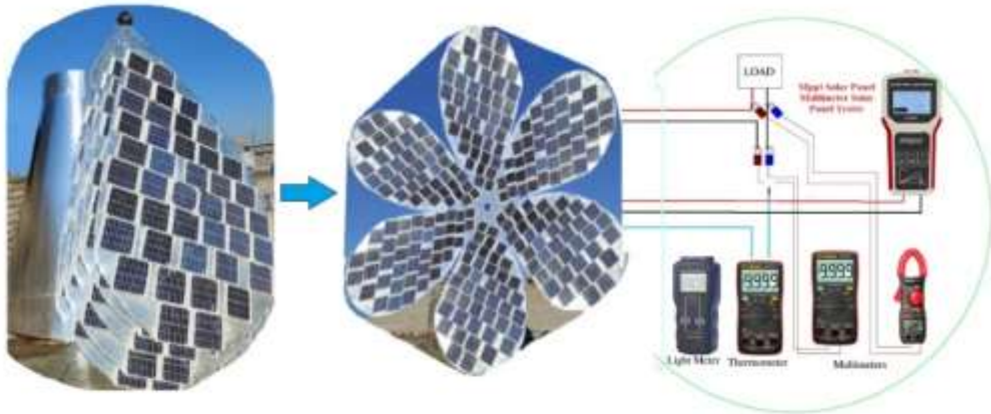

Figure 6. Schematic diagram of the experimental setting of the PV Smart Sunflower system

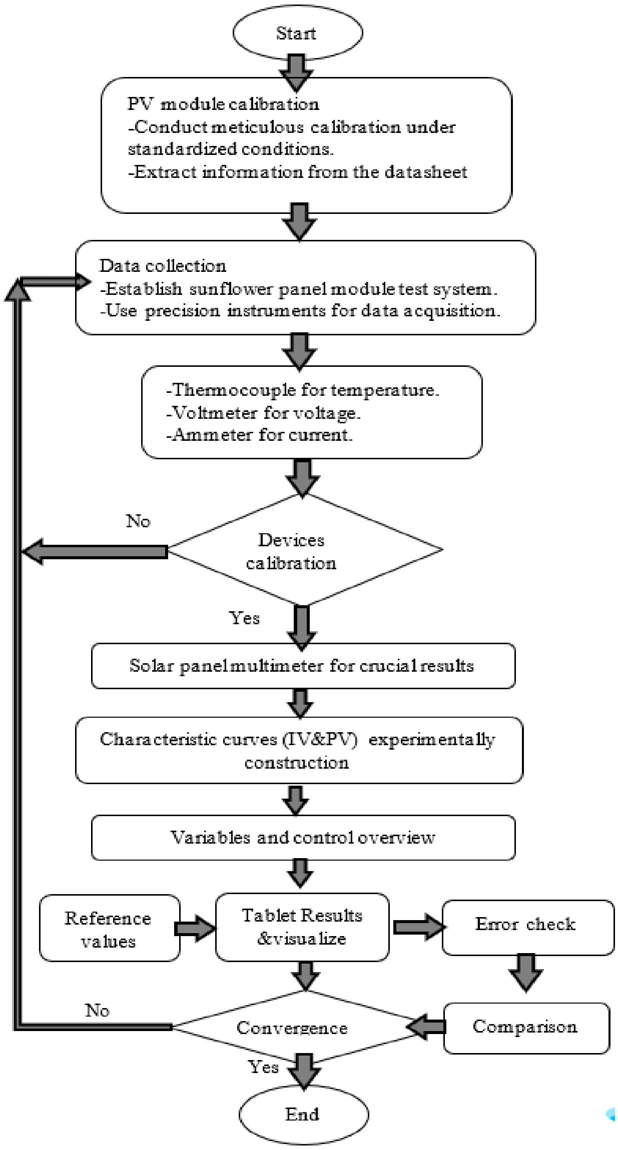

Figure 7. Experimental test procedure flow chart

6. RESULTS AND DISCUSSION

This section provides a comprehensive analysis of experimental measurements, characteristic curves, and key parameters influencing the performance of the solar system. It compares the measured data with the results from analytical models, with particular emphasis on solar radiation levels, module temperature, and operating conditions. The study offers insights into system performance and limitations, ultimately informing recommendations for future improvements in solar energy systems. The analysis is grounded in meticulously collected voltage, current, and power data, which serve as the foundation for constructing IV (current-voltage) and PV (power-voltage) curves—essential tools for characterizing the performance of photovoltaic systems. The validation of the analytical model is conducted by comparing the measured I-V and P-V curves of the Smart Sunflower system with simulation results obtained under representative outdoor conditions.

