

Article

Energy, Exergy Efficiency and Thermal-Electrical Production Assessment for an Active Water Heating System Using Four PV/T Module Models

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Abstract: In order to objectively reflect the energy utilization performance of an active water heating system (AWHS) using photovoltaic/thermal (PV/T) modules, this study proposes a new evaluation method based on energy efficiency, exergy efficiency and thermal-electrical output of a system in year-round weather conditions. Four samples of PV/T modules were surveyed to compare and evaluate the effectiveness of the system, called MD1, MD2, MD3 and MD4, respectively. The simulation program was developed to suit four types of PV/T modules and MATLAB was used as the programming language. The water flow through the four PV/T module samples and the hot water tank volume were investigated for the highest exergy efficiency of the system. The final results illustrate that in the weather conditions of Ho Chi Minh City, Vietnam, the system has the highest energy efficiency, exergy efficiency and thermal output when using MD1 with 57.85%, 15.67% and 2.93 kWh/m²/day, respectively, while the system has highest electrical output when using MD3 with 0.8 kWh/m²/day. In addition, under stable conditions ignoring heat loss, MD1 has the highest thermal efficiency with 54.85% and MD3 type has the highest electrical efficiency with 13.67%.

Keywords: numerical simulation; photovoltaic/thermal (PV/T) module; energy efficiency; exergy efficiency; heat-electricity output; active water heating system



Citation: Hoang, V.V.; Le, H.C.; Nguyen, B.T. Energy, Exergy Efficiency and Thermal-Electrical Production Assessment for an Active Water Heating System Using Four PV/T Module Models. *Energies* **2022**, *15*, 9634. <https://doi.org/10.3390/en15249634>

Academic Editors: Meng Lin, Ligang Wang and Ruikai Zhao

Received: 16 November 2022

Accepted: 14 December 2022

Published: 19 December 2022

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1. Introduction

Using renewable energy sources to help improve “Climate Change” and “Global Warming” is the driving force for sustainable development of the environment and human society. Solar energy, which is stable and almost ubiquitous, is being exploited by humans to generate electricity and heat, but devices that can exploit both electrical and thermal energy are not yet available and fully utilized. Photovoltaic/thermal (PV/T) technology is of great interest because it can simultaneously harness heat and electricity [1,2]. The integration of heat exchangers under existing solar panels not only takes advantage of the waste heat of PV cells to heat water, but also helps to improve the electricity generation efficiency of PV cells because the PV cells are cooling, further enhancing the overall energy efficiency of the system. PV/T technology has many features for wide application and there are many opportunities for industrialization for large-scale production [3]. Systems using PV/T collectors are also known as co-generation of heat and electricity because in addition to the ability to generate electricity, the excess heat removed from PV cells also has great potential for water heating and space warming [4,5]. Moreover, it can be applied in drying technology or providing hot water for water distillation basins at night, helping to increase the output of distilled water.

There are many studies, both theoretical and experimental, for systems using liquid PV/T modules, most of which use water as the working agent. Kern and Russell [6] proposed a PV/T collector to provide both heat and electricity at the same time, where the collector absorbs solar energy to generate electricity and then the energy converted into heat is taken away by water in the passive form. After that, many studies were conducted to analyze many aspects related to the water-based PV/T collector.

In recent years, the number of studies on water-based PV/T collectors for hot water supply purposes has increased dramatically. Huang et al. [7] and Tripanagnostopoulos et al. [8] conducted initial experiments to evaluate a PV/T water-based collector, followed by Zondag et al. [9] to evaluate heat and electricity output for a PV/T collector with glass, using a Coil Tube (CT) type heat exchanger. Kalogirou et al. [10] evaluated the heat and electricity output of a passive hot water supply system using a PV/T module with glass and a Parallel Tube (PT) type heat exchanger. Santbergen et al. [11] evaluated the efficiency of PV/T modules when using anti-reflective and/or low-emissivity coatings for glass and the PV layer. Dupeyrat et al. [12] compared the efficiency of a passive hot water supply system with PV/T modules with and without glass. Chow et al. [13] proposed using an aluminum-alloy flat-box for the heat exchanger of the PV/T module to improve the efficiency of the hot water supply system. Next, Chow et al. [14] analyzed the energy and exergy efficiency for the PV/T modules with and without glass. They found the exergy efficiency of the glazed collector was better than that of no glazing. Bhattarai et al. [15] compared and evaluated the efficiency of a passive water heating system when using the PV/T modules with glass and traditional flat panel solar collectors. Preet et al. [16] experimented to evaluate the efficiency of the PV/T modules with and without phase conversion materials. Kazem [17] conducted an experimental study to analyze and evaluate the thermal-electrical performance for a water-based PV/T module under conditions in Oman. Abdelrazik et al. [18] studied theoretically and experimentally to evaluate the optical and energy efficiency and the stability of water-based MXene nanofluids in PV/T modules. Fadil et al. [19] conducted experiments to analyze a TiO₂/water-based PV/T collector to improve the electrical efficiency of PV cells. Fudholi et al. [20] evaluated the thermal-electrical and exergy efficiency for a TiO₂/water-based PV/T collector. Podder et al. [21] numerically analyzed the water-based PV/T module to evaluate the thermal-electrical efficiency and the exergy efficiency. Alwaeli et al. [22] conducted simultaneous experiments for the PV module, the water-based PV/T module and the water-based PV/T module with phase conversion materials, thereby providing new evaluation criteria for solar energy production based on yield per area/space, yield per weight, yield bias and cost of yield. Hassan et al. [23] conducted experiments and numerical simulations to evaluate the influence of the parameters to improve the heat transfer efficiency characteristics for the water PV/T module.

In setting up thermal analysis models for the water PV/T module, Florschuetz [24] extended the calculation model for a flat plate solar collector of Hottel and Whillier for the first time to apply to the PV/T module. De Vries [25] established a computational model in stable condition of 1D in which there was an additional electrical power component to be suitable for the PV/T module. Next, Zondag [9,26] adapted this model to analyze the efficiency of several PV/T collector samples. Santbergen et al. [11] also used a model that Zondag [9,26] adjusted. Chow [27] wrote about the energy balance equations at the PV/T module components and used the explicit method to analyze the heat in the unstable state. In addition to Chow's studies [13,14], there are many later researchers that performed thermal analysis under unstable conditions for passive hot water supply systems using the PV/T module by writing energy equations for PV/T module components and the hot water tank, then use numerical methods to solve with the help of various mathematical software. Similarly, Bhattarai et al. [15] studied thermal analysis for a flat plate solar collector and a PV/T module simultaneously. Huide et al. [28] conducted a simultaneous thermal analysis for a PV module, flat plate solar collector and PV/T collector. Rejeb et al. [29] evaluated

monthly useful thermal-electrical energy and thermal-electrical efficiency for the PV/T modules.

The above-mentioned literature shows that previous studies have mostly focused on evaluating thermal efficiency, electrical efficiency, exergy efficiency, heat-electricity output, etc., for the PV/T modules. There are a few studies evaluating the heat and electricity output of passive water heating systems using the PV/T modules in which the power output is generated by the PV/T modules. However, for the active water heating system (AWHS), the effect of water flow through the PV/T module and the tank volume on system-wide energy efficiency has not been studied. Therefore, it is necessary to evaluate AWHS by the energy efficiency, exergy efficiency and heat-electricity output. On the other hand, the electrical output of the system used for evaluation should be the net electricity output, that is, minus the power consumed by the pump and the loss through the Inverter. Besides, climatic conditions (intensity of solar radiation, wind speed and ambient temperature) have an influence on the energy efficiency, exergy efficiency and heat-electricity output of AWHS. Therefore, it is necessary to evaluate AWHS objectively by the climatic conditions of the installation site and during the whole year or by typical days of each month of the year. To the best of the author's knowledge, there have been no studies conducted in the sub-equatorial tropical climate, which is hot and humid and has two distinct seasons of sunshine and rain, like the weather in the South of Vietnam. Therefore, this paper will focus on researching and developing a simulation program to evaluate and compare energy efficiency, exergy efficiency and provide heat-power output for AWHS using PV/T modules under climate conditions in Ho Chi Minh City. Ho Chi Minh City is the representative local of the southern climate of Vietnam. Four different PV/T module models called MD1, MD2, MD3 and MD4 are analyzed to compare and evaluate the effectiveness of AWHS, specifically:

- MD1: PV/T module type I (Figure 2a) with a CT type heat exchanger (Figure 3a);
- MD2: PV/T module type I (Figure 2a) with a PT type heat exchanger (Figure 3b);
- MD3: PV/T module type II (Figure 2b) with a CT type heat exchanger (Figure 3a);
- MD4: PV/T module type II (Figure 2b) with a PT heat exchanger (Figure 3b).

In fact, some places have existing power generation systems using PV modules, which have more needs to use hot water for many different purposes, such as living, cleaning, distill water at night, etc. We chose these four models of the PV/T modules because they are highly feasible for practical application, i.e., two heat exchangers of type PT and CT are easily fabricated at low cost, suitable for most localities. Further, MD3 and MD4 can be applied to existing solar power systems and need to integrate more heat exchangers to heat water, while MD1 and MD2 are easily manufactured by manufacturers into PV/T modules in the factory.

2. System Description

The water heating system using the PV/T module is shown in Figure 1. The PV/T module receives solar radiation and converts it into electricity and heat. Part of the power of the DC current is converted by the Inverter into the AC current to mainly supply the pump motor, with the remainder to be brought to the grid. The heat energy is absorbed by the tube and sheet heat exchanger, as shown in Figure 2, to transfer the pure water flowing inside the tube provided by the pump. Purified water after receiving heat with temperature $T_{pw,o}$ is brought to the helical coil heat exchanger to release heat to the water in the tank, then reduced to the temperature $T_{pw,i}$ and pumped continuously to the PV/T module for heating. The use of purified water running inside the tube and sheet heat exchanger of the PV/T module helps to avoid the problem of scaling and stabilize the heat exchanger efficiency. The PV/T module analyzed in the paper is depicted in Figure 2 with 2 types:

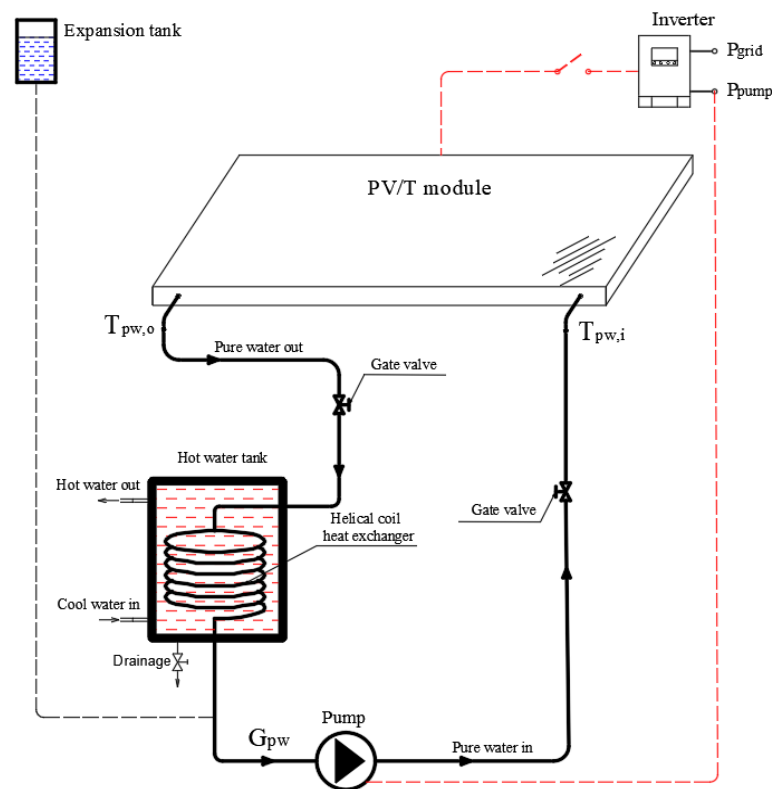


Figure 1. Water heating system using PV/T module.

