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Exergy optimization of a multi-stage solar micro-cogeneration system

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University, Strasbourg, France.
Email: monica.siroux@insa-strasbourg.fr**Abstract**

This paper proposes a dynamic model of a solar-based micro-cogeneration system called photovoltaic-thermal (PVT) collector to perform a design optimization of the multi-stage PVT system. The parametric study reveals the most important design parameters influencing the water-based flat-plate PVT system performance. The analysis also shows an existing trade-off between thermal and electrical efficiencies during the PVT operation. A novel exergy-based multi-objective design optimization method is demonstrated to find a trade-off design solution of the multi-stage PVT collector which compromises between the electrical and thermal exergy efficiencies under different weather conditions. The electrical and thermal exergy efficiencies are defined to be the objective functions of the Matlab gamultiobj-function, which is a multi-objective evolutionary algorithm using non-dominated sorting genetic algorithm-II (NSGA-II). As a result of the algorithm, the Pareto optimal sets were derived that revealed the optimal solutions taking into account the trade-off nature of the optimization problem. The decision-making method called an ideal point method was used in the decision-making process to find the final optimal solutions for different weather conditions. The results revealed that the optimal number of the PVT collectors in series depended on the weather conditions and decreased from 3 to 2 if the conditions got cooler.

1 | INTRODUCTION

The building sector has a high impact on greenhouse gas emissions and final energy consumption in the European Union (EU) by being the largest energy end-use sector with a share of 41% [1]. Renewable energy production is getting a stronger role in energy production. Micro combined heat and power (micro-CHP), or co-generation, systems are operating in the building sector to produce simultaneously from a single fuel source heat and power at high efficiency and close to the consumption point. The systems are used to produce on-site energy for space heating, domestic hot water (DHW) and electricity demand. The European Parliament has defined the micro-cogeneration to be the units up to an electrical output of 50 kW [2]. However, micro-CHP commonly refers to units up to 15 kW of electrical power [3]. The renewable energy-based micro-CHP systems are in a key role in reaching the primary energy and pollutant emissions reduction targets of the EU [4].

Solar energy can be counted to be an inexhaustible source of energy, and its use does not depend on the energy markets. At the moment, solar energy is mostly deployed in the building sector in terms of photovoltaic (PV) panels and thermal collectors [5]. This separated production of electricity and heat can be combined by the technology called photovoltaic-thermal (PVT). The PVT collector is a renewable solar-based micro-cogeneration system that produces electricity by the PV module and useful heat by cooling the PV module with a coolant circulation. That leads to increased overall system efficiency but also an increasing electrical efficiency due to the decreased operation temperature of the PV module [5]. Zhang et al. [6] argued that the most commonly used and installed PVT technologies are air- and water-based collectors. The popularity of the water-based PVT collector is increasing due to its ability to increase the electrical efficiency and better thermal energy utilization in DHW and space heating. The highly dynamic and weather dependent operation of a single PVT collector is widely studied

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in the literature, and a range of theoretical PVT models has been introduced and validated in [5, 7–11]. However, the N number of the PVT collectors can be connected in series to increase the coolant outlet temperature and produce more thermal energy at a higher quality than from a single collector. This kind of multi-stage PVT collector can be used in several applications. In the building sector, the multi-stage PVT collector can be integrated with energy storages, such as thermal storage, battery systems and electrical vehicles (EV). On the other hand, the multi-stage PVT collector is useful for other applications as well. Sahota and Tiwari [12] conducted a review on N series-connected PVT systems. They explored different PVT applications, such as flat plate PVT collectors with solar still and greenhouse dryer. Liang et al. [13] studied the performance of PVT collectors connected in series. They performed a numerical and experimental study, in which six PVT collectors were connected in series resulting in a total amount of 36 collectors. They analysed coolant fluid outlet temperature, PV module temperature, and electrical and thermal efficiencies. Dubey and Tiwari [14] studied flat plate water PVT collectors in series and calculated energy and exergy yield by varying the number of collectors under four different weather conditions in India. They discovered that increasing the mass flow and the number of collectors increased thermal energy gain but only until a certain point.

The performance of the multi-stage PVT system can be analysed in terms of energy and exergy analysis. The energy analysis concerns only the quantity aspects related to the energy production of the system neglecting the quality aspect. For this reason, the exergy method is used to complete the energy assessment of the system. The exergy method takes into account the quality of the produced energy as an ability to work at the temperature, at which a certain energy flow is available. Evola and Marletta [15] performed an exergy-based optimization of a flat plate water-based PVT system. They concentrated on optimizing the coolant inlet temperature in order to maximize the overall exergy efficiency of the system at any operating condition. They discovered that low inlet temperature resulted in very high overall energy efficiency, but in terms of exergy, this is not recommended. The optimized inlet temperature and overall exergy efficiency varied between 30–42 °C and 14–15%, respectively, depending on the mass flow rate and the weather conditions. Tiwari et al. [16] conducted an overall exergy analysis of the N -PVT compound parabolic concentrator collector for constant collection temperature. The system was applicable to the absorption refrigeration system. They concluded that using an exergy approach in design optimization is highly recommended.

In recent years, the conventional correlation- and simulation-based design optimization methods have got alongside new design methods using nature-inspired artificial intelligence methods, such as genetic algorithm (GA), evolutionary algorithm and particle swarm optimization (PSO). The multi-objective optimization techniques are used to solve optimization problems where the objectives have a trade-off with each other. In terms of the PVT collector performance, the electrical efficiency suffers if the thermal efficiency is maximized and the other way round. The energy-based multi-objective optimization of the water-based PVT collector performance parame-

ters with the non-dominated sorting genetic algorithm (NSGA-II) was performed in [5, 17]. The Pareto front was obtained for different optimization problems to illustrate the trade-off between solutions. The multi-objective optimization of the air-based PVT system with the NSGA-II algorithm was investigated in [18]. The single objective optimization of the PVT collector with the genetic algorithm was performed in [19] to maximize the overall exergy efficiency.

Within the given framework, there is a lack of studies considering the multi-objective optimization of the number of collectors in a PVT series based on the genetic algorithm and exergy approach. Additionally, there is a research question if the optimal number of the PVT collectors varies according to the weather conditions.

This paper proposes a dynamic model of a PVT collector with a crystalline silicon roll-bond collector in Matlab/Simulink. The model is extended to describe a multi-stage PVT collector. Energy and exergy analysis is conducted with the simulation model, and the most influencing design variables are identified and evaluated with a parametric study. Due to fact that the optimal design of the multi-stage PVT system cannot be defined with the simulations alone, the multi-objective optimization of the electrical and thermal exergy efficiencies with the non-dominated sorting genetic algorithm (NSGA-II) is conducted and the Pareto optimal set is derived in order to show the set of the optimal solutions taking into account the trade-off between exergy efficiencies.

