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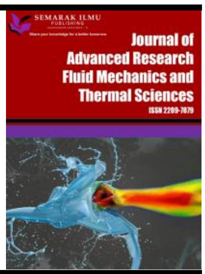

Calculating the Operating Temperature and Efficiency of Photovoltaic Panels in Vietnamese Conditions

Dang Van Binh[1,2,*], Pham Quang Vu[2], Manh-Hai Pham[2]

[1] Hanoi University of Industry, Hanoi, Vietnam
[2] Electric Power University, Hanoi, Vietnam

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ABSTRACT

The efficiency of photovoltaic panels depends heavily on their operating temperature. Typically, this temperature is evaluated under steady-state conditions, which may not fully capture real-world performance. In this study, we calculated the operating temperature of photovoltaic panels under dynamic, unstable conditions using the energy balance method. Environmental data, including ambient temperature and wind speed, were sourced from the hottest days of 2023 in Hanoi, Danang, and Ho Chi Minh City. At solar irradiance levels of 600, 800, and 1000 W/m², the operating temperature increased by 9.6 K, 8.3 K, and 3.8 K, respectively, leading to lower conversion efficiencies to the manufacturer's nominal values. These findings emphasize the importance of considering real-world, dynamic conditions when evaluating the performance of photovoltaic systems.

1. Introduction

Every country's energy mix must incorporate renewable energy to achieve sustainable development. Solar energy is a common renewable energy source that converts into two types of energy: electricity and heat. Photovoltaic (PV) cells use the photovoltaic effect to generate electricity directly from solar energy. Environmental factors and PV operation temperature both have an impact on conversion efficiency [1]. The primary determinant of photovoltaic efficiency is the operating temperature [2].

PV panels transform around 6 - 20% of solar radiation into electricity, with the remainder reflected and transformed into thermal energy to enhance operational temperature [2-9]. When PV panels are installed in areas with high ambient heat, the operating temperature increases, reducing their efficiency and lifespan [10].

Calculating PV's operating temperature is difficult because it depends on variables such as PV's physical qualities and the surrounding environment [11]. Researchers often assess PV operating temperatures under both stable (time-independent) and unstable (dynamic) conditions [12].

* *Corresponding author.*
E-mail address: binhdv@haui.edu.vn

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Calculation under steady conditions is simple but has a significant error rate [13]. Calculating the operating temperature of PV panels in unstable conditions produces more precise results, but it is a more difficult mathematical procedure is often employed than the energy balance method [1].

Currently, researchers are working to improve the methods for calculating the operating temperature of PV panels using experimentally measured parameters, typically under stable conditions [14,15]. However, these calculation methods do not use heat transfer equations to describe and calculate the operating temperature of PV panels.

The efficiency provided by manufacturers does not account the prolonged periods of higher temperatures that can result from thermal inertia or constant irradiance. In real-world conditions, as PV panels heat up beyond the STC temperature of 25°C, the conversion efficiency decreases (as described by the temperature coefficient). The unstable model used in the study provides a more realistic efficiency by accounting for temperature variations and continued heating even when ambient conditions fluctuate.

At STC, the conversion efficiency of PV decreases by 0.4 - 0.5 % when the operating temperature increases by 1 °C [16]. This power output reduction is the maximum power temperature coefficient (P_{max}). The temperature coefficient is different for each photovoltaic technology: -0.44 % (m-Si), -0.45 % (p-Si), -0.38 % (CIGS), -0.39 % (CIS), and 0.25 % (CdTe) [17]. Besides, the climatic conditions of the installation location also affect the temperature coefficient of the PV panel. A. J. Hamad experimented in Baghdad city in Iraq, and the results showed that the temperature coefficient of the maximum power was -0.52 %/K of polycrystalline silicon panels [18].

This study focuses on developing an equation to calculate the operating temperature of PV panels using the energy balance method. This clarifies the heat exchange process between the PV panel and the surrounding environment. We are using environmental data representative of three regions in Vietnam: Hanoi, Ho Chi Minh City, and Danang; the authors calculate the operating temperature of PV at unstable conditions. From the calculated operating temperature, we also panel evaluate the PV panel conversion and exergy efficiency.

The article is structured into sections as follows: Basics and methods of calculation of the operating temperature of PV panel, conversion efficiency, exergy efficiency, calculation data, and parameters of PV panel are presented in section 2; section 3 presents the calculation results and discussions; section 4 provides conclusions.

2. Methods and Calculation Data

2.1 Calculation of Operating Temperature and Efficiency of PV Panel

Considering a PV panel placed in the environment, the heat transfer diagram of the PV panel and the environment is shown in Figure 1.

