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Enhancing Photovoltaic Efficiency with Dual-axis Solar Tracking and Radiative Cooling Technology

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Abstract: Photovoltaic modules' efficiency is often reduced by high operating temperatures and fixed positioning, leading to energy losses and suboptimal solar irradiation capture. The novelty of this study is to improve PV performance using tracking and passive cooling technique. This study integrates a dual-axis solar tracker and a passive cooling system using daytime radiative paint to address these challenges. The dual-axis solar tracker optimizes the module's orientation for maximum sunlight, and the cooling system, incorporating radiative paint and heat sinks, lowers operating temperatures. Three module setups were tested: a reference module, a module with heat sinks, and a module with heat sinks and radiative paint. Simulation results confirmed that the heat sinks and radiative paint effectively reduced the module's temperature. Experimental results showed significant performance improvements, with the highest increase at 12.66%, a 22.63% rise in peak power from 16.79 W to 20.59 W, an average temperature drop of 4.7°C, and an electrical efficiency of 11.77%.

Keywords: Solar tracking; photovoltaic; heat sinks; radiative paint coating

1. Introduction

Photovoltaic module has become a pivotal renewable energy source over the years, but its efficiency is often hindered by factors such as aging and temperature rise during operation which leads to reduced electricity output and shortened lifespan¹. The aging of PV modules leads to degradation which varies between the rate of 0.6% and 0.7% per year according to recent studies conducted by references²⁻⁴. PV module degradation affected by several factors such as solar radiation, ambient temperature, etc. According to Rahman et al¹, PV degradation can cause a 2.8% decline in the performance ratio of the PV module, resulting in a gradual reduction in its efficiency. The integration of dual-axis solar tracker (DAST) and daytime radiative paint as passive cooling solution presents a promising avenue for improving the overall system efficiency and sustainability⁵.

For an extended period, solar systems predominantly relied on fixed configurations. However, recent technological advancements have led to increased efficiency in solar systems through the adoption of single-axis solar tracking (SAST) and DAST⁶. These systems have the capability to dynamically adjust the orientation of PVs, aligning them with the sun's position based on both the season and time of day⁷. The primary objective

of tracking systems is to enhance energy output, as indicated by earlier research and studies, showing an improvement in the range of 22% to 56% when compared to a solar system with a fixed configuration⁸.

PV modules are highly sensitive to temperature, with a decrease in power output occurring as the modules' temperature rises. A study conducted by reference⁹ introduced a combined "photovoltaic/thermal" (PV/T) module equipped with a water-cooling system attached to the rear surface. The findings revealed that the water-cooling system effectively lowers the surface temperature on the back side from 44.80 °C to 30.30 °C and on the front side from 46.60 °C to 36.90 °C. At peak conditions around noon, the PV/T module achieves a maximum thermal heat gain of 230 W, corresponding to an electrical power output of 34.40 W. Furthermore, the PV/T electrical efficiency exceeds that of a conventional PV module by 8%. The maximum and average overall efficiencies of the PV/T module are reported at 76.40% and 68.90%, respectively.

Valiente et al.¹⁰ proposed cooling system for PV modules utilizing underground as a heat sink. The system is theoretically outlined and validated experimentally using a prototype that incorporates a SAST mechanism. The cooling system features a closed-loop, that efficiently

removes excess heat from the rear of the solar module and dissipates it into the underground, which maintains a stable temperature of approximately 16.00 °C at shallow depths. A single “U-shaped copper tube” with an 18 mm diameter is used as the underground heat exchanger, immersed in a 15.5-meter-deep water-filled borehole. The reduction in the cooled module's temperature results in a notable increase in net power output, with observed improvements of up to 12.40% at a coolant flow rate of 1.84 liters per minute per square meter of the solar module. This highlights the technical feasibility and promising potential of the proposed approach.

Meanwhile, Nasrin et. al.¹¹⁾ conducted a study that investigates the use of nanofluids to enhance the efficiency of PV/T systems. A numerical model was developed to test various nanofluid compositions with solid volume fractions up to 3%. Results showed that cumulative the solid volume fraction up to 2% improves thermal performance. Comparisons between water-based systems and those using nanofluids show significant efficiency improvements, ranging from approximately 5% to 7.5%. Nanofluid systems also exhibit better heat transfer rates compared to water, suggesting that nanofluids could optimize PV/T system performance by adjusting compositions and solid volume fractions for enhanced heat transfer.

A research conducted by Kazem et al.¹²⁾ emphasized the utilization of fins on the back of PV modules, focusing on design and performance parameters. The application of fins in nanofluid, and PCM cooling PV/T is explored, showcasing enhanced performance and increased electrical and thermal efficiency within 8 to 10% range. The rise in temperature mainly results in an elevation of the internal resistance within the solar cells. With increased temperature, the cells resistance rises, hindering the smooth current flow. The increased resistance consequently causes a reduction in the current produced by the PV module¹³⁾. Passive cooling, which refers to a method of cooling a system or space without the use of active mechanical systems posed to be a solution to lower the PV temperature without impacting the overall efficiency of the system¹⁴⁾. Daytime radiative paint is an example of passive cooling application where it is a specialized type of coating or paint designed to enhance passive cooling during daylight hours by emitting thermal radiation. Daytime radiative paint is formulated to release heat in the form of thermal radiation, aiding in the cooling of the painted surface. Key features of daytime radiative paint include its ability to effectively reflect sunlight and emit thermal radiation in the infrared spectrum¹⁵⁾. By doing so, this paint facilitates the efficient release of heat, preventing excessive temperature buildup on surfaces exposed to sunlight. The application of daytime radiative paint is often explored in various fields, including building materials, solar panels, and other surfaces exposed to sunlight, with the goal of improving energy efficiency and thermal management. It is particularly useful in mitigating

the effects of solar heating and enhancing the cooling properties of surfaces in a passive and sustainable manner.

The escalating demand for sustainable energy solutions has spurred the exploration of advanced technologies to enhance PV efficiency¹⁶⁾. The ideal usage of PV modules encompasses a multifaceted approach aimed at maximizing efficiency, sustainability, and cost-effectiveness where it is measured by its ability to operate at its peak performance in generating electricity¹⁷⁾. However, temperature-induced degradation and traditional fixed PV installations pose a significant challenge resulting in suboptimal electricity generation. The issue stems from the changing position of the sun and the subsequent reduction in solar irradiation reaching the solar cells, coupled with the rise in operating temperature, both negatively impacting PV performance. The consequence of this issue is detrimental as it leads to increased operational costs and a compromised return on investment for PV installations. The integration of solar trackers, coupled with the application of daytime radiative cooling paint and heat sink fins offers a promising avenue to simultaneously address energy capture and thermal stress¹⁸⁾.

A study used a cooling method for a photovoltaic/thermal (PV/T) system integrating a nano-phase change material (nano-PCM) and a nanofluid cooling system¹⁹⁾. This cooling system achieved a substantial reduction in PV module surface temperature, improved electrical efficiency (from 7.1% to 13.7%), and increased power output. The results underscore the importance of advanced cooling techniques in optimizing PV/T performance

Another study²⁰⁾ highlights advancements in cooling methods for PV/T systems. Key techniques include using nanofluids, nano-phase change materials (nano-PCMs), and combinations of these to enhance thermal and electrical efficiencies. The integration of nanofluids and nano-PCMs into PV/T systems significantly reduces operating temperatures, increasing energy conversion efficiency. This comprehensive review demonstrates the potential of innovative cooling strategies to enhance PV/T systems, paving the way for higher energy productivity and sustainability in renewable energy applications.

