



NUMERICAL SIMULATION AND STRUCTURAL OPTIMIZATION OF PHOTOVOLTAIC SYSTEMS: INVESTIGATING ENVIRONMENTAL AND MATERIAL IMPACTS ON EFFICIENCY AND DURABILITY

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ABSTRACT

The growing demand for renewable energy has led to widespread adoption of photovoltaic (PV) systems. However, the efficient and durable installation of PV panels remains a critical challenge, influenced by environmental factors such as wind and temperature variations. This investigation is aimed at modeling the scheme and improvement of structural systems for PV panel mounting using sophisticated computer calculations and finite element analysis. Moreover, modelling the scheme and improvement of structural systems for PV panel mounting, using sophisticated computer calculations and the finite element analysis. It takes into account like the load distribution, environmental factors, and material qualities, and assesses the approved parameters through parametric studies and sensitivity analyses so as to determine the choice of materials that result in desirable designs. The findings can guide the designers to develop most reliable and cost-effective strategies to overcome certain challenges in PV deployment process. This will further boost the popularity of sustainable energy technologies, leading to the high popularity and efficiency of PV systems. Moreover, determine the effect of wind speed and direction on the solar panels with (CFD), and the stresses and the structure's ability to withstand the weight of the solar panel with (FEM). The numerical simulation results showed that the outgoing working fluid temperature and the average surface temperature of the plate were well obtained when compared with the results of previous studies. It has been observed that in good agreement with previous studies. The study examines the variation in solar radiation intensity over time, with the highest intensity recorded between 9:00 and 12:00 noon. Ambient temperatures in the studied area are generally high, with slight temperature increases with time. Temperature profiles were generated along the thermometer reciprocating and on different sectional surfaces. The convective heat transfer factor increases with velocity, causing an increase in the Reynolds factor. A graph was created showing the convection coefficient for different values of the Reynolds number. The wind angle impact was analyzed with respect to floating panel part movement, adjusting the wind angle from 0o to 180o degrees with a 45o increment. The optimal wave angle for the panel is 33o. Wind forces are important tested for the solar panels and the wind load rating is significant when storms are involved.



1. INTRODUCTION

The concern on utilization of renewable energy in the global market has amplified the significance of proper photovoltaic (PV) system. These systems are critical in capturing solar energy which is one of the most renewable and natural resources of energy. However, the most difficult task is the architectural and structural aspect of the PV installations especially in facing the conditions of maximum performances. Solving these issues becomes paramount in increasing the durability and utilisation of the PV systems in the realistic setup for the general shift towards clean energy worldwide. This type of research is oriented toward the enhancement of the architectural design of PV installations by means of numerical simulations for structural systems with application of finite elements. This research will be covering issues in enhancing the architecture of photovoltaic (PV) installations besides numerical models of structural systems worked out using computers by means of finite element. It is pronounced to increase efficiency and the expectancy of the life by having into view aspects like; working conditions, environment plus interactions of the portions included.

Naik et al. (2024) suggested the use of high-thermal capacity pebbles incorporated in the solar flat plate collectors as a material instead of aluminum or copper by gaining an enhancement factor of 5.82% efficiency increase. Nevertheless, the paper failed to cover the cost-related repercussions or the sustainability outlook of these materials in detail. Showed a rather small efficiency improvement by using pebble materials of which their long-term stability characteristics and costs are still unclear. Other forms of research and development include, (Abu-Hamdeh et al., 2022) pyramid-shaped photovoltaic panels that use a novel cooling system that decreases temperature differential by 29%. While the cooling efficiency was increased, the structures design and possible maintenance issues were not thoroughly discussed. Safeguarded efficient cooling effects with better course solutions but failed in solving the problems and complications resulted from complex designs of these cooling systems. These gaps reveal the need for fundamental studies investigating the developments in materials and portfolios while at the same time evaluating their performance in practical usage. This will be done by conducting this research with the hope of addressing the following gaps; This research shall seek to achieve the following objectives; The following are objectives of this research; This research will seek to achieve the following objectives; Amin et al. (2020) evaluated the applicability of floating structure for desalination facility integrated with hybrid solar-wind system for power supply for which they concluded that this concept is viable mostly for the remote coastal regions . The study, however, failed to explore the nature of the practical difficulties in different weather conditions in relation to operations. In the above examples, the practices and areas, which need

further development and improvement of structural and thermal control of PV systems, are shown.

Plytaria et al. (2019) analyzed the performance of a hundred m² constructed in Athens-Greece the use of a sun cooling gadget, with radiant walls and phase trade substances (PCMs) The examine employs business software called TRNSYS with which it models the radiant wall and estimates other aspects such as auxiliary power consumption, insurance by solar energy, and indoor temperature. Results display that the foremost PCM area is inside the south wall, lowering auxiliary electricity 30%, increasing sun coverage by way of 3.8%, and decreasing total system fee by using three%. (Lin et al., 2019) introduced a constructed-center photovoltaic included Trombe wall (PVMTW) device that mixes energy technology, area heating, and heat protection. The gadget become examined in Hefei, and a mathematical model changed into evolved and confirmed. Results confirmed that the PVMTW device had 65.2% better thermal efficiency in the daylight hours compared to the conventional Trombe wall gadget. The indoor thermal consolation become just like the classic TW device. (Giorges et al., 2014) looked at addresses wind load on a 1:12 scale version of a mild residential shape, studying wind angles, drift, and pressure coefficients. The outcomes show complex maximum and minimal strain places where panels are uncovered to severe conditions, highlighting the need for more conservative mounting methods.