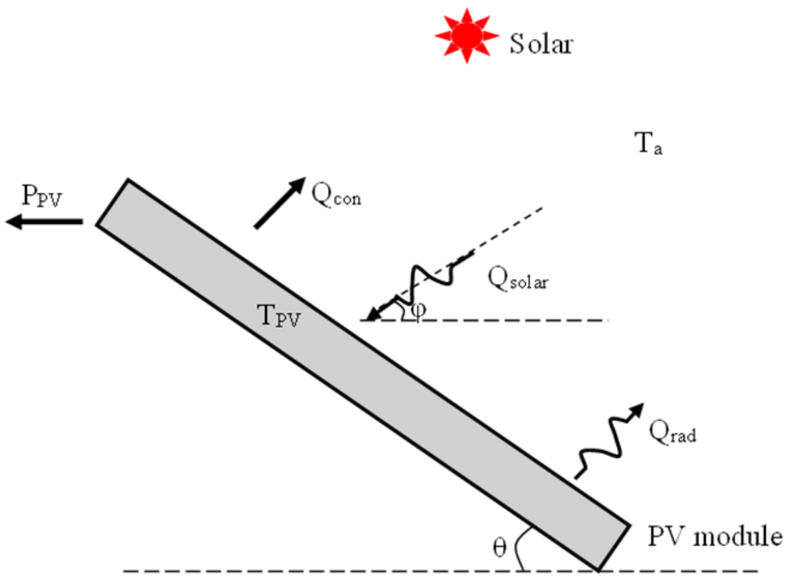

Fig. 1. Heat transfer diagram of PV panel and environment

The energy balance equation of the PV panel at the unstable conditions is shown in Eq. (1) [19].

$$Q_{solar} - Q_{rad} - Q_{con} - P_{PV} = C_{PV}\frac{dT_{PV}}{dt} \tag{1}$$

where Q_{solar}: Gained solar flux, W; Q_{rad}: Radition heat transfer, W; Q_{con}: Convection heat transfer, W; P_{PV}: Electricity power output of PV panel, W; C_{PV}: PV panel heat capacity, J/K; T_{PV}: PV temperature, K.

The heat radiation absorbed by PV panel is calculated using the Eq. (2).

$$Q_{solar} = \alpha_{PV} A E_{solar} \sin(\varphi + \theta) \tag{2}$$

where α_{PV}: Absorptivity of PV panel; A: Area of PV panel, m^2; E_{solar}: Solar flux radiation, W/m^2; θ: Tilt angle of PV panel; for each installation area, we choose the optimal PV panel tilt angle to achieve the best energy efficiency; φ: Complement angle of the solar indication ray angle with vertical axis.

The heat transfer radiation between the PV panel and environment is determined as Eq. (3).

$$Q_{rad} = 2A\sigma\left(\varepsilon_{PV}T_{PV}^4 - \varepsilon_{sky}T_{sky}^4\right) = 2A\sigma\varepsilon\left(T_{PV}^4 - T_a^4\right) \tag{3}$$

where σ: Stephan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4; $\varepsilon_{PV}, \varepsilon_{sky}$: Emissivity of PV surface, sky, respectively, we can be assumed $\varepsilon_{PV} = \varepsilon_{sky} = \varepsilon$; T_{sky}, T_a: Temperature of sky and ambient, K.

The heat transfer convection between the PV panel and the environment is determined as Eq. (4).

$$Q_{con} = h_{PV}\, 2A\left(T_{PV} - T_a\right) \tag{4}$$

where h_{PV}: Convective heat transfer coefficient, W/m^{2}K.

The convective heat transfer coefficient of PV panels depends on various factors such as wind speed, wind direction, surface characteristics, tilt angle, etc. In this study, the authors use experimental formula: h_{PV} = 5.7 + 3.8v (with, v: Wind speed, m/s) [20,21].

The electrical energy generated by PV panel at T_{PV} is determined as Eq. (5).

$$P_{PV} = \alpha_{PV} A E_{solar} \sin(\varphi+\theta)\eta_{PV} = \alpha_{PV} A E_{solar} \sin(\varphi+\theta)\eta_{STC}(1-\beta(T_{PV}-T_{STC})) \tag{5}$$

where η_{PV}: Conversion efficiency of PV, %; η_{STC}: Conversion efficiency of PV at Standard Test Conditions (STC), %; β : Temperature coefficient of PV panel at STC, %/K; T_{STC}: STC temperature, T_{STC} = 298 K.

In Eq. (1), C_{PV} is the heat capacity of the PV panel, and it is determined as Eq. (6) [20]:

$$C_{PV} = \sum_{i=1}^{n} A.l_i.\rho_i C_i \tag{6}$$

where l_i is thickness, ρ_i is density, C_i is specific heat capacity of i[th] layer of PV panel.