The cooling methods for PV panels under harsh weather conditions using thermal and optical modeling has been investigated²¹⁾. It highlights the development of semi-empirical models to predict PV cell temperature by incorporating environmental factors such as irradiation, ambient temperature, wind speed, humidity, and dust accumulation. The cooling approach involves analyzing the effects of these parameters through experimental and computational methods. Outdoor and indoor experiments provided data for validating the proposed models, while ANSYS software was used for thermal and optical simulations. The modeling includes airflow and heat transfer dynamics, ensuring the PV panels operate efficiently under varying environmental conditions. The

study confirms that cooling efficiency can be enhanced by addressing environmental impacts, optimizing airflow, and utilizing thermal modeling techniques.

This study aims to bridge the gap persists regarding the comprehensive understanding of how these integrated technologies collectively impact PV module performance, specifically the intricate interactions between dynamic DAST and the passive cooling capabilities of radiative paint which remain unexplored. This study focusses on evaluating the individual influences of solar tracking systems and a proposed radiative cooling paint on PV module performance and, importantly, investigating their combined effects. The research objectives include assessing the impact of DAST on electricity output, evaluating the efficacy of radiative cooling paint in reducing operating temperatures, and analysing the synergistic influence of these technologies on overall PV module efficiency. Therefore, experiments and simulations will be conducted incorporating solar tracking mechanism and daytime radiative paint with heat sink fins into the conventional PV system to address the issue.

The study objectives are,

- (i) To investigate the effectiveness of daytime radiative cooling paint coupled with heat sinks as a thermal cooling method in reducing the operating temperatures of PV module.
- (ii) To assess the combined influence of DAST with daytime radiative cooling paint and heat sinks on the PV performance.

The study scope is,

- (i) An experimental set-up was implemented by utilizing a DAST mechanism to assess the impact on the PV electricity output.
- (ii) Evaluating the combined effectiveness of DAST coupled with daytime radiative paint and heat sinks in enhancing the PV performance by means of experiment and simulation using CFD models.

2. Solar tracking concept

PV systems are conventionally set up with a fixed orientation and tilt angle, designed to optimize the power output over the course of the year. The changing of sun position, influenced by the tilted axis of the earth and its orbit around the sun, can lead to reduced solar power production in fixed systems. This is where DAST prove beneficial. A study conducted by Karabiber & Güneşn²²⁾, which introduced an innovative solar tracking system, the “Asymmetric Solar Tracker” (AST), featuring a single motor and dual-axis capabilities. The key innovation lies in its adjustable asymmetrical stand that supports PV panels, eliminating the need for heavy concrete or metal structures typical in traditional solar tracking systems²³⁾. The AST achieves SAST with a SAST movement, making it cost-effective like fixed solar systems and efficient like SAST. In an experimental study with two PV panels and under various weather conditions, a comparison of AST

and a fixed PV system was conducted. AST controlled by microcontroller, and “Light-Dependent Resistor” (LDR) sensors tracked the Sun’s position²⁴⁾. The results indicated that, depending on the weather conditions, the implementation of the AST system boosts the daily electrical energy output of PV panels by 25% to 38% compared to a fixed solar system.

2.1 Solar tracking system classification

There are many bases of classification for solar tracking systems. According to Awasthi et al.⁷⁾, solar trackers can be classified by their (i) control system, (ii) driving system, and (iii) degree of freedom.

2.1.1 Control system (open and closed loop)

When sun's position identified by sensors, with the feedback transmitted back to the system, enabling the comparator or microprocessor within the driving system to identify errors and issue the necessary actuating signal for motor adjustment, the system operates based on the principles of a “Feedback Control System”²⁵⁾. This configuration characterizes a closed loop DAST. Open loop tracking systems in DAST utilize controllers that driving motor by generated signal solely based on current data inputs and the system's operating. This differentiates them from closed-loop systems, which lack the capability to observe and assess output data concerning the desired outcome. Consequently, open-loop systems offer a more cost-effective and straightforward implementation with fewer components and lower maintenance requirements²⁶⁾. However, this lack of real-time feedback makes it less adaptable to changing environmental conditions compared to closed-loop control systems, which can adjust their tracking in response to real-time sun position variations.

2.1.2 Driving system

Driving systems used in DAST varies between passive and active as shown in Fig. 1(a) and (b). According to Awasthi et al.⁷⁾, mechanical drives are not present in the passive solar tracking system to align the PV with the irradiation. Instead, it utilizes actuators such as low-boiling point compressed gas fluids or shape memory alloys. When these actuators detect uneven illumination, they induce angular movement in the panel to restore equilibrium of irradiance²⁷⁾. This is achieved by causing thermal expansion in expandable gases or shape memory alloys. When one side of the liquid gas receives more heat energy than the other, it expands and shifts toward the less illuminated side of the tracker. This creates an imbalanced gravitational force, prompting the panel to tilt until an equilibrium point with uniform illumination is attained²⁸⁾.

Unlike the passive solar tracker, the active solar tracking system uses electrical and mechanical gear trains to align the panels perpendicular to the sun’s irradiation²⁹⁾. This system employs sensors, motors and microprocessors for solar tracking, offering higher

accuracy and efficiency compared to passive solar trackers. However, it requires a power source and consumes energy. The sensors detect varying illumination, generating a differential signal when the trackers deviate from optimal alignment with the sun. This signal is then analysed by a comparator or microprocessor, determining the necessary directional adjustments. The calculated signal is subsequently transmitted to the motors, directing them to act accordingly³⁰. The process continues until the PV module is appropriately aligned with the sun's radiation.

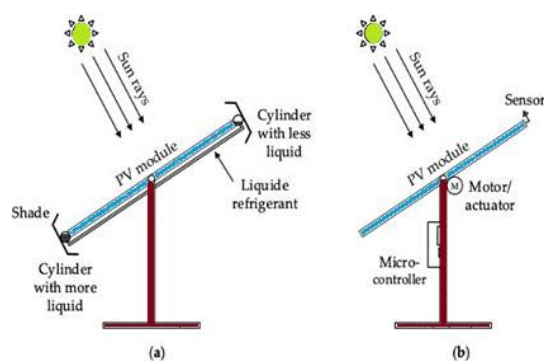


Fig. 1: Driving system solar tracking systems (a) passive, (b) active.

2.1.3 Degree of freedom

The degree of freedom of solar trackers is categorized into SAST and DAST. The SAST has several configurations which includes “Vertical Single Axis Tracker” (VSAT), “Horizontal Single Axis Tracker” (HSAT), and the “Tilted Single Axis Tracker” (TSAT)³¹. Each of these setups involves a singular axis enabling rotation, allowing the panel to align itself perpendicularly to the sun's radiation. DAST involve rotation of two axes which are typically vertical to each other, requiring a more complex control system and are more efficient than SAST. It can be separated into two types which are tip-tilt DAST (TTDAST) and azimuth-altitude DAST (AADAST)³².