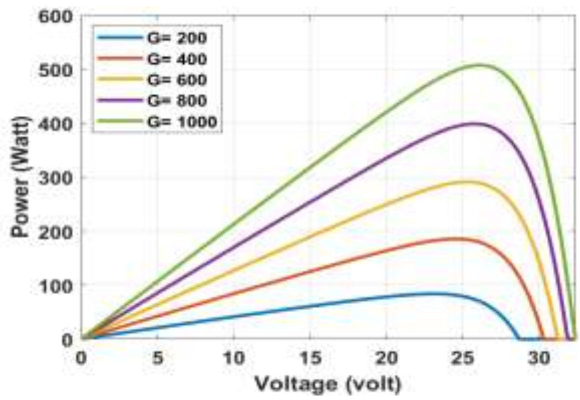

Figure 8. P-V of characteristics curves for different solar radiation values

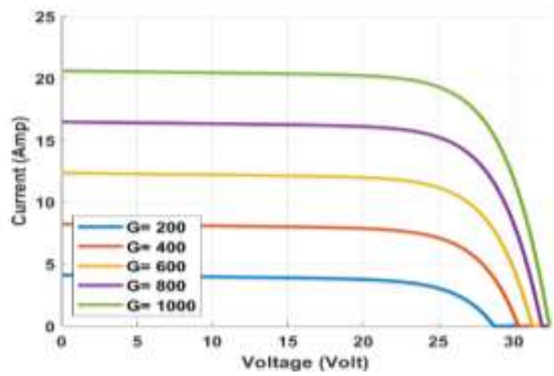

Figure 9. I-V Characteristics curves for different solar radiation values

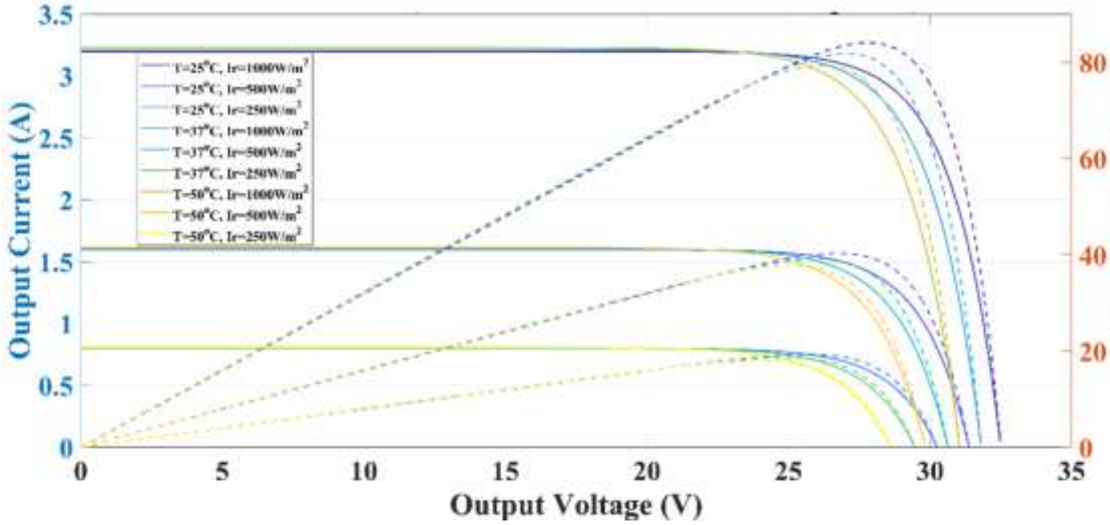

Figure 10. PV module Simulink results at 250, 500, and 1000 W/m^2 and surface temperatures of 25, 37, and 50°C

Meticulously collected voltage, current, and power data form a robust foundation for constructing P-V curves, as shown in Figure 8, and I-V curves, as shown in Figure 9. Validation of the Smart Sunflower system's curves under typical outdoor conditions confirms its exceptional performance. Further analysis across varying solar radiation values' effect on current is presented in Figure 9, which shows a direct correlation of the panel performance at various solar radiation.

Analysing I-V and P-V curves enables optimization of PV panel performance and informed decisions about installation, maintenance, and integration into Smart Sunflower energy systems.