Substituting Eq. (2) until Eq. (6) into Eq. (1) yields:

$$\begin{aligned} C_{PV}\frac{dT_{PV}}{dt} &= \alpha_{PV} A E_{solar}\sin(\varphi+\theta) - 2A\sigma\varepsilon\left(T_{PV}^4 - T_a^4\right) - h_{PV}2A\left(T_{PV}-T_a\right) \\ &\quad -\alpha_{PV} A E_{solar}\sin(\varphi+\theta)\eta_{STC}(1-\beta(T_{PV}-T_{STC})) \end{aligned}$$

Either:

$$\begin{aligned} \sum_{i=1}^{n} l_i.\rho_i C_i \frac{dT_{PV}}{dt} &= -2\sigma\varepsilon T_{PV}^4 - \left[2h_{PV} - \alpha_{PV}E_{solar}\sin(\varphi+\theta)\eta_{STC}\beta\right]T_{PV} \\ &\quad + \left[\alpha_{PV}E_{solar}\sin(\varphi+\theta) + 2\sigma\varepsilon T_a^4 + 2h_{PV}T_a - \alpha_{PV}E_{solar}\sin(\varphi+\theta)\eta_{STC}(1+\beta T_{STC})\right] \end{aligned} \tag{7}$$

Eq. (7) is a nonlinear differential equation, the T_{PV} is a solution to Eq. (7), with the T_{PV} at the beginning being the ambient temperature when the sun rises.

The conversion efficiency of the PV panel depends on the operating temperature, which is determined as Eq. (8).

$$\eta_{PV} = \eta_{STC}.(1-\beta(T_{PV}-T_{STC})) \tag{8}$$

The exergy efficiency of PV (Ψ_{PV}) is the ratio of output exergy (the exergy of the PV - $\dot{E}x_{PV}$) to input exergy (the exergy of solar radiation - $\dot{E}x_{solar}$), as in Eq. (9).

$$\Psi_{PV} = \frac{\dot{E}x_{PV}}{\dot{E}x_{solar}} \times 100\% \tag{9}$$

The exergy of PV consists of two parts: electrical exergy - $\dot{E}x_{electrical}$ (maximum electrical power generated) and thermal exergy - $\dot{E}x_{thermal}$ (amount of heat lost to the surrounding environment). Therefore, the exergy of PV is determined as Eq. (10) [22].

$$\dot{E}x_{PV} = \dot{E}x_{electrical} - \dot{E}x_{thermal} = V_{max}.I_{max} - \left(1-\frac{T_a}{T_{PV}}\right)\left[h_{PV}\,2A(T_{PV}-T_a)\right] \tag{10}$$

where V_{max}, I_{max}: Maximum voltage and maximum current, respectively.

The exergy of solar radiation is determined as Eq. (11) [23].

$$\dot{E}x_{solar} = \left(1-\frac{T_a}{T_{sun}}\right)E_{solar}\sin(\varphi+\theta)A \tag{11}$$

with T_{sun}: Temperature of the Sun, T_{sun} = 5777 K [24].

Substituting Eq. (10) and Eq. (11) into Eq. (9) to obtain the exergy efficiency of PV as Eq. (12).

$$\Psi_{PV} = \frac{V_{max}.I_{max} - \left(1-\frac{T_a}{T_{PV}}\right)\left[h_{PV}\,2A(T_{PV}-T_a)\right]}{\left(1-\frac{T_a}{T_{sun}}\right)E_{solar}\sin(\varphi+\theta)A} \tag{12}$$

2.2 PV Specifications and Calculation Data

In this investigation, we employed a monocrystalline PV panel, designated MSP 50W, with the parameters shown in Table 1. PV's emission coefficient (ε) is 0.91, whereas its absorption value (α_{PV}) is 0.96 [25,26]. For technical and business reasons, manufacturers do not reveal the specific heat capacity of PV. In this work, we determine the specific heat capacity of PV panel using the study by Jones and Underwood [27], which gives C_{PV} = 2194 (J/K). We assume that the radiation angle is always perpendicular to the PV panel (φ = 90°), We also consider the inclination angle of the PV panel, which is approximately 11° in Vietnamese circumstances [28].

Table 1
Specifications of PV

No	Parameter	Value
1	Maximum power, P_{max}	50 W
2	Cell type	Monocrystalline
3	No. of cell	18
4	Dimensions	710×540×30 mm
5	Maximum power voltage, V_{max}	17.8 V
6	Maximum power current, I_{max}	2.78 A
7	Conversion efficiency, η	16.8 %
8	Temperature coefficient at P_{max}, β	-0.38 %/K

The calculations used data from the Vietnam Meteorological and Hydrological Administration, Ministry of Agriculture and Rural Development, Vietnam. Table 2 shows that the ambient temperature indicates the maximum temperature of the day in 2023 for Hanoi (17/7/2023), Ho Chi Minh City (06/5/2023), and Danang (11/8/2023), with average daily wind speeds v_{HN} = 2.7 m/s, v_{HCM} = 3.6 m/s, and v_{DN} = 2.6 m/s, respectively.

