THE PERFORMANCE AND ADVANCED COOLING TECHNIQUES FOR PHOTOVOLTAIC SOLAR PANELS

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The high performance of the photovoltaic cell requires proper and efficient cooling because the electrical efficiency of the photovoltaic cell is affected by the operating temperature. Providing a suitable operating environment for the photovoltaic cell at a low temperature is necessary, which can be achieved using devices with highly effective thermal performance in which heat is transferred from the cell to the external surroundings via pulsating heat pipes, and this process leads to significant energy generation and the best efficiency of the photovoltaic unit. In this work, we use pulsating heat pipes with copper fins to achieve adequate cooling of the cell and make it operate at the best temperature, leading to a higher photovoltaic cell efficiency. The metal used for the pulsating heat pipes is copper, which has high conductivity needed to increase performance. The study showed that pulsating heat pipes are the most suitable options for cooling the photovoltaic cell, which leads to increasing its efficiency and increasing electricity production.

Keywords

PV module cooling, solar power, collector, power plants, heat pipes, photovoltaic temperature

1 INTRODUCTION

A photovoltaic cell is a device that converts light energy into electrical energy through the photovoltaic effect [Abd Ali 2019a, Al-Maliki 2022]. The solar cell system requires high cooling performance to provide an appropriate operating temperature to achieve efficiency and good performance. Providing a working environment for the solar cell at a low temperature is necessary [Abd Ali 2021]. Excessive heat may negatively impact a solar cell's efficiency. A solar cell's efficiency drops with rising temperatures because the increased heat raises the electrical resistance of the cell's components, which in turn reduces the amount of electric current flowing through them [Abd Ali 2020]. Furthermore, extreme heat might permanently harm the cell by causing cracks or warping. The solar cell system requires high cooling performance to provide an appropriate operating temperature to achieve efficiency and good performance [Chandel 2022]. Providing a working environment for the solar cell at a low temperature is necessary, which can be achieved by devices with highly effective thermal performance in which heat is transferred from the solar cell to the external environment, which can occur utilizing pulsating heat pipes [Ge 2022]. This process leads to significant energy generation and better photovoltaic cell efficiency. This work uses pulsating heat pipes with copper fins to adequately cool the cell [Almsater 2016]. The study showed that pulsating heat pipes are the most suitable options for cooling the photovoltaic cell, which leads to increased cell efficiency and thus increases electrical energy production [Abd Ali 2019b]. Cooling the photovoltaic cell can be achieved by many techniques, including passive cooling, which increases the efficiency of the photovoltaic cell despite many drawbacks, including the lack of heat dissipation at high temperatures [Alsharkawi 2016, Pivarciova 2019].

The second type of cooling technology is active cooling, which is considered the best method. It is most suitable from a practical standpoint and is used in cooling systems for photovoltaic cells [Arifin 2020]. Pulsating heat pipes and high heat flow systems are considered more valuable in small devices, for instance, electronic systems, where Pulsating heat pipes [PHPs] are employed due to their remarkable capacity for heat dissipation, and in many applications, which comprise a complex capillary-tube with a minimal internal diameter and are of two basic types: closed loop and open loop. The end of an open-loop capillary tube is an open-loop tube, while it is connected in lines is a closed-loop capillary tube [Zhang 2021].

2 MATERIALS AND METHODS

A pulsating heat tube is utilized in this investigation, per [Kaneesamkandi 2023, Saga 2019] data. Materialized of quartz, the interior diameter of the tube measures 4 mm. Comprising a condenser (30 cm), adiabatic (60 cm), and evaporator (50 cm), the pulsed heat pipe has a total length of 150 centimeters. It is necessary to position the panels in the proper orientation so as to achieve uniform solar irradiation [Conrado 2017, Cheboxarov 2019] and other researchers observed that optimal performance is achieved at an inclination angle ranging from 20 - 40 degrees. The peak radiation output was observed to occur within the inclination angle range of 30 degrees [Guryev 2019]. Moreover, the pulsating heat conduit exhibits superior thermal performance at a filling ratio of 40%. As a result, research was conducted on thermal resistance. In this study, photovoltaic panels were simulated at an inclination angle of 30 degrees and a filling rate of 40% [Saleh 2022, Cheboxarov 2019, Abd Ali 2019b]. In addition to modeling the pulsating heat conduit based on its geometry [Kuric 2022], it is critical to compute its effective thermal conductivity. Thus, the subsequent equation represents its effective thermal conductivity:

$$G = A_C \times g_{PHP} = \frac{\Delta T}{\Delta V} = \frac{\Delta T}{\frac{L_{eff}}{K_{eff} A_C}} \tag{1}$$

Where a PHP's effective length is:

$$l_{eff} = \frac{\int_{L_e}\left(\int_0^x g' dx\right)dx + L_{ad}\, g_{c,max} + \int_{LC}\left(\int_{L_e+L_{ad}}^{X} g' dx\right)dx}{g_{c,max}} \tag{2}$$

The thermal resistance of a pulsing heat pipe is determined by the temperature differential between the condenser and the evaporator. A significant correlation has been identified that demonstrates the association between the two parts. This correlation is used to determine the effectiveness of numerical simulation and thermal conductivity in Equation No. 3, The thermal resistance depends on the temperature differential [Nassar 2023, Kuvshinov 2019]

$$V = -0.0000053990(\Delta T)^3 + 0.001124605(\Delta T)^2 - 0.07636998(\Delta T) + 2.102284 \quad (3)$$

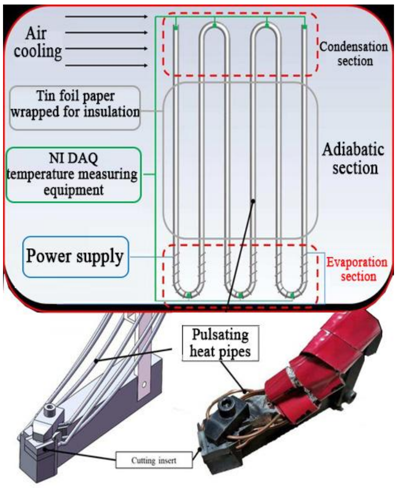


Figure 1. Diagram of the PHP experimental setup

In order to ascertain the surface temperature of the photovoltage cells, an energy balance is used [Kuvshinov 2019a,b]. A portion of the energy that has been absorbed is transported via convective and radiative heat transfer, as depicted in Figure 2. In contrast, the remaining part works to increase the internal photovoltaic cell energy and power production [Abdali 2023].

The equilibrium energy of photovoltage panels:

$$\rho C_p \delta \frac{dT_S}{dt} = g_s - g_{el} - g_h - g_r - g_{PHP} \quad (4)$$

where g_s, denoted by the following calculation, represents the amount of solar radiation received

$$g_s = \varepsilon_0 G_S \quad (5)$$

where g_s represents the typicalsolar pahile ε_0 denotes the absorption rate of the photovoltage cell.

The energy generated by the photovoltaic panel due to solar radiation is represented by the symbol g_{el}. in the energy eq. By applying Equation (6), the generated electricity can be obtained [Kuznetsov 2020]