2.2 Radiative cooling concept

Cui X. et al.³³ investigated the thermal analysis of cooling PV module by coating, “Passive Radiative Cooling” (PRC) which is regularly applied in the form of paint is that cools terrestrial objects through heat exchange with the cold outer universe via thermal radiation in the wavelength region 8-13 μm . PRC does not require energy consumption and the need for a fluid medium. According to the study, combining the PRC coating with PV through the application of a radiative coating on PV surface can enhance power generation by facilitating radiative heat dissipation. Li. X et al.³⁴ explained that the principle involves using materials capable of reflecting sunlight and achieving cooling by radiating energy into space through the atmospheric window (8–13 μm). Therefore, for daytime radiative cooling paints, it is essential that the

material exhibits high solar reflectance and strong emissivity within the atmospheric window to maximize cooling efficiency. Figure 2(a) illustrated a proposed white CaCO_3 paint that can maintain surfaces up to 18 $^\circ\text{F}$ (approximately 8 $^\circ\text{C}$) cooler than their ambient surroundings as claimed by Li. X et al.³⁴. The paint exhibits 95.5% and 0.94 of a high solar reflectance and a high normal emissivity, respectively, as can be seen in Figure 2(a). Field tests demonstrated that the system achieved a cooling power exceeding 37 W/m^2 , with the surface temperature dropping more than 1.70 $^\circ\text{C}$ below ambient levels at noon. Figure 2(b) and (c) presents another experiment from the same study, where a ‘P’ pattern was painted using CaCO_3 -acrylic paint, while the surrounding area was coated with a commercial white paint of identical thickness. When exposed to direct sunlight, the pattern was clearly visible through an infrared (IR) camera, highlighting that the CaCO_3 -acrylic paint maintained a significantly lower temperature compared to the commercial white paint. The tests further revealed that the CaCO_3 -acrylic paint provides a cooling power of 93.1 W/m^2 , resulting in an average temperature reduction of 6.52 $^\circ\text{C}$ during daytime conditions. This highlights the superior cooling performance of CaCO_3 -acrylic paint under solar exposure.

In another study conducted by Li X et al.³⁵, where experiments were the study is showcasing impressive full-daytime sub-ambient radiative cooling capabilities using BaSO_4 nanoparticle films and BaSO_4 nanocomposite paints. BaSO_4 was chosen for its high electron band gap, ensuring low solar absorptance, and its phonon resonance at 9 μm , contributing to high atmospheric window emissivity. The BaSO_4 nanoparticle film, with carefully selected particle size and distribution, achieved 97.6%, which is an exceptionally high solar reflectance and an atmosphere window emissivity of 0.96. Throughout field tests, this film demonstrated a remarkable cooling effect, remaining more than 4.5 $^\circ\text{C}$ under ambient temperature or achieving an average cooling power of 117 W/m^2 .

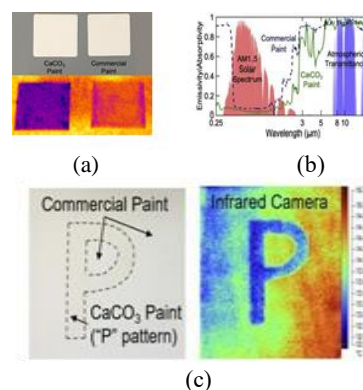


Fig. 2: (a) Infrared image of CaCO_3 paint cooling ability, (b) CaCO_3 Paint emissivity/absorptivity³⁴, (c) ‘P’ Pattern Demonstration³⁵.

2.3 Heat sinks concept

Heat sinks serve as integral components in various

systems and devices aimed at optimizing the flow of fluids or air. Heat sinks enjoy broad usage in heat exchange devices, playing a crucial role in various applications such as car radiators, heatsinks for computer CPUs, and heat exchangers in power plants³⁶). In automotive systems, heat sinks enhance the cooling efficiency of radiators, dissipating heat effectively to maintain optimal engine temperatures. Computer CPU heatsinks utilize heat sinks to increase surface area, facilitating efficient heat dissipation and preventing overheating. Additionally, in power plants, fins are integral components of heat exchangers, contributing to the exchange and transfer of thermal energy in industrial settings³⁷).

According to a study conducted by Kazem et al.³⁸) on the enhancement of PV module performance using fins as passive cooling solution, the study places significant attention on fin configurations as shown in Fig. 3(a) and explores their impact on the thermal performance of PV modules, both positive and negative. Depending on the specific fin design adopted, the study suggests a potential improvement rate of 8%–10% in PV performance.

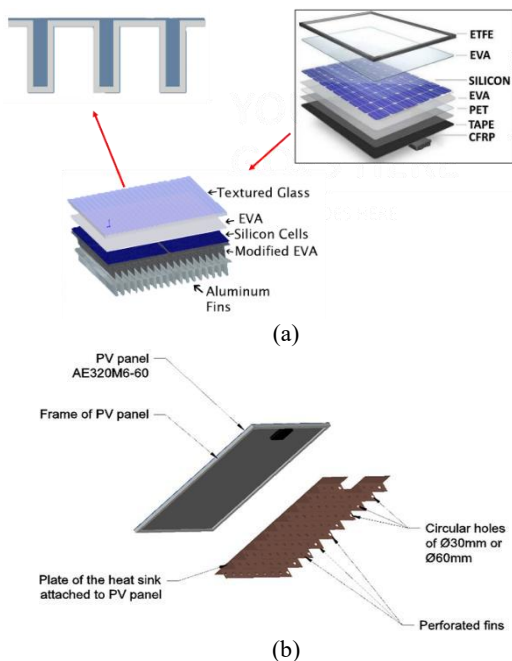


Fig. 3: (a) PV module with fins configuration³⁸), (b) PV module with perforated fins³⁹).

In another study conducted by Hudişteanu et al.³⁹) which introduced a numerical model focusing on the PV passive cooling done the utilization of perforated and non-perforated heat sinks as revealed in Fig. 3(b). The study specifically examined a typical PV panel positioned at a fixed angle of 45° from the horizontal, with the wind direction focused towards its backside. Computational Fluid Dynamics (CFD) simulations were performed by modelling the air volume around the PV under actual wind conditions. Particularly, the cooling effect was most pronounced in low wind conditions and high solar radiation levels. Under specific conditions “ $V_{\text{air}} = 1 \text{ m/s}$,

$G = 1000 \text{ W/m}^2$, and ambient temperature $t_{\text{air}} = 35 \text{ }^\circ\text{C}$ ”, the base case achieved 83.33% of maximum power production, while the best cooling scenario reached 88.74%, resulting in a 6.49% increase in power production.

3. Research methodology and experimental setup

3.1 Research methodology

The research methodology for this study comprises four stages. The first involves preliminary research, followed by the development of experimental methods in the second stage. In addition, the second stage encompasses the actual experiment’s execution. Subsequently, the obtained results will undergo analysis and further discussion in the fourth stage. The final stage involves conclusions on the results and findings obtained.

3.1.1 Preliminary research

The objective of the preliminary research stage was to gain a comprehensive understanding of the fundamental principles of solar tracking systems, daytime radiative paint, and other thermal cooling methods, which has been discussed in section 2. Upon completing this stage, the investigation into the effectiveness of daytime radiative cooling paint coupled with heat sinks as a thermal cooling method in reducing the PV operating temperatures was thoroughly informed by the foundational principles and relevant research.

