Energy and Exergy Performance investigation of Nanofluid-based Concentrated Photovoltaic / Thermal-Thermoelectric Generator (NCPV/T-TEG) hybrid system

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Summary: Nanofluid can be used in a CPV/T solar collector to boost electrical and thermal performances as this technology has drawn great attention of researchers over the last decades. In a CPV/T system, the amount of collected heat could be significantly higher than the amount of electrical power. Combining TEG and nanofluid-based CPV/T system may result in better electrical performance than CPV/T system alone. In the present work, a nanofluid-based CPV/T-TEG hybrid system with cooling channel was designed and tested, and the obtained performance was compared with conventional cooling methods (i.e. natural cooling (CPV/TEG) and water cooling (WCPV/T-TEG) methods). At the optimum value of solar concentration, C=14.6 , the electrical performance of the NCPV/T-TEG configuration was found to be ~89 % higher that the standard PV modules. For the same concentration, the electrical performance of the above configuration was found to be ~ 13.9% and ~8.4% higher than CPV/TEG and WCPV/T-TEG configurations, respectively. In addition, the overall thermal energy of the NCPV/T-TEG was found to be higher by 4.98 % compared to WCPV/T-TEG hybrid system. The NCPV/T-TEG configuration was found to produce 92.47% ,41.06%, and 8.8 % higher daily exergy compared to standard PV cell, CPV/TEG, and WCPV/T-TEG, respectively. Overall, the proposed design of the NCPV/T-TEG hybrid system has potential for further development in high-concentration solar systems.

KEYWORDS: Concentrated PV; Thermoelectric; Nanofluid; Solar hybrid system; Energy conversion efficiency.

List of Symbols and Abbreviations

A	area, m^2
C	solar concentration
C_p	The specific heat of the nanofluid, $J.K^{-1}.kg^{-1}$
G	solar radiation, Wm^{-2}
I_{mp-TEG}	The maximum current that generated by the TEG generator, A
I_{mp-pv}	The maximum current that generated by the PV cell, A
$\dot{m}$	mass flow rate, $kg.s^{-1}$
P_{TEG}	The electrical energy generated by the TEG generator, W
P_{PV}	The electrical energy generated by the PV module, W
P_{HYB}	The maximal electrical power generated by the hybrid system, W
Q_{th}	The collected useful heat, W
$T_{n,in}$	The temperature of the input working fluid, ˚C
$T_{n,out}$	The temperature of the output working fluid , ˚C
U_{mp-TEG}	The maximum voltage generated by the TEG generator, V
U_{mp-pv}	The maximum voltage generated by the PV cell, V

Greek symbols

ΔT	Temperature gradient, ˚C
η	Efficiency.
Ø	Volume fraction.

Subscripts

n	nanofluid
am	ambient
el	Electrical
th	Thermal

Abbreviations

PV	Photovoltaic
TEG	Thermoelectric Generator
CPV/TEG	Concentrated Photovoltaic/Thermoelectric Generator
WCPV/T-TEG	Water-based Concentrated Photovoltaic/Thermal-Thermoelectric Generator
NCPV/T-TEG	Nanofluid-based Concentrated Photovoltaic/ Thermal-Thermoelectric Generator

1. INTRODUCTION

The limitation of fossil energy resources and increase in greenhouse gas emissions related to human activity have led to the emergence of other forms of energy. Solar energy can be considered as an option among other energy resources because it is clean, cheap, sustainable, environmentally friendly, and easy to convert into other practical forms of energy, i.e. electrical or thermal energy. According to the Global Trends in Renewable Energy Investment report 2018 [1], solar energy dominated global investment in new power generation like never before in 2017. This was because the annual investment in solar energy was more than 18% compared to other sources of energy like renewables, fossil fuel, or nuclear. According to the Renewables 2019 Global Status Report [2], the world installed a record 100 GW of new solar capacity in 2018. This increased the overall total PV electrical power to 505 GW by the end of 2018.

The efficiency of photovoltaic (PV) cells and panels can be influenced by external weather conditions, i.e. ambient temperature, wind velocity, and irradiance intermittence. In fact, the solar spectrum is distributed across wavelengths ranging from the near-UV to the far-IR. The PV cells are able to convert only limited range of light wavelengths to electrical energy. Radiation energy outside this range becomes heat [3], which could decrease the efficiency of the PV cell at elevated temperature. This consequently reduces the overall energy conversion efficiency of the PV panel. Concentrator photovoltaics (CPV) is an alternative technology that concentrates the solar light in a small area to increase the incident energy density, which results in high efficiency. Consequently, it may reduce electricity and manufacturing costs by using a lower semiconductor material requirement [4]. However, ~60% of the incident solar energy is still dissipated as heat, and costs of the CPV need to be lowered as much as possible in order to be competitive with the standard PV system [5]. Under high solar concentration, the PV cell temperature rises rapidly, which is undesirable as it degrades the PV cells' performance drastically. With the aim to create efficient solar energy conversion, several researchers have proposed approaches to harvest electricity and heat simultaneously in PV technology by incorporating several engineering optimizations. For this reason, the researchers proposed the use of CPV/T as a hybrid system under different configurations like conventional solar collector "thermally coupled design" [6], solar collector with optical filter, "the volumetric-absorber design" [7,8] or thermally coupled design and the volumetric-absorbed design in one combined system [9,10,11]. Other researchers proposed to combine the thermoelectric generator (TEG) and the PV module in one system to increase electrical energy [12,13,14]. The TEG module acts as a second power generator to boost the overall electrical power generation of the PV/TEG system. However, in conventional PV/TEG hybrid system, the TEG generator may generate small power due to its poor energy conversion efficiency under low temperature gradient [15]. Indeed, most of the cooling methods in PV/TEG hybrid systems use heat sink, where the heat transfer coefficient in the heat sink reaches its optimal value during windy days only.

The feasibility of using solar concentrator in PV/TEG hybrid system might enhance the overall electrical performance to some extent [16,17]. However, concentrated PV/TEG may fail at high concentration ratio due to the low thermal conductivity of the TEG generator, and low performance of the cooling system (it generally uses natural cooling). For these reasons, the overall electrical performance of the PV cell will drop. Moreover, since a TEG generator shares a small amount of electrical energy, the overall performance of the CPV/TEG hybrid system will decrease as well. Consequently, the extra cost of the TEG generator and its cooling process result in ineffective energy production cost against the standard PV system [18,19]. Therefore, it is obvious that in order to come out with a more competitive CPV/TEG hybrid system, the heat transfer rate of the TEG's cold side need to be improved.

Several studies used water for cooling the back side of the TEG generator to boost the overall performance of the CPV/TEG hybrid system [20,21,22,23,24]. Abdo et al.[23] developed a new configuration of a concentrated PV/TEG hybrid system integrated with a microchannel heat sink in the sandwich design, in which the microchannel was installed between the PV cell and TEG cold side to cool both the PV and TEG cold side simultaneously. The authors found that the proposed system performed better compared to the conventional system. Under solar concentration ratio of 20X, the overall electrical and thermal output was approximately 3.2 kW/m^2 and 30 kW/m^2, respectively. Moreover, the average operating PV cell temperature was about 77°C. Mahmoudinezhad et al.[20] investigated numerically and experimentally the performance of a PV/TEG hybrid system under a low solar concentration ratio. The experimental study was established under a low light concentration of solar simulator. The hybrid system contained a PV cell type GaInP/GaInAs/Ge coupled with a TEG generator type Bi_2Te_3, and a heat exchanger with water was placed under the TEG cold side. The mass flow rate of the operating water was maintained constant around 5 L/min. At solar concentrations from 8 to 37 times, the obtained CPV efficiency was 35.33% and 23.02%, respectively, while the TEG efficiency was 0.63% and 1.2% corresponding to the minimum and maximum values of the solar concentration value, respectively.

Mahmoudinezhad et al.[24] investigated experimentally and numerically the transient behavior of a concentrated triple-junction PV/TEG hybrid system under different values of solar concentrations. The experimental study was established under a light concentration of solar simulator and the COMSOL Multiphysics modelling software was used for the numerical study. The mass flow rate of the operating water was maintained constant around 5 L/min. The result indicated the impact of solar radiation variation on the triple-junction solar cell and TEG generator, in which the obtained power by the PV cell changed very fast and followed the solar concentration trend. Moreover, the variation of the produced power by the TEG almost followed the temperature variation. The authors also indicated that the use of the TEG generator in the PV/TEG hybrid system produced a stable power. However, the purpose of these PV/TEG hybrid systems was to produce electricity only and the collected heat was unused. This would reduce the global energy conversion efficiency of the hybrid system.

