

Thermal Behavior and Energy Performance Analysis of a Monocrystalline Photovoltaic Module under Different Tilt Angles

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Abstract—This study presents a thermal analysis of a monocrystalline monofacial photovoltaic module under different tilt angles, focusing on conduction, convection, and radiation heat transfer mechanisms. Real meteorological data for Bitola, North Macedonia, from a Typical Meteorological Year dataset are combined with a physics-based thermodynamic model implemented in Python. Solar irradiance on the tilted module is calculated using the Hay-Davies model, while heat transfer is modeled via the Armstrong-Hurley approach. Results show that tilt angle significantly influences module temperature, heat dissipation, and efficiency. The findings provide insights for optimizing panel orientation to improve photovoltaic thermal performance and energy yield.

Keywords—photovoltaic module, thermal analysis, energy performance, tilt angle, heat transfer mechanisms, efficiency

I. INTRODUCTION

With the ongoing depletion of traditional energy sources and the rising consumption of fossil fuels, the urgent requirement for sustainable alternatives is becoming more pronounced. Renewable energy, including solar energy, is essential for reducing environmental impacts and addressing the challenges of global warming [1]. In addition to renewable technologies, improvements in conventional power systems, such as the transition to combined cycle configurations, have been proposed to enhance efficiency and reduce environmental impact [2]. Furthermore, alternative energy sources such as landfill gas can be effectively utilized for electricity generation, contributing to sustainable energy development [3, 4].

Solar energy is uniquely recognized as a clean and reliable source of energy [5], while photovoltaic (PV) systems play a crucial role in capturing solar energy as one of the most abundant and sustainable energy resources [6]. As time has progressed, enhancements have been made to photovoltaic (PV) panels to optimize their use of the extensive solar resource. However, even with these advancements, PV panels still encounter difficulties in effectively converting solar energy into electrical energy, which adversely affects their efficiency and shortens their operational lifespan [7].

Photovoltaic (PV) systems have been widely studied in terms of system integration, simulation, and operational performance. Numerical models and simulation tools such as MATLAB/Simulink are often used to analyze PV system behavior and grid interaction [8].

Additionally, the architectural and structural aspects of PV installations remain a significant challenge, particularly when aiming to achieve both maximum performance and long-term durability [6]. PV technology has taken a central role in global renewable strategies, although its performance continues to be heavily impacted by thermal processes.

Photovoltaic (PV) panels convert solar energy into direct electrical current using semiconductor materials. During operation, approximately 85% of the absorbed radiation becomes heat, with only the remaining fraction converted to electricity [9]. Increased temperature leads to a reduction in the semiconductor bandgap, a decrease in open-circuit voltage, and a decline in overall performance. Consequently, understanding the thermal behavior of PV modules is essential for optimizing their efficiency. Factors such as solar intensity, ambient temperature, wind speed, and panel orientation significantly affect both electrical properties and thermodynamic performance [10].

From a thermodynamic viewpoint, the photovoltaic (PV) energy conversion mechanism involves both quantitative and qualitative assessments of the energy transformation, which are regulated by the first and second laws of thermodynamics [11]. PV systems concurrently generate electrical energy while also producing heat as a result of absorbing low-grade solar energy, which remains underutilized. A range of irreversibilities, such as optical, thermal, spectral mismatch, and electrical losses, lead to entropy generation, thereby lowering both the theoretical and practical efficiency limits of PV modules [12].

The thermal responses of photovoltaic (PV) modules have been explored in numerous studies, where some researchers simplified the thermal network by neglecting specific heat transfer mechanisms [13]. The operational temperature of a photovoltaic module signifies the balance between the heat produced and the heat released into the surrounding environment [14]. Various empirical

correlations have been proposed for estimating solar cell temperature based on weather variables and module properties [13].

Since a significant portion of absorbed solar energy is dissipated as heat inside the module, understanding the mechanisms of conduction, convection, and radiation is essential [15]. Conductive losses occur due to temperature differences between the module and adjacent materials. Convective heat transfer depends largely on wind conditions, while radiative losses involve longwave emission from the module surface [14]. Under typical operating conditions, convection and radiation are the dominant heat transfer mechanisms from the photovoltaic (PV) surface to the surrounding environment [15].