Wu et al. (2014) take a look at efficiently simulated the temperature distribution of a parabolic trough receiver the use of MCRT code and FLUENT software program. It considered warmth transfer fluid flow, conduction, radiation warmth transfers, temperature-dependent properties, wavelength-structured optical houses, and absorption of sun radiation energy. The outcomes confirmed a mean difference inside 6% in comparison to indoor experimental outcomes. The study also investigated transient behaviors underneath direct focused solar irradiance, critical for designing and optimizing the receiver's shape. (Al-Abidi et al., 2013) investigated the solidification of a section exchange material (PCM) in a triplex tube heat exchanger to beautify warmth transfer at some point of charging and discharging. Using a 2D numerical model, the outcomes of PCM freezing were studied. Results show that Case G (eight-cell PCM unit geometry) accomplished whole solidification in a short time, with simulations agreeing with experimental outcomes. Cheng et al. (2012) reviewed thermal consolation fashions and compares them to the ISO 14505 popular technique and the UC Berkeley model. It unearths that the ISO 14505 index may be implemented carefully to assess thermal comfort in non-uniform, normal thermally impartial environments, as compared to the UCB model.

Cheng et al. (2012) offered an in depth 3-dimensional computational model of a parabolic trough solar collector machine, combining Finite Volume Method and Monte Carlo Ray-Trace strategies. It also presents codes and fixing methods for analyzing the photograph-thermal conversion process. The model and technique are confirmed viable and reliable, revealing traits of solar concentrating, amassing, fluid dynamics, coupled heat transfer, and warmth transfer fluid kinds. (Ievers and Lin, 2009) looked at the usage of computational fluid dynamics software Fluent simulated the outcomes of tank geometry and working situations on thermal stratification in a warm water storage tank. Results confirmed that growing the tank's height/diameter aspect ratio, decreasing inlet/outlet glide quotes, and moving the inlet/outlet to the outer extremities resulted in multiplied ranges of thermal stratification, probably leading to full-size strength financial savings.

Zhu et al. (2009) used Computational Fluid Dynamics (CFD) to analyze the effect of number one Nozzle Exit Position (NXP) and combining section converging perspective (θ) on ejector overall performance. Results show that NXP increases with number one drift strain, while θ is sensitive to performance, with entrainment ratio varying as much as 26.6%. The findings can guide NXP and θ modifications for most effective ejector system performance under unique operating conditions. Ahmad et al. (2006) offered a test-cellular with a new mild wallboard shape containing section change material (PCMs) to boom thermal inertia in contemporary homes. The new shape will increase the apparent warmth ability, stores sun energy without raising indoor cell temperature, and reduces wallboard thickness compared to conventional wallboards. An experimental take a look at and numerical simulation with TRNSYS software program showed the consequences, permitting customers to simulate thermal behavior of buildings with PCM walls.

Zhou and Wang (2018) used Steel and aluminum are the most preferred materials for their support structures because of their poles strength and durability. Due to its corrosion resistance and low density, aluminum is most often used in cases for which the power is mounted on the roof. The duration of the PV systems highly depends on the corrosion allowance of the featured material. Of course, the structure of the building can be improved by many coatings and treatments, which have the greatest importance at the seashore or in industrial centers. Some writers have mentioned that, various procedures have been employed for the determination of wind load acting on the PV panels where, Recommendations, policies, and codes such as the American Society of Civil Engineers' ASCE 7 and the International Electro technical Commission's IEC 61215 give framework on how to calculate wind pressure on different arrangements of PV systems (Martin & Green., 2018). Also, the snow accumulation can increase the loads on the structures of PV system primarily in areas with frequent snowfalls.

Further loads affecting the structure of the panel and potential snow sliding impacts need to be taken into consideration in the design because the forces alter the voltages affecting the electrical performance (Kumar et al., 2019) In the region vulnerable to earthquakes, the PV system designs require consideration on how to mitigate earthquakes in order to avoid system collapse in the event of an earthquake. Some of the mitigation measures include base isolation, and flexible connections. Based on the literature review presented above, (Benemann et al., 2018) employed FEA is widely accepted in analyzing the structural response of PV systems subjected to different loads. It also enables one to define stress, strain, and deflection and get to the best design of systems without implicating many costs.

The problem tackled in his work is the design for improved power transference of structural systems for photovoltaic (PV) systems, necessary in boosting the yield and reliability of these renewable energy systems. The current study uses Computerized fluid dynamics (CFD) and Finite Element Analysis (FEA) to assess the various parameters in the design. Advanced research shows that by maximizing the panel angle to 33°, an increased in the electrical efficiency is experienced. The study also makes a presentation of wind loads whereby the PV could be exposed notwithstanding the fact that the panels could withstand the limits of the winds. Further, this communication shows that the solar radiation intensity as well as the ambient temperature does affect the thermal performance of PV systems. These are useful findings in enhancing PV installations design in order to make them more effective and reliable.

This research concentrates on the improvement of structural systems required for the PV systems aiming at improving the efficiency and service life of the system under different environmental conditions. The study is guided by the following key research questions: The study is guided by the following key research questions:

- 1) What can be done to enhance the mechanical stability and thermal characteristics of PV panels through the selection of materials and geometries?
- 2) What is level of tilt, with respect to the horizontal, of the PV panels that would result in the highest electrical and thermal collection efficiencies during various climate conditions?
- 3) Given that wind is a major factor influencing standing and performance of structures, this paper will elucidate on few questions such as how wind velocity and direction impact on structural integrity and effectiveness of PV techniques; with regards to extreme climate conditions, which adjustments could be made to decrease or eradicate potential harms or losses from natural calamities?