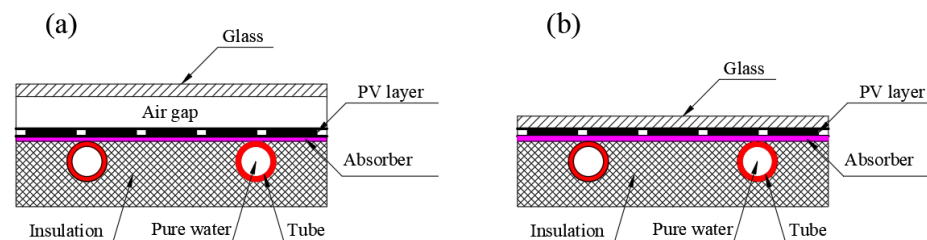


Figure 2. Cross section of PV/T module type I (a) and type II (b).

Type I: PV/T module with air layer between glass and PV layer (Figure 2a);

Type II: PV/T module without air layer between glass and PV layer (Figure 2b).

The heat exchanger is pressed close to the PV layer consisting of an absorber and tubes, also called a tube and sheet heat exchanger with tubes arranged in two ways:

- Coil Tube (CT): The tube is bent like a snake (Figure 3a).
- Parallel Tube (PT): Pipes are arranged in parallel and have a header pipe on both sides (Figure 3b).

CT or PT tube layouts are commonly used because of their ease of fabrication, low cost and suitability for most local conditions. The tube arranged in CT style has the advantage of avoiding leakage but increases the resistance of the pump, while the pipe arranged in the PT style reduces the pump resistance but has many welds, so the possibility of leakage is higher.

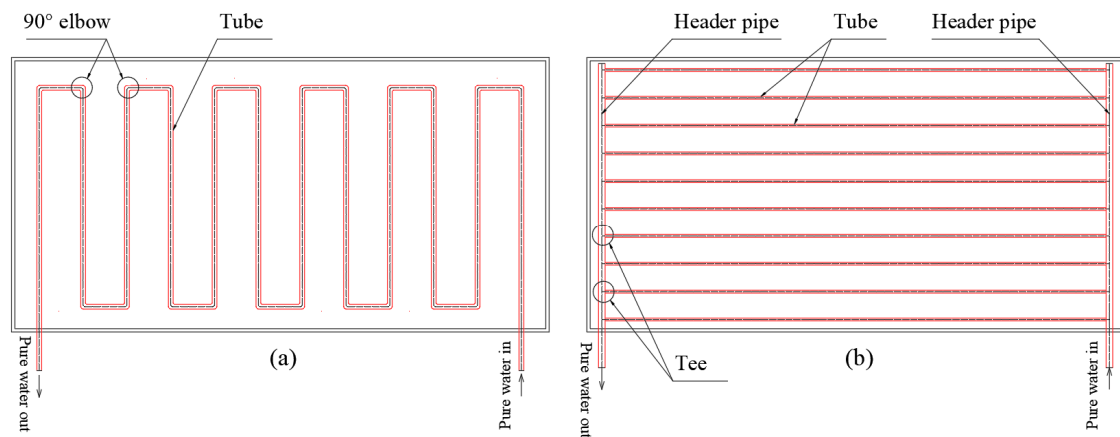


Figure 3. Layout diagram of pipe type CT (a) and type PT (b).

The PV layer is depicted in Figure 4 with components: two layers of EVA glue, PV cells chain and protective layer.

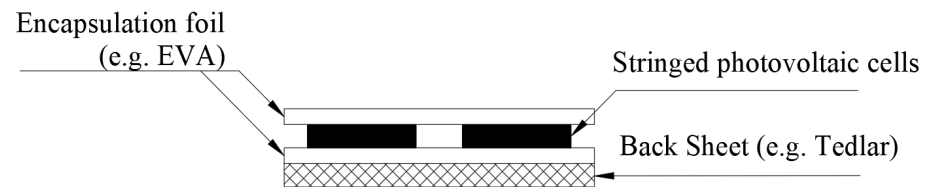


Figure 4. Structure of PV layer.

3. Numerical Modeling

The simulation program is set up by the energy balance equations at the components of the PV/T module and the hot water tank. All equations are written based on the following assumptions:

- Ignore the heat transfer between the environment and the four sides of the PV/T module;
- Neglect the heat loss and the pressure loss on pipes outside the PV/T module and hot water tank;
- Physical parameters at the glass cover, PV layer, absorber, tube and insulation layer of the PV/T module are unchanged;
- Thermophysical parameters of pure water at the PV/T module and hot water in the tank change with temperature;
- Constant flow of pure water according to the length of the tube;
- The temperature of the glass cover, PV layer, absorber, tube, purified water and insulation layer in the PV/T module changes with time;
- The temperature of hot water in the tank is uniform;
- Area of glass cover, PV layer, absorber and insulation layer are equal and are equal to the PV/T module area ($A_g = A_{pvl} = A_{ab} = A_{ins} = A_{PV/T}$).

The energy balance equations at the components of the PV/T module, hot water in the tank are written as follows.

3.1. PV/T Module

Figure 5 illustrates the heat flows between the components of PV/T modules type I and type II. Based on these heat flows, the energy balance equations at the components are established.

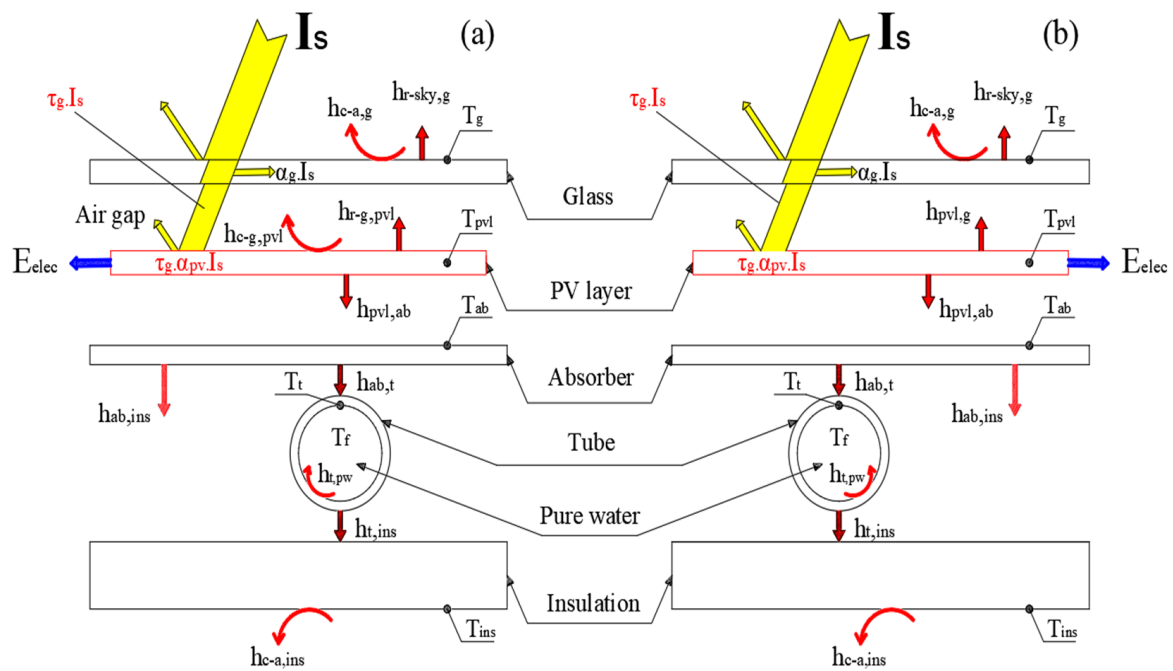


Figure 5. Heat flow between components in type I (a) and type II (b) PV/T modules.

3.1.1. Glass of PV/T Module Type I

The energy balance equation at the glass of PV/T module type I is written as follows:

$$\delta_g \rho_g c_{p,g} \frac{dT_g}{dt} = h_{c-a,g}(T_a - T_g) + h_{r-sky,g}(T_{sky} - T_g) + (h_{r-g,pvl} + h_{c-g,pvl})(T_{pvl} - T_g) + \alpha_g I_s \quad (1)$$

where:

- I_s , T_a , v_a is the average value over time Δt of the solar radiation intensity, ambient temperature and wind speed, respectively;
- Heat transfer coefficient by convection and radiation between medium and glass [27]:

$$h_{c-a,g} = h_{c-a,ins} = 2.8 + 3.v_a \quad (\text{W/m}^2.\text{K}) \quad (2)$$

$$h_{r-sky,g} = \varepsilon_g \sigma \left[(T_{sky})^2 + (T_g)^2 \right] (T_{sky} + T_g) \quad (\text{W/m}^2.\text{K}) \quad (3)$$

- Sky temperature as [30]:

$$T_{sky} = 0.0522(T_a)^{1.5} [\text{K}] \quad (4)$$

- Radiant heat transfer coefficient between glass and PV layer [31]:

$$h_{r-g,pvl} = \frac{\sigma \left[(T_g)^2 + (T_{pvl})^2 \right] (T_g + T_{pvl})}{\frac{1}{\varepsilon_{pvl}} + \frac{1}{\varepsilon_g} - 1} \quad (\text{W/m}^2.\text{K}) \quad (5)$$

- Heat transfer coefficient by convection between glass and PV layer [32]:

$$h_{c-g,pvl} = \frac{Nu_{air} k_{air}}{\delta_{air}} \quad (\text{W/m}^2.\text{K}) \quad (6)$$

Nusselt and Rayleigh number [32]:

$$Nu_{air} = 1 + 1.44 \cdot 0.5 \cdot \left(\left[1 - \frac{1708}{Ra \cdot \cos \theta} \right] + \left| 1 - \frac{1708}{Ra \cdot \cos \theta} \right| \right) \cdot \left[1 - \frac{1708 \cdot (1.8 \cdot \sin \theta)^{1.66}}{Ra \cdot \cos \theta} \right] + 0.5 \cdot \left(\left[\left(\frac{Ra \cdot \cos \theta}{5830} \right)^{1/3} - 1 \right] + \left| \left(\frac{Ra \cdot \cos \theta}{5830} \right)^{1/3} - 1 \right| \right) \quad (7)$$

$$Ra = \frac{g \cdot \beta_{air} \cdot (T_{pvl} - T_g) \cdot \delta_{air}^3}{\nu_{air} \cdot a_{air}} \quad (8)$$

where δ_{air} is the distance between glass and PV layer (m).

The physical parameters of the air are calculated according to the literature [33] with the air layer temperature:

$$T_{air} = \frac{T_{pvl} + T_g}{2} \quad [K] \quad (9)$$

3.1.2. Glass of PV/T Module Type II

The energy balance equation at the glass of PV/T module type II is written as follows:

$$\delta_g \rho_g c_{p,g} \frac{dT_g}{dt} = h_{c-a,g}(T_a - T_g) + h_{r-sky,g}(T_{sky} - T_g) + h_{g,pv}(T_{pv} - T_g) + \alpha_g I_s \quad (10)$$

3.1.3. PV Layer of PV/T Module Type I

The energy balance equation at the PV layer of PV/T module type I is written as follows:

$$\delta_{pvl} \cdot \rho_{pvl} \cdot c_{p,pvl} \frac{dT_{pvl}}{dt} = (\tau_g \cdot \alpha_{pvl}) I_s + h_{pvl,ab}(T_{ab} - T_{pvl}) - f \cdot E_{elec} + (h_{r-g,pvl} + h_{c-g,pvl})(T_g - T_{pvl}) \quad (11)$$

With:

- Specific electricity capacity of PV layer [27]:

$$E_{elec} = I_s \cdot \eta_r \cdot \left[1 - Br(T_{pvl} - T_r) \right] \quad (W/m^2) \quad (12)$$

- Packing factor:

$$f = \frac{A_{pvc}}{A_{PV/T}} \quad (13)$$

3.1.4. PV Layer of PV/T Module Type II

The energy balance equation at the PV layer of PV/T module type II is written as follows:

$$\delta_{pvl} \cdot \rho_{pvl} \cdot c_{p,pvl} \frac{dT_{pvl}}{dt} = (\tau_g \cdot \alpha_{pvl}) I_s + h_{pvl,ab}(T_{ab} - T_{pvl}) - f \cdot E_{elec} + h_{g,pvl}(T_g - T_{pvl}) \quad (14)$$

3.1.5. Absorber

The energy balance equation at the absorber of PV/T module type I and type II is written as follows:

$$\delta_{ab} \rho_{ab} c_{p,ab} \frac{dT_{ab}}{dt} = h_{pvl,ab}(T_{pvl} - T_{ab}) + \frac{A_{t,ab}}{A_{ab}} h_{ab,t}(T_t - T_{ab}) + \left(1 - \frac{A_{t,ab}}{A_{ab}} \right) h_{ins,ab}(T_{ins} - T_{ab}) \quad (15)$$

3.1.6. Tube

The energy balance equation at the tube of PV/T module type I and type II is written as follows:

$$L_t A_t \rho_t c_{p,t} \frac{dT_t}{dt} = A_{t,ab} h_{ab,t} (T_{ab} - T_t) + Pe_i \cdot L_t \cdot h_{pw,t} (T_{pw} - T_t) + A_{t,ins} h_{t,ins} (T_{ins} - T_t) \quad (16)$$

In which:

$$A_{t,ab} = \delta_{ab} \cdot L_t \left(m^2 \right); A_t = \frac{\pi}{4} (D_{t,o}^2 - D_{t,i}^2); A_{t,ins} = L_t \cdot Pe_o - A_{t,ab}; L_t = N_t \cdot L_{1t} \quad (17)$$

With N_t and L_{1t} are the number of pipes and the length of one pipe in the PV/T module, respectively.