The rest of the paper is organized as follows. In the second section, the description of a single PVT collector is presented with the geometrical, thermos-physical and optical properties followed by the modelling approach of a single collector. The main governing equations of the model are presented. Additionally, the exergy approach is introduced. The multi-objective optimization method is presented in the third section with the objective functions. In the fourth section, the results of the parametric study and optimization are presented and discussed. Finally, the main conclusion is drawn in the fifth section.

1.1 | Literature review

In this section, more background on research of the PVT collectors is provided. The current water-based PVT technologies face a challenge in which the electrical efficiency decreases as the operating temperature increases. On the other hand, higher operating temperature increases thermal efficiency. In [20, 21], novel PVT technologies were investigated to overcome this problem. The solution was to decouple thermally the electrical and thermal units of the collector using an optical coolant fluid layer above the PV modules. This layer worked simultaneously as a spectrum splitter of solar radiation and as a coolant fluid of the system, and its spectral properties were modified using nanofluids. The layer absorbed ultraviolet radiation and part of infrared radiation and transmitted to the PV modules only the useful infrared and visible radiation for electricity production. The results were promising, and the spectrum splitting increased the efficiency of the PVT collector.

The multi-stage PVT collector is useful for multiple applications where distributed micro-scale energy production is required, such as desalination. Giwa et al. [22] reviewed comprehensively the polygeneration in different desalination approaches using flat plate and concentrated PVT systems. The integration of the PVT systems with desalination showed increased efficiency. From the economical point of view, the installation costs were higher than PV systems. However, the PVT systems provided cost reduction and reduced environmental impacts in the long term. Anand et al. [23] presented as well a review on PVT integrated desalination technologies. They concluded that the overall performance of the PVT coupled desalination system is better than coupling with separated energy production by PV and solar thermal collectors.

In terms of serial connection, an interesting approach is to connect a flat plate PVT collector in series with another type of solar technology, such as a flat plate solar thermal collector or concentrated PVT to increase thermal and electrical output. Ma et al. [24] studied a novel series connection of a PVT and solar thermal collector (PVT-ST) to produce electricity and heat at an even higher quality level. They compared the serial connection to a glazed and unglazed PVT and a PV panel. As a result, the PVT-ST system was competitive in terms of electrical efficiency and had significantly higher thermal and primary energy savings efficiency. Kazemian et al. [25] conducted a similar study of the PVT-ST system compared to other solar technologies and used the multi-objective Taguchi method to optimize operation variables. They generated 3D-models of each system by SolidWorks software to conduct the study. The results indicated 19% higher daily thermal power of PVT-ST compared to a PVT system but the electrical power was equal.

The exergy analysis is an effective way to investigate the true potential of an energy system. In terms of PVT application, Sarhaddi [26] conducted an exergy analysis of a PVT connected solar still system. The results of the study showed that two PVT collectors in series improved the most the overall exergy efficiency of the PVT-solar still system.

2 | METHODOLOGY

2.1 | Description of the PVT collector

A water-based PVT collector with a direct flow geometry and roll bond channels is simulated, analysed and optimized in this study. Figure 1 shows the geometry and cross-section of the PVT collector [27]. The water-based PVT collector is investigated because they achieve higher overall efficiency than air-based collectors due to the higher heat capacity of water [28]. High efficient PV cells are still relatively expensive and in this study, the PVT collector has a crystalline silicon PV cell with a reference electrical efficiency (η_{STC}) of 18.7% at the reference operating temperature (T_{ref}) of 25 °C. The temperature coefficient (β_T) and packing factor (r_p) are 0.5%/K and 0.95, respectively. The diameter of the tubes is 8 mm and for the initial simulation conditions, the number of tubes is 11. The initial inlet temperature of the coolant fluid is 20°C and the coolant mass

TABLE 1 The main geometrical, thermo-physical and optical properties of the single PVT collector

Property	Glass	Air gap	PV	Thermal absorber	Unit
Emissivity (ϵ)	0.9	–	0.96	–	–
Absorbance (α)	0.1	–	0.9	–	–
Transmittance (τ)	0.93	–	–	–	–
Thickness (H)	0.004	0.02	0.006	0.001	m
Area (A)	2	–	1.9	2	m ²
Density (ρ)	2200	–	2330	2699	kg/m ³
Specific heat (c)	670	–	900	800	J/(kg K)
Thermal conductivity (k)	1.1	–	140	237	W/(mK)
Property	Fluid	Insulation	Unit		
Thickness (H)	–	0.04	m		
Area (A)	–	2	m ²		
Density (ρ)	1050	16	kg/m ³		
Specific heat (c)	3605	1120	J/(kg K)		
Thermal conductivity (k)	0.615	0.035	W/(mK)		

flow 0.017 kg/s (60 kg/h). Table 1 summarizes the main geometrical, thermo-physical, optical properties and the parameters of the single PVT collector used in the simulation and optimization.

The described single PVT collector is multiplied to present a multi-stage PVT collector, in which N number of collectors is connected in series in order to solve a problem of low-temperature heat production of a single PVT collector. The working principle of the multi-stage collector is shown in Figure 2. The coolant mass flow is fed into the first PVT collector, and heat is recovered. The outlet temperature of the first collector is the inlet temperature of the second collector. The coolant temperature is increased by each collector in series, and the thermal exergy efficiency is increased until a certain point.

In reality, the electrical efficiency would be the highest in the collectors at the beginning of the series and the lowest at the end of the series because the temperature of the coolant flow increases towards the end of the series. However, due to simplicity, a global model of the multi-stage PVT collector is used to solve the optimization problem of this study. The model does not calculate the coolant temperature after each PVT or the collector specific electrical efficiency. However, the area, thermal mass and the tube length of the collector array are always increased or decreased by the geometry of the single collector described above.