Recently, researchers have proposed the combination of TEG generator and CPV/T solar collector to raise the overall electrical energy and collect heat as a useful energy. PV/TEG/SC (photovoltaic panel/thermoelectric generator/solar collector) hybrid systems were studied under natural and concentrated light [25,26]. Sripadmanabhan Indira et al.[27] reviewed a various integration options of the CPV-TEG system available in the literature including CPV-TEG with a spectral beam splitter, CPV/thermal-TEG, and CPV-TEG with phase changing materials. Authors found that the integrated CPV-TEG based solar thermal systems have higher electrical and thermal performances than that of non-concentrated PV-TEG systems. Mohsenzadeh et al. [25] established a novel CPV/T-TEG hybrid system to improve the overall system efficiency, where a parabolic concentrator was utilized to concentrate the sun radiation. Water was used as the working fluid. The total efficiency of the CPV/T-TEG system was found to be 60% and 47.30% with and without cover glass, respectively. The proposed hybrid system produced a high rate of thermal energy compared to the electrical energy, in which about 90.53% of the total produced power represented the thermal performance, and only around 9.47% represented the electrical performance. On the other hand, the TEG generator produced 3.3% of the overall electrical performances. Soltani et al.[26] investigated numerically a new cylindrical CPV/TEG system operated under the parabolic trough collector. Water was used as the working fluid with a mass flow rate of 0.03 kg/s. The simulation results revealed that the hybrid system produced 22.714 W of electrical power, while only 2.3 W of the overall electrical power was produced by the TEG generator. However, the PV/TEG hybrid system through parabolic collector had a small absorber area with a single tracking rotation. Consequently, the optical loss could become significant. In addition, the use of water as the cooling fluid had thermal performance limitations due to its low thermophysical properties, particularly under high working temperature.

Recently, the development in nanomaterial science has opened a new axis of research on the use of nanoparticle in many areas, particularly in cooling electronic devices. Researchers have proposed the use of nanofluids as effective heat removal fluids in the field of solar collector system due to their superior thermal properties that can improve the convective heat transfer coefficient. A summary of these works is available in the review papers published by Yazdanifard et al.[28], Said et al.[29], Shah and Ali [30], and Goel et al.[31].

Jia et al.[32] analyze numerically the performances of PV/T collector using nanofluid. The effects of nanofluid type, volume concentration, and PV collector parameters on the PV conversion efficiency, PV cell temperature, thermal and electrical power were investigated. The authors found that the performances of the PV/T collector using Al2O3/water nanofluid were better than those of the PV/T collector using TiO2/water nanofluid. Under nanofluid mass flow rate of 0.03 kg/s, the electrical and thermal power of the PV/T collector were much higher than those of the PV/T collector when the mass flow rate of nanofluid was 0.0005 kg/s. As the channel height reduced, the heat removed by the nanofluid from the PV/T collector grew; the PV/T collector produced approximately 24.00 W of thermal power difference between 0.005 m and 0.015m tube diameter. Motamedi et al.[33] developed a new hydrophobic microchannel PV/T configuration that combined the benefits of these micro- and nanotechnologies with minimal pumping power requirements. In which the performances are experimentally investigated the use of nanofluids in patterned hydrophobic microchannels. The result showed that slip with the walls minimized the effect of increased nanofluid viscosity by raising the smooth channel pressure drop to an average of 17%. In addition, the flow of a selective Ag/SiO2 nanofluid over a silicon surface resulted in a 20% improvement in solar thermal conversion efficiency and a ~3% higher stagnation temperature than pure water usage. Salari et al. [34] developed a three-dimensional (3D) PV/T system integrated with phase change material system with nanofluids. The performances of the proposed hybrid system were investigated by using three different working nanofluids, namely nano-magnesium oxide, multiwall carbon nanotube, and hybrid (mixture of nano-magnesium oxide and multiwall carbon nanotube). The result showed that the use of multiwall carbon nanofluid only reduced the surface temperature of the system by 0.3°C, with an increase in mass fraction from 3% to 6%. The multiwall carbon nanofluid had the highest overall energy efficiency, whereas magnesium oxide nanofluid had the lowest. Moreover, the total energy performance of the device with working water fluids, magnesium oxide nanofluid, multiwall carbon nanofluid, and hybrid nanofluid for a mass fraction of 6% wt was 55.24%, 60.08%, 61.07%, and 60.66%, respectively.

Using nanofluid as a coolant in the CPV/TEG hybrid system is one of the strategies to further improve the performance of hybrid generator. Wu et al.[35] established a theoretical model to assess the performance of glazed/unglazed CPV/TEG systems and nanofluid was adopted as the coolant to enhance heat removal. The authors found that the nanofluid enhanced the system efficiency in comparison with water, and the improvement was more significant for the glazed system. Soltani et al.[36] investigated experimentally the performances of PV/TEG hybrid system with five different cooling techniques, namely natural, forced air, water, SiO_2/water, and Fe_3O_4/water cooling modes. The results showed that the water cooling method produced 47.7% more power compared to the natural cooling method. Moreover, the SiO2/water nanofluid cooling yielded 54.29% and 3.35% power and efficiency improvement, respectively, compared to natural cooling. Besides, Fe_3O_4/water nanofluid cooling showed 52.40% and 3.13% enhancement in power production and efficiency, respectively, compared to natural cooling. The nanofluid-based method had an average improvement of 5.7% in power production compared to the pure water cooling method. Nonetheless, the concentration system was not considered in the experiment. It is important to note that the objective of Soltani's work was to boost the overall electrical performance of the hybrid system by using nanofluid as a coolant. However, the assessment of thermal energy was not included in the manuscript. In the energy conversion point of view, this "missed" energy reduces the overall efficiency of the system. On other hand, the daily exergy analyses of the proposed system by using a different cooling mode were not considered as well.

Rajaee, et al.[37] investigated experimentally the performances of a PV/TEG hybrid system using six cooling methods including water and 0.25%, 0.5%, and 1% nanofluid flow, and 1% nanofluid flow with pure PCM and PCM with alumina powder. The obtained result indicated that the electrical performances of hybrid system using Co3O4/water nanofluid with 1% nanoparticle concentration were improved by 10.91% compared to water. In addition, the overall electrical efficiency of the proposed system improved by 4.52% with the use of both PCM and 1% nanofluid. In terms of exergy efficiency, the proposed hybrid system performed better using nanofluid 1% and PCM/alumina powder compared to the other cooling methods. However, the concentration system was not considered in the experiment.

In our previous published modeling study by Lekbir et al.[38], a novel design of nanofluid-based CPV/T-TEG hybrid system was proposed to convert heat generated by a PV cell to electrical and thermal energy in order to improve the overall performance of the proposed hybrid system. Based on the theoretical finding, the electrical energy of the proposed NCPV/T-TEG was improved by ~10%,~47.7%, and ~49.5% compared to NCPV/T (nanofluid-based concentrated photovoltaic/thermal), CPV (concentrated photovoltaic), and CPV/TEG (concentrated photovoltaic/thermoelectric generator) systems, respectively. Moreover, the NCPV/T-TEG configuration could harvest 2.87 kW of thermal energy and approximately 2.3 kWh of exergy daily.

To the best of the authors' knowledge, currently there is no experimental study investigating the feasibility of using nanofluids in the cooling process of a concentrated photovoltaic/thermal-thermoelectric (NCPV/T-TEG) hybrid system. Therefore, in this work, we present an outdoor experimental study to investigate the performance of the proposed NCPV/T-TEG configuration by using carbon nanotube nanofluid (CNT-H_2O) based coolant with a low volume fraction. Furthermore, a comparison between the obtained experimental results from the NCPV/T-TEG configuration against the standard PV cell, concentrated PV/Thermoelectric generator under natural cooling (CPV/TEG), and water-based concentrated PV/thermal-thermoelectric generator under water cooling mode (WCPV/T-TEG) is presented.

2. METHODS

The main objective of this experimental study is to investigate the performance of the NCPV/T-TEG hybrid system. The following subsections are different methods opted to assess the instant thermal and electrical performances of the hybrid system, i.e. voltage, current, and the working temperatures.

2.1 Electrical and thermal efficiencies models

The NCPV/T-TEG hybrid system consisted of two electrical devices for electricity production, namely PV cells and TEG generator, and a thermal unit was used to collect the excess heat from the TEG generator during the cooling process using CNT-H2O working fluid. The overall electrical power generated by the proposed NCPV/T-TEG hybrid system can be expressed as follows [39]:

$$P_{HYB} = P_{PV} + P_{TEG} \quad (1)$$

Where P_{PV} is the output electrical power of the PV module, It can be expressed as follow:

$$P_{PV} = I_{mp-PV} \times U_{mp-PV} \quad (2)$$

Where I_{mp-PV} and U_{mp-PV} is the maximum current and the voltage that can be collected from the PV cell during the testing time.

The P_{TEG} is the output electrical power of the TEG generator, and it is determined using Eq. (3):

$$P_{TEG} = I_{mp-TEG} \times U_{mp-TEG} \quad (3)$$

Where I_{mp-TEG} and U_{mp-TEG} is the maximum current and the voltage that generated by the TEG generator.