- Heat transfer coefficient by convection of pure water and tube [34]:

$$h_{pw,t} = \frac{Nu_{pw} \cdot k_{pw}}{D_{t,i}} \quad \left(\frac{W}{m^2 \cdot K} \right) \quad (18)$$

- The velocity of water in a tube of the heat exchanger is determined by the formula:

$$\omega_{pw1} = \frac{4G_{pw}}{N_t \cdot \rho_{pw} \cdot \pi \cdot D_{t,i}} \quad (m/s) \quad (19)$$

- Nusselt number [34]:

$$+ \text{With : } Re_{pw} < 2300 \Rightarrow Nu_{pw} = 4.364 \quad (20)$$

$$+ \text{With : } Re_{pw} > 2300 \Rightarrow Nu_{pw} = 0.023 \cdot (Re_{pw})^{0.8} \cdot (Pr_{pw})^{0.4} \quad (21)$$

The thermophysical parameters of water are calculated according to the literature [35].

3.1.7. Pure Water

The energy balance equation of the pure water inside the tube of PV/T module type I and type II is written as follows:

$$L_t A_{pw} \rho_{pw} c_{p,pw} \frac{dT_{pw}}{dt} = Pe_i \cdot L_t \cdot h_{pw,t} (T_t - T_{pw}) - 2G_{pw} \cdot c_{p,pw} (T_{pw} - T_{pw,i}) \quad (22)$$

$$\text{With : } T_{pw} = \frac{T_{pw,o} + T_{pw,i}}{2} \Rightarrow T_{pw,o} = 2T_{pw} - T_{pw,i} \quad (23)$$

3.1.8. Insulation

The energy balance equation at the insulation of PV/T module type I and type II is written as follows:

$$\delta_{ins} \rho_{ins} c_{p,ins} \frac{dT_{ins}}{dt} = \left(1 - \frac{A_{t,ab}}{A_{ab}} \right) h_{ins,ab} (T_{ab} - T_{ins}) + \frac{A_{t,ins}}{A_{ins}} h_{t,ins} (T_t - T_{ins}) + h_{c-a,ins} (T_a - T_{ins}) \quad (24)$$

3.2. Hot Water in Tank

The energy balance equation at the hot water in the tank is written as follows:

$$Q_{hw} = V_{hw} \rho_{hw} c_{p,hw} \frac{dT_{hw}}{d\tau} = Q_{c1} - h_{hw1,a} (T_{hw} - T_a) - 2A_n h_{hw2,a} (T_{hw} - T_a) \quad (W) \quad (25)$$

where Q_{hw} is the heat received by the hot water (W).

- The heat of pure water released at the coil is calculated by one of the following two formulas:

$$Q_{c1} = G_{pw} c_{p,pw} (T_{pw,o} - T_{pw,i}) \quad (W) \quad \text{or} \quad Q_{c2} = F_{coil} \cdot h_{hw,t} \cdot (T_{pw} - T_s) \quad (W) \quad (26)$$

In which:

- T_{pw} and T_s are the average temperature of pure water in the coil and the wall temperature, respectively.

$$\text{Given : } T_s = \frac{T_{pw} + T_{hw}}{2} \quad [K] \quad (27)$$

- Heat exchange area between pure water inside coil and hot water in tank:

$$F_{coil} = \pi \cdot D_{c,i} \cdot L_c \quad (m^2) \quad (28)$$

- Velocity of pure water in coil:

$$\omega_{pw2} = \frac{4G_{pw}}{\rho_{pw} \cdot \pi \cdot D_{c,i}} \quad (m/s) \quad (29)$$

- The Reynolds, Nusselt values and the convection heat transfer coefficients of the pure water in the coils are like those of the water in the heat exchange tubes of the PV/T module.
- Coefficient of total heat transfer from hot water through the wall of the tank to the surrounding environment [36]:

$$h_{hw1,a} = \frac{1}{\frac{1}{2\pi H_{ins} k_{ins}} \ln\left(\frac{D_{ins,o}}{D_{ins,i}}\right) + \frac{1}{\pi D_{ins,o} H_{hw} h_{c-a,ins}}} \quad (W/K) \quad (30)$$

- Coefficient of total heat transfer from hot water through the lid and bottom of the tank to the surrounding environment [36]:

$$h_{hw2,a} = \frac{1}{\frac{\delta_{ins,hw}}{k_{ins}} + \frac{1}{h_{c-a,ins}}} \quad (W/m^2.K) \quad (31)$$

$$\text{With : } D_{ins,o} = D_{ins,i} + 2\delta_{ins,hw}; H_{hw} = V_{hw}/A_n; A_n = \pi \cdot D_{hw}^2/4 \quad (32)$$

where $D_{ins,i}$, $D_{ins,o}$ are the inner and outer diameters of the hot water tank insulation (m); D_{hw} is the diameter of the hot water in the tank (m) (for $D_{hw} = D_{ins,i}$); $H_{ins} = H_{hw}$ is the height of the insulation layer (m); A_n is the area of the bottom of the tank or the lid of the tank (m^2).

3.3. Water Pump

3.3.1. Pressure Loss (ΔH)

The pressure loss through the water pump now includes two gate valves, the heat exchanger of the PV/T module and the coil inside the hot water tank. It is calculated according to [37]:

$$\Delta H = \Delta H_{fl} + \Delta H_{ll} + \Delta H_{buoy} \quad (N/m^2) \quad (33)$$

In which:

- Assume that PV/T module is placed equal to the hot water tank, so the pressure loss due to the buoyancy is ignored ($\Delta H_{buoy} = 0$).
- ΔH_{fl} is the friction loss according to Darcy-Weisbach [37]:

$$\Delta H_{fl} = f \left(\frac{L_t}{N_t \cdot D_{t,i}} \right) \left(\frac{\rho_{pw} \omega_{pw}^2}{2} \right) \quad (\text{N/m}^2) \quad (34)$$

where:

- ω_{pw} is the velocity of water in tubes (m/s);
- + With the CT or PT type heat exchanger: $\omega_{pw} = \omega_{pw1}$;
- + With the helical coil heat exchanger: $\omega_{pw} = \omega_{pw2}$.
- The friction factor f [38]:

With the laminar flow:

$$f = \frac{64}{\text{Re}_{pw}} \quad (35)$$

With the turbulent flow, according to Lewis F. Moody (1947) [37].

$$f = 5.5 \cdot 10^{-3} \left[1 + \left(20000 \cdot \frac{\varepsilon_t}{D_{t,i}} + \frac{10^6}{\text{Re}_{pw}} \right)^{1/3} \right] \quad (36)$$

- ΔH_{ll} is the local loss [38]:

$$\Delta H_{ll} = \frac{1}{2} K_{ll} \cdot \rho_{pw} \cdot \omega_{pw}^2 \left(\frac{N}{m^2} \right) \quad (37)$$

With the local loss coefficient K_{ll} of Gate valve, Tee, 90° Elbow calculated as in [37].

3.3.2. The Real Power of Pump

The actual capacity of the pump is calculated according to the following formula [37]:

$$P_{pump} = \frac{G_{pw} \cdot \Delta H}{\eta_{pump} \cdot \rho_{pw}} \quad (\text{W}) \quad \text{with } \eta_{pump} = 0.8 \text{ is the electricity efficiency of pump} \quad (38)$$

3.4. The Investigation Values

The investigated energy values for analysis and evaluation include:

- Power generated by the PV/T module:

$$P_{elec0} = f \cdot A_{PV/T} \cdot E_{elec} \quad (\text{W}) \quad (39)$$

- Power after converted in the inverter [38]:

$$P_{elec1} = \eta_{inv} \cdot P_{elec0} \quad (\text{W}) \quad (40)$$

With $\eta_{inv} = 0.95$ is the efficiency of inverter.

- Power to the grid:

$$P_{grid} = P_{elec1} - P_{pump} \quad (\text{W}) \quad (41)$$

- Energy efficiency of the system:

$$\eta_{energy} = \frac{P_{grid} + Q_{hw}}{I_s \cdot A_{PV/T}} \quad (42)$$

- Exergy efficiency of the system is calculated according to Petela Model [39]:

$$\eta_{\text{exergy}} = \frac{P_{\text{grid}} + Q_{\text{hw}} \left(1 - \frac{T_a}{T_{\text{hw}}}\right)}{I_s \cdot A_{\text{PV/T}} \left[1 - \frac{4}{3} \left(\frac{T_a}{T_{\text{sun}}}\right) + \frac{1}{3} \left(\frac{T_a}{T_{\text{sun}}}\right)^4\right]} \quad (43)$$

With the sun temperature $T_{\text{sun}} = 5770$ [K].

- Heat output of the system during the day:

$$Q_{\text{th}} = \left(\frac{\Delta t \cdot 10^{-3}}{3600 \cdot A_{\text{PV/T}}}\right) \sum_1^{\text{Sumtime}/\Delta t} Q_{\text{hw}} \quad \left(\frac{\text{kWh}}{\text{m}^2}\right) \quad (44)$$

- Electricity output of the system during the day:

$$P_e = \left(\frac{\Delta t \cdot 10^{-3}}{3600 \cdot A_{\text{PV/T}}}\right) \sum_1^{\text{Sumtime}/\Delta t} P_{\text{grid}} \quad \left(\frac{\text{kWh}}{\text{m}^2}\right) \quad (45)$$

With Sumtime as the total investigated time (s).

4. Solution Method

The numerical method in the heat transfer was used to solve the unstable heat transfer differential equations in the components of the water heating system using the PV/T module. In particular, the unstable heat transfer differential equations will be discrete in time with the implicit finite difference method. Then, the equations are grouped into systems of equations and solved by the inverse matrix method to find out the temperature over time of the glass (T_g), PV layer (T_{pvl}), absorber (T_{ab}), tube (T_t), purified water (T_{pw}), insulation layer (T_{ins}) and hot water temperature (T_{hw}).

The software MATLAB 2018b was chosen to perform the simulation for the whole system, with all steps shown in the Figure 6 diagram.

Step 1: Start the program.

Step 2: Set design and operation parameters as Table 1.

Step 3: Load weather data including solar radiation, ambient temperature and wind speed. The simulation program allows loading values of solar radiation, ambient temperature and wind speed in different time steps $\Delta t = (1 \div 3600)$ s.

Step 4: Assume the temperature parameters of the components at the initial time ($n = 0$).

Step 5: Put the water temperature in the PV/T module equal to the hot water temperature in the tank.

Step 6: Calculate the energy equations at the components to find the temperature at time $n + 1$. Calculation results will be saved into vector (V) and compared between computations using the number of iterations (k).

- + If $|V^k - V^{k-1}| > 10^{-6}$ continue the iteration at $k + 1$
- + If $|V^k - V^{k-1}| \leq 10^{-6}$ results converged

Step 7: Results in Step 6 are used to calculate the values of Q_{c1} and Q_{c2} .

- + If $\left|\frac{Q_{c1} - Q_{c2}}{Q_{c1}}\right| > 10^{-2}$ repeat Step 5 with $T_{\text{pw},i} = T_{\text{pw},i} - 0.01$
- + If $\left|\frac{Q_{c1} - Q_{c2}}{Q_{c1}}\right| \leq 10^{-2}$ results converged

Step 8: Output the values of temperatures $T_g^{n+1}, T_{\text{pvl}}^{n+1}, T_{\text{ab}}^{n+1}, T_t^{n+1}, T_{\text{pw}}^{n+1}, T_{\text{ins}}^{n+1}, T_{\text{hw}}^{n+1}$ at time $n + 1$.