The focus of this research is to undertake an optimization and reliability analysis of structural systems support photovoltaic (PV) devices. The application of the findings is crucial for managers and decision-makers in the renewable energy industry as confirmed from the results of the study. Thus, understanding the best angles and materials for PV panel installations the research is useful and offers practical recommendations for cutting costs, boosting energy generation, and increasing the life-span of systems. Further, the paper's discussion on the wind load effects is approachable in consideration of developing power installations that have lasting durability of weather vagaries, reduction in maintenance costs, and time. These are valuable findings especially for organizations that wish to achieve optimal ROI on PV systems and long-term reliability.

2. THEORETICAL ANALYSIS

Ansys software was used to simulate the photovoltaic cells with the coolant supplied with the cell, and to simulate the performance of the system. The steps are presented through engineering creation, network development, governing equation formulation, formation of boundary conditions, and obtaining results.

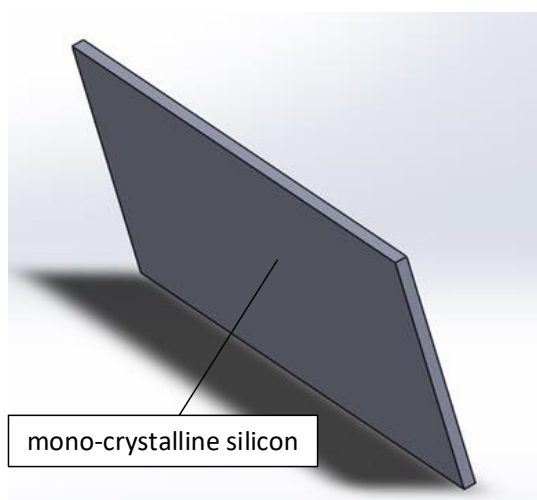


Figure 1. Geometric PV model

In this study, the computational fluid dynamics (CFD) package, ANSYS FLUENT was used to simulate both the developed thermal model of an uncooled HCPV system for heat transfer of a system.

2.2 Boundary conditions

The boundary conditions are taken as follows (table 1):

- The HCPV layers, the top surface of the solar cell experiences a combined heat loss and radiation heat loss as a thermal limit condition.
- In these roofs, the average ambient temperature is 43 °C, the wind speed is (1.5-2) m/s, the heat transfer by wind convection, the solar radiation and the intensity is (800-1100) W/m², as shown in tables 1 and 2.

2.1 Model description

The studied model consists of:

- The PV panel (148 cm length × 67 cm width × 3.3 cm thickness) mono-crystalline silicon PV cells with (170 Watt) will be used with maximum power. The GMA Solar panel model GMAM6-36-190, which features these exact dimensions and power specifications. This panel is equipped with a junction box that has IP65 protection, ensuring durability and resistance to environmental factors. It is certified under various standards, making it suitable for use in a wide range of applications.
- Aluminum plate of (0.5 cm) thickness.
- In HCPV systems, the cell absorbs energy through solar radiation. Part of the absorbed solar radiation is converted into electricity, while the remaining part is converted into heat.

The four distinct designs come from different angle (25°, 30°, 33° and 40°) (figure 1).

- Second, in our research, the angle of inclination of angle (25°, 30°, 33° and 40°) to the south was fixed, so the main factors are solar radiation and ambient temperature. The study observes that the angle of 33° provides the highest electrical efficiency and is optimal for the conditions studied, particularly in terms of handling solar radiation and wind forces.

Table 1. Boundary conditions used during the simulation for the three cases.

Type	Boundary Conditions
Average ambient temperature	43 °C
Wind speed	1.5 - 2 m/s
Average wind speed	1.7 m/s

- The highest intensity of solar radiation was recorded between the hour 9: 00 and the hour 12:00 noon.
- The back of the solar cell is subjected to convective heat loss with the outer medium having an average ambient temperature is 42 °C, the wind speed is (1.5-2) m/s (figure 2).

Table 2. Results of practical experiments for ambient temperatures, solar radiation, and wind speed measured

Time	Day	Solar radiation (W/m ²)	Wind velocity (m/s)	Ambient temperature (°C)
9:00	10/6/2023	830	1.58	39
10:00		895	1.7	42
11:00		1030	1.7	43
12:00		1080	2	43

2.3 Mesh generation

The geometry is designed for the cases of the photovoltaic cell, and the type of network in these models is determined in the form of a tetrahedral network, consisting of triangular elements. Which does a program Ansys FLUENT program do the Information and size of the network of cells, faces, and nodes presented in this study Nodes is 255240 and Elements 157028, while the figure 2 shows the density of the network generated in this study.

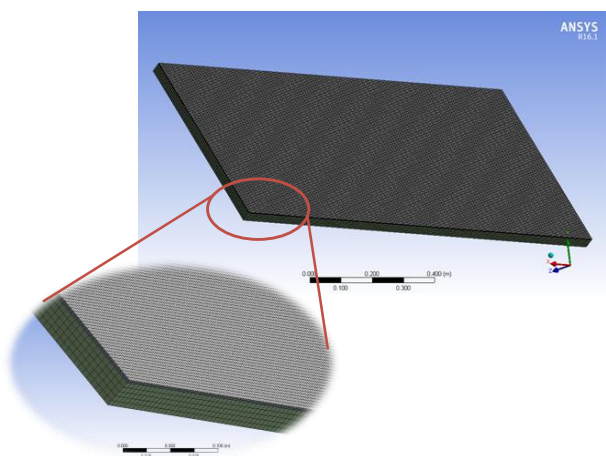


Figure 2. Mesh generation in the PV

Figure 2. Mesh generation in the PV.

Experimental Validation: This involves conducting physical experiments to measure key parameters such as temperature distribution, wind load effects, and electrical efficiency. The experimental data can then be compared with the simulation results to verify the accuracy of the computational model. This process helps identify any discrepancies and refine the model to better reflect real-world conditions.