2.2 | Modelling approach for energy and exergy analysis

The numerical modelling of a single water-based PVT collector is based on the following main governing equations of the

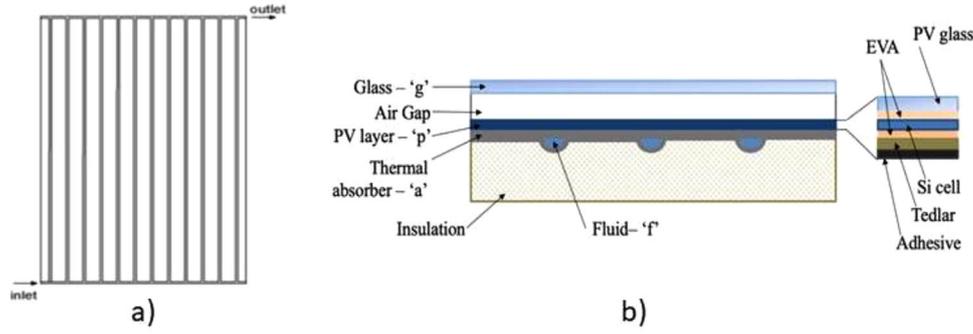


FIGURE 1 The single PVT collector: (a) Direct flow collector geometry, (b) cross section of the PVT collector [27]

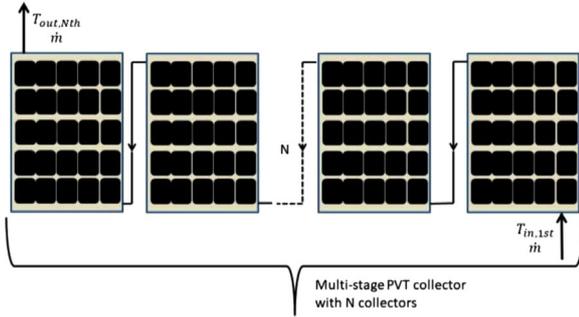


FIGURE 2 The working principle of the multi-stage PVT collector

energy balance in the various layers of the collector. The more detailed derivation of the governing equations and the validation of the model is presented in [10] where the used heat transfer coefficient are defined as well

The glass cover (g):

$$m_g \times c_g \times \frac{dT_g}{dt} = b_{g-e,CV} \times A \times (T_e - T_g) + b_{g-e,RD} \times A \times (T_{sky} - T_g) + b_{g-pv,CV} \times A \times (T_{pv} - T_g) + b_{g-pv,RD} \times A \times (T_{pv} - T_g) + A \times \alpha_g \times G_{irr} \quad (1)$$

The photovoltaic layer (pv):

$$m_{pv} \times c_{pv} \times \frac{dT_{pv}}{dt} = b_{g-pv,CV} \times A \times (T_g - T_{pv}) + b_{pv-g,RD} \times A \times (T_g - T_{pv}) + b_{pv-a,CD} \times A_{pv-a} \times (T_a - T_{pv}) + b_{pv-t,CD} \times A_{pv-t} \times (T_t - T_{pv}) + G_{irr} \times A \times (\alpha\tau)_{pv} - G_{irr} \times A \times r_c \times \eta_{pv}(T) \quad (2)$$

In which r_c is the ration of the cell area to the PVT collector area, in the other words, packing factor. The electrical efficiency $\eta_{pv}(T)$ depends on the photovoltaic layer temperature T_{pv} . Due

to this, the electrical efficiency of the PV depends linearly on the temperature T_{pv} , the temperature coefficient β_{pv} and on the efficiency at standard conditions T_{ref} . The efficiency is calculated according to the following relation:

$$\eta_{pv}(T) = \eta_{STC} \times [1 - \beta_{pv} \times (T_{pv} - T_{ref})] \quad (3)$$

Additionally, the photovoltaic layer temperature T_{pv} depends on the following parameters based on the geometry of the collector [8, 10]:

$$A_{pv-a} = A \left(1 - \frac{D_o}{W}\right) \quad (4)$$

$$b_{pv-t,CD} \times A_{pv-t} = \frac{H_{pv} \times L}{\frac{W \times k_{pv}}{2} + \frac{H_{adh}}{k_{adh}} \times \frac{H_{pv}}{D_o}} \quad (5)$$

$$m_{pv} = \rho_{pv} \times H_{pv} \times A \times r_c \quad (6)$$

The absorber layer (a):

$$m_a \times c_a \times \frac{dT_a}{dt} = b_{a-pv,CD} \times A_a \times (T_{pv} - T_a) + b_{a-t} \times A_{a-t} \times (T_t - T_a) + b_{a-i,CD} \times A_{a-i} \times (T_i - T_a) \quad (7)$$

The tube bonding (t):

$$m_t \times c_t \times \frac{dT_t}{dt} = b_{t-pv,CD} \times A_{pv-t} \times (T_{pv} - T_t) + b_{t-a} \times A_{a-t} \times (T_a - T_t) + b_{t-i,CD} \times A_{t-i} \times (T_i - T_t) + b_{t-f} \times A_{t-f} \times (T_f - T_t) \quad (8)$$

The insulation layer (i):

$$m_i \times c_i \times \frac{dT_i}{dt} = b_{a-i,CD} \times A_{a-i} \times (T_a - T_i) + b_{t-i,CD} \times A_{t-i} \times (T_t - T_i) + b_{i-e,CD+CV} \times A \times (T_e - T_i) \quad (9)$$

The coolant fluid (f):

$$m_f \times c_f \times \frac{dT_f}{dt} = b_{t-f} \times A_{t-f} \times (T_a - T_f) + \dot{m} \times c_f \times (T_{f,in} - T_{f,out}) \quad (10)$$

Equations (1)–(7) are implemented into Matlab/Simulink with details to assess the energy and exergy performance of the PVT collector. In the case of multiple PVT collectors, the area, thermal mass of each layer and the tube length of a single panel are multiplied by the number of the collectors in order to assess the performance of the PVT series.

Compared to energy analysis, the exergy analysis is based on the Second Law of Thermodynamics and takes into account the quality of the produced energy.

The exergy balance of the system can be expressed as follows:

$$\sum Ex_{in} - \sum (Ex_{th} + Ex_{el}) = \sum Ex_d \quad (11)$$

In the case of the PVT collector, the exergy flow to the system Ex_{in} comes from the solar irradiation. However, solar irradiation is not seen as pure exergy and due to this a conversation coefficient is included in the calculation of the PVT incoming exergy [29]:

$$Ex_{in} = A \times N_c \times G_{irr} \times \left(1 - \frac{4}{3} \frac{T_0}{T_{sol}} + \frac{1}{3} \left(\frac{T_0}{T_{sol}} \right)^4 \right) \quad (12)$$

In Equation (9) T_{sol} is the solar temperature and T_0 is the reference temperature, which according to the literature, should be a constant, for example, $T_0 = 20$ °C, $T_0 = 25$ °C or the minimum temperature of the month. In this study, $T_0 = 20$ °C is selected. N_c is the number of collectors.