Table 2
Environment temperature data (unit: °C)

STT	Time	Hanoi (17/7/2023)	Danang (11/8/2023)	Ho Chi Minh City (06/5/2023)
1	5h30	29	28	28
2	6h00	29	29	29
3	6h30	29	30	29
4	7h00	30	32	30
5	7h30	31	33	30
6	8h00	32	34	31
7	8h30	32	34	32
8	9h00	33	35	32
9	9h30	35	35	33
10	10h00	35	36	34
11	10h30	36	37	35
12	11h00	36	38	36
13	11h30	36	39	35
14	12h00	36	37	36
15	12h30	37	36	36
16	13h00	37	36	36
17	13h30	38	36	38
18	14h00	38	35	38
19	14h30	37	36	37
20	15h00	37	34	38
21	15h30	38	33	38
22	16h00	38	33	38
23	16h30	37	32	37
24	17h00	36	32	37
25	17h30	36	32	35
26	18h00	36	31	33
27	18h30	35	30	33

3. Results and Discussion

From Eq. (7) and Eq. (12) and calculation data in section 2.2, we calculate the operating temperature and exergy efficiency of PV panel with solar irradiance of 600, 800, and 1000 W/m^2, with the results as follows:

3.1 Operating Temperature of PV Panel

The operating temperature of PV panel at solar irradiation of 600 W/m^2, 800 W/m^2, and 1000 W/m^2 under temperature circumstances in Hanoi, Danang, and Ho Chi Minh City is shown in Figure 2, Figure 3, and Figure 4, respectively. The findings show:

i. A portion of solar light is absorbed, raising the operating temperature of PV panels. Under Hanoi's climatic circumstances, the operating temperature of PV rises to a maximum of 9.6 K at 1000 W/m^2 solar irradiation. The operating temperature of PV panel in Danang and Ho Chi Minh City increases to 8.3 K and 3.8 K, respectively.
ii. Under the same ambient conditions, as solar radiation rises, so does the operating temperature of PV panel. In Hanoi, when solar radiation is 600 W/m^2, 800 W/m^2, and 1000 W/m^2, the operating temperature of PV rises by 7.9 K, 8.8 K, and 9.6 K. Danang's operating temperature rises by 6.7, 7.4, and 8.3 K. Ho Chi Minh City's operating temperature rises by 2.2, 3.0, and 3.8 K.

iii. With the average ambient temperature during the day in Hanoi and Ho Chi Minh City being 34.8 K and 34.2 K, respectively, and the corresponding wind speeds being 2.7 m/s and 3.6 m/s, we can observe that the operating temperature increase of PV panel under the environmental conditions of Ho Chi Minh City is lower than that of Hanoi at all different solar radiation: 2.2 K and 7.9 K (at 600 W/m^2); 3.0 K and 8.8 K (at 800 W/m^2); 3.8 K and 9.6 K (at 1000 W/m^2).