Verification of Time Step and Mesh Independence: It is crucial to guarantee that the obtained results do not depend on the chosen time step or mesh. This requires carrying out a convergence study whereby one examines the effect that various time steps and mesh sizes may have on the outcome. If the outputs of the model do not change with the changes in the model inputs, then it could

be concluded that model is robust and results obtained from the model are accurate.

In conjunction with these validations, the author should describe the processes to be followed for these validations in the study as well as discuss the results obtained. This will be beneficial in increasing the samples validity and increase the reliability of the findings presented from the simulations.

2.4 The assumptions and the governing equations

In order to simplify the simulation model, the following assumptions were made in the simulation studies:

- Neglecting heat loss from the edge of the collector.
- Neglecting the internal reflections of the sun between the different surfaces.
- Neglecting the effect of the capacity of the glass cover and closed air.

A layer of glass with a thickness of 2 mm was placed and below it a layer of air with a thickness of 2 mm on the face adjacent to the solar radiation, because the Ansys Fluent program to study a case containing solar radiation requires that.

2.5 Governing equations

The HCPV consists of several layers; the heat transferred by conduction between the layers of the solar cell is given by the equation, (Martin & Green (2018):

$$\nabla \cdot (k_i \nabla T_i) + q_i = 0 \quad (1)$$

Where:

ki: thermal conductivity

Ti: temperature

Qi: solar irradiance heat generated source term of layer i

The heat transfer equation for the Ge layer becomes:

$$\nabla \cdot (k_{Ge} \nabla T_{Ge}) + q_{Ge} = 0 \quad (2)$$

Where:

TGe: Ge layer temperature

qGe: heat transfer rate for Ge layer

The heat transferred by convection of the cell layer to the periphery is given by the equation qconv, (Zhou and Wang, 2018):

$$q = h \cdot \Delta T \quad (3)$$

Where:

q: convection heat transferred

h: Heat transfer factor by convection

ΔT : The temperature difference between the layer and the fluid

Heat transfer in cryogenic photovoltaic panels involves solid and multi-fluid fields

$$\left[\rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial y} + \rho w \frac{\partial H}{\partial z} \right] = K \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (4)$$

Where:

K and H are the thermal conductivity and the enthalpy of the fluid respectively. Moreover, the heat conduction equation for each solid layer is:

$$\left[\rho c p_i \left(\frac{\partial T_i(x,y,z)}{\partial t} \right) \right] = K_i \left(\frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} \right) + q_i \quad (5)$$

Where:

T_i: represents the temperature

q_i: heat transfer rate and i is the layer number

The efficiency of solar cells is one of the important things that researchers seek to develop and raise its value under laboratory conditions and maintain it under external weather conditions (Hussein et al., 2013). The net energy absorbed by the cooling governed by the

$$E_c = p \bar{\alpha}_c \tau_g G(t) \quad (6)$$

Where:

G_t: Solar irradiation incident on the cover

P: Cell packing factor

α_c : Sunlight cell absorptivity

τ_g : Transmitted faction

Calculation of, Reynolds, Prandtl and Nusselt numbers are as follows (Hussein et al. (2013):

$$Re = \frac{uD}{\nu} \quad (7)$$

$$Pr = \frac{\nu}{\alpha} \quad (8)$$

$$Nu = \frac{h_c l}{K} \quad (9)$$

The radiation measurements were taken experimentally during the days specified in the experimental section, and then the data was converted as an equation to express the change in solar radiation during the said day, and write the equation in C language and add it as program code.

Table 3. Results of practical parameters for temperatures for the angle 25°

Time/ Day	Cell face temperature (°C)	Cell back temperature (°C)
9:00	61.2	62.25
10:00	61.46	64.3
11:00	66.23	68.9
12:00	67.9	71

Table 4. Results of practical parameters for temperatures for the angle 30°

Time/ Day	Cell face temperature (°C)	Cell back temperature (°C)
9:00	60	65.9
10:00	61	66.7
11:00	65.46	71.25
12:00	67.2	75

3. RESULTS AND DISCUSSION

This chapter presents the results of the numerical simulation of the studied photovoltaic cell and the results will be discussed. The chapter includes two main sections, and the following is a review of the sections of this chapter: The chapter includes two main sections, and the following is a review of the sections of this chapter: The first part summarizes the numerical results acquired by means of Ansys program. Moreover, proving impact of change of the researched angle on the thermal performance of the PVT unit. The second part examines the comparison of results of the numerical analysis with a reference study which we conducted using the Ansys program.

3.1 Numerical results

The photovoltaic model based on study literature studies; which used to determine important factors such as intensity

Solar radiation, ambient temperature and temperature of the face of the photovoltaic cell exposed to solar radiation, as well as the temperature of the back of the cell.

As mentioned earlier, the four outdoor photovoltaic cells were tested, Fixed conditions for the plate, at an angle of inclination of 33° south, Baghdad City, Iraq.

This studying was conducted approximately from 09:00 AM until 12:00 PM. For weather conditions on clear days from Baghdad, Iraq.

3.1.1 The daily results

The efficiency of a photovoltaic cell is affected by several factors; these factors are summarized as follows:

- Solar radiation
- Angle of inclination
- Ambient temperature

Table 5. Results of practical parameters for temperatures for the angle 33°

Time/ Day	Cell face temperature (°C)	Cell back temperature (°C)
9:00	60	64.4
10:00	61.4	65
11:00	65.5	69.9
12:00	67	72

Table 6. Results of practical Parameters for temperatures for the angle 40°

Time/ Day	Cell face temperature (°C)	Cell back temperature (°C)
9:00	60.5	66.3
10:00	62.02	70.7
11:00	67.3	75.23
12:00	68.25	78

Figure 3 shows the variation in the intensity of solar radiation over time. The results show that the solar radiation increased gradually over time.