Electrical energy is seen as pure exergy, but the exergy content of thermal energy depends on the temperature at which the heat is made available. In the model, the exergy of thermal (Ex_{th}) and electrical (Ex_{el}) energy are calculated as follows, respectively [29]:

$$Ex_{th} = \dot{m} \times c_f \times \left[(T_{out} - T_{in}) - T_0 \times \ln \frac{T_{out}}{T_{in}} \right] \quad (13)$$

$$Ex_{el} = \eta_{pv} \times G_{irr} \times r_c \times A \times N_c \quad (14)$$

By Equations (8)–(11) the both thermal (ξ_{th}) and electrical exergy (ξ_{el}) efficiencies and the overall exergy efficiency (ξ) of the PVT collector can be calculated as follows:

$$\xi_{th} = \frac{Ex_{th}}{Ex_{in}} \quad (15)$$

$$\xi_{el} = \frac{Ex_{el}}{Ex_{in}} \quad (16)$$

$$\xi = \frac{Ex_{el} + Ex_{th}}{Ex_{in}} \quad (17)$$

The following assumptions are taken into account in the modelling:

- The temperature distribution is uniform in the layers and in the PVT collectors in series.
- It is assumed that there are no heat losses through the edges.
- The optical and thermal properties of the materials and fluids are constant.
- No surrounding shading or dust is taken into account.
- The thermal resistance between the layers is negligible.

3 | MULTI-OBJECTIVE OPTIMIZATION OF THE PVT COLLECTOR

The energetic and exergetic performance analyses based on the simulations of the thermal PVT model show a trade-off between performance parameters, such as thermal and electrical energy and exergy efficiencies as functions of various decision variables. The simulation results have shown a trade-off between thermal and electrical exergy efficiencies of the PVT collector. The electrical efficiency of the PV panel decreases when the operating temperature of the collector increases. On the other hand, increased operating temperature leads to higher thermal exergy efficiency. This means that both efficiencies cannot be directly maximized at the same time but a solution has to be found, which satisfies both trade-off objectives (electrical and thermal exergy efficiencies) at the same time. The thermal simulations of the PVT system alone do not provide a set of optimal solutions of decision variables in terms of thermal and electrical exergy efficiencies. Instead of simulations alone, the set of optimal solutions can be found by using the multi-objective optimization (MOO) technic using an evolutionary algorithm.

3.1 | Multi-objective optimization using gamultiobj-function

In this paper, the Matlab function called *gamultiobj* of Global Optimization Toolbox is used to run the multi-objective optimization of the multi-stage PVT collector. The *gamultiobj*-function creates a set of optimal solutions in the space of decision variables on the Pareto front. The function uses a controlled, elitist genetic algorithm, which is a variant of NSGA-II [30]. Generally, the multi-objective optimization problem of two or more trade-off objectives is described mathematically as follows [5]:

Minimized/Maximized $f_m(x)$, $m = 1, 2, \dots, M$;

Subject to $g_j(x) \geq 0$, $j = 1, 2, \dots, J$;

$h_k(x) = 0$, $k = 1, 2, \dots, K$;

$x_i^{(L)} \leq x \leq x_i^{(U)}$, $i = 1, 2, \dots, n$;

TABLE 2 Decision variables for multi-objective optimization problem

Symbol	Decision variable	Bounds	Unit
\dot{m}	Mass flow rate	$0.008 \leq x(1) \leq 0.042$	kg/s
N_c	No. of collectors	$1 \leq x(2) \leq 10$	
T_{in}	Inlet temperature	$15 \leq x(3) \leq 40$	°C

In this formulation, the objective functions are minimized or maximized subject to certain constraints.

In this work, the overall electrical and thermal exergy efficiencies are two objectives to be optimized. Due to the fact that the NSGA-II is a minimization tool the objective functions are multiplied by (-1) in order to get the maximum values [5]. The 2-dimensional optimization problem of the exergy efficiencies is formulated as follows:

To minimize:

$$\begin{aligned}
 f_1(\mathbf{x}) &= -\frac{E_{x_{el}}}{E_{x_{in}}} \\
 &= -\frac{\eta_{STC} \times [1 - \beta_{PV} \times (T_{pv} - T_{ref})] \times G_{irr} \times A_{pv} \times N_c}{A \times N_c \times G_{irr} \times \left(1 - \frac{4}{3} \frac{T_0}{T_{sol}} + \frac{1}{3} \left(\frac{T_0}{T_{sol}}\right)^4\right)} \\
 &= -\xi_{el}
 \end{aligned} \quad (18)$$

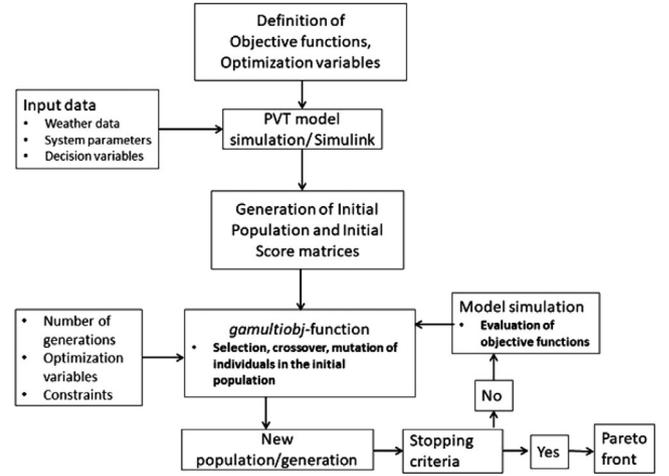
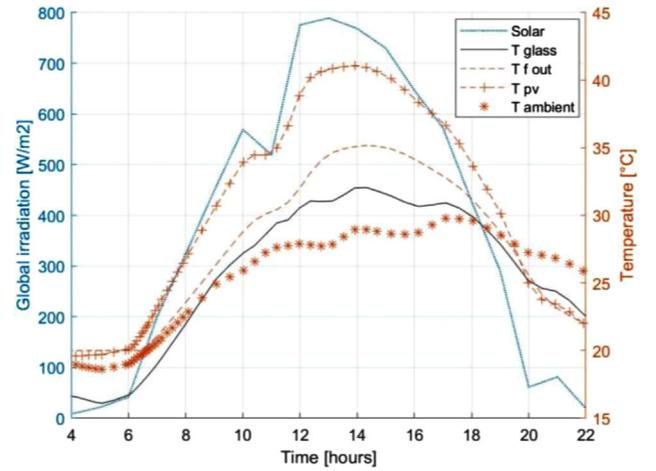
$$\begin{aligned}
 f_2(\mathbf{x}) &= -\frac{E_{x_{th}}}{E_{x_{in}}} = -\frac{\dot{m} \times c_f \times \left[(T_{out} - T_{in}) - T_0 \times \ln \frac{T_{out}}{T_{in}}\right]}{A \times N_c \times G_{irr} \times \left(1 - \frac{4}{3} \frac{T_0}{T_{sol}} + \frac{1}{3} \left(\frac{T_0}{T_{sol}}\right)^4\right)} \\
 &= -\xi_{th}
 \end{aligned} \quad (19)$$

where ξ_{el} and ξ_{th} are the electrical and thermal exergy efficiencies, respectively. The electrical exergy efficiency is influenced by the number of the PVT collectors in terms of the thermal mass and tube length according to Equations (2)–(6).