$$g_{el} = \beta G_S \quad (6)$$

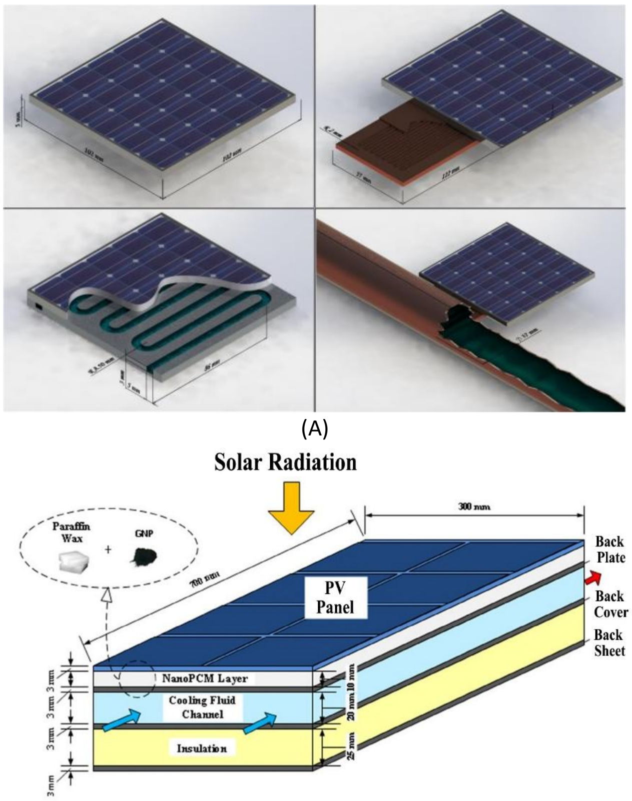
The efficiency of the photovoltaic panel is referred to as variable g_{el} in the above equation, and its efficiency is affected by the temperature of operating photovoltage cell [Rimar 2020]. The relationship between efficiency and surface temperature of the photovoltaic cell can be expressed by the following equation:

$$\beta = -0.1757\, T_S + 21.737 \quad (7)$$

where g_h and g_r denote heat transfer resulting from convection and radiation, respectively, in the energy equation. g_h and g_r are computed using Equations (8) and (9), respectively

$$g_h = h_h(T_S - T_a) \quad (8)$$

$$g_r = 2\varepsilon_1 G_{sb}(T^4{}_S - T^4{}_a) \quad (9)$$



(B)

Figure 2. PV panel energy conservation

Table 1. The PV panel's specifications

Power	6 w	Power-tolerance	± 5
Operating voltage	18 v	Open-circuitvoltage	21.7 v
Operating current	278 mA	Short-circuitcurrent	301 mA

Silicon monocrystalline photovoltaic cells are the type of photovoltage panel. The irradiance =1000(W/m^2); A.m=1.5; the module temperature = 298K

Where ε_1 represents the emissivity of the surfaces of the PV panels. The coefficient of convective heat transfer in Eq. (8) computed using Eq. (10)

$$\overline{Nu_L} = \left\{0.825 + \frac{0.387 Ra_L^{1.6}}{\left[1.0 + \left(0.4920/_{Pr}\right)^{9./16.}\right]^{8./27.}}\right\}^2 \quad (10)$$

The convective heat transfer coefficient on the posterior side of the photovoltage panel was calculated by Equation (10). In contrast, Utilizing Equation (11), the convective heat transmission coefficient in the top of panel computed

$$h_h = 2.8 + 3.8\, u_{wind} \quad (11)$$

As illustrated below, Equation (4) might be reformulated as a differential equation:

$$\frac{\partial}{\partial t}(Ph) + \nabla.(\vec{v}Ph) = \nabla.(K\nabla T) + S_h \quad (12)$$

The temperature variable is determined for each control volume in this study through the process of separating and integrating the aforementioned equation (Vologdin 2019). Under various solar radiations, the temperature of the photovoltaic panels is studied in the first step. In the simulation, a three-layer photovoltaic panel, including the glass cover, was chosen.