On the other side, panel inclination plays a critical role in determining the amount of solar radiation received and the heat transfer mechanisms active at the module surface. When photovoltaic (PV) modules are perpendicular to the sun's rays, maximum irradiance is achieved, but temperature effects intensify [16]. Inclination angle affects natural convection, forced convection, and radiative heat losses. Many studies analyze natural convection from inclined surfaces using empirical correlations for isothermal flat plates, with Nusselt-Rayleigh relationships commonly applied to quantify convective heat transfer behavior [16].

For example, the authors in [16] introduce comprehensive correlations for natural convection from both surfaces of an isothermal plate across inclination angles from 0° to 90° , with emphasis on laminar convection on photovoltaic (PV) modules with an insulated underside. These correlations were used to estimate heat-transfer coefficients for ground-mounted PV panels under varying ambient conditions, accounting for solar radiation, forced convection, and radiative losses. The authors also applied the same correlations to model the transitional and turbulent flow regimes, providing a unified approach for PV thermal analysis. Furthermore, the study [6] 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. It was concluded that the optimal panel angle is 33° when compared to other tilt angles that were used in the study inclusive of 25° , 30° and 40° .

The rise in the use of renewable energy sources, particularly photovoltaic systems, underscores the necessity of ensuring stability and effective operation within power systems [17]. Despite significant research on photovoltaic (PV) performance, there is limited work systematically analyzing how tilt angle influences all three major heat transfer mechanisms, specifically in monocrystalline PV modules. Most current research tends to either oversimplify the thermal network, focus on a single mechanism, or assess temperature through empirical means without establishing a connection between thermal behavior and physical orientation. As a result, the overall thermal response of PV modules at different tilt angles is not well understood, particularly under realistic operational and environmental conditions.

The objective of this study is to conduct a comprehensive thermal analysis of a monocrystalline photovoltaic (PV) module by assessing the impact of varying tilt angles on the intensity and distribution of conductive, convective, and radiative heat transfer. The results are intended to deepen the understanding of PV thermal

dynamics and offer guidance for optimizing panel orientation to improve overall photovoltaic performance.

II. METHODOLOGY

The simulations were carried out for the location of Bitola, using a Typical Meteorological Year (TMY) dataset [18]. The site is characterized by a latitude of 41.050° N, a longitude of 21.367° E, and an elevation of 589 [m]. The official WMO (World Meteorological Organization) station identifier for Bitola is 135830 [19]. The TMY data were obtained from the SRC-TMYx source, representing a composite period from 2009 to 2023. This means that the representative year was generated through a statistical selection of hourly records within the specified period to create an "average" year suitable for engineering calculations. From this dataset [18], hourly information was retrieved, including Global Horizontal Irradiance (GHI) [Wm^{-2}], Direct Normal Irradiance (DNI) [Wm^{-2}], Diffuse Horizontal Irradiance (DHI) [Wm^{-2}], ambient air temperature (T_a) [$^\circ\text{C}$], and wind speed (w) [m/s].

Based on these hourly data, it is possible to obtain the total daily, monthly, and annual energy production, as well as the total thermal losses according to the three fundamental heat-transfer mechanisms of the photovoltaic (PV) panel. In addition to the Global Horizontal Irradiance (GHI) obtained from the TMY dataset, the applied solar radiation Hay-Davies model [20] is also used to calculate the irradiance on the PV panel, G_r .

The subject of analysis is a monofacial monocrystalline module Canadian Solar HiKu5 (CS3Y-490MS). The relevant manufacturer specifications, as well as the parameters and engineering assumptions are: Module dimensions: $2252 \times 1048 \times 35$ [mm]; Area (A): 2.360 [m^2]; Mass (m): 25.7 [kg]; Front glass type: Tempered glass; Frame type: Anodized aluminum alloy; Nominal power (P_N): 490 [W]; Open-circuit voltage (V_{oc}): 53.3 [V]; Short-circuit current (I_{sc}): 11.67 [A]; Module efficiency (η): 20.8% ; NOCT (T_{NOCT}): 42 ± 3 [$^\circ\text{C}$]; Reference temperature (T_{ref}): 25 [$^\circ\text{C}$]; Temperature coefficient (β_T): 0.0034 [$^\circ\text{C}^{-1}$]; Absorptivity (α_a): 0.90 ; Emissivity (ϵ): 0.88 ; Thermal conductivity (k): 0.63 [$\text{Wm}^{-1}\text{K}^{-1}$]; Layer thickness (d): 0.0046 [m]; Material density (ρ): 2400 [kgm^{-3}]; Specific heat capacity (c): 900 [$\text{Jkg}^{-1}\text{K}^{-1}$]; Characteristic length (L): 2.252 [m].