In terms of exergy efficiency, the sensitivity analysis has shown that the most sensible variables of the multi-stage-PVT collector operation are the cooling-water mass flow, inlet temperature and number of collectors. Table 2 presents the decision variables to be optimized and their upper and lower bounds to be used in the optimization.

4 | RESULTS AND DISCUSSION

The simulation-based multi-objective optimization process was conducted with the PVT model in Matlab/Simulink. The main objective of the optimization was to find an optimal number of PVT collectors in series to satisfy the operational purpose of the multi-stage PVT collector. First, the decision variables were varied, and the initial population and score matrixes for the genetic algorithm were generated by the simulation model. These matrixes were given for the *gamultiobj*-function of Global Optimiza-

**FIGURE 3** The simulation-based multi-objective optimization process**FIGURE 4** The temperatures of the PVT layers, the solar irradiation and ambient temperature

tion Toolbox, which started the iterative process by evaluating the fitness functions with the simulation model and making selection, crossover and mutation of the population. Based on this process, a new population or generation was created. The new generations were created as long as a stopping criterion was met. The criterion was selected to be the number of generations and set to be 100 generations. The population size was 50. The multi-objective optimization process is described in Figure 3.

The optimization was conducted with the weather data concerning three steady-state climate conditions: hot summer day conditions, of which solar irradiation was 1000 W/m^2 , ambient temperature 30 °C and wind speed 1 m/s ; medium conditions with 800 W/m^2 , 25 °C and 1 m/s ; and cooler summer conditions with 600 W/m^2 , 18 °C and 5 m/s . According to [31], these weather conditions can be addressed for different European locations, such as the southern Mediterranean, central and northern Europe, respectively.

Figure 4 presents the simulated temperatures of the different PVT collector layers, ambient temperature and solar irradiation over a summer day.

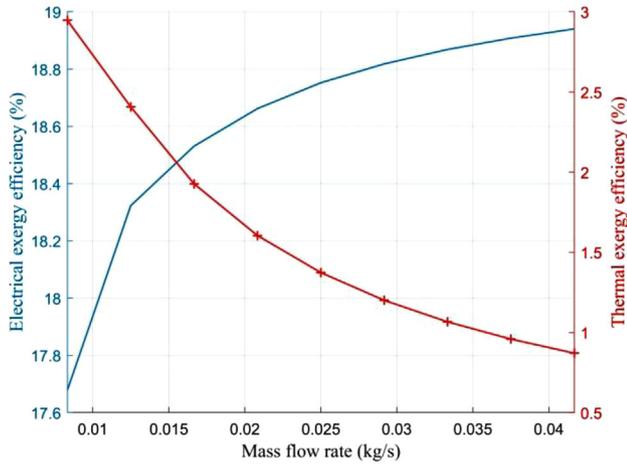


FIGURE 5 The variation of electrical and thermal exergy efficiency with the coolant mass flow rate

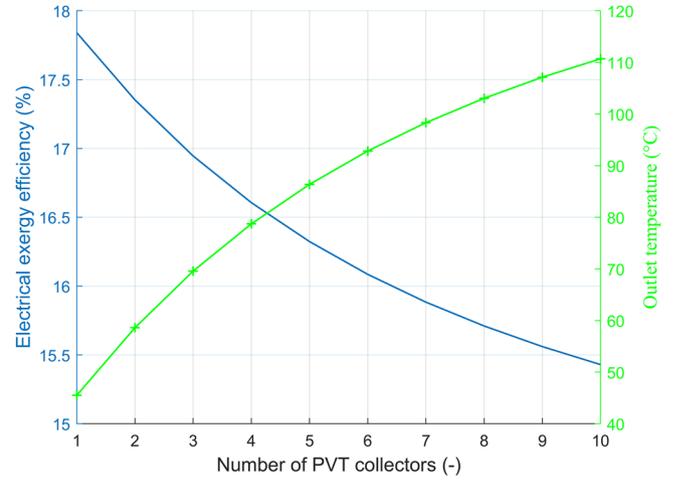


FIGURE 7 The variation of electrical exergy efficiency and the coolant outlet temperature with the number of the PVT collectors

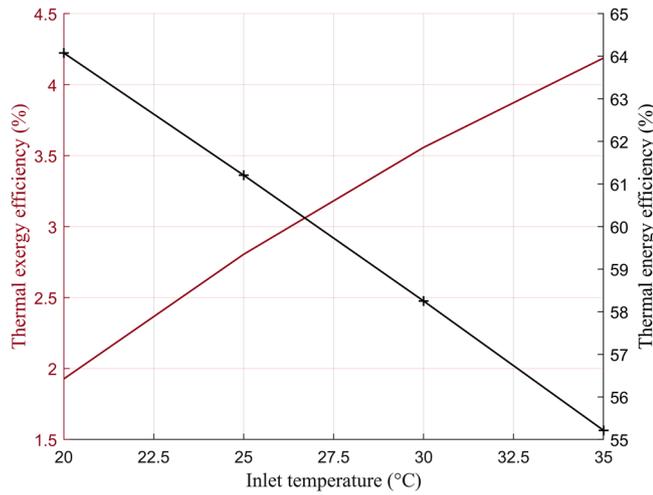


FIGURE 6 The variation of thermal exergy and energy efficiency with coolant inlet temperature

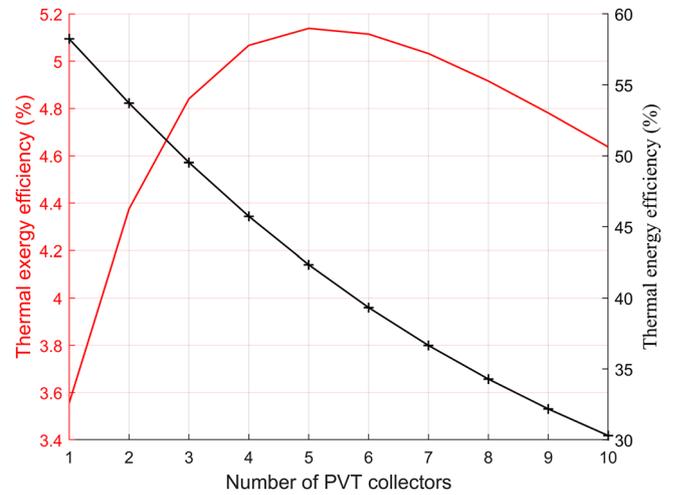


FIGURE 8 The variation of thermal exergy and energy efficiency with the number of the PVT collectors in series