The highest intensity of solar radiation was recorded between the hour 9: 00 and the hour 12:00 noon. The importance of the solar panels is only during the daytime, which is represented by the presence of solar radiation, and because the highest value of solar radiation is at 12 noon, readings are taken before 12 noon (table 3, 4, 5 and 6).

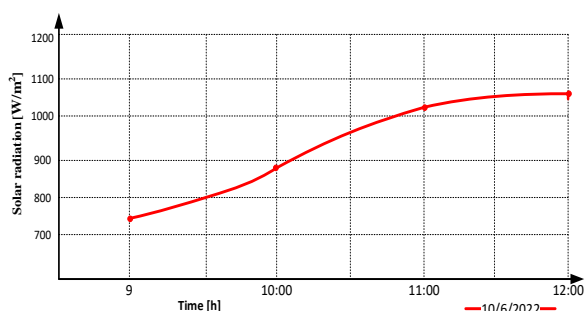


Figure 3. Solar radiation with time

It was noted that the ambient temperature in the studied area is generally high, and the temperature increase with time is slight as shown in figure 4.

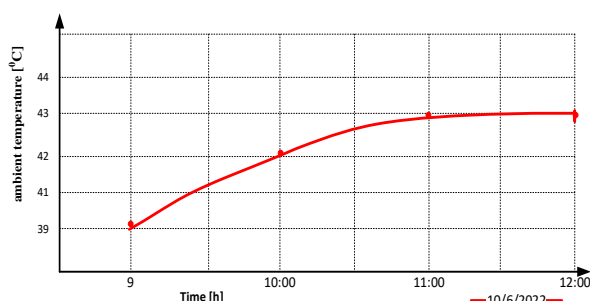


Figure 4. Ambient temperature with time

3.1.2 Temperature distribution of front surface of PV

Figures 5, 6, 7 and 8 show the temperature distribution on the back surface (face) of the photovoltaic cell for the four angles at 11 O'clock respectively in (10/6/2022).

Figures 9, 10, 11 and 12 show the temperature distribution on the back surface (back) of the photovoltaic case for the four angles at 12 O'clock respectively in (10/6/2022).

As shown in Figure 5, which shows the solar panel at an angle of 25 degrees and at 11 o'clock, the temperature reaches 325 Kelvin, while in the solar panel at an angle of 30 degrees and at 11 o'clock, the temperature reaches 379 Kelvin and at the angle of 33 degrees. At 11 o'clock, the temperature reaches 379 Kelvin, and at the angle of 40 degrees, and at 11 o'clock, the temperature reaches 75 degrees Celsius.

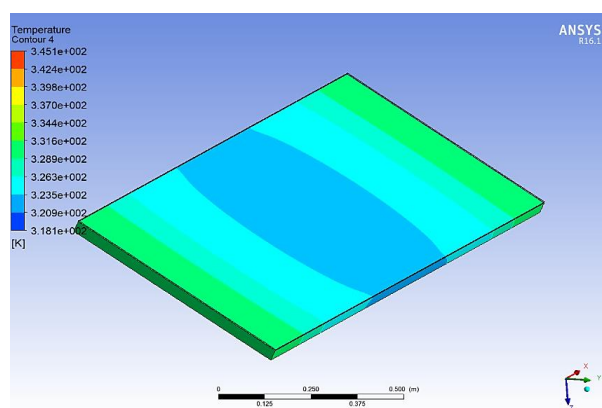


Figure 5. Average temperature distribution on the back surface for angle 25° at 11 O'clock

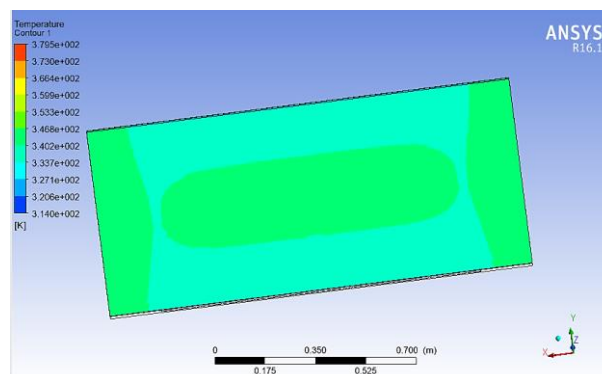


Figure 6. Average temperature distribution on the back surface for angle 30° at 11 O'clock

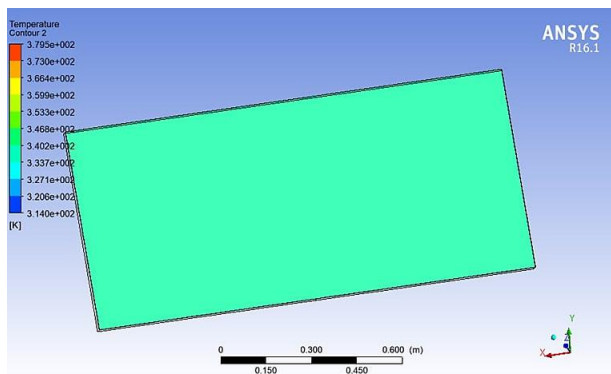


Figure 7. Average temperature distribution on the back surface for angle 33° at 11 O'clock

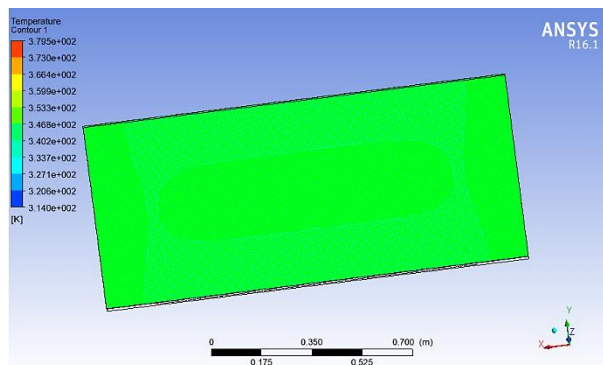


Figure 10. Average temperature distribution on the back surface for angle 30° at 12 O'clock