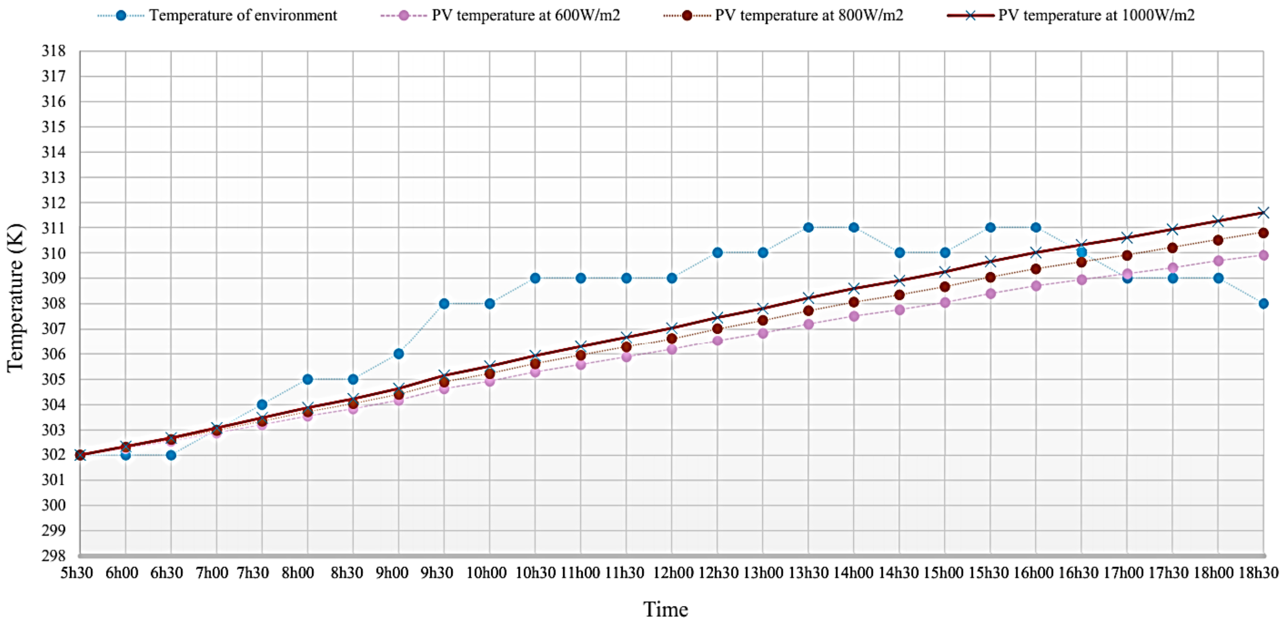

Fig. 2. Operating temperature of PV panel at solar irradiance of 600 W/m^2, 800 W/m^2, 1000 W/m^2 under the temperature conditions in Hanoi

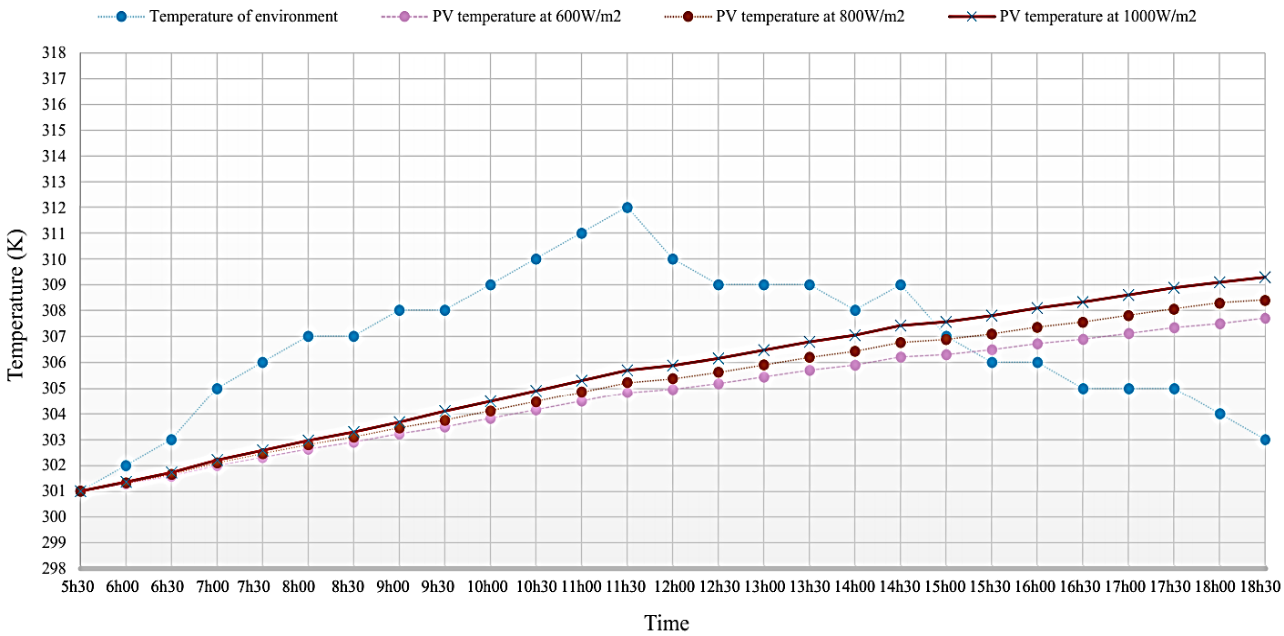

Fig. 3. Operating temperature of PV panel at solar irradiance of 600 W/m^2, 800 W/m^2, 1000 W/m^2 under the temperature conditions in Danang