Characterization of the developed system from the point of view of the PV surface temperature is an effective and sensitive operational parameter on the solar PV. The measured quantities of the module current and voltage have been used to predict the power at various temperature using the set of equations 3 to 7 solved in SIMLINK at 250, 500 and 1000 W/m^2 solar irradiation and the optimization curves are presented in Figure 10.

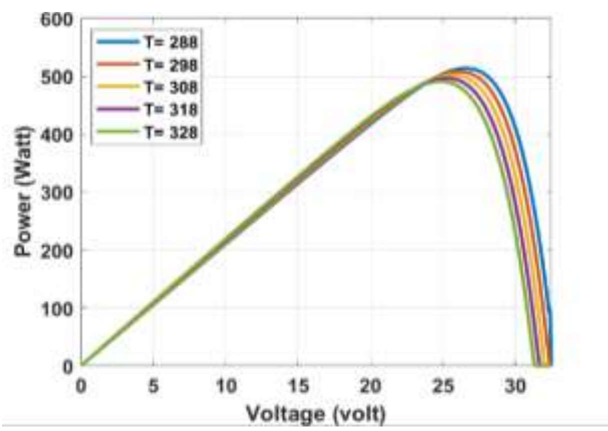

Figure 11. P-V measured characteristics curves for different temperature values

Temperature's impact on PV modules is studied in-depth, revealing sensitivity to variations (Figures 11 and 12). Elevated temperatures increase short-circuit current but decrease maximum power generation due to larger voltage drops. The obtained data allows the generation of characteristic curves, achieving a notable output power of 504 W through meticulous analytical calculations (Figure 11).

By looking onto the data of P-V at various surface temperatures, shown in Figure 11, and the results of the P-V at various solar irradiation, shown in Figure 8, one could realize that the solar irradiation influences the power output from the PV much significant compared to the module temperature.

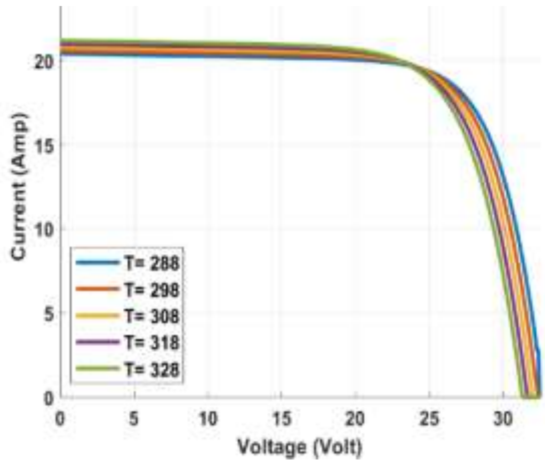

Figure 12. I-V measured characteristics curves for different temperature values

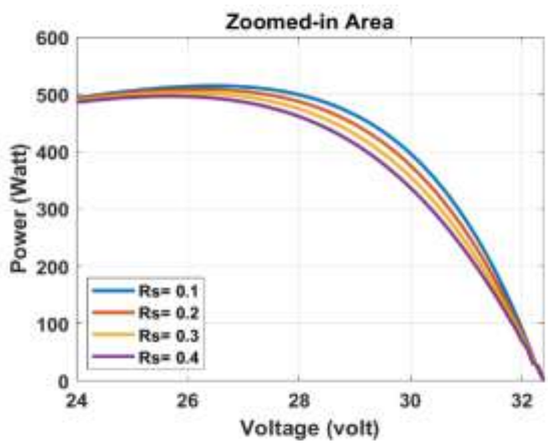

Figure 13. P-V measured characteristics curves for different R_s values

Figure 13 emphasizes minimizing series resistance for maximizing power output. Elevating parallel resistance, *Rp,* from 50 to 450 ohms in a photovoltaic cell has pronounced effects (Figure 14), mitigating shunt losses and fortifying system efficiency. Idealized conditions of infinite Rp and zero series resistance serve as benchmarks for assessing and improving real-world photovoltaic system efficiency.

A comprehensive comparison between measured and analytical curves of the sunflower PV panel (Figures 15 and 16) reveals an elevated level of agreement, supporting the accuracy of modeling and experimental procedures in this study.