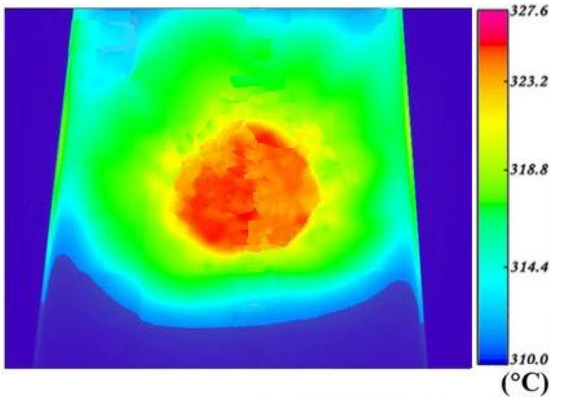


Figure 3. The temperature contours of photovoltaic (PV) panels subjected to different levels of solar radiation

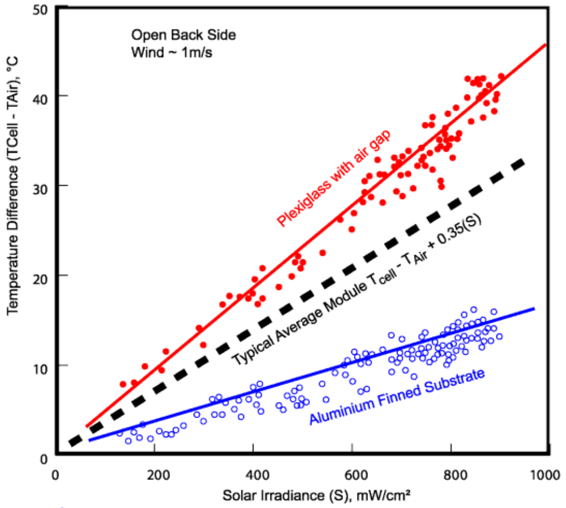


Figure 4. Comprehensive comparative analysis, juxtaposing the findings of the present study with those derived from previous research endeavors

The photovoltage panel is distinguished by its 3.2 mm thickness and the presence of conductive layers on both surfaces [Al-Rufaee 2021]. Additionally, the panel features a PVF layer that functions as insulation at its base. The magnitude of the thickness of the PVF The stratum measures 2mm. Table 1 presents a dimensions, electrical attributes, and operating temperature of the panel.

Figure 3 illustrates the anticipated temperature contours within the photovoltaic panel domain, corresponding to five distinct radiation levels [Drwiega 2023, Xing 2017]. This article employs a specified ambient temperature of 291 K. The data presented in Figure 3 clearly demonstrates a positive correlation between elevated temperatures and increased sun radiation levels. As illustrated in Figure 4, the simulated outcomes are verified through comparisons with analytical and experimental tests. Upon doing a comprehensive analysis of Figure 4, it becomes evident that the anticipated results align favorably with the previously established conclusions derived from both the analytical model [AlAmri 2021] and the experimental investigation [Kuvshinov 2021]. In order to examine the effects of implementing PHP (Phase Change Material Heat Pipe) in photovoltaic (PV) cooling systems, a geometric representation of the photovoltage cell integrated with pulsating heat pipe was generated and subsequently divided into a mesh structure.

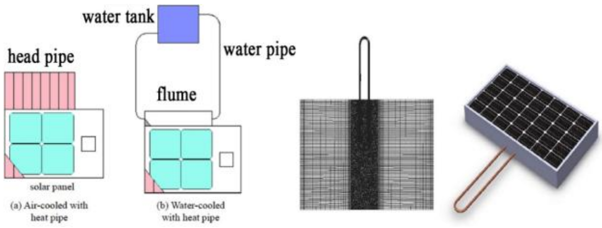


Figure 5. The three-dimensional configuration and grid pattern of a photovoltaic cell incorporating a photovoltaic heat pump system

Figure 5 illustrates the three- dimensional types to the photovoltage cell and the configuration of the numerical domain's grid. This study aimed to investigate grid independence as a means of evaluating the accuracy of the numerical simulation. The investigation involved the analysis of the PV surface temperature, considering various mesh sizes and levels of irradiation. The grid independence study was conducted using a mesh consisting of approximately 2,300,000 elements. This research aims to in this analysis, we will compare the outcomes or findings of the study the numerical modeling with an observed insensitivity at the temperature of the photovoltaic panels at different mesh densities.