Step 9: Take the values found in step 8 and go back to step 1 to find the values at the next time ($t + \Delta t$), and so on until the end.

In this $n \in \left[0, 1, 2, \dots, \left(\frac{\text{Sumtime}}{\Delta t} - 1\right)\right]$

Step 11: Output all results.

Step 12: Stop the program.

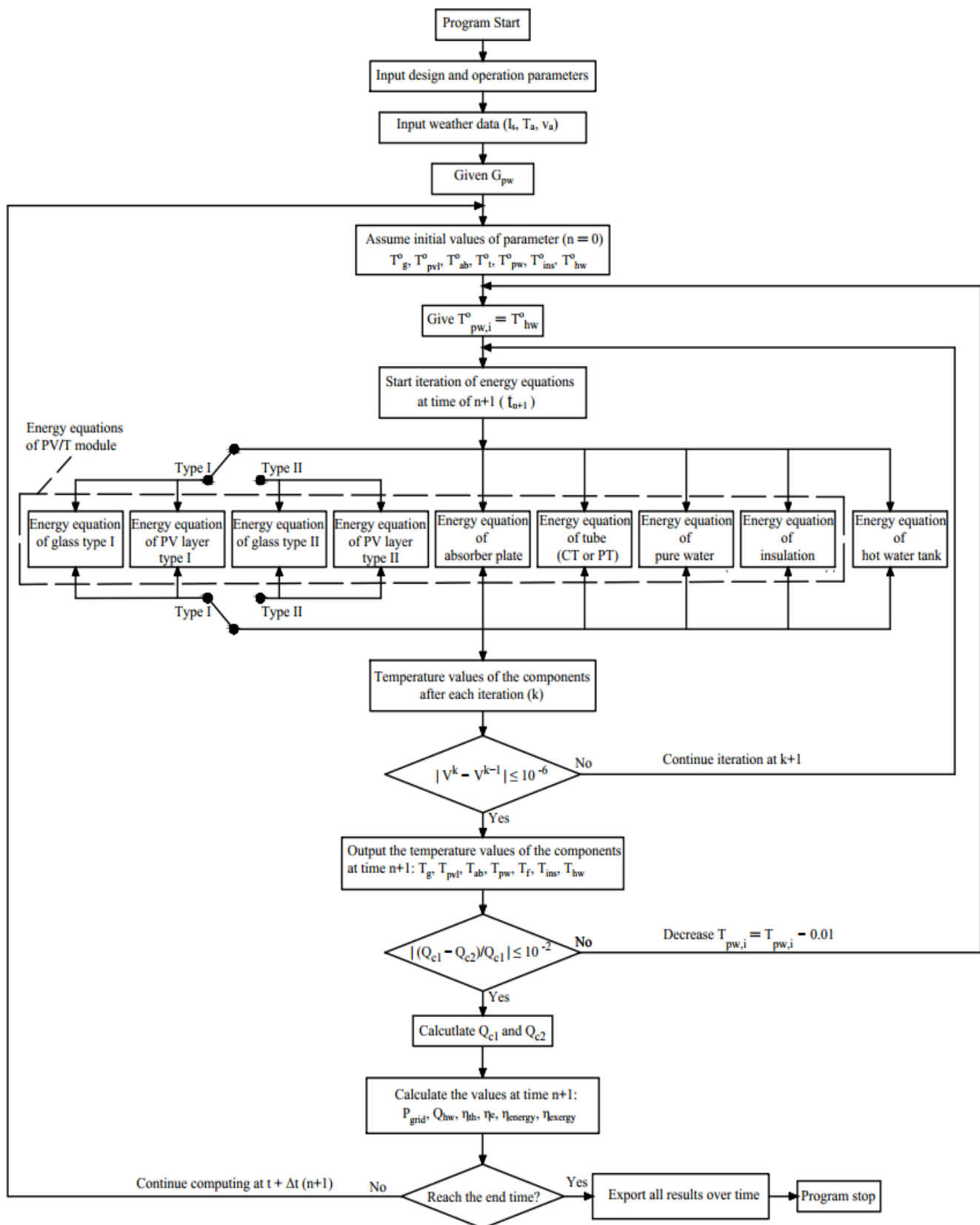


Figure 6. Simulation diagram for AWHs using PV/T module.

Table 1. Parameters used in the simulation program [15,40].

Components	Parameters	Value	Unit	Components	Parameters	Value	Unit
PV/T collector	$A_{PV/T}$	2	m^2	Tube	$D_{t,o}$	0.00952	m
	θ	30°			$D_{t,i}$	0.00792	m
Glass	δ_{air}	0.03	m		ρ_t	8933	$Kg\ m^{-3}$
	δ_g	0.004	m		$c_{p,t}$	896	$J\ kg^{-1}\ K^{-1}$
	ρ_g	2200	$Kg\ m^{-3}$		k_t	396	$W\ m^{-1}\ K^{-1}$
	$c_{p,g}$	670	$J\ kg^{-1}\ K^{-1}$	+ Coil tube	L_{1t}	12	m
PV layer	k_g	0.9	$W\ m^{-1}\ K^{-1}$	(CT)	N_t	1	tube
	ε_g	0.88		+ Parallel tube	L_{1t}	1.916	m
	α_g	0.05		(PE)	N_t	10	tube
	τ_g	0.85		Insulation	δ_{ins}	0.03	m
	f	0.804			ρ_{ins}	20	$Kg\ m^{-3}$
	δ_{pvl}	0.0011	m		$c_{p,ins}$	670	$J\ kg^{-1}\ K^{-1}$
	ρ_{pvl}	2320	$Kg\ m^{-3}$		k_{ins}	0.034	$W\ m^{-1}\ K^{-1}$
	$c_{p,pvl}$	900	$J\ kg^{-1}\ K^{-1}$	Hot water tank	L_c	15	m
	k_{pvl}	140	$W\ m^{-1}\ K^{-1}$			$D_{ins,i}$	0.5
	Absorber	α_{pvl}	0.95			$\delta_{ins,hw}$	0.04
η_r		17.8	%		V_{hw}	0.1	m^3
B_r		0.00405	1/K				
I_r		1000	W/m^2				
T_r		298.15	K				
δ_{ab}		0.0002	m				
ρ_{ab}		2702	$Kg\ m^{-3}$				
$c_{p,ab}$		896	$J\ kg^{-1}\ K^{-1}$				
k_{ab}		310	$W\ m^{-1}\ K^{-1}$				

5. Results and Discussion

5.1. Verify the Simulation Results

The mean root square percentage deviation (RM-Squared) of Sobhnamayan et al. [41] was used to evaluate the accuracy of simulation results for the PV/T module type MD2 compared with experimental results of Bhattarai et al. [15] and simulation results of Bellos et al. [40]. With the same input parameters as shown in Table 1, the simulation program gives the results of thermal and electrical efficiency as shown in Figure 7.

$$RM - Squared = \sqrt{\frac{\sum_{k=1}^{k=m} [100(Y_{LR,k} - Y_{SR,k})/Y_{LR,k}]^2}{m}} \quad (46)$$

where $Y_{LR,k}$ is the experimental value of Bhattarai or the simulated value of Bellos at the k_{th} sampling; $Y_{SR,k}$ is the simulated value for PV/T module type MD2 of this study at the k_{th} sampling time; and m is the total number of samples to compare.

Table 2 presents the RM-Squared value when evaluating the error between the author's simulation results and the experimental results of Bhattarai and the simulation results of Bellos. The results show that the simulation program has high reliability with the average error of thermal efficiency, the electrical efficiency compared to Bhattarai is 2.38% and 0.89%, respectively, while comparing with Bellos, is 3.9% and 1.14%, respectively.

With the obtained results, four PV/T module samples will be analyzed to compare and evaluate the effectiveness for AWHs based on the energy efficiency, exergy efficiency and heat-electricity output.

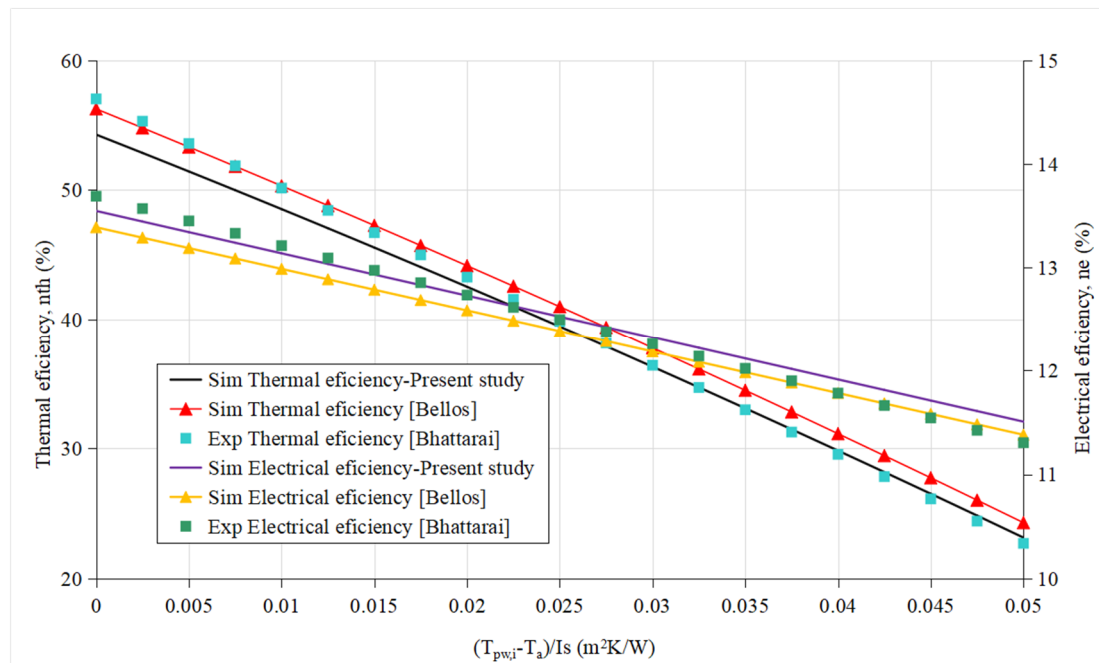


Figure 7. Comparison of the thermal-electrical efficiency of the research results with Bhattarai and Bellos.

Table 2. Evaluation of RM-Squared.

	RM-Squared	
	Bhattarai [15]	Bellos [40]
Thermal efficiency	2.38%	3.9%
Electrical efficiency	0.89%	1.14%

5.2. Evaluating the Energy Efficiency, Exergy Efficiency and Heat-Electricity Output of the System

To evaluate the energy efficiency, exergy efficiency and heat and electricity output of AWHs, the authors analyzed the water flow levels entering the four PV/T module samples and the tank volume levels under weather conditions in Ho Chi Minh City, Vietnam, which has typical climatic conditions for the southern region of Vietnam and a sub-equatorial tropical climate. Specifically, we conducted the analysis of 14 flow levels from 0.01 kg/s to 0.14 kg/s for four PV/T module models and tank volumes from 50 L to 250 L. Solar radiation and ambient temperature data of 12 typical days for 12 months of the year in Ho Chi Minh City, Vietnam are shown in Figure 8. Further, the hourly value of solar radiation intensity obtained from the solar data generation program of Bao Nguyen et al. [42], hourly environmental temperature data are collected from the report of the Vietnam Meteorological Department as shown in Figure 9, assuming wind speed is fixed at 1.3 m/s. To increase accuracy, from hourly data, the simulation program will automatically subdivide the solar radiation and ambient temperature values to calculate for the time period $\Delta t = 60$ s.

Figure 8 indicates that the characteristic of solar energy in HCMC is high radiation intensity most of the time, especially in the months of the dry season, from December to April; however, there are times of the day when the radiation intensity is suddenly reduced due to the influence of clouds. During the rainy season months, from May to November, the radiation intensity fluctuates strongly. Figure 9 shows that the ambient temperature in HCMC is generally quite stable during the day, the hottest in May is from 32 °C to 37 °C and the lowest in October is from 25 °C to 28 °C.