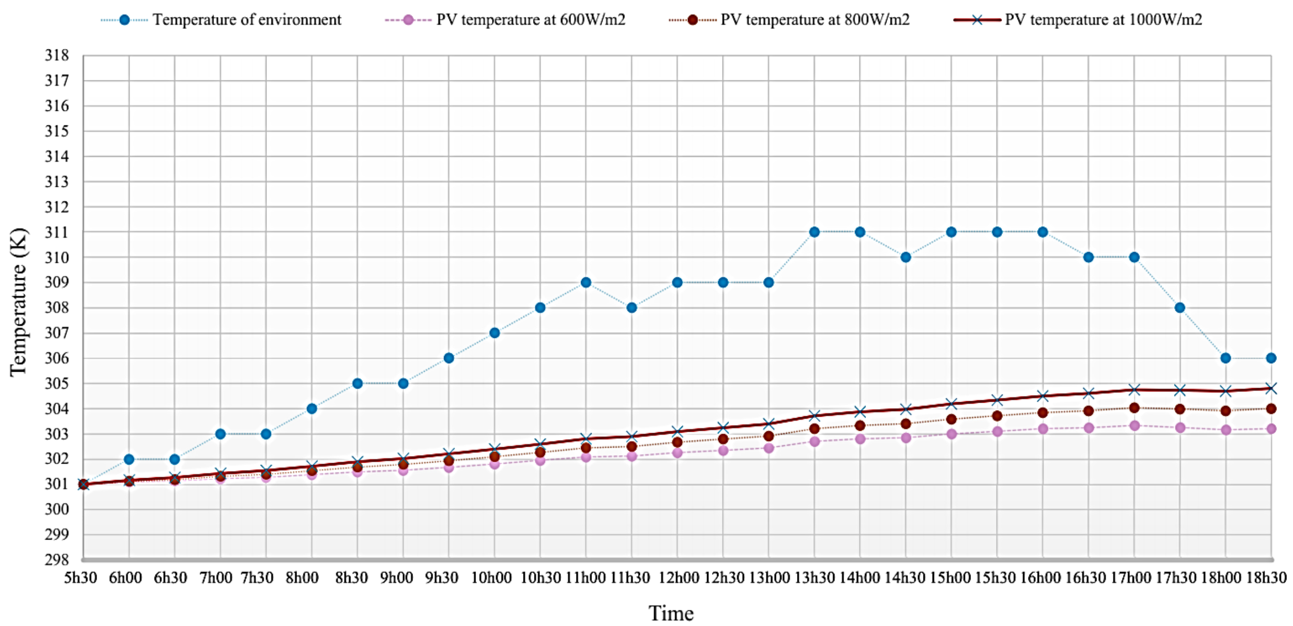

Fig. 4. Operating temperature of PV panel at solar irradiance of 600 W/m^2, 800 W/m^2, 1000 W/m^2 under the temperature conditions in Ho Chi Minh City

Thus, the results show that ambient temperature and solar radiation intensity directly affect the operating temperature of PV panels. The operating temperature of PV panel in Ho Chi Minh City is lower than in Hanoi due to the higher wind speed in Ho Chi Minh City.

3.2 Efficiency of PV Panel

Based on the operating temperature estimate in section 3.1, we calculated the conversion and exergy efficiency of PV panel at various solar irradiances, as shown in Figure 5, Figure 6, and Figure 7. The findings show:

i. The PV conversion efficiency is lower than the manufacturer's claimed conversion efficiency. Under Hanoi's climatic circumstances, the average PV conversion efficiency at 600 W/m^2, 800 W/m^2, and 1000 W/m^2 is 16.28 %, 16.25 %, and 16.23 %, respectively. In Danang's environmental circumstances, the average PV conversion efficiency is 16.37 %, 16.35 %, and 16.31 %. In the environmental circumstances of Ho Chi Minh City, the average PV conversion efficiency is 16.53 %, 16.50 %, and 16.48 %. As solar irradiation rises, so does the working temperature of PV panels, resulting in a drop in conversion efficiency, according to Eq. (8).
ii. The exergy efficiency of PV varies dramatically with solar radiation. In Hanoi's climatic circumstances, the average exergy efficiency of PV panel at solar radiation levels of 600 W/m^2, 800 W/m^2, and 1000 W/m^2 is 23.04 %, 17.29 %, and 13.84 %. In Danang's environmental circumstances, PV has an average exergy efficiency of 22.87 %, 17.16 %, and 13.74 %. In Ho Chi Minh City's environmental circumstances, the average PV conversion efficiency is 22.42 %, 16.90 %, and 13.57 %.