The collected useful heat from the TEG back side can be determined as follow:

$$Q_{th} = \dot{m}\, C_p (T_{out} - T_{in}) \quad (4)$$

Where $\dot{m}$ is the mass flow rate, C_p is the specific heat of the working fluid (i.e. water or nanofluid) and T_{in} and T_{out} are the temperatures of the input and the output working fluid, respectively.

The electrical efficiency of the PV cell and the TEG generator, η_{PV} and η_{TEG} respectively, are directly depended to the intensity of solar radiation, concentrator ratio and PV cell area. These can be calculated as follow:

$$\eta_{el} = \frac{P_{PV} + P_{TEG}}{C \times A \times G} \quad (5)$$

The thermal efficiency of the WCPV/T-TEG and NCPV/T-TEG system can be given as below [11]:

$$\eta_{th} = \dot{m} \frac{cp\ (T_{out} - T_{in})}{C \times A \times G} \quad (6)$$

Where C is the solar concentration, A is the area of the PV cell and G is the solar irradiation.

2.2 Overall exergy analysis

Exergy analysis is a useful tool to assessing the merits of energy conversion in the system. While energy analysis provides only quantitative analysis of the energy, Exergy analysis provides both quantitative and qualitative analysis of energy that obtained from the system. Exergy is the overall working capacity that can be extracted from the device and indicates the quality of energy [40]. For the solar harvesting devices such as PV, thermal collector, PV/T system, the input exergy amount is only the radiation intensity obtained from sunlight and the exergy concept is the maximum amount that of the solar energy converted into useful work (i.e. electricity or thermal)[41]. However, Electrical and thermal energy have different quality grades [11]. Electrical energy is a high-grade energy and $1W$ of electrical power is similar to $1W$ of electrical exergy. While the amount of thermal energy is always lower than its exergy especially at low temperature application [42].

Exergy analysis for the solar harvesting devices is conducted considerably especially in the PV/T hybrid system. However, Exergy analysis of the PV/TEG hybrid system has a low degree of exposure in the literature compared with other solar harvesting devices [43]. Therefore, in this work, the exergy analysis of the proposed hybrid system is evaluated experimentally. The obtained result is presented and compared with conventional systems.

The exergy efficiency for NCPV/T-TEG configuration can be calculated by Eq. (7) [11]:

$$\eta_{ex} = \eta_{el} + K(1 - \frac{T_0}{T_{out}})\eta_{th} \tag{7}$$

Where $(1 - \frac{T_0}{T_{out}})$ is the Carnot efficiency and K is the fraction of thermal energy converted to electrical output. It should be noted that the exergy factor of solar radiation is taken into consideration during the exergy efficiency calculation for NCPV/T-TEG system. In which the exergy factor of solar radiation equal to 0.93[11,44,45]

2.3 Material and design description

The experimental setup is presented schematically in **Fig. 1**. The sunlight was concentrated onto a small solar PV cell. On the back side of the cell, a TEG generator was installed to convert the generated heat by the PV cell into electricity. The TEG cooled down by means of CNT-H_2O coolant nanofluid. The hybrid system was maintained permanently perpendicular to solar radiation, and the experimentation was carried out under clear sky only. It was observed the system was not practical during cloudy conditions.

The NCPV/T-TEG hybrid system was designed by using the Blender 3D software. The sun tracking system was considered in three directions through x, y, and z axes, in which the PV/TEG and lens were fixed in a moving box that could provide tracking of the sun's direction by an angle of 180° through the x and y axes. In addition, a tracker frame was used to follow the sun's direction, in which this base provided the sun tracking by an angle of 360° through the x and z axes. It should be noted that the tracking system was controlled manually.

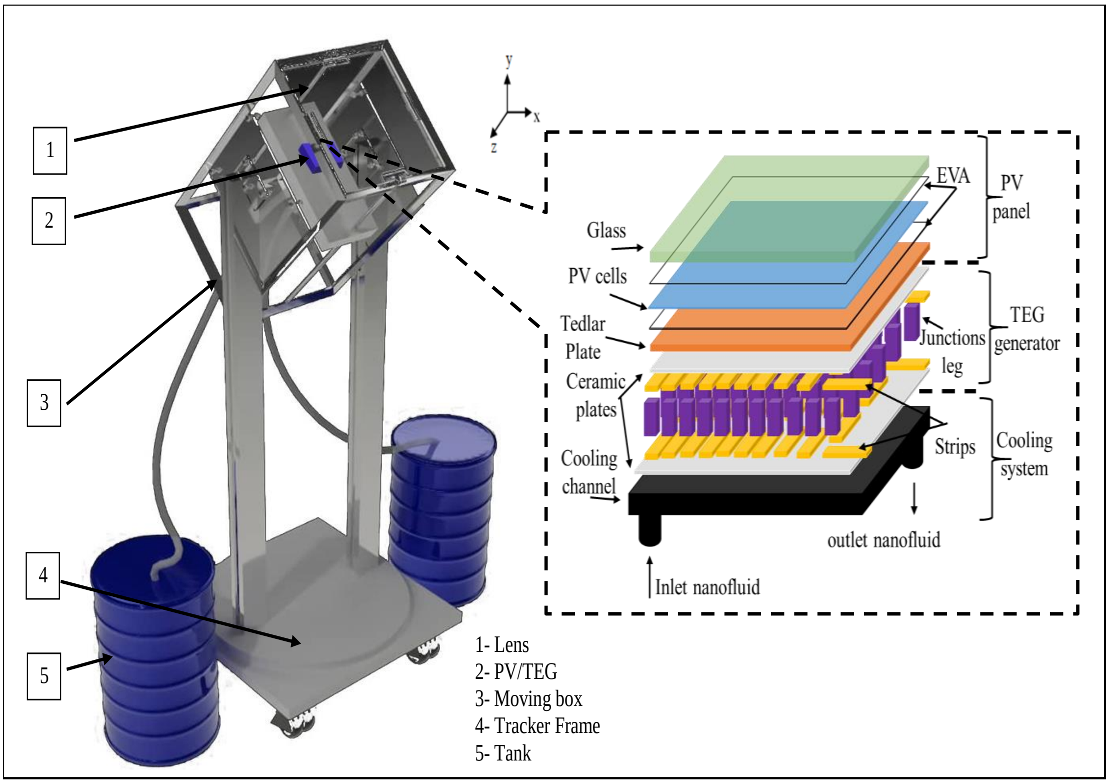

Figure 1: The proposed design of the NCPV/T-TEG by using Blender 3D software.

2.4. Nanofluid preparation

The CNT and graphene nanofluids are among the best nanofluids coolant with good thermal performance compared to other types of nanofluids [46,47] due to the excellent thermophysical properties of the CNT and graphene nanoparticles. In this work, CNT nanoparticles were selected and dispersed in distilled water with 0.1% concentration by weight. The sonication process of large quantity of nanoparticle with large volume of pure water cannot be achieved in a single process, otherwise, the stability and thermal performance quality of the nanofluid will be deteriorated. For this reason, 1l of distilled water was divided into 10 portions of 100 ml and 100 mg of CNT nanoparticles were dispersed in each sample. By using an ultrasonicator bath (POWERSONIC 410), the nanofluid samples were exposed to ultrasonication process for 30 min, as depicted in **Fig. 2**.

A DLS analysis of CNT nanofluid was performed at the Research Center for Nano-Materials and Energy Technology (RCNMET), Sunway University, using Litesizer 500 Anton Paar to analyse the size distribution of CNT nanoparticles in pure water. The results obtained are shown in **Fig. 3**.

Figure 2: Nanofluid preparation steps.

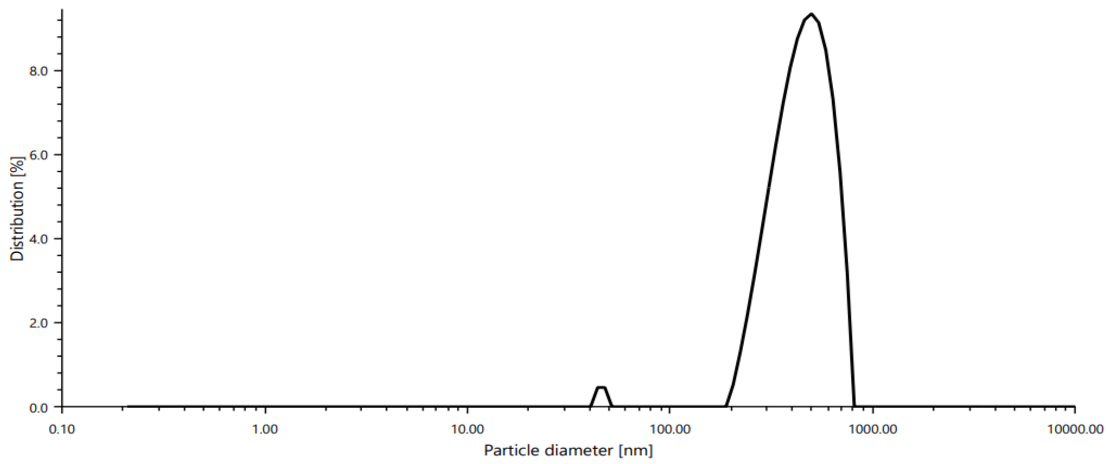

Figure 3: Particle size distribution of CNT Nanofluid

2.5. Experiment set up

Fig.4 shows the experimental setup of the NCPV/T-TEG. Combined electrical output power of PV/TEG and collected heat from the back side of TEG generator were assessed as the overall performance. In order to evaluate the compatibility of the proposed hybrid system, the performance of the latter was compared with the performance of other configuration systems, namely standard PV cell, CPV/TEG system, and WCPV/T-TEG hybrid system.