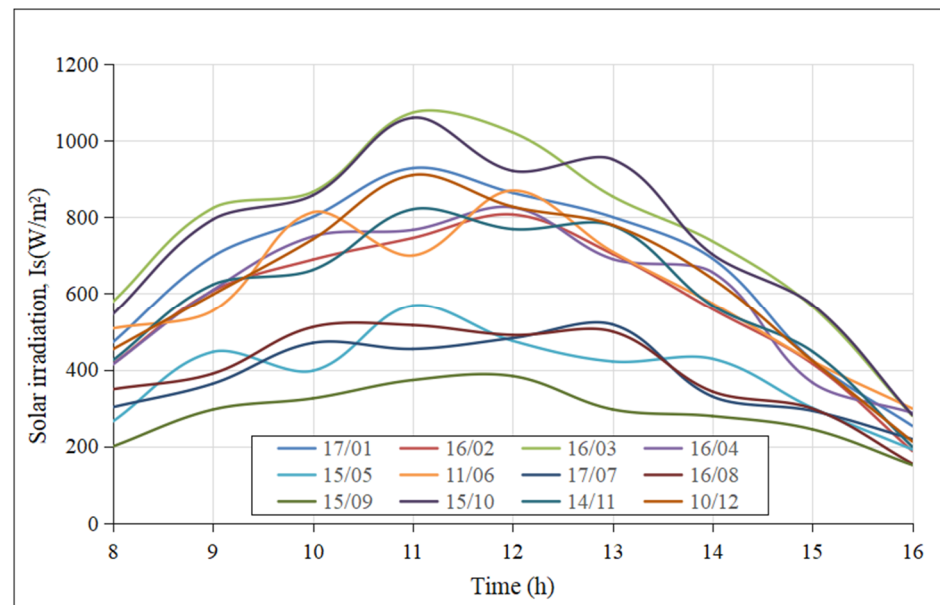


Figure 8. Solar radiation intensity of typical days of the year.

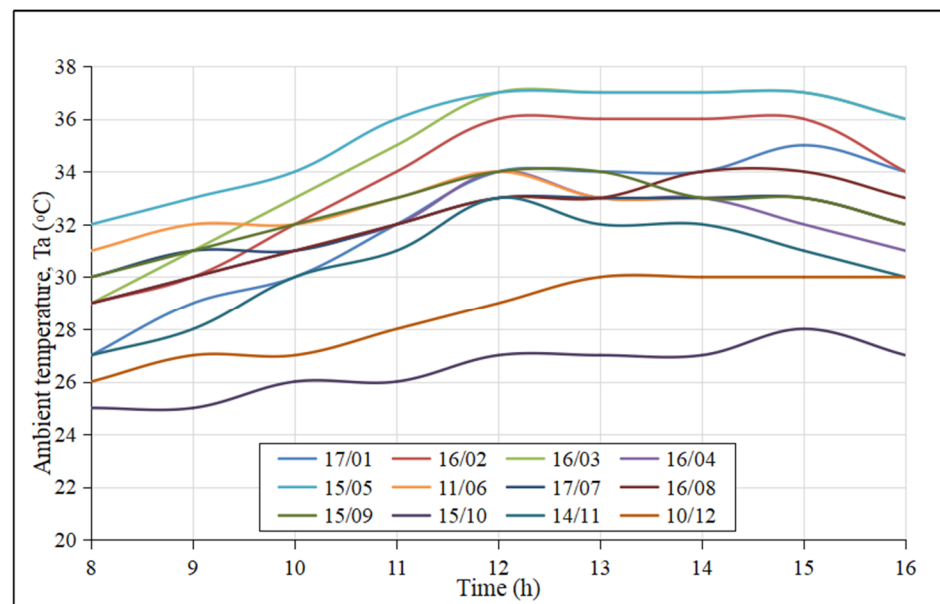


Figure 9. Ambient temperature of typical days of the year.

To evaluate the effect of water flow into the four PV/T module models on the average energy efficiency and average exergy efficiency of AWHs, we fixed the tank volume at 100 L. Figures 10 and 11 show the change in average energy efficiency and average exergy efficiency of AWHs, respectively, when the water flow into the PV/T modules varies from 0.01 kg/s to 0.14 kg/s. Figure 10 illustrates that the average energy efficiency of AWHs gradually increases with increasing flow rate and reaches its maximum value when AWHs is in use:

- + MD1: In March and October, with a flow rate of 0.04 kg/s, in the remaining months, it is 0.03 kg/s.
- + MD2: In January and June, with a flow rate of 0.08 kg/s, in the months of May, July, August and September, it is 0.03 kg/s and in the remaining months, it is 0.09 kg/s.
- + MD3: In July and September, with a flow rate of 0.02 kg/s, in the remaining months, it is 0.03 kg/s.

+ MD4: In March, with a flow rate of 0.09 kg/s, in July and September, it is 0.02 kg/s and in the remaining months, it is 0.03 kg/s.

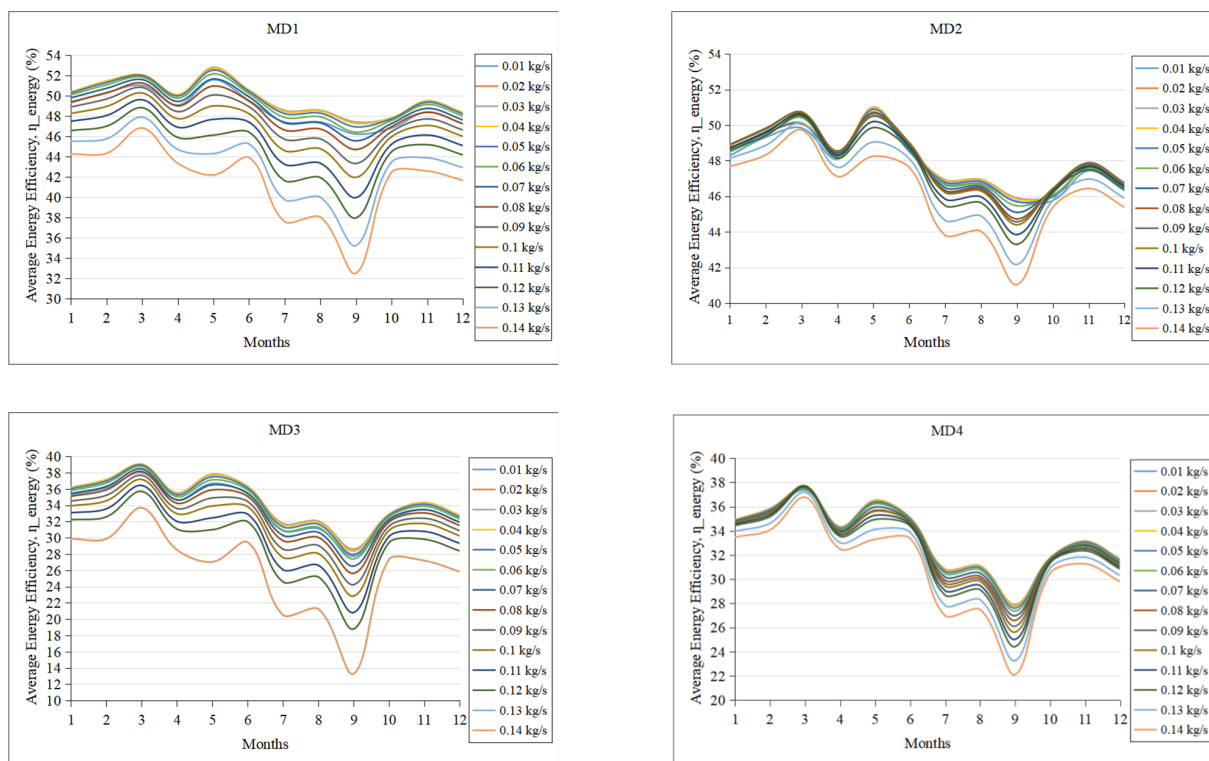


Figure 10. The average energy efficiency of AWHs under flow change.

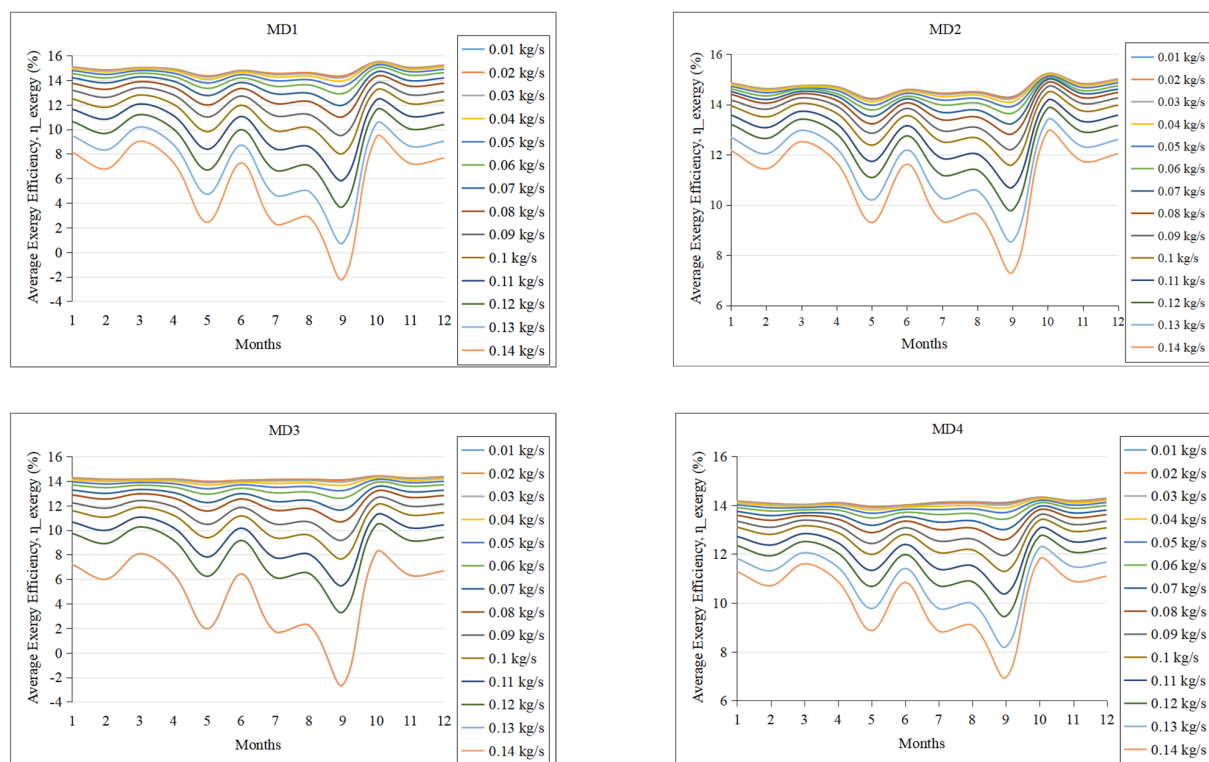


Figure 11. The average exergy efficiency of AWHs under flow change.

After reaching maximum energy efficiency, AWHs has a decreasing energy efficiency with increasing water flow. This phenomenon occurs in all four models of the PV/T module. Further, it can be explained that, as the water flow increases, the pump power consumption (P_{pump}) increases significantly because the pump runs at a fixed flow rate from 8 a.m. to 16 p.m. This greatly reduces P_{grid} while Q_{hw} has peaked (no change with increasing water flow). As a result, energy efficiency is reduced accordingly.

Figure 10 also illustrates that the system has a high energy efficiency when using MD1 and MD2 compared to the other two models because MD1 and MD2 have an air layer between the glass and PV layer. The air layer creates a greenhouse effect, so it absorbs more heat when the water temperature in the PV/T module is low (first stage). At the same time, the air layer acts as an insulation layer to reduce heat loss when the water temperature in the PV/T module is high (later stage).

Figure 10 also shows that, with increasing water flow, the difference in energy efficiency in MD1 and MD3 is more pronounced than in the other two samples. The reason is that MD1 and MD3 use the Coil Tube (CT) heat exchanger while MD2 and MD4 use the Parallel Tube (PT). As the water flow increases, the pressure loss in the CT tube is much larger than that in the PT tube. So, P_{pump} increases dramatically and causes P_{grid} to drop rapidly. As a result, energy efficiency is reduced.

Figure 11 indicates that AWHs has the highest average exergy efficiency in all months in the four PV/T modules when the flow rate reaches 0.02 kg/s. After reaching maximum exergy efficiency, the exergy efficiency of AWHs decreases as the water flow increases. Further, the exergy efficiency at flow rate 0.14 kg/s is significantly lower than other flow rates. Similar to the explanation above, because at the flow rate of 0.14 kg/s, the pump's power consumption is quite large because the pump runs at a fixed flow rate during the survey period., especially with MD1 and MD3 with a long pipeline, large pressure loss, which greatly reduces P_{grid} .