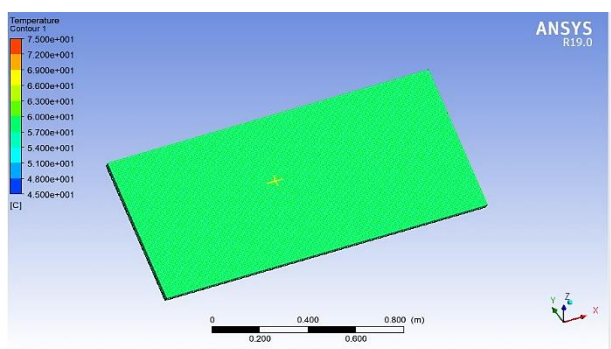


Figure 8. Average temperature distribution on the back surface for angle 40° at 11 O'clock

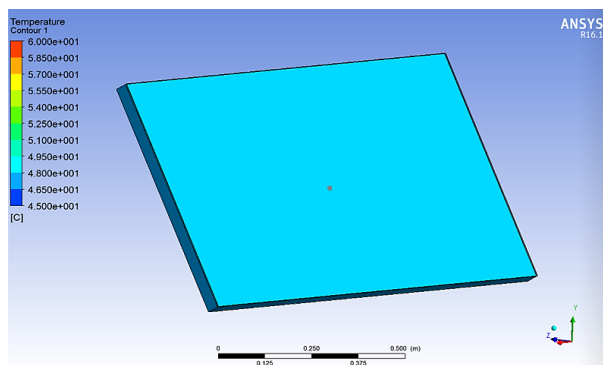


Figure 11. Average temperature distribution on the back surface for angle 33° at 12 O'clock

The solar panel at an angle of 25 degrees and at 12 o'clock, the temperature reaches 345 Kelvin, while in the solar panel at an angle of 30 degrees and at 12 o'clock, the temperature reaches 379 Kelvin and at the angle of 33 degrees. At 12 o'clock, the temperature reaches 60 degrees Celsius, and at the angle of 40 degrees, and at 12 o'clock, the temperature reaches 379 Kelvin.

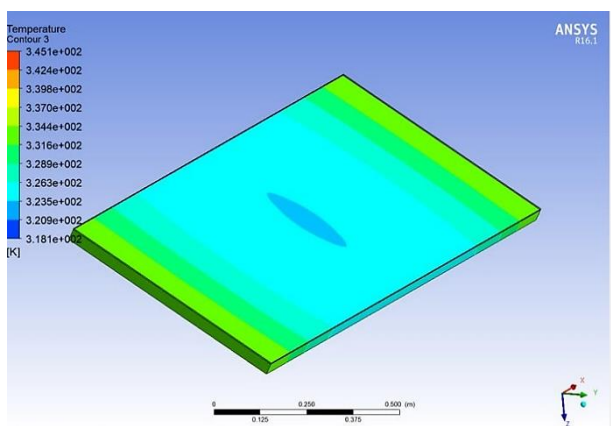


Figure 9. Average temperature distribution on the back surface for angle 25° at 12 O'clock

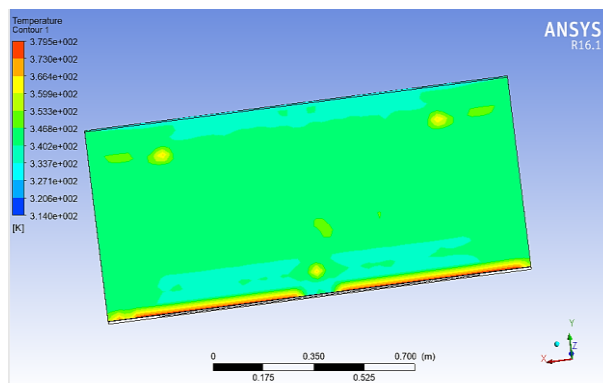


Figure 12. Average temperature distribution on the back surface for angle 40° at 12 O'clock

3.1.3 Analysis of solar cell electrical efficiency

The level of solar cell electrical efficiency which indicates that how much of incoming sunlight energy can be transformed into workable electrical energy is defined in this case. A fundamental factor provides crucial information of the PV system performance and efficiency. Solar cells make use of the photovoltaic effect: sunshine photons falling on the semiconductor focus the generated voltage in the cell producing electric current. The photovoltaic efficiency of a solar cell is determined by many features, namely, the materials

employed, cell architecture, and the weather circumstances. Features maximization space efficiency of the solar cell is dependent on the Shockley–Queisser-limit, where the bandgap energy of the semiconductor material plays a vital role. This IF would indicate that a single-junction solar cell under the standard conditions will reach about 39.7% of this limit.

The equation for calculating the electrical efficiency (η) of a solar cell is typically expressed as:

$$\eta = \frac{P_{\text{att}}}{P_{\text{min}}} \times 100\% \quad (10)$$

Where:

η is the electrical efficiency of the solar cell (expressed as a percentage).

P_{out} is the electrical power output of the solar cell.

P_{in} is the incident optical power from sunlight absorbed by the solar cell.

The electrical power output (P_{out}) can be calculated as the product of the voltage (V) and current (I) generated by the solar cell:

$$P_{\text{out}} = V \times I \quad (11)$$

The incident optical power (P_{in}) is the power of sunlight falling on the solar cell's surface, typically measured in watts per square meter (W/m^2). It depends on factors such as solar irradiance, angle of incidence, and shading (figure 13).