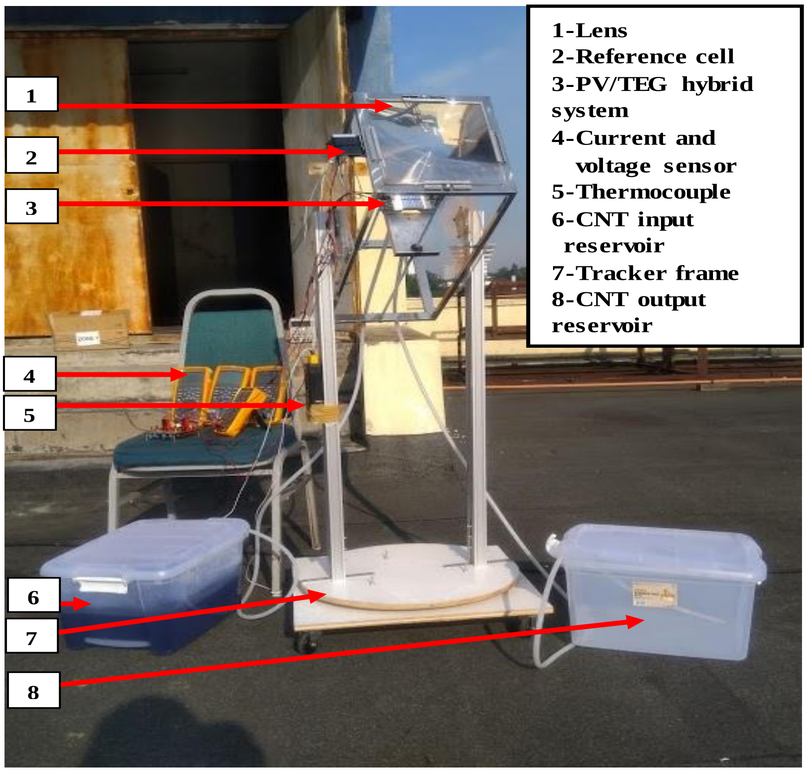

Figure 4: The experimental set up of the NCPV/T-TEG.

The experimental setup included a solar concentrator lens (CP300-230(CPV, F=300 mm)) with dimensions of 238 mm×238 mm (for more details see **Table 1**), a monocrystalline solar cell (STAR SOLAR cnc55x55-4) of the size 55 mm×55 mm, and a commercial thermoelectric generator (TEG1-199-1.4-0.5). The characteristics of the PV cell and TEG generator are given in **Table 2 and Table 3**, respectively.

The Fresnel lens's manufacture provides a focal length of 300 mm when the target is at the size of a dot. However, in our case study, the target was a PV cell with an area 30.25 cm^2. Therefore, the position of the concentrator to the PV cell needs to be adjusted to widen the focal point and cover the entire PV cell surface. Therefore, the focal length was adjusted to 270 mm with the resulting concentration, C=14.

Table 1: Lens characteristics

Parameter	Value
Focal Length	$270\ mm$
Size	$238 \times\ 238\ mm$
Groove Pitch	$0.5\ mm$
Thickness (mm) :	$3.5\ mm$
Material	PMMA
Concentration	14

Table 2: PV cell characteristics

Parameter	Value
Material	Silicon
Maximum current	$60\ mA$
Maximum voltage	$4\ V$
Maximum power	$0.24\ W$
Dimension	$55 \times 55\ mm$
Thickness	$4\ mm$

The mini PV module consisted of six monocrystalline PV cells, connected in series, and attached to a copper sheet on the back side and covered by using a silicone resin. To ensure a good thermal connection between the PV, TEG, and cooling pipes, a heat conductive glue was used. To circulate the working fluid (either water or nanofluid), a small pump was used. The technical characteristics of the pump are given in **Table 4**.

Table 3: TEG generator characteristics

Parameter	Value
Material	Be_2Ti_3
Dimension	$40 \times 40 \times 4.2\ mm$
P/N junction cross-sectional area size	$1.4 \times 1.4\ mm$
P/N junction height	$0.5\ mm$
Output current	$1.8\ A$
Open circuit voltage	$11.1\ V$
Output power	$10\ W$
Temperature gradient	120 °C
Heat flux density	$12\ W/cm^2$

Table 4: Brushless DC pump characteristics

Model	$QR30A - 1230$
H_{max}	$300\ cm$
Q_{max}	$240\ L/h$
Maximum Input DC power	$4.8\ W$
Maximum Input voltage	$12\ V$
Maximum liquid temperature	$60\ ^{\circ}C$

2.6. Data collection

The experiment was carried out under tropical weather conditions, at the rooftop of the Engineering Faculty, University of Malaya. A set of sensors and K-type thermocouple were connected to a data logger to measure different parameters, i.e. wind speed, solar radiation, ambient temperature, and TEG, PV cells, and nanofluid temperature. The interval time between two successive measurements was set to 5 min. The open circuit voltage, short circuit current, and resulting electrical power from PV cell and TEG module were measured using four Fluke 289 True-RMS multimeters. Details of the equipment used are summarized in **Table 5**.

Table 5: Measurement apparatus specific data

	Device type	Measurement accuracy
Multimeter-voltage	Fluke 289 True rms Multimeter	0.025 % for DC voltage
Multimeter-current	Fluke 289 True rms Multimeter	0.05 % for DC current
Irradiation sensor	sunny sensor box	$\pm 8\%$
Wind speed sensor	Clima wind sensor	$\pm 0.5\ m/s$
Ambient temperature sensor	TEMPSENSOR-AMB	$\pm\ 0.5\ ^{\circ}C$
Thermocouple	k-types	± 1°C
Temperature record device	Digital thermometer	$\pm$(0.015% rdg + 1°C/1.8°F)

3. RESULTS AND DISCUSSION

The thermal and electrical performances of the proposed NCPV/T-TEG hybrid system using CNT-H_2O coolant are presented and discussed in the following sections. It is worth to note that the prototype was tested under three cooling operating scenarios, i.e. natural (CPV/TEG system), water-based (WCPV/T-TEG system), and the proposed configuration. In addition, the proposed hybrid system was compared under similar working conditions against the standard PV module of the same size (denoted as PV-ref in the manuscript).

3.1 Outdoor operating conditions

The overall performance of the prototype under different operating scenarios was dependent on the variation in weather conditions. Different operating scenarios were carried out on different days. Due to the nature of the tropical weather (mostly cloudy and rainy), more than four months were spent to finalize the data collection for all operating scenarios. Although tests were ran at different days, only similar days' weather conditions were used for the comparative study. It is worth to note that the experimental section was the most challenging task of the present work due to sudden and unexpected change in weather conditions. It is also worth mentioning that the WCPV/T-TEG cooling mode was tested on 23/01/2019, the CPV/TEG cooling mode was tested on 15/03/2019, and the NCPV/T-TEG cooling mode was tested on 15/04/2019.

The solar radiation intensity is the main parameter that significantly affects the production of energy in any solar technology system. In this work, the solar radiation values are presented in **Fig.5**. The daily average solar radiation for the three operating configurations (i.e. CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG) was ~665 Wm^{-2}, ~700 Wm^{-2} and ~674 Wm^{-2}, respectively. **Fig. 6** shows the instantaneous value of the ambient temperature. It can be seen that the temperature is gradually increasing by a narrow margin during the day. In addition, the daily average ambient temperature was reported to be ~33°C for the water-based cooling mode and ~34°C for the natural and CNT nanofluid based cooling modes. The instantaneous values of wind speed are depicted in **Fig. 7**, where the daily average value of the wind speed is ~0.69 m/s, ~2.31 m/s, and ~1.21 m/s for the natural, water, and CNT nanofluid based cooling modes, respectively. It should be noted that the average operating conditions, the obtained electrical and thermal performances, and the daily exergy referred to the testing period of five and half hour.