The exergy efficiency is affected by the power to the grid (P_{grid}), solar radiation intensity (I_s), heat of hot water (Q_{hw}) and hot water temperature (T_{hw}). There are cases where exergy efficiency is lower than zero when the system uses MD1 and MD3 at a flow rate of 0.14 kg/s. The reason is that in the months with low radiation intensity (September), Q_{hw} and T_{hw} are low while P_{grid} is less than 0 during most of the survey time, especially in the morning and afternoon (because P_{pump} is large while P_{elec1} is small). As a result, the average exergy efficiency for the day is less than 0.

From the point of view of energy utilization efficiency, we selected a flow rate of 0.02 kg/s as the optimal value to further investigate the energy efficiency and exergy efficiency of AWHs when using the four PV/T modules with tank volume varying from 50 L to 250 L. The results are depicted in the Figure 12 chart.

Figure 12 illustrates that, in all months when using the four models of the PV/T module, the energy efficiency of AWHs increases as the tank volume increases. As the tank volume increases, the water temperature tends to increase slowly. Therefore, the water in the coil will transfer heat to the water in the tank faster. This helps PV cells to be better cooled and increases the power generation efficiency of PV cells. As a result, it not only increases P_{elec1} , which increases P_{grid} , but also helps to increase Q_{hw} , resulting in increased energy efficiency (the water flow is fixed at 0.02 kg/s so that P_{grid} is not affected by P_{pump} but only by P_{elec1}).

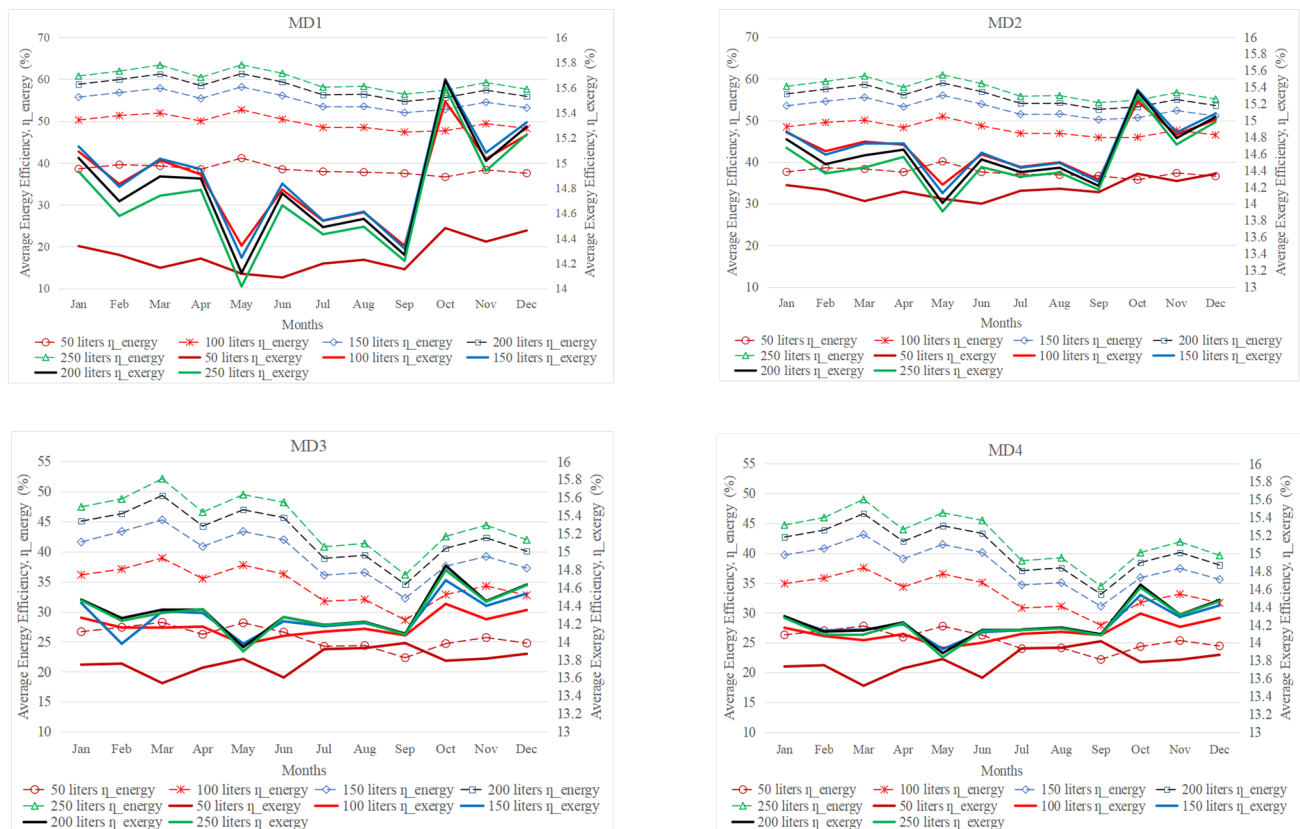


Figure 12. The average energy and exergy efficiency of AWHs when changing tank volume.

The average exergy efficiency of AWHs increases with increasing tank volume and has a maximum value when AWHs uses:

- + MD1: In the months of February, May and September, with the tank volume at 100 L, in the remaining months, it is 150 L.
- + MD2: In February, March, May, July, August and September, with the tank volume at 100 L, in the remaining months, it is 150 L.
- + MD3: In all months, with tank volume at 150 liters.
- + MD4: In the months of February, March, May and September, with the tank volume at 150 liters, in the remaining months, it is 200 liters.

Just like energy efficiency, exergy efficiency is affected by P_{grid} , I_s , Q_{hw} values. Besides, exergy performance is also affected by T_{hw} . As just explained above, as the tank volume increases, P_{grid} increases and Q_{hw} increases but causes T_{hw} to decrease. It reduces exergy performance. Therefore, after the system reaches the maximum exergy value, if the tank volume increases, the exergy efficiency increases.

In the next step, the study uses the found optimal values of the tank volume to calculate the average energy efficiency, average exergy efficiency and heat-electricity output of AWHs when using the four PV/T module samples. The results are presented in the charts in Figures 13 and 14.

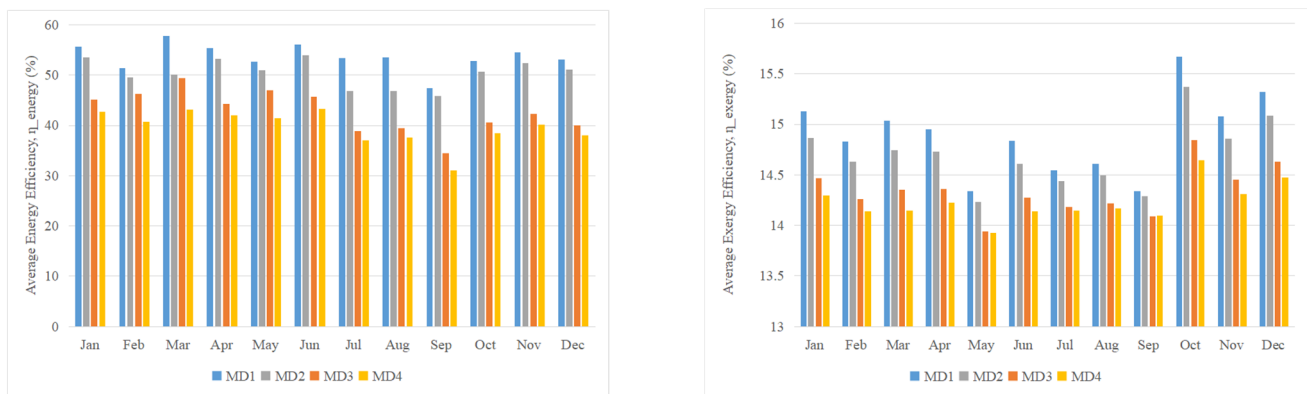


Figure 13. The average energy and exergy efficiency of AWHs over the months.

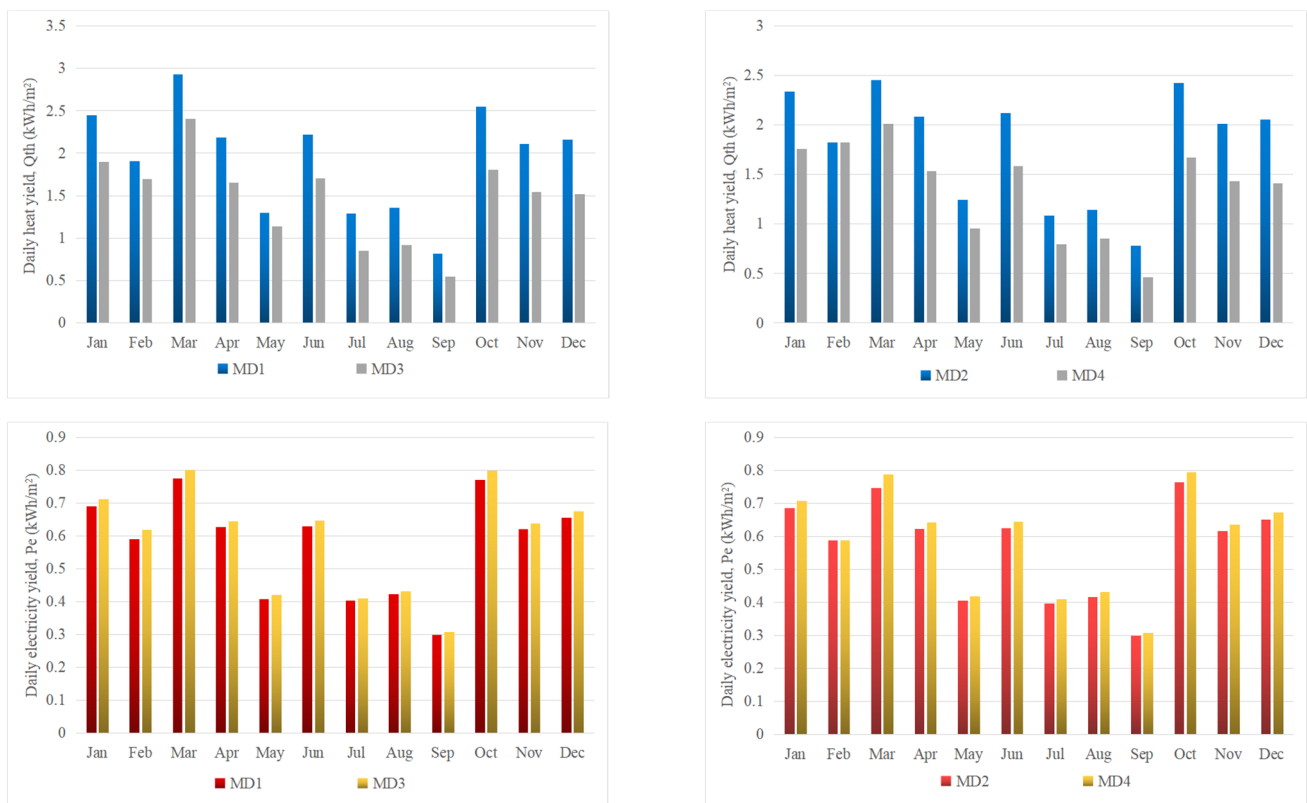


Figure 14. Output of Heat and electricity in typical days of the months.

Figure 13 indicates that the average energy efficiency of AWHs has the highest value in all months when using MD1, followed by MD2, MD3 and MD4. The average energy efficiency of AWHs with the highest values when using MD1 and MD3 was in March, reaching 57.85% and 49.23%, respectively; with MD2 and MD4, they are in June, reaching 53.94% and 43.31%, respectively. Figure 13 also shows that the average exergy efficiency of AWHs has the highest value for most of the months when using MD1 and the lowest value for most of the months when using MD4. The main reason is due to:

- + MD1 and MD2 have an air layer creating a greenhouse effect, so Q_{hw} increases compared to MD3 and MD4.
- + The temperature of the water in the tank when the system uses MD1 and MD2 is higher than that of MD3 and MD4 because the tank volume is less and receives more heat.

The average exergy efficiency of the system had the highest value in October, reaching 15.67%, 15.37%, 14.85%, 14.64%, respectively when using MD1, MD2, MD3, MD4, respectively.