The mounting geometry of the photovoltaic (PV) panel determines the projected component of direct solar irradiance, the distribution of diffuse irradiance, and the ground-reflected component:

- Azimuth (orientation relative to cardinal directions): the analyzed orientation is south (180°).
- Tilt angle: simulations are performed for the range [20° , 34°] with a 2° increment.
- Solar angles: zenith/azimuth/hour angle are obtained using the pvlib.solarposition module [21] in Python, which calculates the position of the sun in the sky for a given time and location. The solar irradiance on the PV panel is computed using the Hay-Davies model [20], with a ground reflectance of 0.20 [22]. For the direct component, Incidence Angle Modifier (IAM) [23] is applied using the ASHRAE beam transmittance model [24, 25].

The model for calculating total thermal losses is based on the Armstrong-Hurley model [26], which considers a photovoltaic (PV) panel under variable climatic conditions. The thermal properties of the PV panel are analyzed, and heat transfer from the panel surface is examined under different external conditions.

Conduction losses within the internal layers are:

$$Q_{cond} = \frac{k \cdot A}{d} (T_{PV} - T_b) \quad (1)$$

Q_{cond} – conductive heat losses [W]

k – thermal conductivity [Wm⁻¹K⁻¹]

A – area of the PV panel [m²]

d – layer thickness [m]

T_{PV} – front-surface temperature of the panel [°C]

T_b – back-surface temperature of the panel [°C]

Front-surface convective losses:

$$Q_{conv, front} = h_{c, front} \cdot A \cdot (T_{PV} - T_a) \quad (2)$$

h_c – convective heat-transfer coefficient [Wm⁻²K⁻¹]

T_a – ambient air temperature [°C]

Rear-surface convective losses:

$$Q_{conv, rear} = h_{c, rear} \cdot A \cdot (T_b - T_a) \quad (3)$$

Two different convection processes occur on each side:

- Forced convection

$$h_{c, forced, front} = 2.56 \cdot w + 8.55 \quad (4)$$

$$h_{c, forced, rear} = 0.4 \cdot h_{c, forced, front} \quad (5)$$

w – wind speed [m/s]

- Natural convection

Rear-surface Nusselt number:

$$\overline{Nu}_{rear} = \left[0.825 + \frac{0.387 \cdot Ra_{rear}^{\frac{1}{6}}}{\left(1 + \left(\frac{0.492}{Pr_{rear}} \right)^{\frac{9}{16}} \right)^{\frac{8}{27}}} \right]^2 \quad (6)$$

Front-surface Nusselt number:

$$\overline{Nu}_{front} = 0.14 \cdot \left[\left(Gr_{front} \cdot Pr_{front} \right)^{\frac{1}{3}} - \left(Gr_{cr} \cdot Pr_{front} \right)^{\frac{1}{3}} \right] + 0.56 \cdot \left(Gr_{cr} \cdot Pr_{front} \cdot \cos \theta \right)^{\frac{1}{4}} \quad (7)$$

For $10^5 < Gr_{front} \cdot Pr_{front} \cdot \cos \theta < 10^{11}$ and $15^\circ < \theta < 75^\circ$, otherwise, the rear-surface formula is used [26], where $\theta = 90^\circ - \beta$ is the tilt angle measured from the vertical.

The critical Grashof number corresponds to the onset of deviation from laminar behavior: $(Gr \cdot Pr)_{cr} = 10^9 = Ra_{cr}$ [27].