The parametric study was conducted. The PVT collector was investigated under steady-state medium weather conditions of $G_{irr} = 800 \text{ W/m}^2$, $T_e = 25^\circ\text{C}$ and $v = 1 \text{ m/s}$. The used simulation parameters of the PVT were presented in Section 2. Additionally, when the number of PVT collectors was increased, the coolant inlet temperature of 30°C was used in the simulation. The relation of the decision variables to the energy and exergy efficiencies are shown in Figures 5,6. The relation of the PVT collectors in series to the efficiencies and outlet water temperature is presented in Figures 7–9. The mass flow rate had a similar relation to the thermal energy and exergy efficiencies. Both efficiencies decreased when the mass flow increased. However, if the number of the collectors and coolant inlet temperature were increased, the thermal energy and exergy efficiencies behaved differently. This is shown in Figure 8.

Figure 5 shows the trade-off nature of the PVT collector operation. Increasing the mass flow rate of the coolant fluid, increased the electrical exergy efficiency due to the stronger cooling effect. However, at the same time, thermal exergy effi-

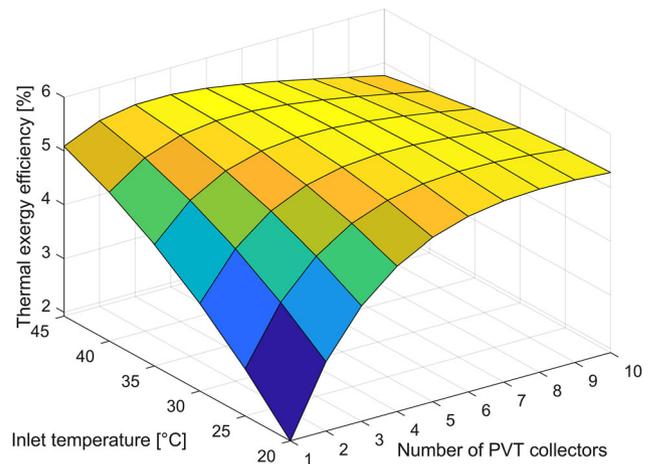


FIGURE 9 The variation of the thermal exergy efficiency in terms of the coolant inlet temperature and the number of the PVT collectors

ciency was decreased. Due to this relation, a multi-objective optimization was used to optimize the design of the multi-stage PVT collector. Table 2 presents the selected decision variables of the optimization problem.

Figure 6 reveals that increasing the inlet temperature of the coolant fluid increased the thermal exergy efficiency but decreased thermal energy efficiency. Additionally, the electrical efficiency suffers when increasing the inlet temperature because of the higher operating temperature.

Figure 7 presents the increasing coolant outlet temperature and decreasing electrical efficiency when the number of PVT collectors in series was increased. The electrical efficiency was decreased because of the higher operating temperature of the multi-stage PVT collector. Increasing the temperature level of the coolant outlet flow with additional PVT collectors leads to the higher quality of the produced thermal energy. However, there is a certain optimal point to increase the number of collectors although the outlet temperature increases. Figure 8 presents the thermal exergy and energy efficiencies with the additional PVT collectors.

The thermal energy efficiency decreased if the number of collectors was increased due to the increased total collector area and its relation to the gained outlet temperature. However, the exergy approach takes into account the quality of the produced energy and the additional collectors increased the thermal exergy efficiency until a certain point. This point was also influenced by the coolant inlet temperature. Figure 9 presents the thermal exergy efficiency in terms of the inlet temperature and the number of collectors in series.

Figure 9 reveals that the lower coolant inlet temperature required more PVT collectors in series to achieve higher thermal exergy efficiency. If the inlet temperature was increased, the relatively smaller number of the collectors led to higher thermal exergy efficiency.

The parametric study revealed the relations of the decision variables to the performance of the multi-stage PVT system. It revealed the trade-off nature of the PVT operation in terms of thermal and electrical performance. The design of the multi-stage PVT collector was optimized in terms of the thermal and electrical exergy efficiencies as objective functions in order to maximize the quality of the produced energy. The optimization was performed by using *gamultiobj*-function of Matlab Global Optimization Toolbox. The function is based on NSGA-II algorithm. The set of optimal solutions called Pareto front was obtained with the generation number of 100 and the population size of 50. Figure 10 presents the obtained Pareto front of the optimal solutions under the medium weather conditions of 800 W/m², 25 °C and 1 m/s.

The decision variable values are shown for three selected solutions. The values of each solution are presented in Table 3. The values of the decision variables show the same behaviour as in the parametric study. This can be seen in Figures 11,12 where each optimal solution of Table 3 is presented in terms of electrical and thermal exergy efficiency.

In Figure 11 the electrical exergy efficiency was the highest in the optimal solutions with the high coolant flow and low number of the PVT collectors. The solutions with the

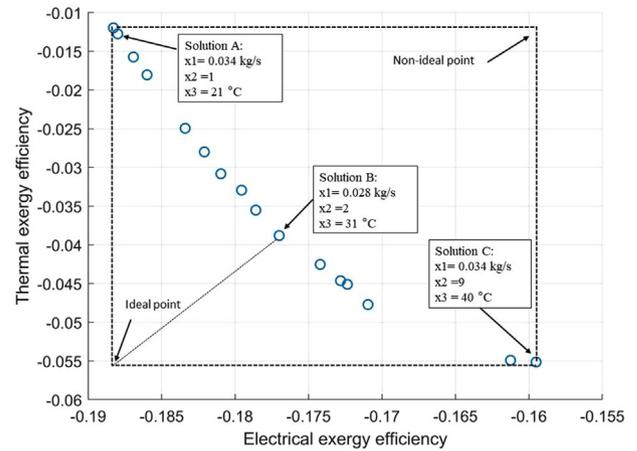


FIGURE 10 The Pareto optimal front in the objective space of the electrical and thermal exergy efficiencies

TABLE 3 Decision variables for the multi-objective optimization problem in the Pareto front

\dot{m} [kg/s]	N	T_{in} [°C]	ξ_{el}	ξ_{th}
0.0344	9	40	-0.1595	-0.0551
0.0367	1	21	-0.1883	-0.0120
0.0367	1	21	-0.1883	-0.0120
0.0306	1	22	-0.1869	-0.0157
0.0175	3	25	-0.1728	-0.0446
0.0294	2	22	-0.1834	-0.0249
0.0283	2	31	-0.1770	-0.0388
0.0242	2	27	-0.1786	-0.0355
0.0344	9	40	-0.1595	-0.0551
0.0144	1	27	-0.1796	-0.0329
0.0244	1	22	-0.1860	-0.0180
0.0269	4	31	-0.1710	-0.0477
0.0178	3	23	-0.1742	-0.0425
0.0336	1	21	-0.1880	-0.0127
0.0269	2	23	-0.1821	-0.0280
0.0289	1	30	-0.1810	-0.0308
0.0161	3	24	-0.1724	-0.0451
0.0311	7	40	-0.1613	-0.0549
0.0344	9	40	-0.1595	-0.0551
0.0367	1	21	-0.1883	-0.0120

high inlet temperature resulted in the lowest electrical exergy efficiency.