Figure 14 clearly shows the system with the largest heat output when using MD1, followed by MD2, MD3, MD4, respectively. In terms of electricity yield, in general, the system has relatively equal electricity output when using the four PV/T module samples. The system has the largest electricity output when using MD3, followed by MD4, MD1, MD2, respectively. Overall, the system had the largest heat output in March, reaching 2.93 kWh/m²/day, 2.45 kWh/m²/day, 2.41 kWh/m²/day and 2.01 kWh/m²/day with MD1, MD2, MD3 and MD4, respectively. At the same time, the system also had the largest electricity output in March, reaching 0.78 kWh/m²/day with MD1, 0.75 kWh/m²/day with MD2, 0.8 kWh/m²/day with MD3 and 0.79 kWh/m²/day with MD4.

5.3. Thermal and Electrical Efficiency Analysis of 4 PV/T Module Models

Using the optimal water flow into the PV/T modules of 0.02 kg/s, combined with the reference parameters in Table 3, the simulation program calculates the thermal efficiency and electrical efficiency in stable condition for the four PV/T module models simultaneously. The results are shown in the chart in Figure 15, Figure 16 and the equations in Table 4.

$$\text{Set: } VHB = \frac{T_{pw,i} - T_a}{I_s} \left(\frac{\text{m}^2\text{K}}{\text{W}} \right) \quad (47)$$

Table 3. Values of reference parameters.

Parameters	Value	Unit
I_s	800	W/m ²
T_a	30	°C
v_a	1.3	m/s
θ	10.5°	

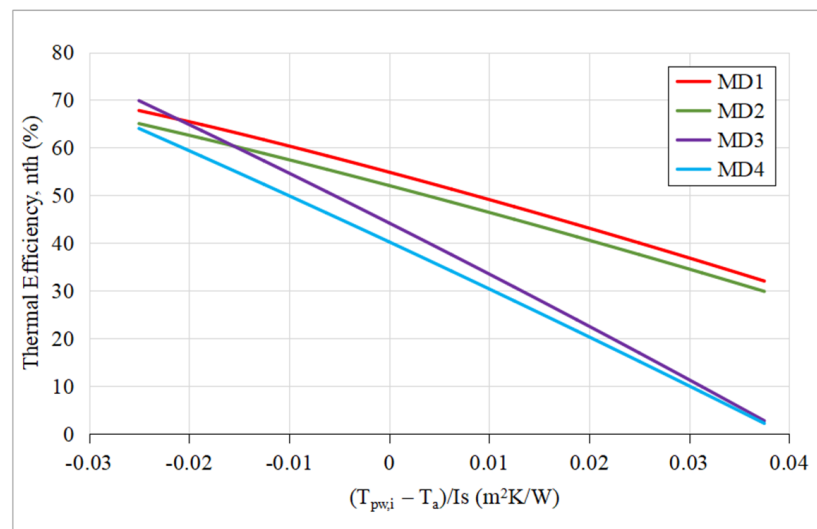


Figure 15. Thermal efficiency of four PV/T module models.

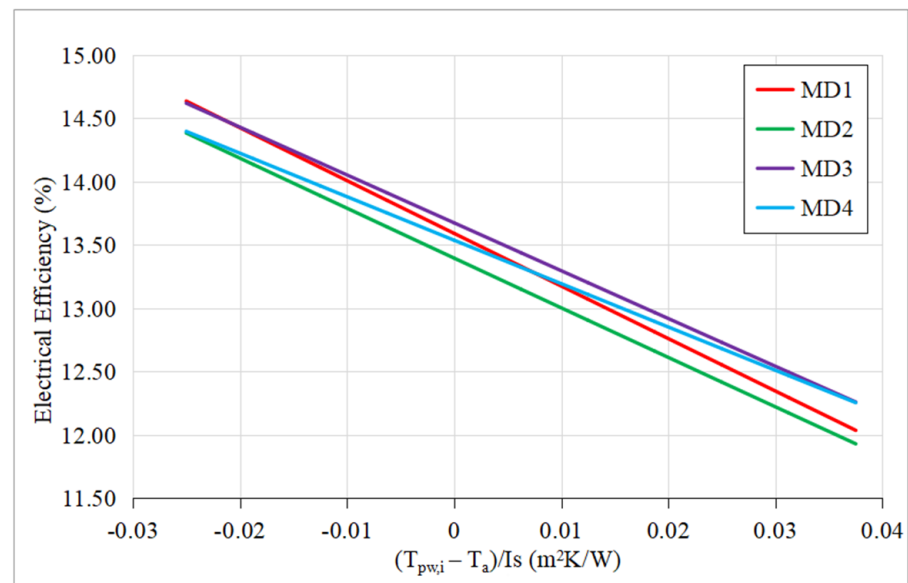


Figure 16. Electrical efficiency of four PV/T module models.

Table 4. Thermal and electrical efficiency formula of four PV/T module models.

4 Models of PV/T Module	Thermal Efficiency	Electrical Efficiency
MD1	$\eta_{th} = 0.5484 - 5.5604 \frac{T_{pw,i} - T_a}{I_s} - 0.0171 \frac{(T_{pw,i} - T_a)^2}{I_s}$	$\eta_e = 0.1359 - 0.4152 \frac{T_{pw,i} - T_a}{I_s}$
MD2	$\eta_{th} = 0.5205 - 5.4818 \frac{T_{pw,i} - T_a}{I_s} - 0.01421 \frac{(T_{pw,i} - T_a)^2}{I_s}$	$\eta_e = 0.1399 - 0.3919 \frac{T_{pw,i} - T_a}{I_s}$
MD3	$\eta_{th} = 0.4422 - 10.5746 \frac{T_{pw,i} - T_a}{I_s} - 0.0160 \frac{(T_{pw,i} - T_a)^2}{I_s}$	$\eta_e = 0.1367 - 0.3772 \frac{T_{pw,i} - T_a}{I_s}$
MD4	$\eta_{th} = 0.4026 - 9.9763 \frac{T_{pw,i} - T_a}{I_s} - 0.0127 \frac{(T_{pw,i} - T_a)^2}{I_s}$	$\eta_e = 0.1354 - 0.3422 \frac{T_{pw,i} - T_a}{I_s}$

Figure 15 shows that MD1 has the highest thermal efficiency and MD4 has the lowest thermal efficiency compared to others at most VHB values. When the water temperature entering the PV/T module ($T_{pw,i}$) is equal to the ambient temperature (T_a), which means $VHB = 0$, the thermal efficiency of MD1 is the highest, reaching 54.85%, followed by MD2, MD3 and MD4, reaching 52.06%, 44.22% and 40.26%, respectively. Figure 16 indicates the electrical efficiency of the four PV/T module models in which MD3 has the highest electrical efficiency and MD2 has the lowest electrical efficiency at most VHB values. When $VHB = 0$, the electrical efficiency of MD3 is the highest, reaching 13.67%, followed by MD1, MD4 and MD2 at 13.59%, 13.54% and 13.4%, respectively.

Through the diagrams of Figures 15 and 16, we see that, as the value of VHB is larger, the thermal-electrical efficiency of the PV/T modules decreases due to increased heat loss and large PV cells temperature. As the VHB value is smaller, the electrical and thermal efficiency of the PV/T modules increases as the PV cells temperature decreases and more heat is received from the environment. It is clear that MD3 and MD4 have a faster increase in thermal efficiency than MD1 and MD2, which can be explained because MD3 and MD4 have no air layer, so the ability to receive heat from the environment is faster than the other two types. In general, MD1, MD3 and MD4 are suitable for applications with low water temperature, especially MD3.

Analysis in the case of water temperature entering the PV/T module is equal to the ambient temperature at different solar radiation levels from 400 W/m^2 to 1000 W/m^2 ; we have the thermal and electrical efficiency of the four PV/T module samples shown in Figures 17 and 18, respectively. Figure 17 shows that, the higher the radiation intensity, the higher the thermal efficiency of the PV/T modules, in which the thermal efficiency of MD1

is highest, followed by MD2, MD3 and MD4. Figure 18 shows that the electrical efficiency of the PV/T modules decreases as the radiation intensity increases, when the radiation intensity is greater than 400 W/m^2 , the electrical efficiency of MD3 is the highest, followed by MD1, MD4, MD2.

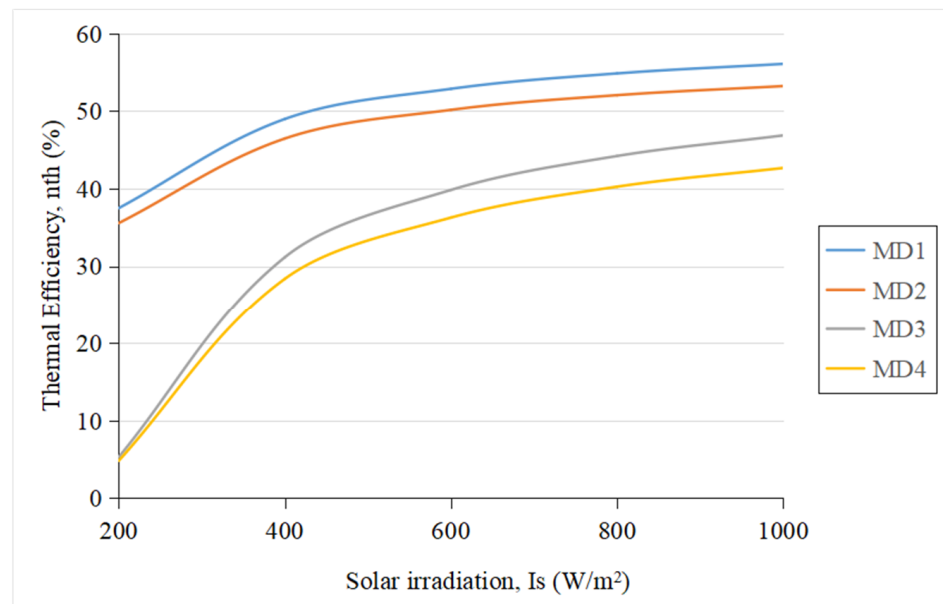


Figure 17. Thermal efficiency of four PV/T module models when changing solar radiation intensity.

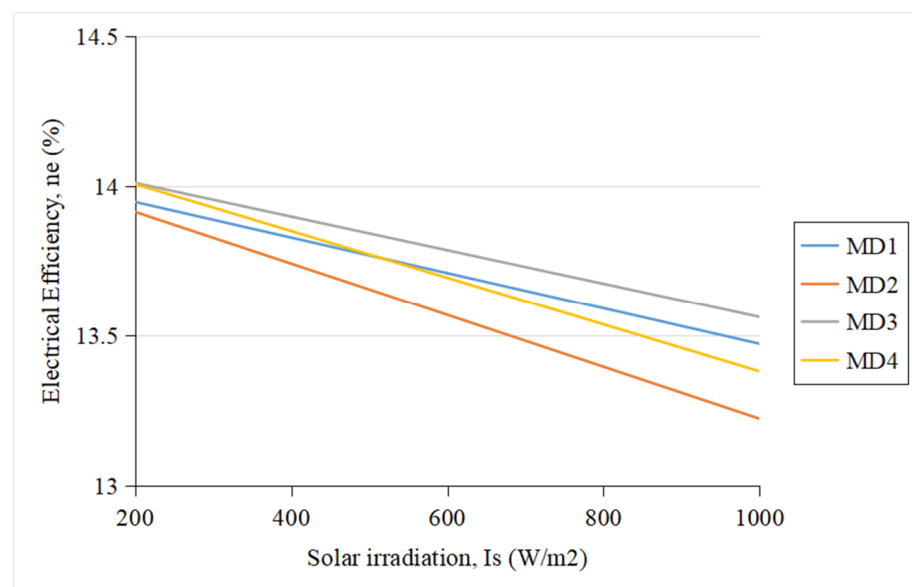


Figure 18. Electrical efficiency of four models of PV/T modules when changing solar radiation intensity.