3.1.2 Experimental setup

To optimize solar tracking and assess radiative cooling paint on PV performance, a DAST installed at a chosen location with different configurations. A suitable radiative cooling paint was chosen and applied uniformly to specific PV module surfaces. Paint application techniques will be controlled to minimize potential influences. Instruments such as solar irradiance and temperature sensors used to collect data on metrics like PV performance and surface temperatures. Continuous monitoring throughout the experiment was capture variations in weather conditions. Simulations using CFD software was also conducted to analyse and justify the findings. The experiment and simulations were conducted in alignment with the study objectives. The investigation focused on collecting data on the improvement in performance of PV modules.

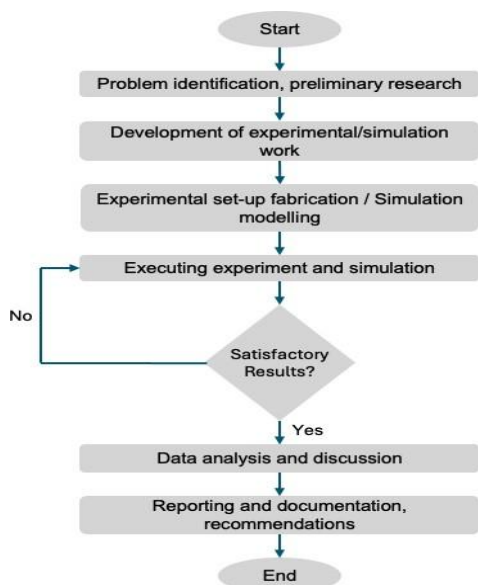


Fig. 4: Flowchart of research methodology.

3.1.3 Results analysis and discussion

The experiment results were systematically analysed and compared with relevant data of literature. This comparative analysis aimed to ascertain a significant improvement in the PV performance. The reliability of the results underwent careful evaluation to determine whether adjustments were necessary in the experimental procedure or methodology. If any enhancements or refinements were identified during this evaluation, appropriate modifications were implemented to ensure the validity and effectiveness of the experimental approach. The research methodology flowchart is as shown in Fig. 4.

3.1.4 Conclusions and recommendations

This section concludes the main finding and suggests recommendations for further improvement and research.

3.2 Experimental setup

This section contains the key components and software that are required for the study as shown in Table 1. The PV module specifications are illustrated in Table 2.

The experiment was conducted at the Solar Research Centre in Universiti Teknologi PETRONAS. Seri Iskandar, Perak, Malaysia, experienced typical tropical weather conditions. Daily high temperatures ranged from approximately 28.3°C to 30.0°C, with lows between 23.3°C and 26.1°C. Humidity levels were consistently high, averaging around 85% to 90%, characteristic of the region's humid climate. Wind speeds were generally light, averaging between 4 to 7 km/h, predominantly from the northeast and east directions. These conditions are consistent with the area's tropical rainforest climate, which features significant rainfall and high humidity throughout the year.

Table 1. Experimental setup components and software.





Components/ Software	Description
	PV modules with a dimension of 630 × 340 × 17 mm is utilised.
	Dual axis solar tracking mechanism complete with actuators, controller, and light sensor.
	The PRC coating and Aluminium alloys 6060 heat sinks will be applied at the back surface of the PV module.
	The thermal management of PV module will be simulated to verify the results obtained from the experiments.

Table 2. PV module specifications.

Peak Power (P _{max})	30 W
Production Tolerance	±3 %
I _{MP}	1.67 A
V _{MP}	18.00 V
I _{SC}	1.82 A
V _{OC}	22.28 V
V _{MAX}	750 V

As for the set-up, the heat sinks were installed evenly at the back surface of two PV modules using weather resistant thermal adhesive tape. Each individual heat sink has a dimension of 140×120×20 mm with a thermal conductivity, k of 201 W/m·K. Using PRC coating and aluminum alloy 6060 heat sinks on the back surface of the PV module offers significant benefits. The PRC coating enhances radiative cooling by increasing heat dissipation through thermal radiation, particularly under high-temperature conditions. Aluminum alloy 6060, known for its excellent thermal conductivity and corrosion resistance, efficiently conducts heat away from the PV module. Together, these materials improve the cooling performance, leading to lower module temperatures, enhanced efficiency, and extended lifespan of the PV system. Meanwhile, one panel with heat sinks has been coated with radiative paint. Figure 5 illustrates used components. Both panels along with a reference panel were then installed onto the DAST which was fabricated using 4040 Aluminum profile as shown in Fig. 5(a), (b) and (c). The DAST consists of a controller, 2 respective

actuators for East-West and North- South rotation along with a light sensor to track the sun’s movement.

A Solar Module PV Analyzer as shown in Fig. 5(d) was connected to the modules to collect the data regarding the Voltage, Current and Power output while a Solar Irradiance Meter as shown in Fig. 5(e) used to measure the irradiance in W/m^2 and the ambient temperature in $^{\circ}C$. Meanwhile, a K-Type Thermometer as shown in Fig. 5(f) was used to measure the module temperature. The solar irradiance meter was calibrated by comparison with the SL101 as a reference device at the study location. Additionally, the K-Type thermometer was calibrated using a certified temperature calibrator, testing its accuracy across multiple temperature ranges. Data collections were conducted for the period from 1 May till 30 May 2024, at 3 different periods of the day that at 9:00AM, 12:00PM and 3:00PM for 10 minutes each on 30 days and 3 different days (5, 11, and 16 May 2024) selected to obtain sufficient data for comparison and analysis. At time 9:00AM – 9:10AM, the solar irradiance and ambient temperature $740.2 W/m^2$, $158.7 W/m^2$, $327.3 W/m^2$, and $35.7 ^{\circ}C$, $28.8 ^{\circ}C$, $31.4 ^{\circ}C$, respectively.



Fig. 5: (a) PV module with heat sinks, (b) PV module with heat sinks and radiative paint coating, (c) PV modules installed on DAST, (d) solar module PV analyzer, (e) Fluke-IRR1- SOL solar irradiance meter, (f) K-Type Thermometer.

4. Results and discussion

4.1 Simulation results

The ANSYS software used to conduct the simulation. The physical system of the PV module was modelled which is composed by a stratification of sheets made by different materials as shown in Fig. 3(a). The dimensions were modelled accordingly to the module used for the experiment which are $630 \times 340 \times 17$ mm. The physical and thermal properties of each layer are configured as shown in Table 3⁴⁰. In addition, Table 4 illustrates boundary conditions considered such as the absorptivity, transmissivity and reflectivity of the layers, etc.

Table 3. PV module structure of physical and thermal properties.

Materials	Density ($kg \times 10^3/m^3$)	Thermal conductivity ($W/m \cdot K$)	Specific heat capacity ($J \times 10^3/kg \cdot K$)
ETFE	1.73	0.24	1.17
EVA	0.94	0.35	2.09
Silicon	2.33	148.00	0.70
PET	1.35	0.27	1.27
CFRP	1.49	6.83	1.13
Tape	1012	0.19	2000

Table 4. Absorption, transmission and reflection of surfaces.