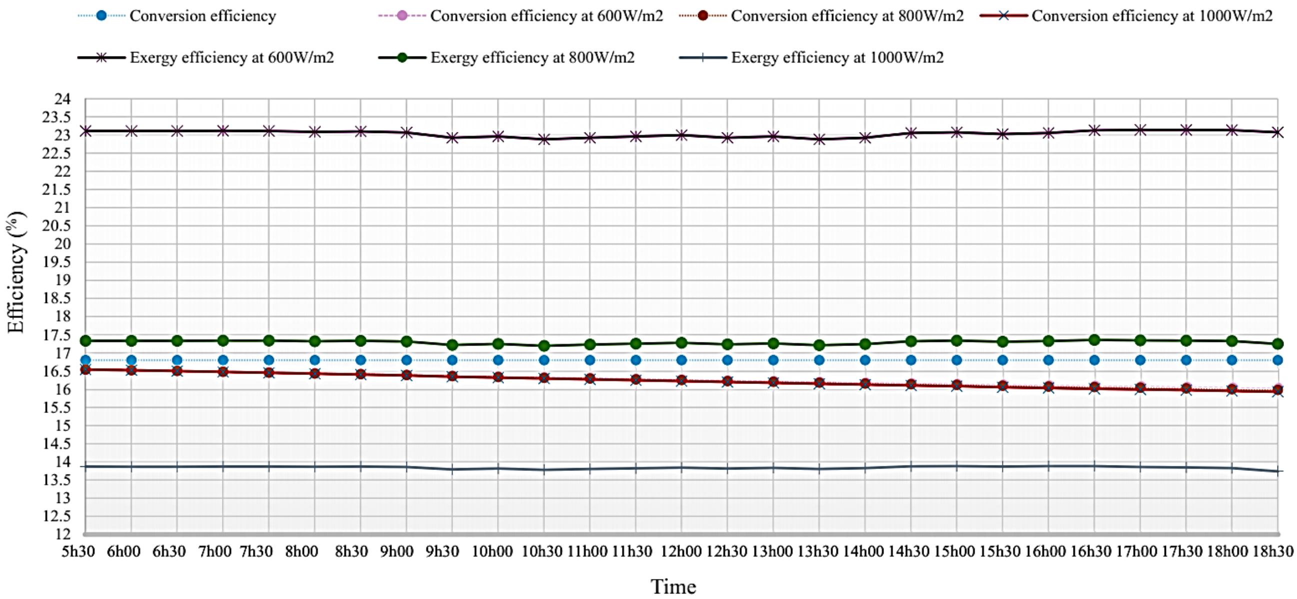

Fig. 5. Conversion efficiency, and exergy efficiency of PV panel at solar irradiance of 600 W/m², 800 W/m², 1000 W/m² under the temperature conditions in Hanoi

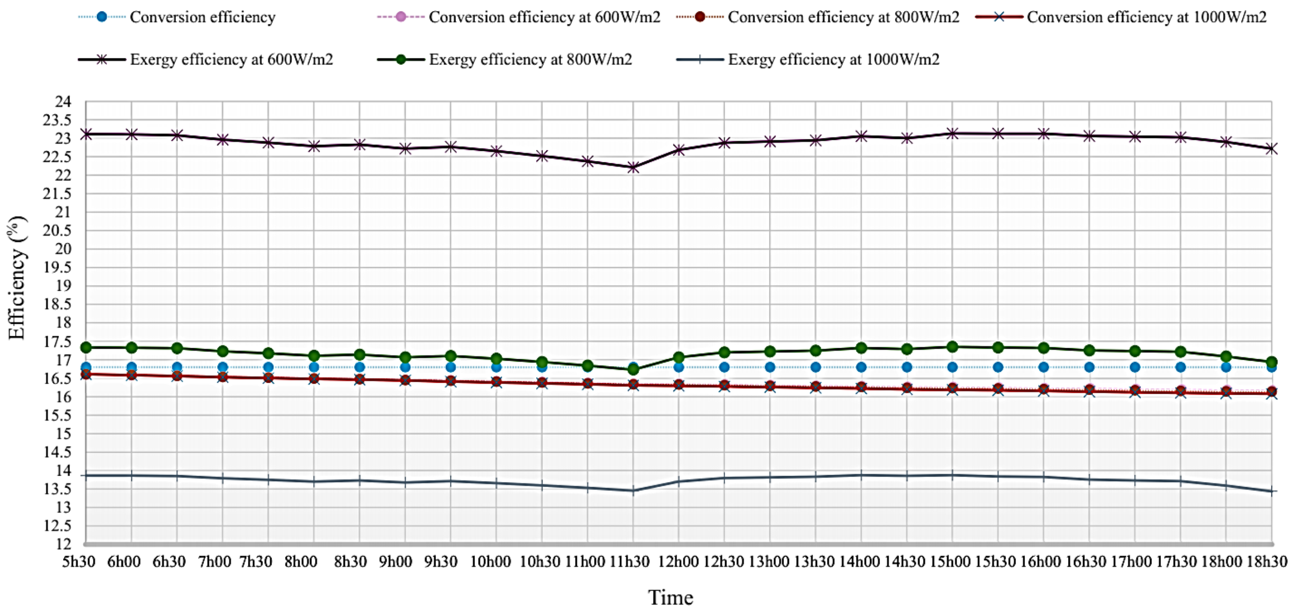

Fig. 6. Conversion efficiency, and exergy efficiency of PV panel at solar irradiance of 600 W/m², 800 W/m², 1000 W/m² under the temperature conditions in Danang