In Figure 12 the thermal exergy efficiency was the highest if the optimal solution had the high inlet temperature and high number of the PVT collectors in series.

The results revealed that the number of collectors in the set of optimal solutions varied from 1 to 9. The higher number of the collectors resulted in the higher thermal exergy efficiency and the lower number to the higher electrical efficiency. The Pareto

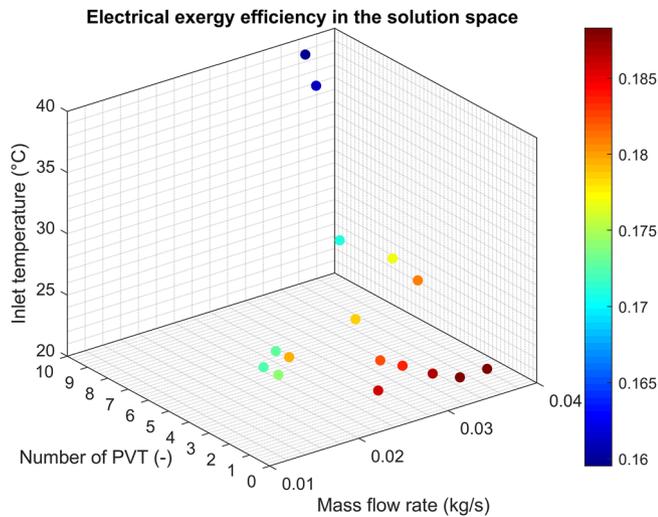


FIGURE 11 The set of optimal solutions from Table 3 in terms of the electrical exergy efficiency

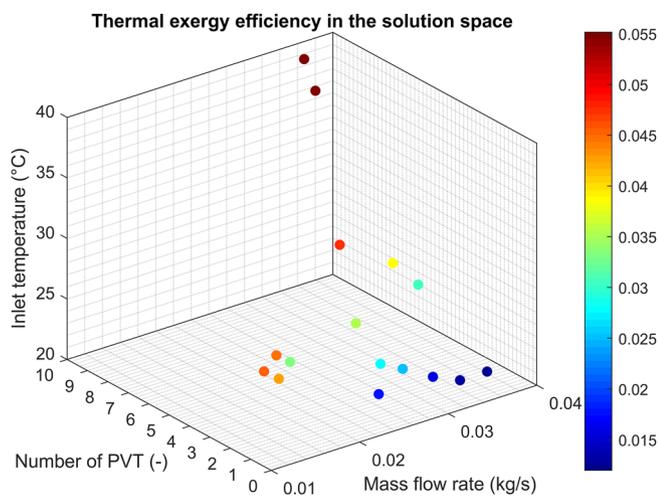


FIGURE 12 The set of optimal solutions from Table 3 in terms of the thermal exergy efficiency

front showed a trade-off of the different solutions in which the electrical exergy efficiency varied from 15.95% to 18.8% and the thermal exergy efficiency from 1.2% to 5.5%. If electricity production is the priority of operating the multi-stage PVT system, the decision-maker can select the solution with the higher electrical exergy efficiency by increasing the coolant mass flow rate and decreasing the inlet temperature. On the other hand, the higher thermal exergy efficiency can be achieved by increasing the number of the PVT collectors and increasing the inlet temperature. The Pareto front does not show a single optimal solution but a set of solutions presented in Figures 10–12 that can be used to help decision-makers to design the optimal multi-stage PVT system depending on the purpose.

Figure 13 presents the overall exergy efficiency of each solution in Table 3 according to Equation (17).

The overall exergy efficiency varied from 20.03% to 21.87% between the solutions. The results revealed a solution which

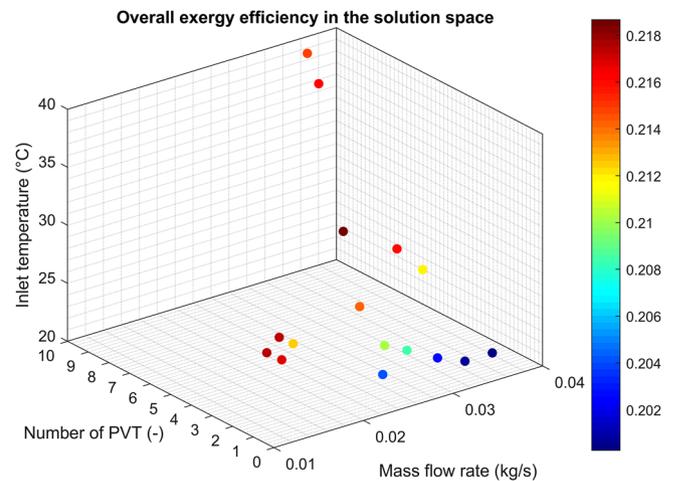


FIGURE 13 The set of optimal solutions from Table 3 in terms of the overall exergy efficiency

maximizes the overall exergy efficiency by having the inlet temperature of 31 °C, 4 collectors in series and the mass flow rate of 0.0269 kg/s. This solution results to electrical, thermal and overall exergy efficiencies of 17.1%, 4.77% and 21.87%, respectively.

The decision-making process is required to select the final optimal solution from the set of optimal solutions. A hypothetical point called an ideal point can be used to help the decision-makers [32]. At this point, marked in Figure 10, both objectives have their independent optimal values, but it is not a feasible solution in the multi-objective optimization and not located on the Pareto front. However, the final optimal solution might be the closest point of the Pareto front to the ideal point. In this case, Solution B in Figure 10 would be the final optimal solution if the decision-maker does not have any particular desire to maximize electrical or thermal exergy efficiency within the Pareto front optimal solutions. On the other hand, in the case of PVT collectors, the decision makers can select the final solution which maximizes the overall exergy efficiency showed in Figure 13. However, in this case, the ideal point method in Figure 10 did not result in the same solution but to the solution with only 0.3% lower overall exergy efficiency.