$\overline{Nu}$ – Nusselt number [-]

Ra – Rayleigh number [-]

Pr – Prandtl number [-]

Gr – Grashof number [-]

Gr_{cr} – critical Grashof number [-]

θ – tilt angle measured from the vertical [°]

Ra_{cr} – critical Rayleigh number [-]

According to the Nusselt number, it follows that:

$$h_{c, free, front} = \frac{\overline{Nu}_{front} \cdot k_{air} (T_{film, front})}{L} \quad (8)$$

$$h_{c, free, rear} = \frac{\overline{Nu}_{rear} \cdot k_{air} (T_{film, rear})}{L} \quad (9)$$

k_{air} – thermal conductivity of air [Wm⁻¹K⁻¹]

T_{film} – film temperature [K]

The total convective heat transfer coefficient is:

$$h_{c, front} = \sqrt[3]{h_{c, forced, front}^3 + h_{c, free, front}^3} \quad (10)$$

$$h_{c, rear} = \sqrt[3]{h_{c, forced, rear}^3 + h_{c, free, rear}^3} \quad (11)$$

The total convective heat losses are:

$$Q_{conv} = h_{c, front} \cdot A \cdot (T_{PV} - T_a) + h_{c, rear} \cdot A \cdot (T_b - T_a) \quad (12)$$

Heat losses due to radiation from the panel surface are calculated as [26]:

- Radiative heat losses to the sky from the front surface:

$$Q_{rad, front-sky} = \varepsilon \cdot F_{front-sky} \cdot \sigma \cdot A \cdot (T_{PV}^4 - T_s^4) \quad (13)$$

$$F_{front-sky} = \frac{1}{2} (1 + \cos \beta) \quad (14)$$

- Radiative heat losses to the sky from the rear surface:

$$Q_{rad, rear-sky} = \varepsilon \cdot F_{rear-sky} \cdot \sigma \cdot A \cdot (T_b^4 - T_s^4) \quad (15)$$

$$F_{rear-sky} = \frac{1}{2} (1 + \cos(\pi - \beta)) \quad (16)$$

- Radiative heat losses to the ground from the front surface (it is assumed that the ground temperature is equal to the ambient temperature [26]):

$$Q_{rad, front-ground} = \varepsilon \cdot F_{front-ground} \cdot \sigma \cdot A \cdot (T_{PV}^4 - T_g^4) \quad (17)$$

$$F_{front-ground} = \frac{1}{2} (1 - \cos \beta) \quad (18)$$

- Radiative heat losses to the ground from the rear surface:

$$Q_{rad, rear-ground} = \varepsilon \cdot F_{rear-ground} \cdot \sigma \cdot A \cdot (T_b^4 - T_g^4) \quad (19)$$

$$F_{rear-ground} = \frac{1}{2} (1 - \cos(\pi - \beta)) \quad (20)$$

The sky temperature is estimated as [28]:

$$T_s = 0.0553 \cdot T_a^{1.5} \quad (21)$$

Q_{rad} – radiative heat losses [W]

ε – emissivity [-]

F – view factor for radiative heat exchange [-]

σ – Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ [Wm⁻²K⁻⁴])

T_s – sky temperature [K]

β – tilt angle [°]

T_g – ground temperature [K]

For hours with very low solar irradiance ($G_t < 30$ [Wm⁻²]) it is assumed that $Q_{conv} \approx 0$ and radiative losses dominate.

III. RESULTS AND DISCUSSION

The obtained results for total solar irradiance (G_t), for a typical meteorological summer day, as shown on Fig. 1, exhibit a clear diurnal pattern, with values gradually increasing from 5:00 and reaching a pronounced maximum between 11:00 and 12:00, where the highest irradiance of approximately 950 [Wm⁻²] is recorded for the 20° tilt angle. The analysis indicates that lower tilt angles (20°-26°) yield higher irradiance throughout the entire day, particularly during the morning and late afternoon hours, where the differences relative to the highest considered tilt (34°) reach up to 36% at 6:00 and around 18% at 17:00. Near solar noon, the differences between the tilt angles reduce to only about 3%, which is expected due to the high solar altitude. Under summer conditions, the optimal tilt angle for maximizing daily irradiance is close to 20°. Higher tilt angles (30°-34°) consistently produce lower irradiance because they reduce the perpendicular exposure to the sun's rays.