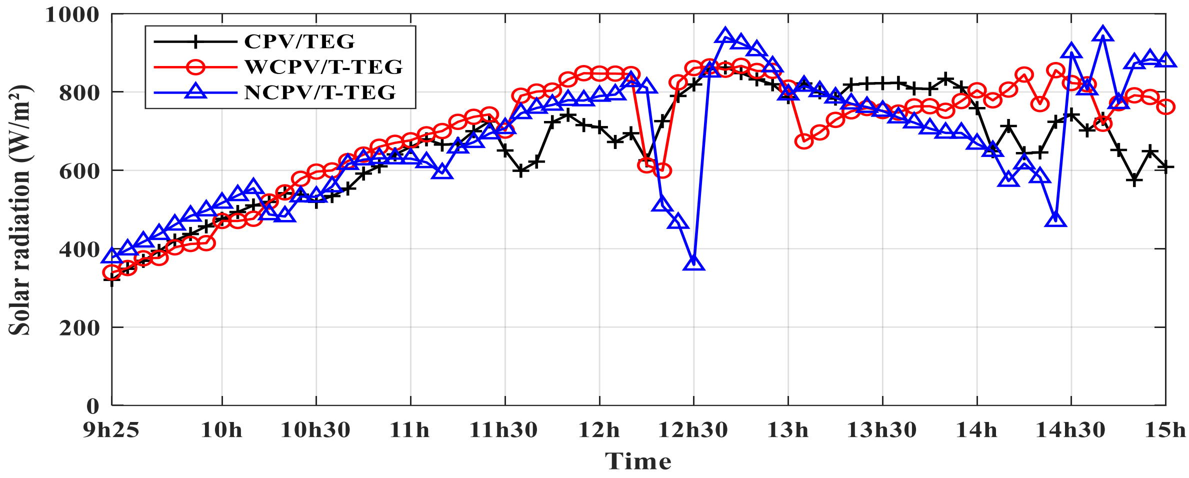

Figure 5: Solar radiation during the testing days for the different configurations.

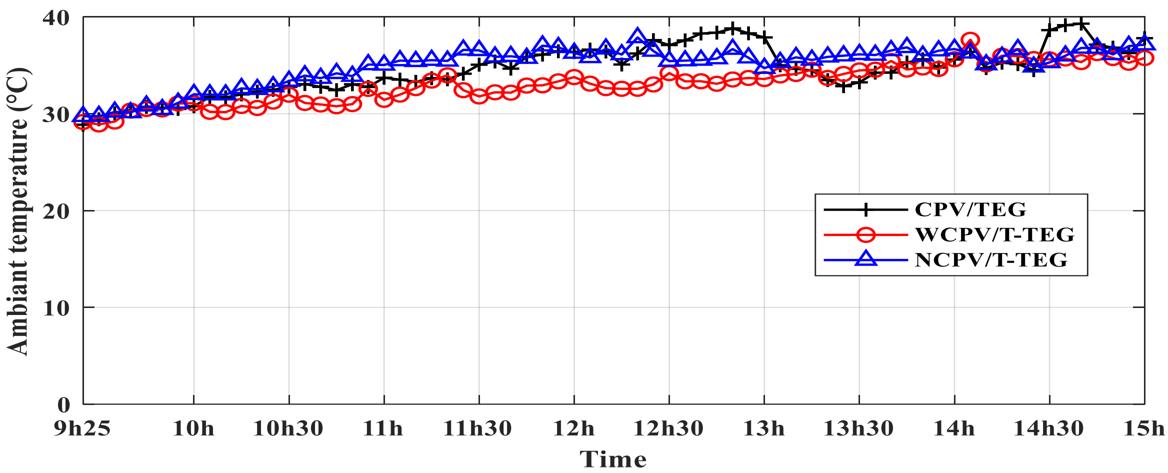

Figure 6: Ambient temperature during the testing days for the different configurations.

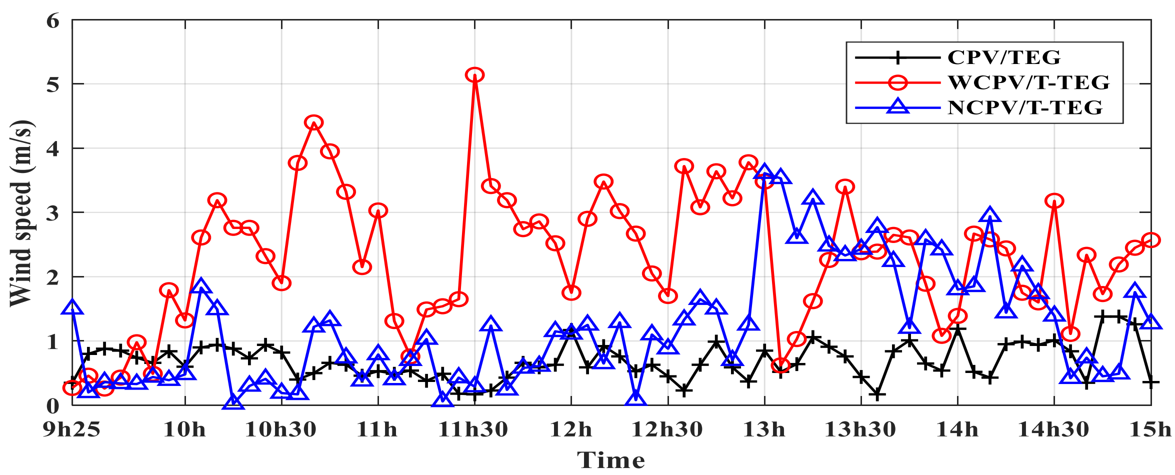

Figure 7: Wind speed during the testing days for the different configurations.

3.2 PV cell performance

This section is devoted to analyze the effects of outdoor conditions, solar concentration ratio, and cooling method on the temperature of PV cells, open circuit voltage, and electrical power for four tested configurations. The configurations were: (i) standard PV cells (i.e. PV-ref), (ii) CPV/TEG, (iii) WCPV/T-TEG, and (iv) NCPV/T-TEG.

Fig. 8 shows the surface temperature of the PV cell. It can be seen that in most cases, the standard PV cells temperature is lower than that of the configurations with a concentrator. In addition, when the concentrator is applied, the temperature of the PV cells in CPV/TEG configuration (the natural cooling method) is higher than other configurations. This is because the heat sink used in the CPV/TEG has a low heat transfer coefficient compared to water in the WCPV/T-TEG and CNT nanofluid in NCPV/T-TEG configurations. It was noticed that the temperature of PV cells in the WCPV/T-TEG configuration was almost similar to the temperature of PV cells in the NCPV/T-TEG configuration. This was due to the higher wind speed during the day for the configuration with water cooling (see **Fig. 7**). This increased the convective effect between the PV cell and the surrounding environment. It was also noted that the temperature of PV cell in the NCPV/T-TEG configuration was the highest (around 13:30) compared to other configurations, even though the wind was higher for NCPV/T-TEG, the solar radiation was higher for CPV/TEG, and the ambient temperature was almost the same. This was because the pump stopped working momentarily.