Material	Absorptivity	Transmissivity	Reflectivity
ETFE	0.10	0.83	0.07
EVA	0.00	1.00	0.00
Si	0.97	0.00	0.03

To ensure the reliability and accuracy of the results, a mesh independence study was conducted. Several mesh sizes were tested, progressively refining the mesh to determine the point at which further refinement did not significantly affect the simulation outcomes. This study confirmed that the chosen mesh resolution provided a balance between computational efficiency and result accuracy.

In addition, sensitivity analyses were performed to evaluate the impact of variations in key parameters, such as thermal conductivity, heat transfer coefficients, and boundary conditions. These analyses ensured that the model's outputs remained consistent and robust under different scenarios. The combination of mesh independence studies and sensitivity analyses validated the reliability of the CFD simulations and reinforced their alignment with the experimental data.

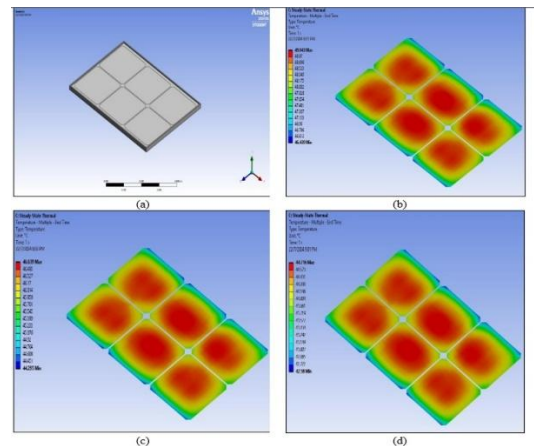


Fig. 6: (a) model of PV module, (b) reference module, (c) module with heat sinks, (d) module with heat sinks and radiative paint.

The simulation was conducted with the following weather conditions:

- Air flow: 1 m/s, Ambient Temperature: 25 °C and Solar Irradiance: 900 W/m².
- The heat sinks were modelled according to the 6060 Aluminium Heat Sinks used in the experiment.

Meanwhile, to simulate the radiative paint on the panel, the parameters in the model were adjusted according to the emissivity of the paint which is 0.95. This configuration was adjusted in the properties setting of the back surface of the module which is the CFRP layer.

Figure 6 (a) shows the module structure with all the layers while the simulation results as revealed in Fig. 6 (b), (c), and (d) are the thermal distribution for the silicon cells itself as it is the component of study that is responsible for the power generation. The module with heat sinks and radiative paint had the lowest maximum temperature 44.716 °C compared with module with heat sinks, and reference module which have 46.639 °C and 49.043 °C, respectively.

Under weather conditions of 25°C ambient temperature and a irradiance of 900 W/m², the simulated results show significant temperature differences among the modules. For the reference module, Fig. 6(c) indicates a temperature range of 46.44°C to 49.04°C. In contrast, the module with heat sinks, as shown in Fig. 6(b), experiences temperatures from 44.30°C to 46.64°C. The module with both heat sinks and radiative paint, depicted in Fig. 6(d), maintains the lowest temperature range, from 42.58°C to 44.72°C.

These temperature differences highlight the effectiveness of heat sinks and radiative paint in reducing the PV surface temperature. This reduction in temperature correlates with experimental results, demonstrating that the module with heat sinks and radiative paint achieves better efficiency and performance due to its lower operating temperatures.

4.2 Experimental results

The data collected from the experiment is shown in Fig. 7, 8, and 9. I-V and P-V curves are plotted for each test executed showing the Voc, Isc, Vmp, Imp and Pmax for all 3 modules. The three tested days are 5 May (day 1), 11 May (day 2) and 16 May (day 3). The time of measurements are 9:00AM – 9:10AM, 12:00PM – 12:10PM, and 3:00PM – 3:10PM.

The general observation indicates a significant improvement in power production, with the module equipped with both heat sinks and radiative paint demonstrating the highest power output. This module outperformed the one with only heat sinks and the reference PV module. Additionally, it was noted that power production peaked around midday, corresponding to the period of highest solar irradiance. This suggests that the combined use of heat sinks and radiative paint effectively enhances the module's efficiency, particularly during peak sunlight hours, by optimizing thermal management and maximizing solar energy capture.

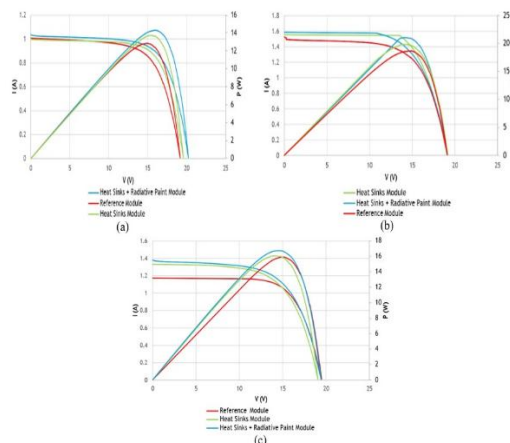


Fig. 7: I-V and P-V curves for day 1 (a) 9:00AM – 9:10AM, (b) 12:00PM – 12:10PM, and (c) 3:00PM – 3:10PM.

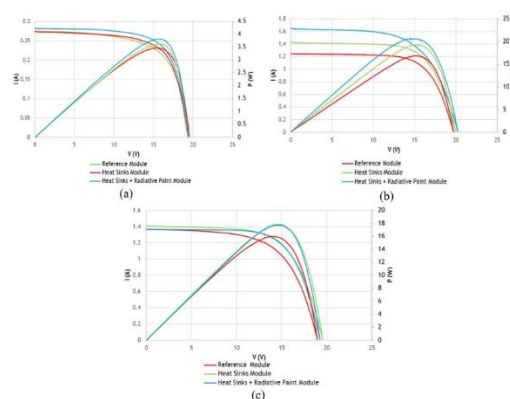


Fig. 8: I-V and P-V curves for day 2 (a) 9:00AM – 9:10AM, (b) 12:00PM – 12:10PM, and (c) 3:00PM – 3:10PM.

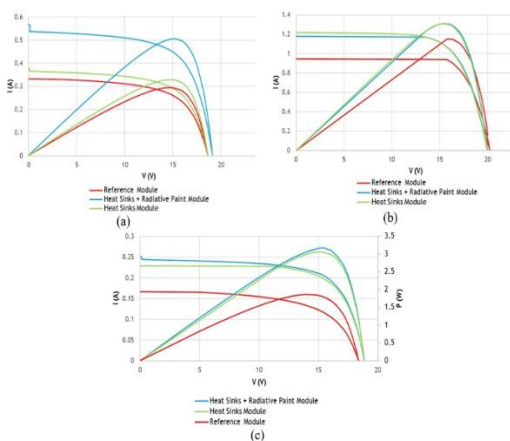


Fig. 9: I-V and P-V curves for day 3 (a) 9:00AM – 9:10AM, (b) 12:00PM – 12:10PM, and (c) 3:00PM – 3:10PM.