Fig. 2 shows the hourly temperature profile of the photovoltaic (PV) module which indicates a strong dependence on solar irradiance intensity, with a steady rise from early morning values of 18-20 [°C] to a pronounced peak of approximately 52-54 [°C] between 11:00 and 13:00, coinciding with the period of maximum global irradiance. Across all hours, lower tilt angles (20°-26°) consistently produce slightly higher surface temperatures – up to 2-3 [°C]

more at peak hours – because these orientations receive a larger normal component of solar radiation, resulting in greater absorbed heat. Conversely, higher tilt angles (30°-34°) exhibit a modest cooling effect due to reduced incident radiation, particularly in the morning and late afternoon when the sun is positioned higher relative to the panel plane. After 14:00, temperatures gradually decline as irradiance decreases, approaching 22-24 [°C] by 19:00-20:00. Overall, the thermal behavior aligns directly with the irradiance trends: angles that maximize G_t also maximize T_{PV} , reinforcing the strong coupling between solar geometry and PV operating temperature. This has important performance implications, as higher T_{PV} typically reduces electrical efficiency and increases thermal losses.

The heat-loss distribution across different tilt angles (Fig. 3) reveals that conduction dominates the thermal losses of the photovoltaic (PV) module, consistently contributing roughly 1.78-1.84 [kW], which corresponds to more than 60% of the total thermal losses. Convection represents the second-largest mechanism, ranging from 831-861 [W], while radiative losses remain the smallest component at approximately 752-776 [W]. A clear decreasing trend is observed in all three heat-loss components as the tilt angle increases from 20° to 34°, with conduction losses dropping by about 59 [W], convection by ~30 [W], and radiation by ~24 [W]. This decrease is directly linked to the reduction in absorbed solar energy at higher tilt angles, which results in lower PV surface temperatures and consequently lower temperature gradients driving conduction, convection, and radiation. Notably, the proportional relationship among the three mechanisms remains nearly constant across all angles, indicating that tilt angle affects the magnitude of heat losses but not their relative shares. These findings align with the temperature results, confirming that lower tilt angles intensify thermal loading on the PV module, which can negatively impact electrical efficiency through increased entropy generation and thermal stress.