3 RESULTS AND DISCUSSION

To assess the efficacy of a pulsating heat pipe in photoelectric cooling, A numerical simulation with transient behavior is conducted. The heat flux is accounted for in the simulation at $1{\times}10^3$. W/m², while the ambient temperature is maintained at 294K. The condenser section temperature of the pulsating heat conduit is presumed to be equivalent to that of the surrounding environment. Additionally, to facilitate comparison, a further simulation is performed in which a copper tube is employed as a fin to augment the photovoltaic panel's cooling capabilities. A comparative analysis of the expected results obtained from the simulations mentioned above is seen in Fig. 6. The findings presented in this figure illustrate that the application of photovoltaic cooling via a copper tube fin or a pulsating heat pipe results in a corresponding reduction of 16.1 K or 4.9 K in the plate's temperature. The results suggest that the implementation of pulsing heat conduit PC The process of cooling induces a significant decrease in temperature caused by its enhanced thermal effectiveness when compared to a copper tube fin and the worse result that shows in solar panels without using a cooling method. Furthermore, research has shown that the utilization of a pulsing heat conduit rather than a copper tube fin results in a shorter period needed to attain a consistent operating temperature when it comes to cooling personal computers. Figure 7 depicts the temperature limitations associated with the utilization of a pulsating heat conduit for cooling panels. The highest recorded temperature at the plate's surface is approximately 309.4 K, specifically in the vicinity of the plate's extremities.

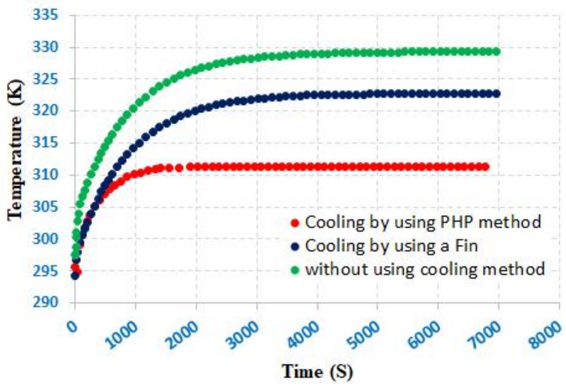


Figure 6. The PV's transient average temperatures when being cooled by copper fins and a pulsating heat pipe

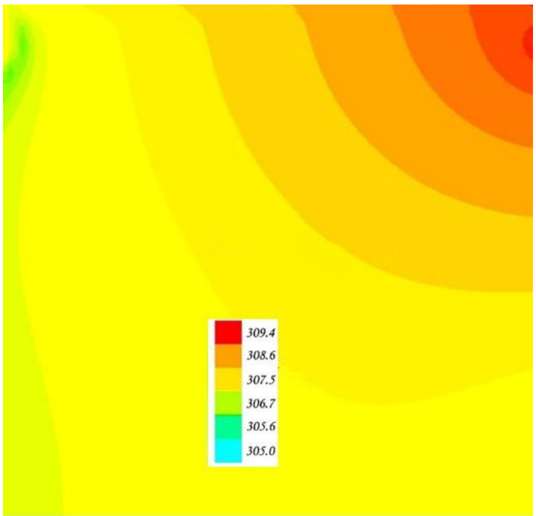


Figure 7. Asymmetric distribution of the photovoltaic cell to solar radiation1×103 (W/m2).

In the vicinity of the Peltier Heat Pump, the minimal plate temperature of around 307.3 K is taken into account when assessing the efficacy of the pulsating heat pipe cooling system across a range of environmental conditions. In order to simulate the cooling process of photovoltaic panels, defined boundary conditions are applied to the panels' walls. Transient computations are performed on two cooling methods, pulsating heat pipe, and copper fins, in order to evaluate their cooling capacities. The simulation outcomes for the given condition are illustrated in Figure 8.