The optimization was performed under three different weather conditions cold, medium and hot to see an impact of the conditions on the Pareto optimal solutions. In Figure 14 are presented three Pareto fronts under different weather conditions.

Figure 14 shows that the set of optimal solutions was different depending on the weather conditions. In terms of exergy efficiency, it seems to be beneficial to select the number of PVT collectors in series depending on the weather conditions of the system location. However, the different Pareto fronts had also an area where they overlap each other. This combined area of the Pareto front rather maximizes the electrical exergy efficiency than thermal exergy efficiency within the objective space. The highest electrical exergy efficiency of 19.1% was reached under cold conditions and the highest thermal exergy efficiency of 7% was reached under hot conditions. The weather conditions had

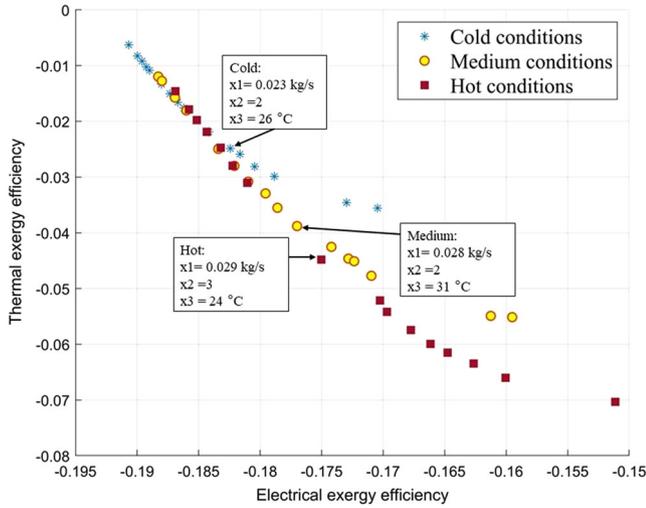


FIGURE 14 The Pareto optimal front for the electrical and thermal exergy efficiencies under three different steady-state weather conditions

an impact on the range of optimal solutions in the objective space. The cold conditions resulted in the smallest range while the hot conditions had the widest range.

By using the ideal point method of the decision making, the three final optimal solutions of each weather condition were selected and marked in Figure 11. The inlet temperature varied from 24 to 31 °C. The number of PVT collectors was decreased from 3 to 2 if the weather conditions were changed from hot to cold. The selected optimal solutions revealed that under the colder weather conditions the multi-stage PVT collector had better electrical performance compared to the optimal solution under medium and hot conditions. In this case, it can be reasonable to couple the multi-stage PVT collector with electric storage and use heat as a by-product. On the other hand, under hotter weather conditions the reasonable coupling application can be a heat-driven desalination system.

5 | CONCLUSION

In this paper, solar cogeneration based hybrid energy system was modelled into Matlab/Simulink environment. The parametric study was conducted and the optimal sizing problem was solved using NSGA-II algorithm. The ideal point method was used in the decision-making process to select the final optimal solution from the Pareto front for three different weather conditions.

The dynamic model of the water-based multi-stage PVT system was optimized using *gamultiobj*-function of Matlab Global Optimization Toolbox which is based on the fast elitist multi-objective optimization algorithm NSGA-II. The electrical and thermal exergy efficiencies were used as objective functions because of their trade-off nature in the PVT operation which leads to difficulties for decision-makers to select the electrical and thermal efficiencies and the design variables. In this study, the selected decision variables were the coolant mass flow rate, number of PVT collectors and coolant inlet temperature to

the system. The results showed that multi-objective optimization based on the genetic algorithm has a high potential when designing the multi-stage PVT system. The used multi-objective optimization approach finds the Pareto front which is a set of optimal solutions in the objective space. This set can be used by decision-makers to find the final optimal solution.

The main findings of the parametric study and multi-objective optimization were:

- Increasing the inlet temperature of the coolant fluid increased the thermal exergy efficiency but decreased thermal energy efficiency. The exergy approach revealed the hidden efficiency although the energy efficiency indicated inefficiency.
- Increasing the coolant mass flow rate increased the cooling effect and electrical exergy efficiency but decreased thermal exergy efficiency.
- Increasing the number of PVT collectors decreased the electrical exergy efficiency and thermal energy efficiency. However, the thermal exergy efficiency indicated the efficiency of the collectors in series by increasing until a certain point.
- Electrical and thermal exergy efficiencies of the PVT operation cannot be maximized at the same time. The multi-objective optimization based on NSGA-II is a suitable method to optimize PVT and multi-stage PVT system design.
- The Pareto optimal front can be used by the decision-makers to select a suitable optimal design of the multi-stage PVT system depending on the purpose and the weather conditions.
- The higher number of the PVT collectors in series resulted in the higher thermal exergy efficiency and the lower number to the higher electrical efficiency.
- The climate conditions had an impact on the optimal number of the PVT collectors in series. Under the cooler weather conditions, a smaller amount of the PVT collectors is recommended compared to warmer conditions.

In future work, the investigation of using the multi-objective optimization approach to the dynamic hybrid energy system including multi-stage PVT collector, thermal and electrical storage, electrical vehicle and demand-side will be conducted. The multi-stage PVT collector model will be developed to show the outlet temperature of each collector in series. Additionally, analysis and optimization of the flat plate multi-stage PVT collector coupled with concentrated PVT collectors would be interesting for future work.

NOMENCLATURE

- A PVT collector area (m^2)
- c specific heat (J/kg K)
- D diameter (m)
- Ex exergy rate (W)
- G solar irradiation density (W/m^2)
- H thickness (m)
- h heat transfer coefficient ($\text{W/m}^2\text{K}$)
- k thermal conductivity (W/mK)
- L tube length

m	mass, (kg)
\dot{m}	mass flow rate (kg/s)
N	number of collectors
r	packing factor
T	temperature (K, °C)
W	tube spacing
Greek symbols	
$(\alpha\tau)$	effective absorbance
α	absorbance
ε	emissivity
ζ	exergy efficiency
η	efficiency
ρ	density (kg/m ³)
τ	transmittance
Subscripts	
0	reference
a	absorber
adh	adhesive layer
c	collector
CD	conduction
CV	convection
d	destruction
e	environment
el	electrical
f	fluid
g	glass cover
in	inlet
irr	irradiation
o	outer
out	outlet
pv	photovoltaic
ref	reference
sol	solar
STC	standard test conditions
t	tube
th	thermal

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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