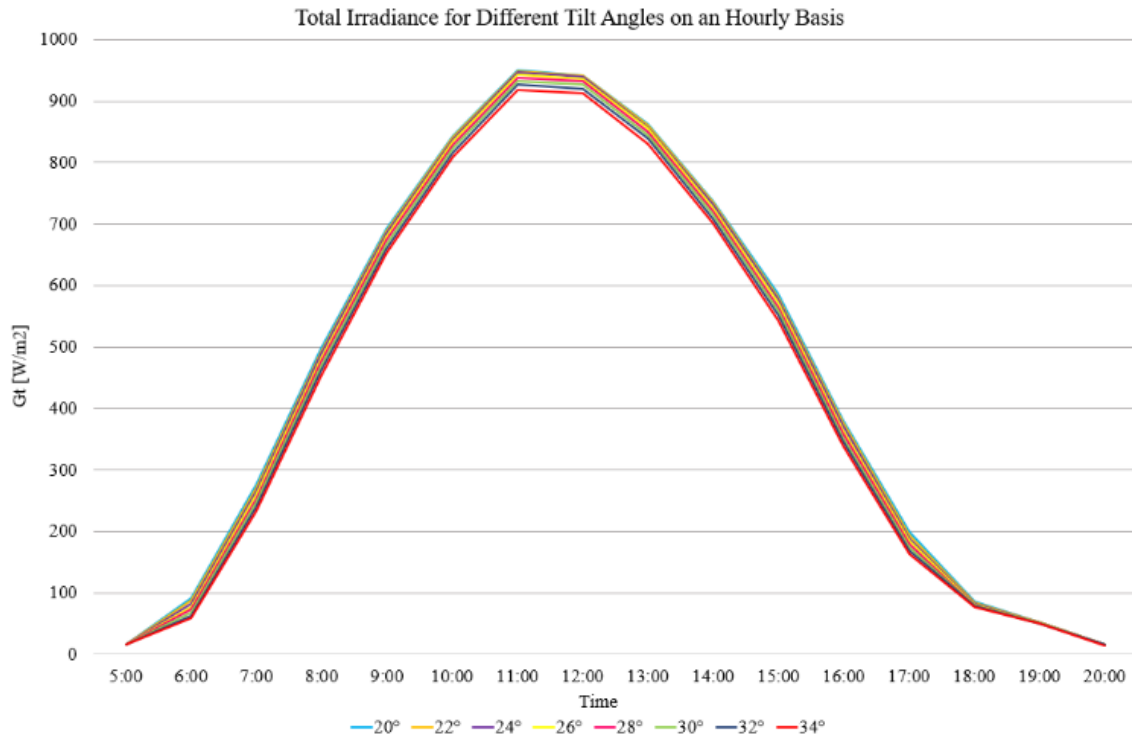


Fig. 1. Hourly Total Solar Irradiance for Different Tilt Angles for a TMY summer day

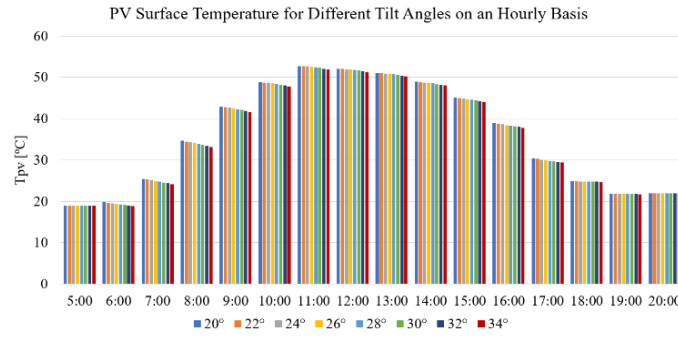


Fig. 2. Hourly PV Surface Temperature for Different Tilt Angles for a TMY summer day

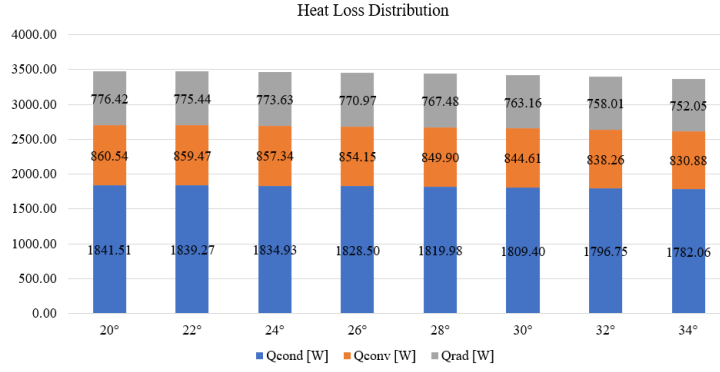


Fig. 3. Analysis of the Heat Transfer Mechanisms for Different Tilt Angles (at 11:00)

The combined analysis of photovoltaic (PV) surface temperature (T_{PV}) and heat-loss mechanisms (Fig. 4) reveals a clear interdependence between thermal loading and the distribution of conduction, convection, and radiation losses. As the tilt angle increases from 20° to 34° , the PV temperature decreases from $52.75\text{ }^\circ\text{C}$ to $51.89\text{ }^\circ\text{C}$, corresponding to a gradual reduction in all heat-loss components. The smooth downward curvature of the T_{PV} trend mirrors the reductions in thermal losses, confirming that heat-loss magnitudes scale directly with PV temperature and absorbed irradiance.

The relationship between heat-loss mechanisms and photovoltaic efficiency across the examined tilt angles shows a consistent and physically meaningful trend (Fig. 5).