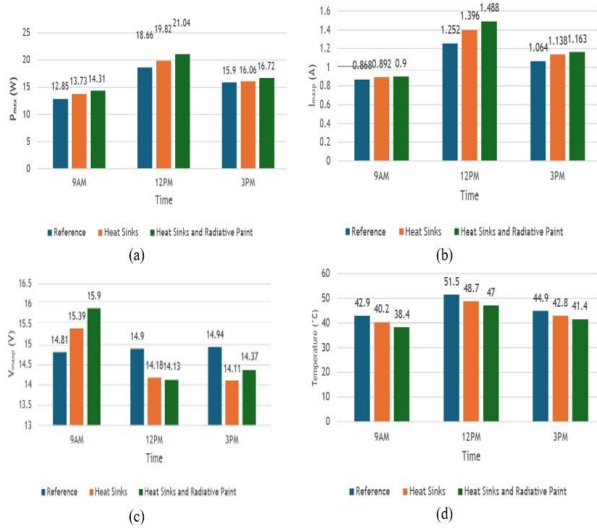


Fig. 10: Comparison of day 1 results (a) Pmax, (b) Imp, (c) Vmax, (d) temperature.

4.3 Comparison and analysis

The analysis of the three graphs of Fig. 10 (a), (b) and (c) reveals that the solar module equipped with both heat sinks and radiative paint exhibited superior performance in terms of Imp “Maximum Power Point Current” and Vmp “Maximum Power Point Voltage”, resulting in the highest overall Pmax “Maximum Power Output”. This observation clearly demonstrates that the addition of cooling systems—specifically, heat sinks and radiative paint—consistently enhances the maximum power output at various times throughout the day. The combination of these cooling technologies provides the highest power output, underscoring that this configuration is the most effective in boosting the system’s performance. This indicates that the integration of advanced thermal management solutions is critical for optimizing the DAST efficiency and energy yield.

The comparison of peak power output among the different module configurations highlights significant improvements. The highest peak power increase observed between the reference module and the module equipped with both heat sinks and radiative paint is 3.80 W. This represents an impressive increase of 22.63%, with the power rising from 16.79 W to 20.59 W, recorded at 12:00 PM on Day 2. In contrast, the peak power increase between the reference module and the module with only heat sinks is 2.42 W, which was also recorded on the same day and time. This accounts for a 14.41% increase in power output.

These results emphasize the effectiveness of incorporating advanced cooling techniques into photovoltaic modules. The module with heat sinks and radiative paint not only achieved a higher power increase compared to the module with only heat sinks but also demonstrated the critical role of thermal management used to enhancing the PV performance of DAST. The substantial gains in peak power output at midday, a time of high solar irradiance, underscore the potential for these

innovations to significantly boost energy production and efficiency in solar energy systems.

Figure 10 (d) illustrates the impact of various cooling enhancements on the temperature of PV modules throughout the day. The graph shows a significant reduction in PV module temperatures with the implementation of these cooling enhancements, with the lowest temperatures observed in the configuration that combines heat sinks and radiative paint. These cooling mechanisms enhance heat dissipation: heat sinks increase the surface area for heat exchange, while radiative paint reflects more solar radiation and emits heat more effectively. This dual approach reduces the thermal load on the PV modules, maintaining lower operational temperatures, which in turn improves their efficiency and power output.

Therefore, the combination of heat sinks and radiative paint proves to be the most effective strategy for enhancing PV system performance. By maintaining lower operating temperatures and increasing power output, this configuration underscores the importance of effective cooling mechanisms in optimizing PV module efficiency.

The PV electrical efficiency, (η_e) refers to the fraction of incident solar energy that is converted into electrical energy. The equation provided for η_e is⁴¹:

$$\eta_e = \eta_r [1 - \beta (T_c - T_r)] \tag{1}$$

where: η_r is the reference PV efficiency at a reference temperature. β is the “temperature coefficient of efficiency”, which indicates how the efficiency of the module changes with temperature. T_c is the PV actual operating temperature. T_r is the reference temperature.

Table 5. PV module electrical efficiency.

Day 1						
Time	Reference Module		Module with Heat Sinks		Module with Heat Sinks and Radiative Paint	
	T_c (°C)	η_e (%)	T_c (°C)	η_e (%)	T_c (°C)	η_e (%)
9:00 AM	42.9	11.03	40.2	11.18	38.4	11.28
12:00 PM	51.5	10.57	48.7	10.72	47.0	10.81
3:00 PM	44.9	10.93	42.8	11.04	41.4	11.11
Day 2						
9:00 AM	29.9	11.74	29.2	11.77	29.2	11.77
12:00 PM	48.2	10.75	44.2	10.96	43.8	10.98
3:00 PM	43.5	11.00	41.4	11.11	38.3	11.28
Day 3						
9:00 AM	37.9	11.30	36.0	11.41	35.0	11.46
12:00 PM	42.2	11.07	40.3	11.17	40.1	11.18
3:00 PM	34.3	11.50	33.8	11.52	33.4	11.55

In this context, the electrical efficiency of the PV module decreases as the operating temperature T_c increases above T_r . The term β quantifies this decrease, where β is a negative value indicating the rate of efficiency loss per

degree Celsius increase in temperature.

From Table 5, the module equipped with heat sinks and radiative paint achieved the highest electrical efficiency on Day 1 at 11.28%. Additionally, the highest recorded electrical efficiency on day 2 is 11.77%, observed in both the module with heat sinks and the module with heat sinks and radiative paint. Overall, the module with heat sinks and radiative paint consistently exhibits the highest electrical efficiency, averaging 11.55% on day 3.

A comparison with the solar tracking system and cooling approach in Reference⁴²⁾ by Taheri et al., where efficiency increased from 11.13% to 11.41%, demonstrates the superiority of the current study. Moreover, Taheri et al.⁴²⁾ utilized a dual-axis tracking system combined with active cooling using nanofluid, a high-cost and complex technique.

It is worth to address potential deployment challenges in large-scale PV systems, such as the initial costs of implementing advanced cooling materials, structural considerations for integrating radiative paint, and the impact of varying environmental conditions on system performance. Additionally, exploring the maintenance requirements and potential trade-offs between efficiency gains and operational complexity in large-scale deployments is essential. This enhancement could provide a more comprehensive perspective on the practicality of the proposed solution.

5. Conclusions

The study successfully integrated PV modules with a DAST and daytime radiative paint as a passive cooling system, achieving both primary objectives. The first objective, to investigate the effectiveness of daytime radiative cooling paint combined with heat sinks as a thermal cooling method, was met as the combination improved heat dissipation, significantly lowering the operating temperature of the modules. The second objective, to assess the combined influence of the DAST, daytime radiative cooling paint, and heat sinks on the performance of PV modules, was also accomplished. The solar tracker optimized solar irradiance capture throughout the day, and the cooling mechanisms further enhanced performance, resulting in a 12.66% improvement in overall efficiency. Simulation results confirmed that the heat sinks and radiative paint effectively reduced the module's temperature.

However, the outdoor experiment presented challenges, particularly the frequent need for manual monitoring and data collection under the hot sun. Each data collection cycle required manual input to start and end the I-V tracer, complicating the process.

Future improvements could include integrating machine learning algorithms for predictive maintenance and optimal tracking, ensuring maximum performance and longevity. These advancements, combined with continuous monitoring and data analysis, will pave the way for a more

robust, efficient, and sustainable solar energy solution.

Future research in enhancing PV tracking and cooling systems using fins and radiative paint could focus on optimizing fin designs for maximum heat dissipation, integrating advanced materials with higher thermal conductivity, and evaluating the long-term performance of radiative paints under diverse climatic conditions.