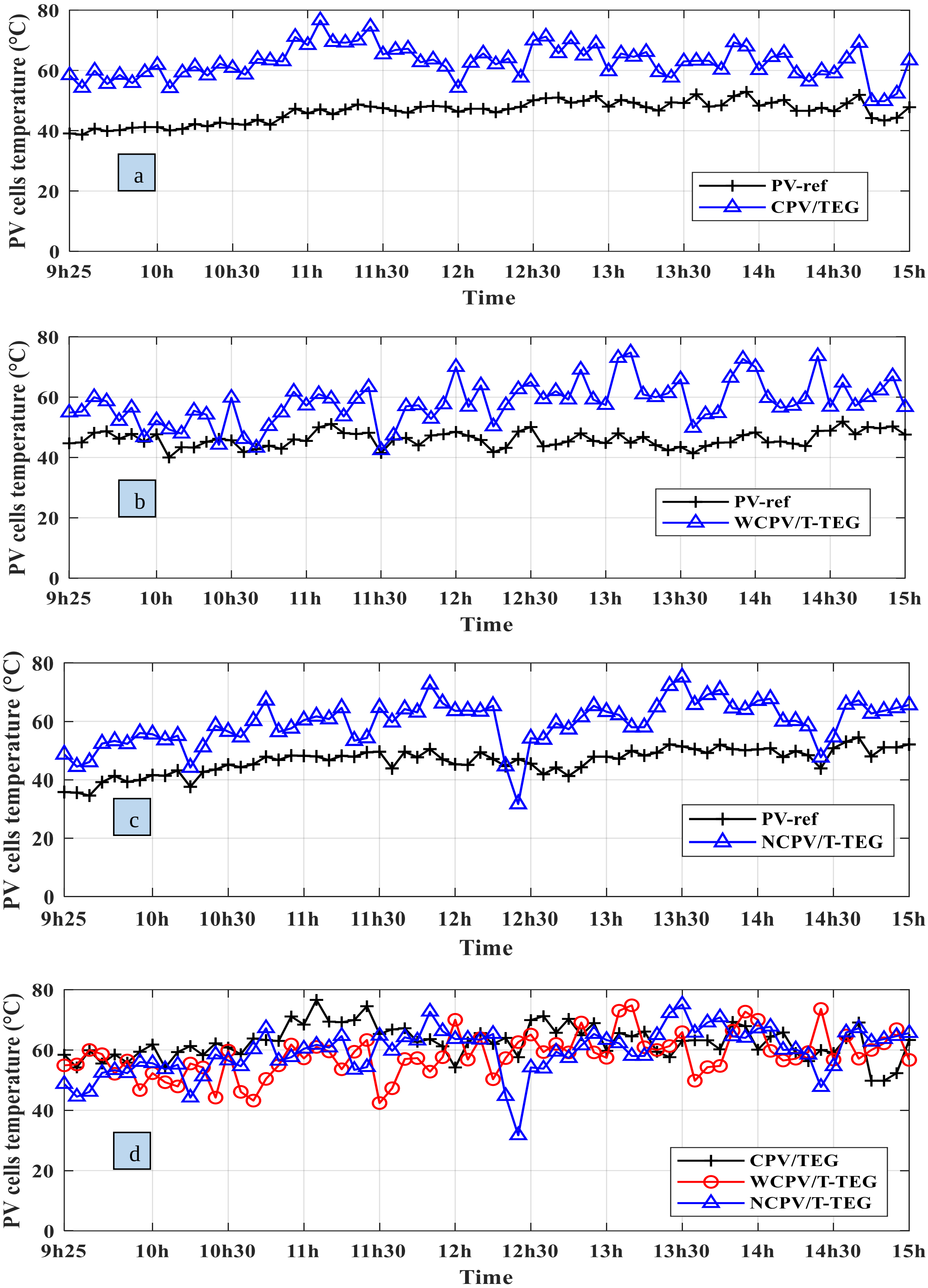

Figure 8: PV cell temperature comparison between: a) standard PV cells (i.e. PV-ref) and the PV cells in CPV/TEG; b) PV-ref and the PV cells in WCPV/T-TEG; c) PV-ref and the PV cells in NCPV/T-TEG; d) the PV cells in CPV/TEG, WCPV/T-TEG and NCPV/T-TEG.

Fig. 9 shows the open circuit voltage of PV cells in different configurations. As shown in **Fig. 9**, due to the low cooling performance of the heat sink with the natural cooling method (CPV/TEG), the produced voltage was lower than other configurations. It should be noted that the produced voltage is proportional to the solar irradiation and wind speed for all configurations. Voltage improves with the increase in radiation and wind speed, but decreases spontaneously with the rise of PV cell temperature. The average value of the open circuit voltage was ~3.85 V, ~4.07 V and ~4.06 V for the PV cells in CPV/TEG, WCPV/T-TEG and NCPV/T-TEG, respectively. The open circuit voltage for the standard PV cell alone under the three operating conditions was found to be similar, i.e. ~4.44 V.

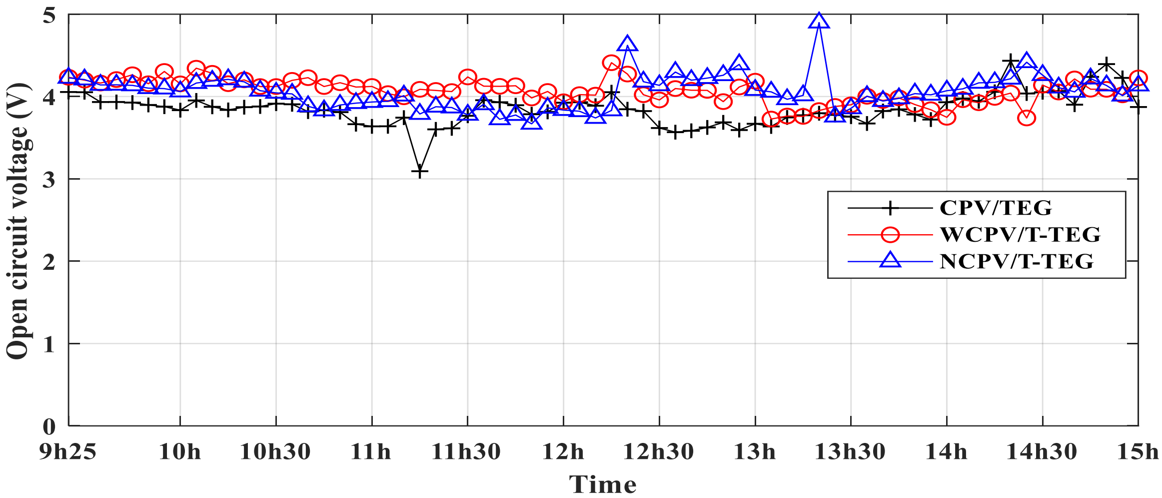

Figure 9: PV cells open circuit voltage output comparison between CPV/TEG, WCPV/T-TEG and NCPV/T-TEG configurations.

Fig. 10 demonstrates the electrical power produced by the PV cells. It was observed that the average output electrical power for the standard PV cells (PV-ref) was ~0.22 W. By using a solar concentrator, the electrical performance of the PV cells in the three configurations (i.e. CPV/TEG, WCPV/T-TEG and NCPV/T-TEG) was boosted to ~1.7 W,~1.76 W , and ~1.92 W, respectively, and was found to be around eight times higher than the PV-ref cells.

It should be noted that the optical performance of the solar concentrator lens is very sensitive to outdoor operating conditions. Therefore, any optical losses in the focal point will deteriorate the electrical and thermal performances of the system. This was seen during the first morning testing hours for the water cooling day, where a partial shading caused by fleeting clouds affected the system's optical performance.

The performance of the PV cells in all configurations dropped with the increase of cell temperature. This was clearly noticed for PV cell with CPV/TEG configuration compared to other cooling methods.

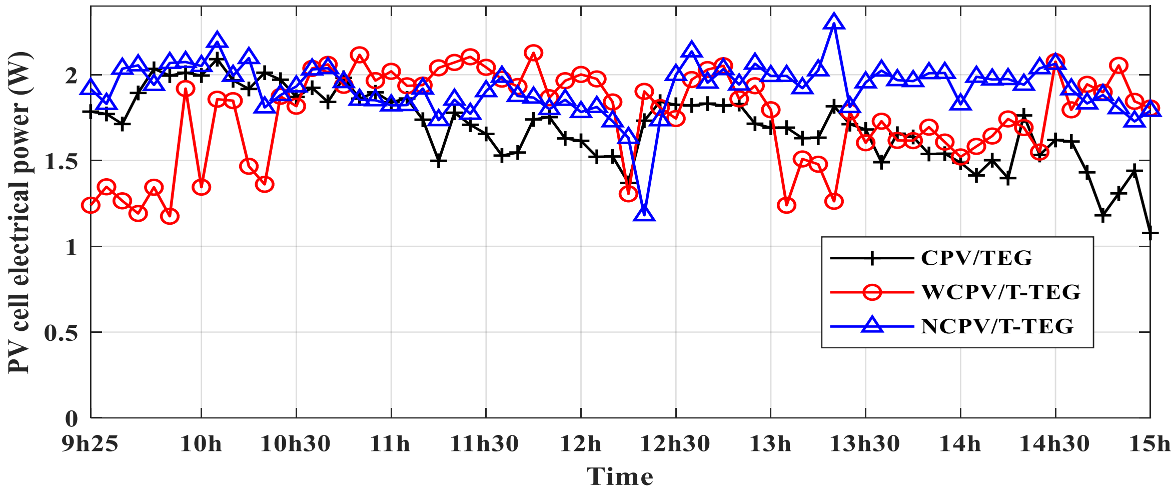

Figure 10: PV cells electrical power output comparison between CPV/TEG, WCPV/T-TEG and NCPV/T-TEG configurations.

3.3 TEG performance

In this section, temperature gradient (temperature difference between TEG hot and cold sides (ΔT)), open circuit voltage, and produced electrical power of the TEG module are presented and discussed for the different configurations (i.e. CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG). **Fig. 11** shows the temperature gradient across the cold and hot sides of the TEG generator. The temperature gradient depends on the radiation intensity and cooling method. It was found that when the solar radiation increased, temperature of the hot side of the TEG generator increased as well. However, the cooling mode greatly affected the amount of gradient of the temperature value. Due to the low cooling performance of the heat sink in the CPV/TEG hybrid system (i.e. natural cooling mode), the average temperature gradient, ΔT of the TEG generator was ~11°C, whereas for WCPV/T-TEG and NCPV/T-TEG, the value was ~16°C and ~17°C, respectively. It is worth to note that the small difference in the temperature gradient found in WCPV/T-TEG and NCPV/T-TEG was due to the working fluid input temperature during the experimental day. The average input temperature of the water and CNT nanofluid was found to be ~27°C and ~30°C, respectively.