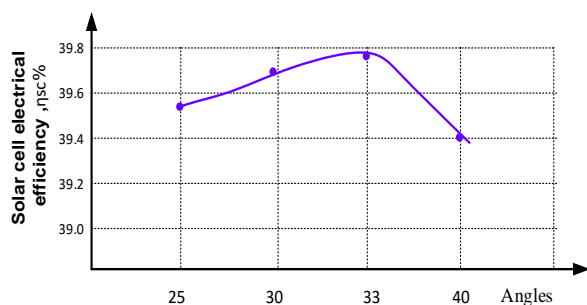


Figure 13. Solar cell electrical efficiency for the different cases with different angles

3.1.4 Analysis of thermal efficiency

Thermal efficiency is a measure of how effectively a system converts thermal energy into useful work or other forms of energy. It is commonly used in the analysis of heat engines, power plants, and other thermal systems. The analysis of thermal efficiency involves understanding the input energy, the output energy, and the losses incurred during the energy conversion process. The general equation for thermal efficiency (η_{th}) can be expressed as:

$$\eta_{\text{th}} = \frac{\text{Useful Output Energy}}{\text{Input Energy}} \times 100\% \quad (12)$$

Where:

Useful Output Energy: This represents the energy obtained from the system that is considered useful for the intended purpose. For example, in a heat engine, it could be the mechanical work output. In a power plant, it could be the electrical energy generated.

Input Energy: This is the total energy supplied to the system, typically in the form of heat or fuel.

From the electrical efficiency, figure 14, the optimal angle for the panel is 33°.

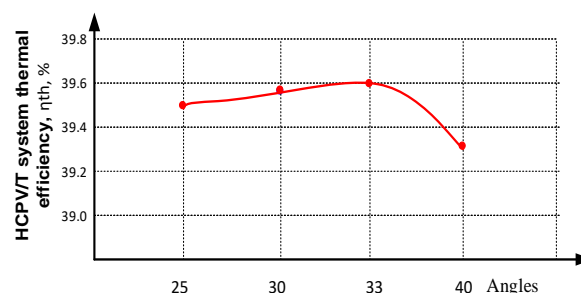


Figure 14. Thermal efficiency for the different cases with different angles

3.1.5 Analysis of temperature

Temperature profiles have been generated along the reciprocating thermometer and on different sectional surfaces to stress on Temperature, figure 15 show the variation in the mean temperature of the front surface of the photovoltaic cell (cell face) with time, and the back surface. The variation in the average temperature of the back surfaces of the four cases (the four angles) with time in (10/6/2022). While the variation in the average temperature of the back surfaces with (the four angles) in (10/6/2022).

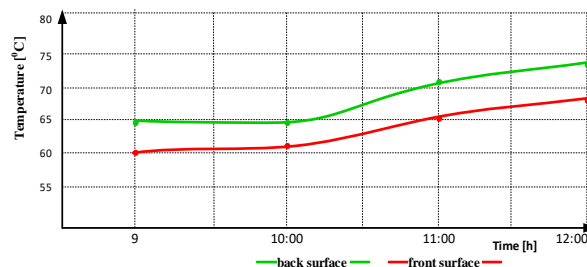


Figure 15. Average temperature of PV (with angle 33°)

3.1.6 Analysis of the heat convection coefficient

It was observed that the value of the convective heat transfer factor increases with the increase in velocity, which in turn causes an increase in the Reynolds factor.

A graph was created showing the convection coefficient for different values of the Reynolds number, as shown in figure 16.

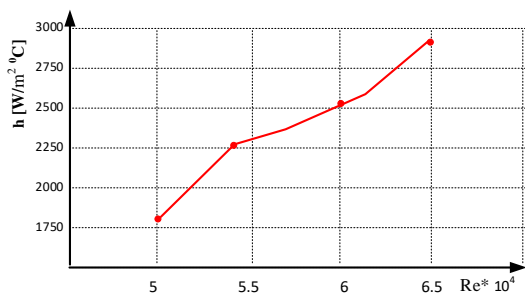


Figure 16. The heat convection coefficient for the different angles with Reynolds number

While the graph was created showing the convection coefficient for different values of the panel's angle, as shown in figure 17.

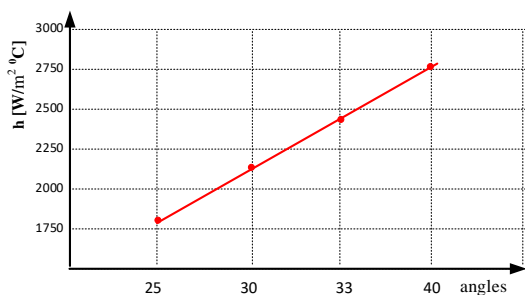


Figure 17. The heat convection coefficient for the different cases with different angles

3.1.7 Analysis of wind load

In this section, the wind angle impact has been analyzed with respect of the floating panel part movement. The incidence of the wind angle and wind wave has been taken into account in order to specify the variation in the structure surface pressure and the lift coefficient as well. Along these lines, the lift force has been figured out through changing the wind wave slope as well as the wind roll angle for the upper side of the PV panel structure. Because of the optimal angle for the panel, so the wave angle for the wind is 33° (figure 18, 19 and 20).