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Declaration of interest statement

“We the authors declare no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript”.

Conflict of Interests

“The authors declare that there is no conflict of interests regarding the publication of this brief note”.

Data Availability

“The research data is available upon request. To request the data, contact the first author of the article”.

References

- 1) Rahman, T., Mansur, A., Hossain Lipu, M., Rahman, Md., Ashique, R., Houran, M., Elavarasan, R., & Hossain, E. “Investigation of degradation of solar photovoltaics: A review of aging factors, impacts, and future directions toward Sustainable Energy Management”. *Energies*, 16(9), 3676-3706 (2023). <https://doi.org/10.3390/en16093706>
- 2) Annigoni, E., Virtuani, A., Caccivio, M., Friesen, G., Chianese, D., & Ballif, C. “35 years of photovoltaics: Analysis of the tiso-10-kw solar plant, lessons learnt in safety and performance—part 2”. *Progress in Photovoltaics: Research and Applications*, 27(9), 760–778 (2019). <https://doi.org/10.1002/pip.3146>
- 3) Fonseca, J. E., de Oliveira, F. S., Massen Prieb, C. W., & Krenzinger, A. “Degradation analysis of a photovoltaic generator after operating for 15 years in southern Brazil”. *Solar Energy*, 196, 196–206 (2020). <https://doi.org/10.1016/j.solener.2019.11.086>
- 4) Kazem, H. A., Chaichan, M. T., Al-Waeli, A. H., &

- Sopian, K. "Evaluation of aging and performance of grid-connected photovoltaic system northern Oman: Seven years' experimental study". *Solar Energy*, 207, 1247-1258 (2020). <https://doi.org/10.1016/j.solener.2020.07.061>
- 5) O. R. Alomar, O. M. Ali, B. M. Ali, V. S. Qader, and O. M. Ali, "Energy, exergy, economical and environmental analysis of photovoltaic solar panel for fixed, single and dual axis tracking systems: An experimental and theoretical study," *Case Stud. Therm. Eng.*, 51 103621-103635 (2023). <https://doi.org/10.1016/j.csite.2023.103635>.
 - 6) D. Keiner, L. Walter, M. ElSayed, and C. Breyer, "Impact of backtracking strategies on techno-economics of horizontal single-axis tracking solar photovoltaic power plants," *Solar Energy*, 267 112211-112228 (2024). <https://doi.org/10.1016/j.solener.2023.112228>.
 - 7) Awasthi, A., Shukla, A. K., S.R., M. M., Dondariya, C., Shukla, K. N., Porwal, D., & Richhariya, G. "Review on Sun Tracking Technology in solar PV system". *Energy Reports*, 6 392-405 (2020). <https://doi.org/10.1016/j.egy.2020.02.004>
 - 8) Seme, S., Štumberger, B., Hadžiselimović, M., & Sredenšek, K. "Solar photovoltaic tracking systems for electricity generation: A Review". *Energies*, 13(16) 4221-2024 (2020). <https://doi.org/10.3390/en13164224>
 - 9) Salem Ahmed, M., Mohamed, A. S. A., & Maghrabie, H. M. "Performance Evaluation of Combined Photovoltaic Thermal Water Cooling System for Hot Climate Regions". *Journal of Solar Energy Engineering*, 141(4) 41000-41010 (2019) <https://doi.org/10.1115/1.4042723>
 - 10) Valiente-Blanco, I., Lopez-Pascual, D., Diaz-Villar, P., Mallol-Poyato, R., Barragan, A., Ocaña, M., Granello, G., & Diez-Jimenez, E. "Efficiency Improvement of Photovoltaic Solar Modules by Cooling Using an Underground Heat Exchanger". *Journal of Solar Energy Engineering*, 144(6) (2022). <https://doi.org/10.1115/1.4055299>
 - 11) Nasrin, R., Hasanuzzaman, M., & Rahim, N. A. "Effect of nanofluids on heat transfer and cooling system of the photovoltaic/thermal performance". *International Journal of Numerical Methods for Heat & Fluid Flow*, 29(6) 1920-1946 (2019). <https://doi.org/10.1108/HFF-04-2018-0174>
 - 12) Hussein A. Kazem, Ali H A Al-Waeli, Miqdam T Chaichan, K. Sopian, A. A. Al-Amiery. "Enhancement of photovoltaic module performance using passive cooling (Fins): A comprehensive review". *Case Studies in Thermal Engineering*, 49 103286-103316 (2023). <https://doi.org/10.1016/j.csite.2023.103316>
 - 13) Christopher, S., Vikram, M. P., Bakli, C., Thakur, A. K., Ma, Y., Ma, Z., Xu, H., Cuce, P. M., Cuce, E., & Singh, P. "Renewable energy potential towards attainment of net-zero energy buildings status – A critical review". *Journal of Cleaner Production*, 405 136922-136942 (2023). <https://doi.org/10.1016/j.jclepro.2023.136942>
 - 14) Yuli Setyo Indartono, Aditya Muhammad Nur, Ameirza Divanto, Aura Adiyani. "Design and Testing of Thermosiphon Passive Cooling System to Increase Efficiency of Floating Photovoltaic Array." *Evergreen*, 10(01) 480-488 (2023). <https://doi.org/10.5109/6782151>
 - 15) Kalsia, Mohit, Ankit Sharma, Rajneesh Kaushik, and Raja Sekhar Dondapati. "Evaporative Cooling Technologies: Conceptual Review Study." *Evergreen*, 10(01) 421-429 (2023). <https://doi.org/10.5109/6781102>
 - 16) Vineet Singh, Vinod Singh Yadav, Manoj Kumar, Niraj Kumar. "Optimization and validation of solar pump performance by MATLAB Simulink and RSM." *Evergreen*, 09(04) 1110-1125 (2022). <https://doi.org/10.5109/6625723>
 - 17) Neha Kumari, Sanjay Kumar Singh, Sanjay Kumar, "MATLAB-based simulation analysis of the partial shading at different locations on series-parallel PV array configuration." *Evergreen*, 09(04) 1126-1139 (2022). <https://doi.org/10.5109/6625724>
 - 18) Sharma, Sachin, and Rajesh Maithani. "A Computational Study on Thermal and Sustainability Analysis of Solar Air Heater with S and Airfoil Tabulators." *Evergreen*, 11(01) 295-305 (2024). <https://doi.org/10.5109/7172283>
 - 19) Al-Waeli, Ali HA, Hussein A. Kazem, Jabar H. Yousif, Miqdam T. Chaichan, and Kamaruzzaman Sopian. "Mathematical and neural network models for predicting the electrical performance of a PV/T system." *International Journal of Energy Research* 43(14) 8100-8117 (2019). <https://doi.org/10.1002/er.4807>
 - 20) Al-Waeli, Ali HA, Hussein A. Kazem, Miqdam T. Chaichan, and K. Sopian. "A review of photovoltaic thermal systems: Achievements and applications." *International Journal of Energy Research* 45 (2) 1269-1308 (2021). <https://doi.org/10.1002/er.5872>
 - 21) Gholami, Aslan, Mohammad Ameri, Majid Zandi, Roghayeh Gavagsaz Ghoachani, Saeed Jafarzadegan Gerashi, Hussein A. Kazem, and Ali HA Al-Waeli. "Impact of harsh weather conditions on solar photovoltaic cell temperature: Experimental analysis and thermal-optical modeling." *Solar Energy* 252 176-194 (2023). <https://doi.org/10.1016/j.solener.2023.01.039>
 - 22) Karabiber, A., & Güneş, Y. "Single-Motor and Dual-Axis Solar Tracking System for Micro Photovoltaic Power Plants". *Journal of Solar Energy Engineering*, 145(5) 50994-51004 (2023). <https://doi.org/10.1115/1.4056739>
 - 23) Jaffar, Hussein A., Ali A. Ismaeel, and Ahlam Luaibi