When analyzing at different radiation intensity levels from 400 W/m^2 to 1000 W/m^2 with the water temperature entering the PV/T module ranging from 10°C to 50°C , the thermal and electrical efficiency of the four PV/T module models were investigated in four graphs in Figure 19. In general, in all the four PV/T module models, the electrical efficiency decreases as $T_{pw,I}$ increases; this is understandable because the more $T_{pw,I}$ increases, the temperature of PV cells increases with the negative impact on the power generation performance of PV cells. On the thermal efficiency side, in all four types of PV/T modules,

the thermal efficiency lines corresponding to the solar radiation intensity levels all have an intersection point, where the thermal efficiency is equal to a value $T_{pw,i}$. If $T_{pw,i}$ is less than $T_{pw,I}$ of the interference point, the thermal efficiency increases as the radiation intensity becomes smaller. Conversely, if $T_{pw,i}$ is larger than the $T_{pw,I}$ of the interference point, the thermal efficiency decreases as the radiation intensity lowers. The thermal efficiency crossover point of MD1 is 61% with $T_{pw,I} = 22^\circ\text{C}$, MD2 is 58% with $T_{pw,I} = 22^\circ\text{C}$, MD3 is 58% with $T_{pw,I} = 20^\circ\text{C}$ and MD4 is 53% with $T_{pw,I} = 20^\circ\text{C}$.

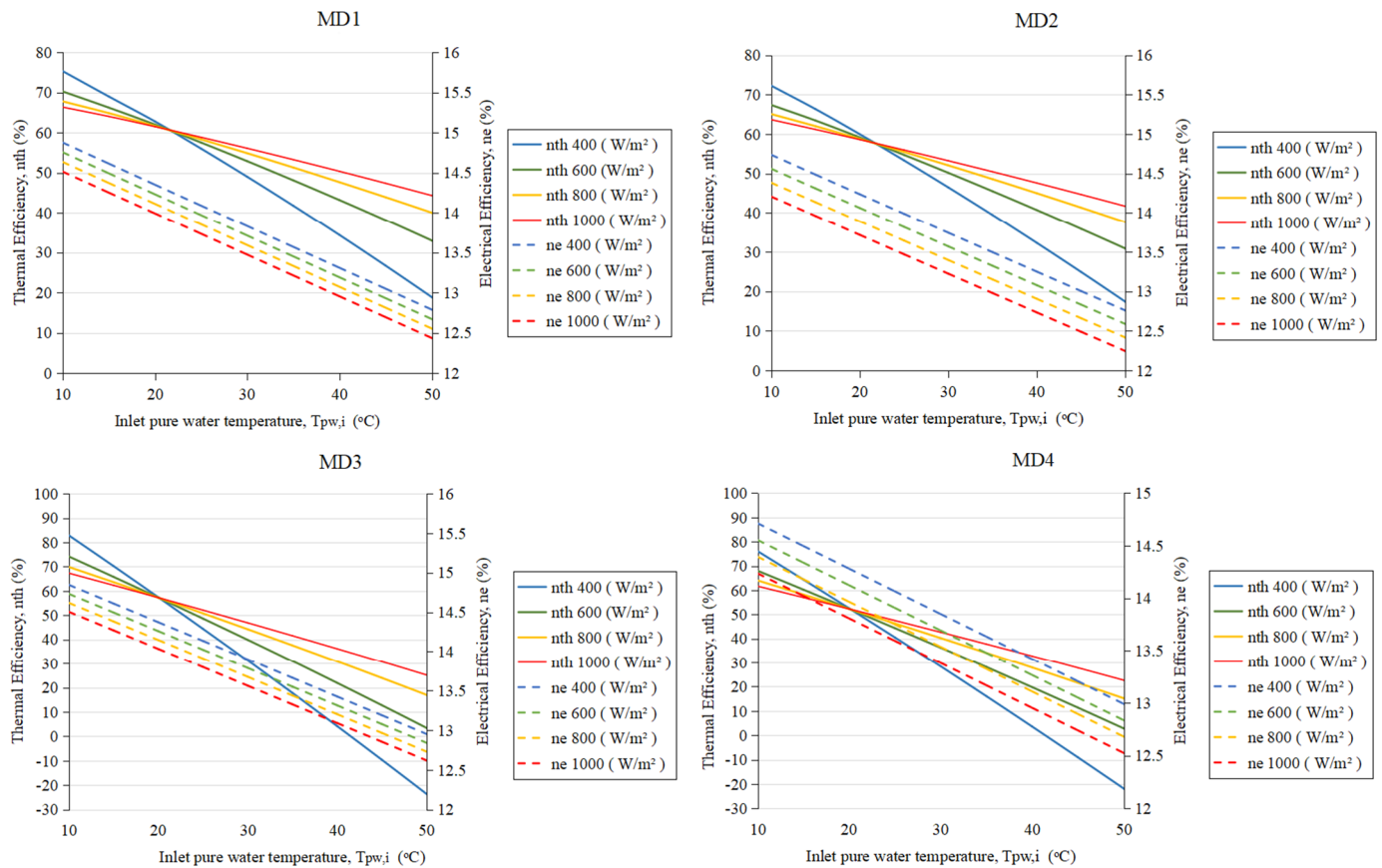


Figure 19. Thermal and electrical efficiency of four PV/T module models when changing $T_{pw,i}$.

Figure 20 shows the thermal efficiency and electrical efficiency straight lines of the four PV/T module samples when varying the reference efficiency of PV cells (η_r) and packing factor (f). The results show that, in all the four PV/T module models, the thermal efficiency decreases with increasing f and/or increasing η_r while electrical efficiency increases with increasing f and/or increasing η_r .

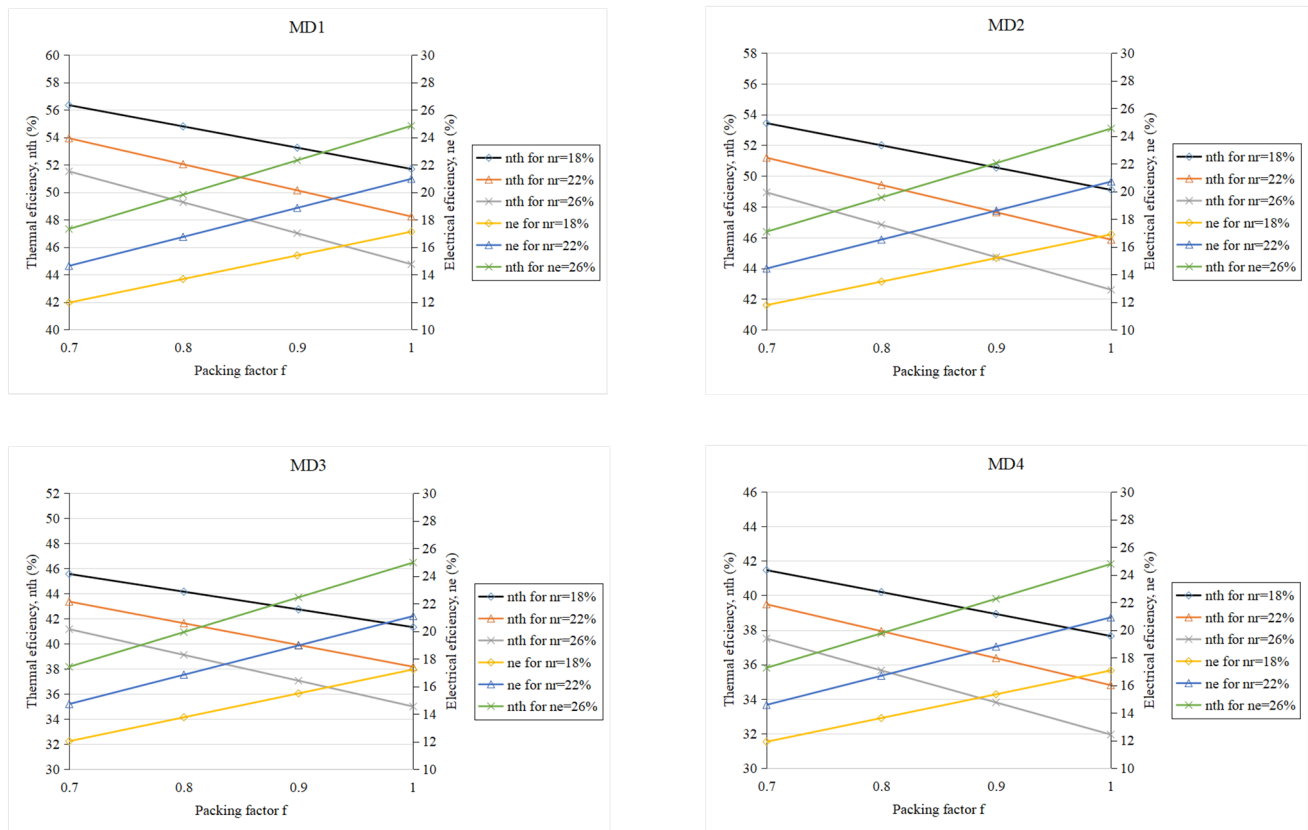


Figure 20. Thermal and electrical efficiency of four PV/T module models when changing the reference efficiency of PV cells and packing factor.

6. Conclusions

In summary, a numerical simulation program is developed in the paper to evaluate and compare the energy, exergy efficiency and heat-electricity output for an active water heating system using four PV/T module models of MD1, MD2, MD3 and MD4. At the same time, the study also conducted thermal and electrical efficiency analysis for four PV/T module models.

In year-round weather conditions in Ho Chi Minh City, Vietnam, the study found the optimal water flow and tank volume for the system to achieve the highest exergy efficiency when using each model of the PV/T module in different months. The energy and exergy efficiency of the system has the highest value when using MD1, reaching 57.85% and 15.67%, respectively. The system has the largest heat output when using MD1, reaching 2.93 kWh/m²/day and the largest electricity output when using MD3, reaching 0.8 kWh/m²/day.

The paper indicates that, under stable conditions with no heat loss, MD1 has the highest thermal efficiency of 54.85%, while the electrical efficiency of MD3 is the highest at 13.67%. The study also illustrates that: (i) The higher the radiation intensity, the greater the thermal efficiency of the PV/T module, while the electrical efficiency decreases; (ii) The electrical efficiency of PV/T module increases as $T_{pw,i}$ decreases; (iii) Thermal efficiency decreases with increasing coverage factor and/or increasing cell efficiency, while electrical efficiency increases with increasing coverage factor and/or increasing cell efficiency. Besides, the study also discovered the thermal efficiency interference point, where the thermal efficiency is equal when having the same value of $T_{pw,i}$. If $T_{pw,i}$ is less than $T_{pw,i}$ of the interference point, the thermal efficiency increases with smaller radiation intensity and vice versa.

Finally, the study recommends using the MD1 type PV/T module for the active water heating system because it has the greatest energy, exergy efficiency and heat output while

electricity output is equivalent. The simulation and analysis method of the paper can be applied to similar systems when using different types of PV/T modules for evaluation in specific weather conditions.

Author Contributions: Investigation, writing and original draft preparation, V.V.H.; Editing on original and the article finalization, H.C.L. and B.T.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, under grant number BK-SDH-1680962.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Nomenclature

Nomenclature

h	Heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
h_c	Convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
h_r	Radiative heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
k	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
Q	Energy rate (W)
M	Mass (kg)
A	Surface area (m^2)
v_a	Wind speed (m/s)
c_p	Specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
T	Temperature (K)
D	Diameter (m^2)
Pe	Perimeter (m)
H	Height (m)
L	Length (m)
p	Pressure (Pa)
P	Electrical power (W)
E	Specific electrical power (W/m^2)
f	Packing factor, Friction factor
Re	Reynolds number
Nu	Nusselt number
I_s	Solar radiation intensity (W/m^2)
G	Mass flow rate (kg/s)
t	Time (s)
Δt	Time step (s)
ΔH	Head loss (N/m^2)
B	Solar cell temperature coefficient ($1/\text{K}$)
a	Thermal diffusivity (m^2/s)
ε_t	Roughness of tube, 0.0025×10^{-3} (m)

Subscripts

g	Glass
pw	Pure water
hw	Hot water in tank
a	Ambient
ab	Absorber
pvc	Photovoltaic cell
PV/T	Photovoltaic/thermal module
pvl	PV layer
t	Tube
c	Convection, Coil
r	Radiation, Reference
ins	Insulation
$grid$	On grid
th	Thermal
$e, elec$	Electrical
i	In
o	Out
ad	Thermal adhesive
inv	Inverter
LR	The literature result
SR	The simulation result
fl	Friction loss
ll	Local loss
AWHS	Active water heating system

Greek

α	Absorptivity
τ	Transmittance
ρ	Density (kg/m^3)
ω	Velocity (m/s)
ε	Emissivity
δ	Thickness, distance (m)
σ	Stefan-Boltzman constant, 5.67×10^{-8} ($\text{W m}^{-2} \text{K}^{-4}$)
η	Efficiency
θ	PV/T module slope

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