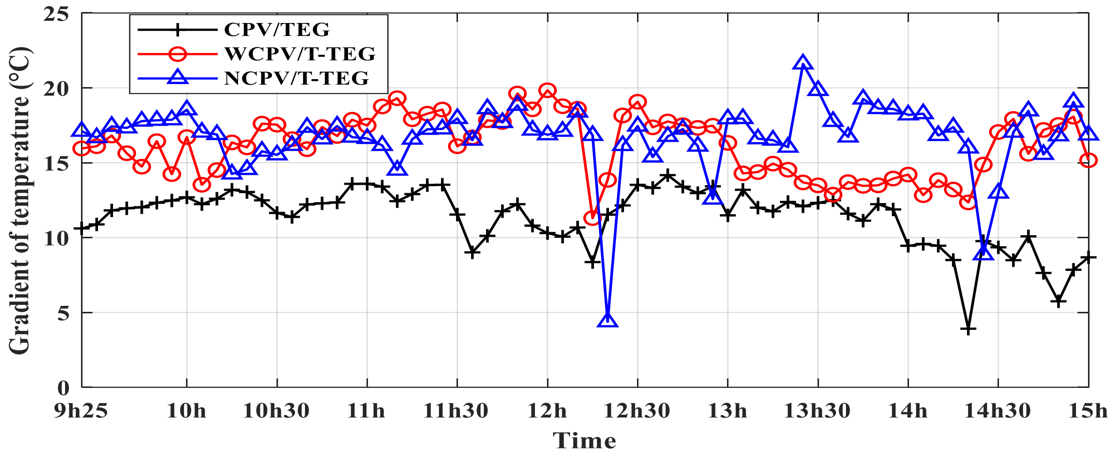

Figure 11: Temperature gradient between the TEG generator sides for the configurations CPV/TEG, WCPV/T-TEG and NCPV/T-TEG.

Indeed, the open circuit voltage generated in the TEG module was strongly proportional to the available radiation intensity and temperature gradient. Based on **Fig. 12**, the open circuit voltage produced under the natural cooling mode was much lower compared to that produced under water and nanofluid cooling modes. Another fact is that the voltage generated in WCPV/T-TEG and NCPV/T-TEG depends on the mass flow rate and thermophysical properties of the working fluid. The higher the mass flow rate, the higher the cooling performance. However, in the nanofluid mode, the constraint of the pumping power imposes certain limits that are dependent on the mass flow rate and nanoparticle concentration. In the present experimental values for mass flow rate and nanofluid concentration, both were selected such that the pumping power would be reasonable against the overall electrical power of the system. The operational mass flow rate was set to 0.0021 kg/s, thus, the resulting pumping power was 0.22 W.

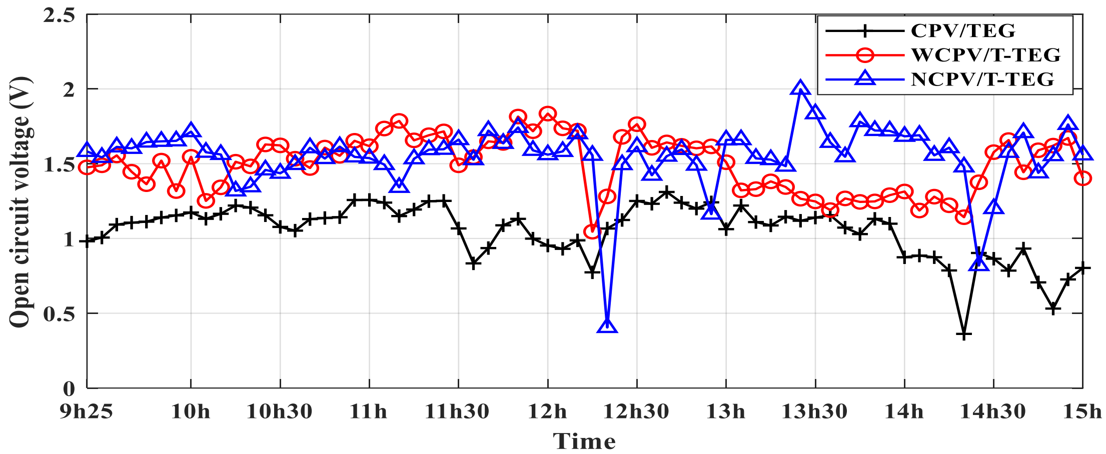

Figure 12: TEG open circuit voltage for the configurations CPV/TEG, WCPV/T-TEG and NCPV/T-TEG.

The output electrical power of the TEG module for the three different configurations is depicted in **Fig. 13**. Similar to the open circuit voltage, the electrical power is also dependent on the temperature gradient. The average power produced by the TEG module was ~0.0274 W, ~0.0828 W and ~0.0923 W for the CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG configurations, respectively. It should be noted that the average solar radiation during the experimental day for the WCPV/T-TEG system was higher than that of the NCPV/T-TEG experimental day. Moreover, the inlet temperature of the cooling fluid for water was lower (~27°C) than that of nanofluid (~30°C). The authors believe that if both configurations (WCPV/T-TEG and NCPV/T-TEG) are tested under similar weather conditions, the overall performance of the NCPV/T-TEG hybrid system will exceed that of the WCPV/T-TEG system. Nevertheless, despite the lower operating conditions, NCPV/T-TEG still performed better than the WCPV/T-TEG system.

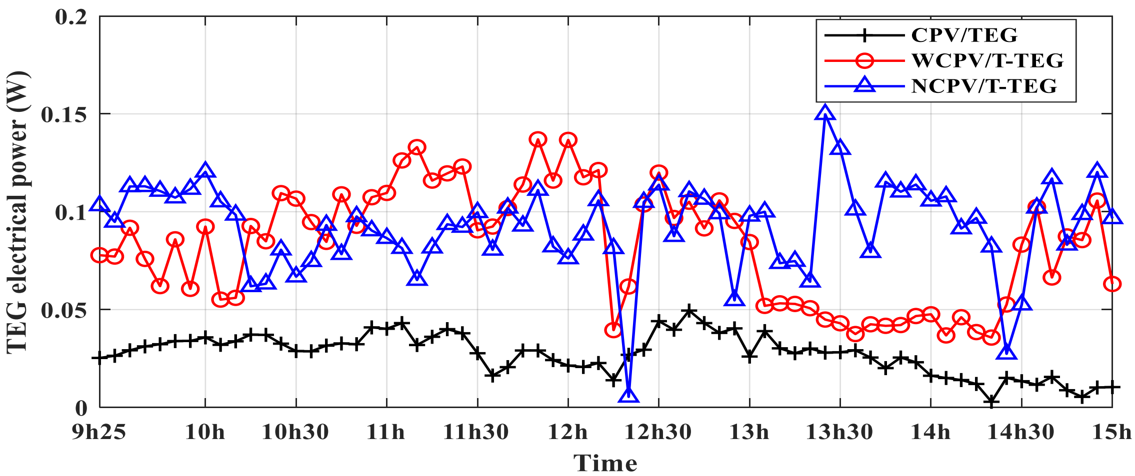

Figure 13: Electrical power of TEG generators for the configurations CPV/TEG, WCPV/T-TEG and NCPV/T-TEG.

3.4 Overall electrical performance

Once the output electrical performance of the PV cells and TEG generators for different configurations has been evaluated, determination of the overall performance of each system is required. **Fig. 14** shows the different electrical power outputs from CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG.