- Shuraiji. "Review of hybrid photovoltaic-air updraft solar application: present and proposed state models." *Evergreen*, 09(04) 1181-1202 (2022). <https://doi.org/10.5109/6625729>
- 24) Fahmizal, Hanung Adi Nugroho, Adha Imam Cahyadi, Igi Ardiyanto. "Trajectory Tracking Control of Quadrotor using LQ-Servo Control with SimMechanics." *Evergreen*, 10(04) 2412-2422 (2023). <https://doi.org/10.5109/7160931>
- 25) Gangadharan, Shaina, Ruqaiya Khanam, and Veeraiyah Thangasamy. "A Multilevel Supply Modulator for RF Power Amplifier using 130nm CMOS Technology: Comparator Based Approach." *Evergreen*, 11(02) 974-983 (2024). <https://doi.org/10.5109/7183379>
- 26) Melo, A. G., Oliveira Filho, D., Oliveira Junior, M. M., Zolnier, S., & Ribeiro, A. "Development of a closed and Open Loop Solar Tracker Technology". *Acta Scientiarum. Technology*, 39(2) 177-183 (2017). <https://doi.org/10.4025/actascitechnol.v39i2.29306>
- 27) Chaudhary, Hemant Kumar, Kartikeya Saraswat, Harshita Yadav, Hrithik Puri, Asha Rani Mishra, and Sansar Singh Chauhan. "A real time dynamic approach for management of vehicle generated traffic." *Evergreen*, 10(01) 289-299 (2023). <https://doi.org/10.5109/6781078>
- 28) D. Keiner, L. Walter, M. ElSayed, and C. Breyer, "Impact of backtracking strategies on techno-economics of horizontal single-axis tracking solar photovoltaic power plants," *Solar Energy*, 267(2023) 112228 (2024). <https://doi.org/10.1016/j.solener.2023.112228>.
- 29) C. S. Chin, A. Babu, and W. McBride, "Design, modeling and testing of a standalone single axis active solar tracker using MATLAB/Simulink," *Renewable Energy*, 36(11) 3075–3090 (2011). <https://doi.org/10.1016/j.renene.2011.03.026>.
- 30) Shallal, Basam A., Engin Gedik, Hasanain A. Abdul Wahhab, and Mohammed G. Ajel. "Impact of Alumina nanoparticles additives on open-flow flat collector performance for PV panel thermal control application." *Evergreen*, 10(02) 870-879 (2023). <https://doi.org/10.5109/6792842>
- 31) M. Mirdanics, "Astronomy algorithm simulation for two degrees of freedom of solar tracking mechanism using Clanguage," *Energy Procedia*, 68 60–67 (2015). <https://doi.org/10.1016/j.egypro.2015.03.233>.
- 32) S. Racharla and K. Rajan, "Solar tracking system—a review," *Int. J. Sustain. Eng.*, 10(2) 72–81 (2017). <https://doi.org/10.1080/19397038.2016.1267816>.
- 33) Cui, X., Ma, W., Zheng, Y., Luo, M., Han, S., Sun, X., Zhou, L., & Wei, X. "Thermal analysis of radiative cooling coating on the rear surface of photovoltaic tile". *Solar Energy*, 248 210-220 (2022). <https://doi.org/10.1016/j.solener.2022.11.007>
- 34) Li, X., Peoples, J., Huang, Z., Zhao, Z., Qiu, J., & Ruan, X. "Full Daytime Sub- Ambient Radiative Cooling in Commercial-like Paints with High Figure of Merit". *Cell Reports Physical Science*, 1(10) 100208-100221 (2020). <https://doi.org/10.1016/j.xcrp.2020.100221>
- 35) Li, X., Peoples, J., Yao, P., & Ruan, X. "Ultrawhite BaSO4 Paints and Films for Remarkable Daytime Subambient Radiative Cooling". *ACS Applied Materials & Interfaces*, 13(18) 21733-21739 (2021). <https://doi.org/10.1021/acsami.1c02368>
- 36) Hussein A. Kazem, Ali H A Al-Waeli, Miqdam T. Chaichan, K. Sopian, Ahmed Said Al Busaidi, and Aslan Gholami. "Photovoltaic-thermal systems applications as dryer for agriculture sector: A review." *Case Studies in Thermal Engineering* 47 103033-103047 (2023). <https://doi.org/10.1016/j.csite.2023.103047>
- 37) Siti Nuraisyah Razali, Adnan Ibrahim, Ahmad Fazlizan, Mohd Faizal Fauzan, Raheem K. Ajeel, Emy Zairah Ahmad, Win Eng Ewe, and Hussein A. Kazem. "Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS)." *Case Studies in Thermal Engineering* 50 103392-103400 (2023). <https://doi.org/10.1016/j.csite.2023.103400>
- 38) Ahmed, Hamdi E., B. H. Salman, A. Sh Kherbeet, and M. I. Ahmed. "Optimization of thermal design of heat sinks: A review." *International Journal of Heat and Mass Transfer* 118 129-153 (2018). <https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.099>
- 39) Hudişteanu, S. V., Țurcanu, F. E., Cherecheş, N. C., Popovici, C. G., Verdeş, M., & Huditeanu, I. (2021). Enhancement of PV Panel Power Production by Passive Cooling Using Heat Sinks with Perforated Fins. *Applied Sciences*, 11(23) 11303-11323 (2021). <https://www.mdpi.com/2076-3417/11/23/11323>
- 40) Pavlovic, A., Fragassa, C., Bertoldi, M., & Mikhnych, V. (2021, July 1). "Thermal behavior of monocrystalline silicon solar cells: A numerical and experimental investigation on the module encapsulation materials". *Journal of Applied and Computational Mechanics*, 7(3) 1847-1855 (2021). <https://doi.org/10.22055/jacm.2021.37852.3101>
- 41) Stanciu, Camelia, and Dorin Stanciu. "Optimum tilt angle for flat plate collectors all over the World—A declination dependence formula and comparisons of three solar radiation models." *Energy conversion and management* 81 133-143 (2014). <https://doi.org/10.1016/j.enconman.2014.02.016>
- 42) Taheri, A., Malayjerdi, M., Kazemi, M., Kalani, H., Nemati-Farouji, R., Passandideh-Fard, M. and Sardarabadi, M. "Improving the performance of a nanofluid-based photovoltaic thermal module utilizing dual-axis solar tracker system: Experimental examination and thermodynamic analysis", *Applied Thermal Engineering* 196, 117172-117178 (2021) <https://doi.org/10.1016/j.applthermaleng.2021.117178>