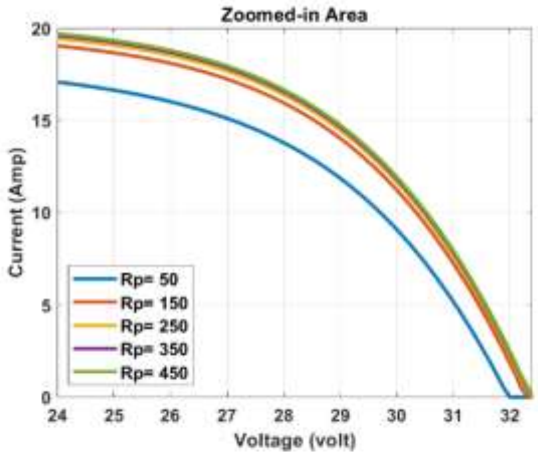

Figure 14. I-V characteristics curves for different *Rp* values

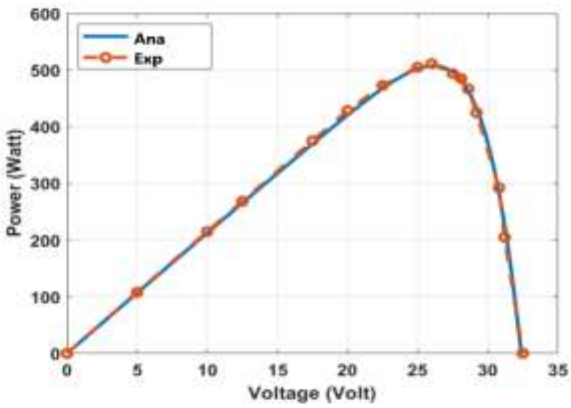

Figure 15. P-V characteristics curve based on experimental measured data

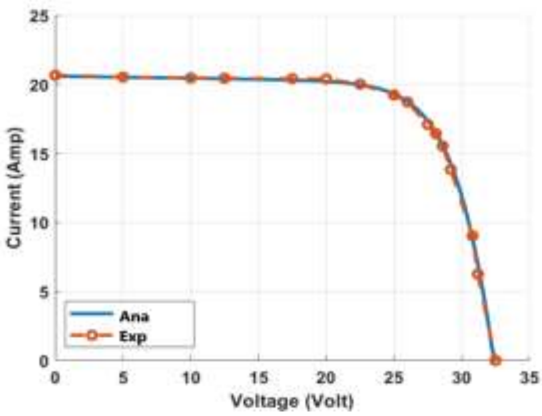

Figure 16. I-V characteristics curve with experimental measured data

7. CONCLUSIONS

The sunflower solar panel arrangement represents a breakthrough in solar PV power generation, underscored by significant advancements in efficiency and performance. Critical points revealed in the study include:

- A clear correlation between solar insolation, system efficiency, and power generation.
- A 25% increase in solar radiation leads to a remarkable 26% boost in output power.
- Efficient thermal management emerges as a crucial factor, as even a modest 10°C temperature rise results in a 1% drop in panel output.
- Moreover, regular panel cleaning emerges as a vital practice, potentially enhancing output by up to 4.5% and overall efficiency.
- The smart flower design of the sunflower solar panel offers an area-saving advantage, making it suitable for urban environments where space is limited.

The author suggests future research efforts should focus on advancing thermal management techniques to further improve panel performance and durability. Exploring innovative cooling solutions tailored to sunflower panel specifications could mitigate temperature-induced degradation, optimizing long-term performance.

In summary, the sunflower panel holds tremendous promise for transforming solar energy systems, particularly in urban design contexts.

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NOMENCLATURE

G	solar irradiance (W/m^2)
G_{stc}	solar irradiance at standard rating conditions (1000 W/m^2)
I	current generated by panel (A)
I_d:	diode current (A)
I_{ph}:	photocurrent (A)
Imp	current at the maximum power point (A)
I_{SC}	panel short circuit current (A)
I_{sat}	saturation current (A)
K	thermal correction factor (Ω/°C)
k	Boltzmann constant (1.381×10^{-23} J/K)
∇	Nabla operator (del)
u	velocity vector field
ρ	density of the fluid
p	pressure (Pa)
μ	dynamic viscosity
n	diode quality factor
P	power generated by the PV panel (W)
q	electron charge (1.602×10^{-19} ℃)
R_L	electrical load (Ω)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
V	Voltage generated by the PV panel (V)
V_{mp}	The maximum power point voltage (V)
V_{oc}	Open circuit voltage of the panel (V)
μI_{SC}	short circuit current Thermal coefficient (A/℃)
μV_{oc}	thermal coefficient of the open circuit voltage (V/℃)
g	acceleration due to gravity
cp	specific heat capacity
∇T	gradient of temperature
k	thermal conductivity ($W/m^2 \cdot K$)
q	heat generation (W/m^3)