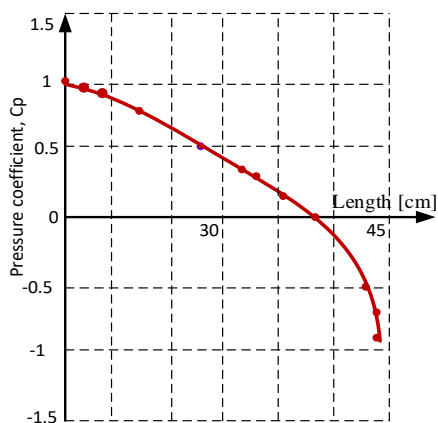


Figure 18. Pressure coefficient with length for angle 33°

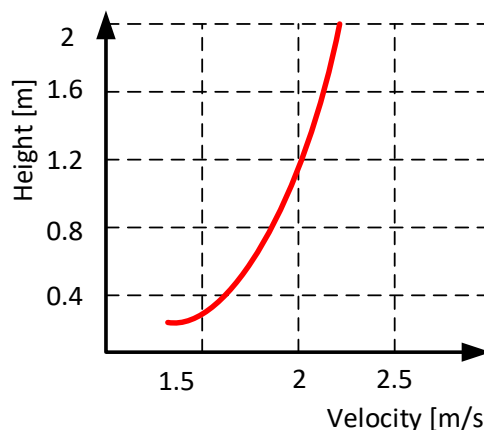


Figure 19. Wind velocity with the height of the panel

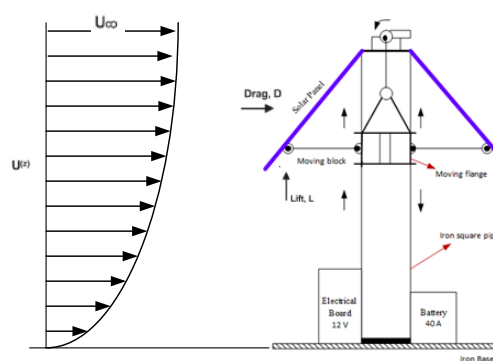


Figure 20. Physical model and wind velocity

Solar panels from manufacturers are rigorously tested to ensure they are engineered to withstand wind forces that push down on the panel from above and push up from the gap underneath the panel. The PV wind load rating is especially important to determine how the panel can hold up in an extreme storm. The wind load is directly related to wind speed (The stress applied on panel by wind calculated by the wind force per area of panels), and measured in Pascal (N/m²); which is a unit of pressure measurement (figure 21).

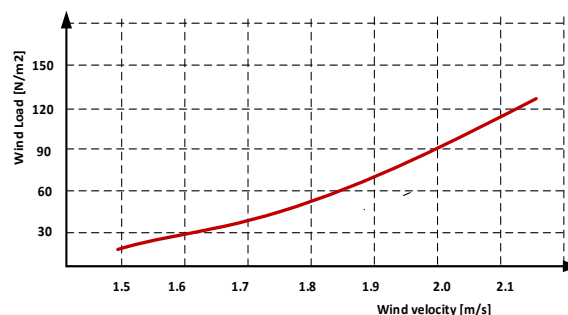


Figure 21. Wind load with wind velocity

4. CONCLUSION

This study investigated the structural optimization of photovoltaic (PV) systems using advanced numerical simulations, focusing on factors like solar radiation

intensity, temperature distribution, and wind load resistance. The key findings are summarized as follows:

- 1) **Optimal Panel Angle:** A 33° panel angle was established to be the most energy productive or the highest electrical conversion efficiency when compared to other angles that were used in the study inclusive of 25° 30° and 40°. This optimal angle has been proved to match the absorption of the sun and structure stability to provide the best solution to the generation of energy.
- 2) **Material Impact:** The study examined and compared the performance and density of various materials and it was established that utilizing constituents with high thermal capacity this device improves in thermal conductivity for example using pebbles as opposed to metallic constituents like aluminum or copper association. This innovation in turn produced a significant efficiency upswing, proving that there may be considerable further efficiency to be bought by get a finer handle on material necessities for PV applications.
- 3) **Wind Load Analysis:** When different wind speeds and angles of wind were tested structurally on PV panels, it was ascertained that the systems can endure and could be properly installed for withstanding extreme winds. It gave a procedure on how to make PV systems safe from wind forces of storms relevant for places with frequent storms.
- 4) **Temperature and Solar Radiation Effects:** These simulations revealed that the level of irradiation and environmental temperature severely affect the thermal and electrical efficiency of the PV panel. The highest level of solar radiation was received between the period of 9:00 AM and 12:00 PM, proof that the panel should be well positioned when sunlight is at its best.
- 5) **Convective Heat Transfer:** The convective heat transfer coefficients were also studied through research and based on the results, the increase in

convective heat transfer coefficient through wind velocity influences the overall convective heat transfer of the PV system.

4.1 Contributions and distinctions from previous studies

The present research nests with the existing literature in three main ways, which are highlighted below. Moreover, unlike previous works where researchers concentrated on certain material or cooling methods, this research is aimed at developing an all-encompassing view of the subject by coalescing factors relating to structures and environment into a unified framework of analysis. For instance, (Naik et al., 2024) and (Abu-Hamdeh et al., 2022) focused on certain individual materials and system designs but fell short of examining all the factors in the various environmental classes in terms of their influence on the overall system performance. This research addresses that lacuna by presenting a comprehensive review analysis of PV panel designs under functional performance environments and hence presents more benchmarks that are relevant to the practice for the industry.

4.2 Enrichment of the field

Thus, this research contributes to the analysis of PV systems and development of the corresponding designs by identifying the interconnectedness of the design attributes and external conditions. In light of this, design considerations indicated in relation to the angle of inclination, type of material used and the wind load severity are revealed by the study. Thus, solving these issues, the study gives priorities that reveal the best solution of the PV installation problems to achieve high power production and long time durability depending on the climate. These contributions are vital for the promotion of renewable energy technologies and the improvement of energy systems' sustainability worldwide.

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