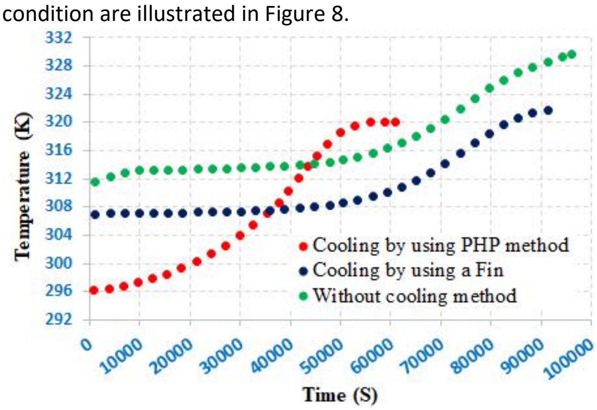


Figure 8. The PV panel's transient adiabatic temperature as copper fins and pulsating heat pipe are cooling it

The vertical axis on the left side of a representation depicts the temperature to the surface of the photovoltaic as the plate undergoes cooling via a pulsating heat conduit. On the contrary, the right indicator axis of the photovoltaic plate temperature that is cooled by copper fins.

As illustrated in Figure 8, the results indicate that the implementation of a phase change material (PCM) during the cooling procedure results in enhanced efficiency in the cooling of the photovoltaic panel. Moreover, empirical evidence suggests that the photovoltage panel temperature does not significantly rise along with the time when passive heat pipe (pulsating heat pipe) cooling is implemented. Within the realm of copper fin cooling, a discernible upward trend in temperature is documented over time.

The results of this research indicate that the implementation of pulsating heat conduit cooling is more effective at facilitating the transfer of heat produced through the photovoltaic cell to the fluid. In order to assess the cooling effectiveness of a Pulsating Heat Pipe (pulsating heat pipe) across diverse scenarios, a sequence of simulations was performed, incorporating five distinct types of solar radiation. The temperature discrepancies observed in the context of solar cooling, specifically when utilizing a Peltier heat pump (pulsating heat conduit) versus a copper tube with equivalent diameters, are depicted in Figure 9. Figure 10 describes the improving in electrical efficiency by using the PHP technique.

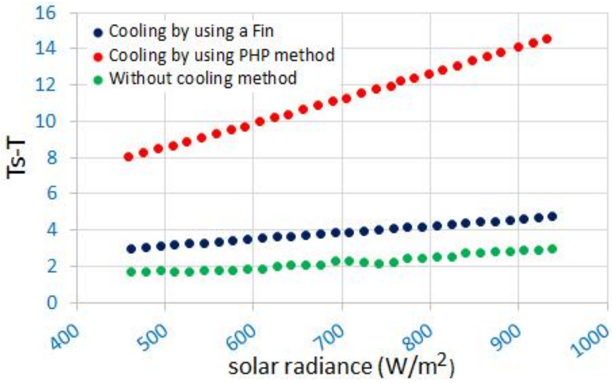


Figure 9. Temperature differential of the photovoltaic panel under varying solar radiations cooled by the pulsating heat pipe and copper fin

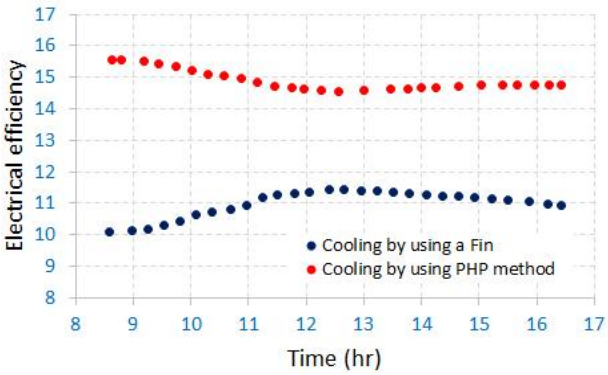


Figure 10. The comparison of electrical efficiency between the two methods for PV cooling

As can be seen in Figure 11, a photocurrent-voltage curve (I-V) may be used to describe the performance of solar cells.