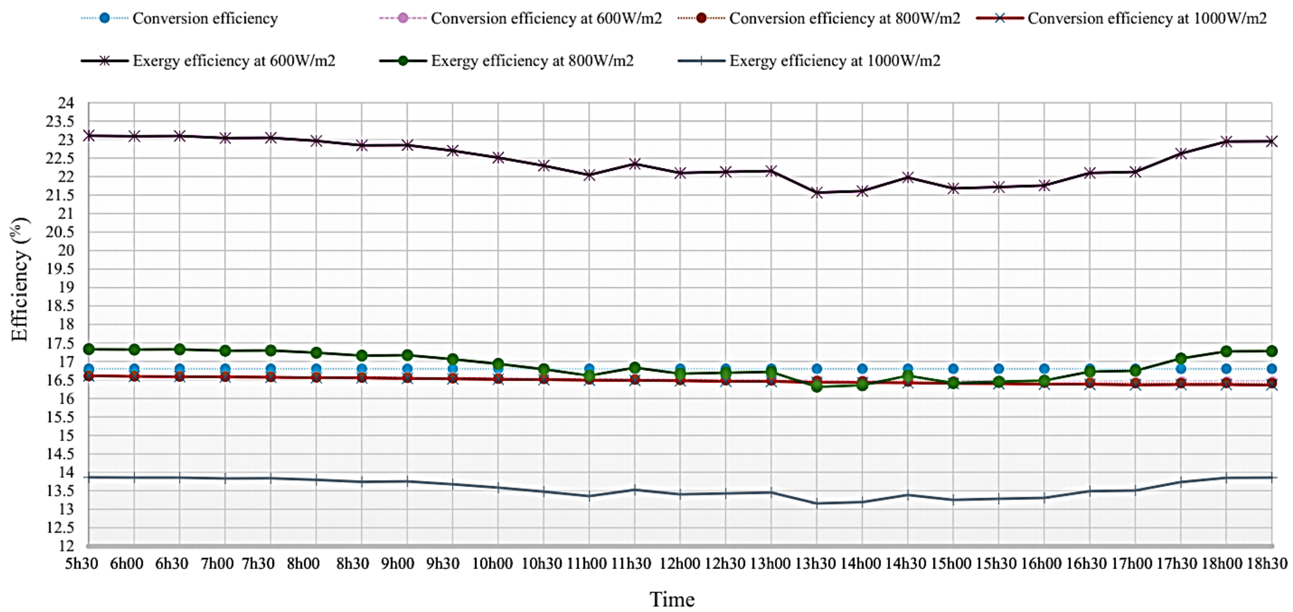

Fig. 7. Conversion efficiency, and exergy efficiency of PV panel at solar irradiance of 600 W/m^2, 800 W/m^2, 1000 W/m^2 under the temperature conditions in Ho Chi Minh city

The calculation results confirm that, as operating temperature increases, the conversion efficiency of PV panels typically decreases. In Hanoi, the operating temperature of PV panel increased by about 9.6 K, and PV efficiency would be expected to drop by approximately 3.4 % at 1000 W/m^2. This helps operators predict energy and conversion efficiency, making plans and strategies for controlling and operating the PV systems.

4. Conclusions

In this work, we calculated the operating temperature of the PV panels using the energy balance approach while the ambient temperature changed over time. The ambient temperature utilized in the computation indicates the maximum temperature of the day in 2023 in Hanoi, Danang, and Ho Chi Minh City. The findings are as follows:

i. When solar radiation reaches 1000 W/m^2, the operating temperature of PV panel in Hanoi, Danang, and Ho Chi Minh City rises to their maximums of 9.6 K, 8.3 K, and 3.8 K, respectively.
ii. The average PV conversion efficiency at solar radiation of 600 W/m^2, 800 W/m^2, and 1000 W/m^2 is 16.28 %, 16.25 %, and 16.23 % (Hanoi); 16.37 %, 16.35 %, and 16.31 % (Danang); and 16.53 %, 16.50 %, and 16.48 % (Ho Chi Minh City). As solar radiation increases, the operational temperature of PV systems rises, resulting in a drop in conversion efficiency.
iii. The average exergy efficiency of PV panel at solar radiation levels of 600 W/m^2, 800 W/m^2, and 1000 W/m^2 is: Hanoi: 23.04 %, 17.29 %, and 13.84 %; Danang: 22.87 %, 17.16 %, and 13.74 %; Ho Chi Minh City: 22.42 %, 16.90 %, and 13.57 %.

Calculating and determining operating temperature helps us manage the operation process of PV panels, and predict conversion efficiency and energy efficiency. The operating temperature of PV panels in areas with high wind speed increases lower than in areas with low wind speed and long-term operation of PV panels system without additional cooling technologies. As for areas with low wind speed, it is necessary to combine additional cooling to maintain the optimal operating efficiency of the PV panels system.

In the future, we will undertake an experimental study on PV's operating temperature and conversion efficiency under real-world settings in many sites around Vietnam. Based on those results, we will propose cooling techniques for PV panels suitable for the specific conditions of each installation area to optimize energy efficiency.

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