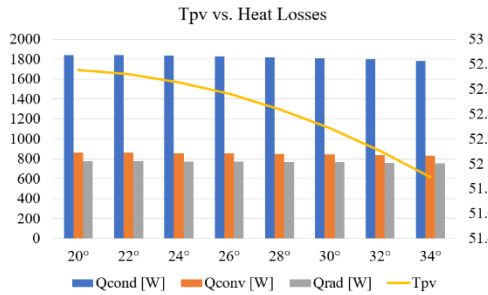


Fig. 4. PV Panel Temperature vs. Heat Losses at Different Tilt Angles

As mentioned previously, as the tilt increases from 20° to 34° , all heat-loss components – conduction, convection, and radiation – decrease steadily. Despite these declines, the module efficiency (η) exhibits a monotonic and slightly nonlinear increase, rising from 0.18837 to 0.18898. This improvement, although modest in absolute terms ($\sim 0.3\%$ points), aligns with the expected thermal behavior: reduced heat accumulation leads to lower photovoltaic (PV) cell temperatures, thereby decreasing internal resistive losses and enhancing electrical conversion efficiency. The opposite

directionality between heat losses and η confirms that higher tilt angles mitigate thermal stress and improve overall module performance. However, the small magnitude of efficiency change suggests that thermal effects are present but not dominant within this tilt range, indicating that optical factors remain the primary driver of performance.

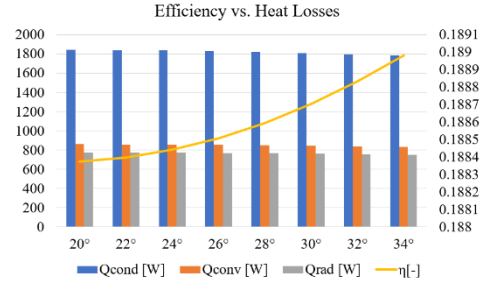


Fig. 5. Efficiency vs. Heat Losses at Different Tilt Angles

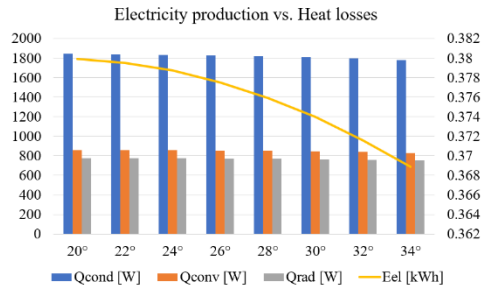


Fig. 6. Electricity Production vs. Heat Losses at Different Tilt Angles

The variation of electrical energy output (E_{el}) with respect to heat-loss components across the examined tilt angles reveals a clear inverse relationship (Fig. 6). Despite the progressive reduction in thermal dissipation, the electrical energy output shows a continuous downward trend, decreasing from 0.3799 kWh at 20° to 0.3688 kWh at 34° .

IV. CONCLUSION

This research offers an in-depth thermal analysis of a monocrystalline photovoltaic module functioning at different tilt angles, emphasizing the relative roles of conduction, convection, and radiation. The findings indicate that even minor adjustments in tilt angle result in significant changes in solar irradiance and the PV surface temperature, subsequently affecting the extent and distribution of heat losses.

Among the mechanisms analyzed, conductive heat transfer remains the predominant loss pathway, greatly affected by the internal temperature gradient present between the front PV surface and the rear surface. Convective losses steadily decrease as the tilt angle rises. Radiative losses show the least responsiveness to tilt angle.

An important observation is that smaller tilt angles are related to higher photovoltaic (PV) temperatures, which cause greater conduction and convection losses, consequently leading to a reduction in electrical efficiency. Conversely, larger tilt angles tend to moderately decrease the surface temperature and improve performance, although this effect is partially limited by reduced incident irradiation. The established correlations between photovoltaic (PV) temperature, heat losses, efficiency, and electrical output illustrate the significant thermodynamic interdependence present within the module. These observations emphasize the critical role of integrated thermal-geometric optimization.

The model is limited by its fixed geometry without tracking or cooling and by the exclusion of local effects such as shading, soiling, and seasonal changes in reflectance. The use of TMY data captures only average conditions and fails to represent extreme or rapidly changing weather events that can significantly affect real photovoltaic performance. Furthermore, the presented results are based solely on simulation and have not yet been experimentally validated. Future work should incorporate field measurements under real operating conditions to verify the model predictions and extend its applicability to dynamic and site-specific scenarios.

In summary, this study highlights the importance of precise thermal modeling for evaluating performance, recognizing loss mechanisms, and enhancing the operation of photovoltaic (PV) modules. The methodology introduced can be easily adapted to various climates, module types, and mounting configurations, thereby offering a solid foundation for forthcoming assessments of thermal performance and energy optimization research.

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