When comparing the use of a copper tube to the result of refrigeration, it becomes evident that the latter generates a considerably greater temperature differential. Furthermore, it has been demonstrated that as solar radiation levels increase, the deviation in temperature difference for both chilling methods increases. Higher heat inputs resulted in enhanced thermal efficacy for the pulsating heat pipe, according to the data.

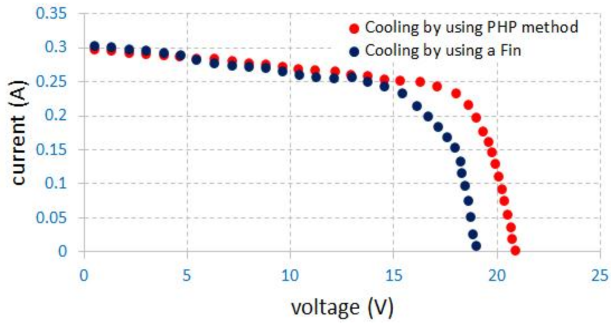


Figure 11. The comparison of photocurrent-voltage curve between the two methods for PV cooling

The coefficient of heat rise is increased by increasing the thermal energy supplied to the evaporator portion of the PHP via the amplified steam alloy capacity frequency. Furthermore, an increase in thermal energy input may cause the formation of vortices that are more expansive within the flow regime, thereby causing the heat transfer coefficient to rise. A correlation between the quantity of electricity output and the temperature of the photovoltaic panel is evident from Equation (7), suggesting that lower temperatures correspond to more significant electricity generation. Therefore, Figure 12 illustrates the comparative in electrical power generated in the case under investigation. Based on the data depicted in Figure 12, it is evident that pulsating heat pipe cooling results in an increased output power. In contrast to copper fin cooling, which exhibits a 5.5% increase in electric power output when exposed to 1000 W/m^2 of solar radiation, PHP cooling demonstrates a 20% increase.

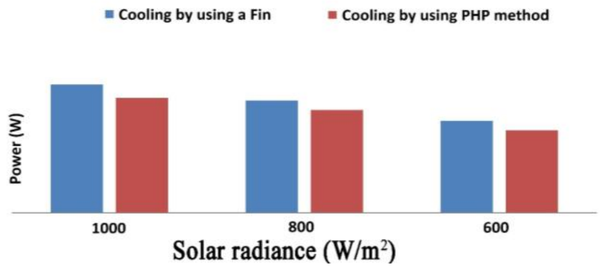


Figure 12. Various scenarios for the generation of electrical power

CONCLUSIONS

A comprehensive investigation was conducted in this study regarding the implementation of solar cooling via a single-loop pulsed heat pipe (pulsating heat pipe). The determination of the thermal performance of a photovoltaic panel is contingent upon two factors: the optimal inclination angle and a fill ratio of 40%. A numerical investigation is performed to determine the surface temperature of an uncooled photovoltaic panel. The results obtained from this investigation exhibit a satisfactory degree of consistency with previous research. Additionally, a simulation was undertaken to assess the functionality of a photovoltaic panel that utilized pulsating heat pipe ventilation. The findings suggest that the introduction of intermittent heat pipe cooling leads to a 16.1 K decrease in photovoltage surface temperature. A metal fin (copper), on the other hand, effectively decreases the temperature by a mere 4.9 K. The results of this study indicate that pulsating heat pipe cooling exhibits superior thermal cooling capabilities in comparison to a solid copper fin. In addition, by employing pulsating heat pipes to chill the photovoltaic panels, efficiency is increased in a shorter period, and the cooling process is accelerated. The electric power experiences a 20% increase when subjected to 1000 W/m^2 of solar radiation due to the pulsating heat pipe's enhanced cooling efficiency.

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