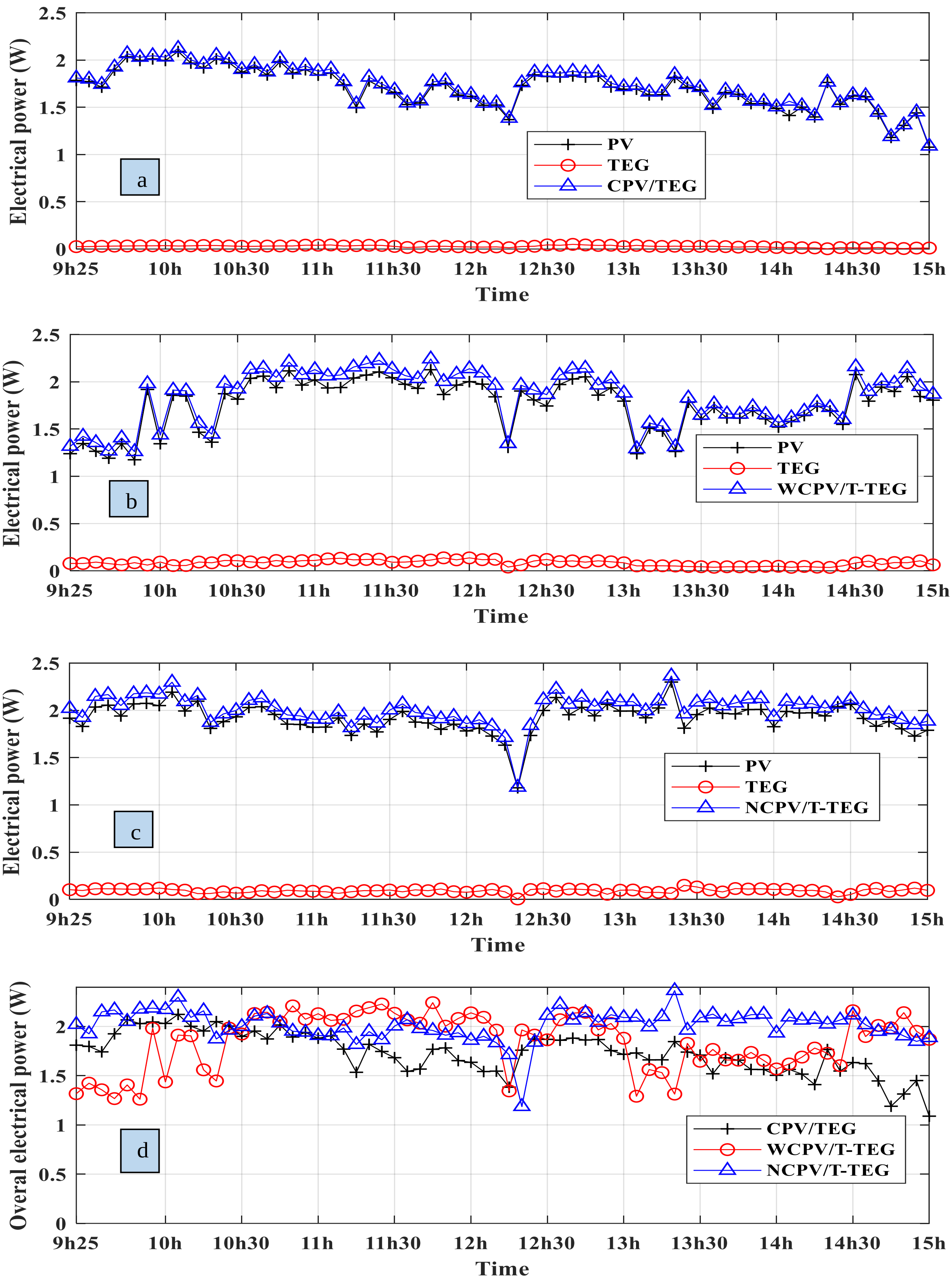

Figure 14: The different electrical power output from the a) the PV and TEG in CPV/TEG, and CPV/TEG power; b) the PV and TEG in WCPV/T-TEG, and WCPV/T-TEG power; c) the PV and TEG in NCPV/T-TEG, and NCPV/T-TEG power; d) overall electrical performances of CPV/TEG, WCPV/T-TEG and NCPV/T-TEG

Based on **Fig. 14 (d)**, the overall electrical performance of the CPV/TEG configuration was lower than that of WCPV/T-TEG and NCPV/T-TEG configurations, and the proposed hybrid system NCPV/T-TEG outperformed other configurations. The total net electrical power generated was 1.731 W, 1.843 W, and 2.012 W for the CPV/TEG, WCPV/T-TEG and NCPV/T-TEG configurations, respectively. As discussed previously in **Fig. 13**, the difference in output performance was due essentially to the efficient cooling modes in WCPV/T-TEG and NCPV/T-TEG compared to the CPV/TEG system.

The TEG generator in CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG contributed ~1.58%, ~4.4%, and ~4.6% from the total net electrical power generated, respectively, as depicted in **Fig. 14 (a), (b), and (c)**.

3.5 Daily exergy under average working conditions

Based on the discussion above, it can be concluded that the NCPV/T-TEG hybrid system is an advanced design with high electrical energy yield. Furthermore, in this study, the thermal output performance of the hybrid system was evaluated. The obtained results proved that the hybrid system may produce a high rate of electrical and thermal energy simultaneously.

In addition, exergy analysis was carried out to assess the profitability of the NCPV/T-TEG hybrid system compared to the CPV/TEG and WCPV/T-TEG hybrid systems using Equation (7) and the result is presented in **Table 6**. Moreover, the different improvement for each configuration was rated in contrast to a standard PV reference module. The obtained results are summarized in **Table 6**.

Based on **Table 6**, the electrical performance improvement in CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG configurations in contrast to the standard PV reference module was ~87.30%, ~87.97%, and ~89.01%, respectively. In addition, the electrical energy enhancement in nanofluid-based cooling mode was found to be higher than that in the natural and water cooling modes by ~13.95% and ~8.4%, respectively.

In terms of thermal energy improvement, the NCPV/T-TEG hybrid system outperformed the WCPV/T-TEG hybrid system by ~4.98%.

The pumping power consumed in NCPV/T-TEG was almost similar to the amount of power consumed for pumping pure water in WCPV/T-TEG at ~0.22 W equivalent to 10.9% and 11.5% of the total electrical power generated by NCPV/T-TEG, and

WCPV/T-TEG, respectively. Therefore, self-powering of the pump could be guaranteed by the system without using an external power supply.

The overall electrical and thermal performances presented in **Table 6** were exploited to calculate the daily exergy performance of the different studied configurations by applying Equation (7). The exergy analysis result revealed that the NCPV/T-TEG hybrid system produced higher daily exergy in contrast to the standard PV cells, CPV/TEG, and WCPV/T-TEG. For instance, the NCPV/T-TEG generated 92.47% of exergy higher than the standard PV cells, and 41.06% and 8.8 % higher than the CPV/TEG and WCPV/T-TEG configurations, respectively.

Based on the calculated and measured overall performances, it can be concluded that the proposed configuration, i.e. NCPV/T-TEG hybrid system outperforms other configurations in terms of exergy yields, and electrical and thermal power.

It is worth pointing out that the proposed NCPV/T-TEG hybrid system can be optimized further to collect more electrical power using PV cells and TEG generator with higher conversion efficiency. In fact, the PV cells and TEG generator used in this study were bought from local markets with low conversion efficiency. With the advances in semiconductor science in the future, the proposed design of the NCPV/T-TEG hybrid system is expected to produce large amounts of exergy and electrical power.

The overall electrical and thermal performances were investigated under a real outdoor operating condition. The fact that the output power changes with fluctuations in the environmental operating conditions negatively affects the use of energy produced for the long run. Improving the operating conditions can help boost the overall performances. For example, covering the four sides of the moving box may reduce sun light loss and the impact of wind speed, which affect the thermal performances of the proposed hybrid system. Other possibilities, such as covering the fluid tanks and canals with high performance thermal insulation compared to that used in the experiment can improve the cooling process and hence, boost the overall performances of the hybrid system. Further improvement of the tracking system by using an intelligent control method for the tracking system can produce a very precise sun tracking operation and improve the electrical and thermal power.

Table 6: Overall performance data comparison of different configuration

	Natural cooling	**Water based cooling**	**CNT based cooling**

Average performance	Standard PV cell	CPV/TEG	Standard PV cell	WCPV/T-TEG	Standard PV cell	NCPV/T-TEG
Solar radiation (W/m^2)	664.96		700.15		674.51	
Wind speed (W/s)	0.69		2.30		1.21	
Ambient temperature($^{\circ}C$)	34.61		33.10		34.97	
Pumping power (W)	/		0.21		0.22	
Electrical power (W)	0.22	1.732	0.22	1.84	0.222	2.01
Thermal power (W)	/	/	/	25.91	/	27.27
Daily exergy (Wh)	1.12	8.86	1.13	13.70	1.13	15.02

3.6 Levelized cost of electricity for different systems (LCOE)

Recently, the economy and reliability of PV power generation have been very good. However, the purposes of a CPV system are to boost the performances of the PV cell, reduce the solar cell amount size, and hence reduce energy cost. In this work, the hybrid system was designed to be efficient in terms of energy production, and economically competitive.

The LCOE is an economic estimate of the total cost of building and maintenance of the different studied technologies (standard PV, CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG) over their lifetime, divided by the asset's total energy production over that lifetime. The general equation for LCOE is given by Equation (8) [48].

$$\text{LCOE} = \frac{\text{Lifecycle cost}}{\text{Lifetime energy production}} \tag{8}$$

In this part, an LCOE assessment was carried to prove the economic competitiveness of the NCPV/T-TEG hybrid system compared to the standard PV, CPV/TEG, and WCPV/T-TEG using Equation (8) and the results are summarized in **Table 7**.

Based on **Table 7**, it can be seen that the total cost of NCPV/T-TEG hybrid system is higher by 38.21,144.94,and 266.06 RM compared to the total cost of WCPV/T-TEG, CPV/TEG, and standard PV, respectively. However, the LCOE of the NCPV/T-TEG hybrid system is lower by 0.0028,0.0304,and 0.6863 RM/Wh compared to the LCOE of WCPV/T-TEG, CPV/TEG, and standard PV, respectively.

Table 7: Levelized cost of electricity comparison of different configuration

Component cost (RM)	Standard PV	CPV/TEG	WCPV/T-TEG	NCPV/T-TEG
PV cell	6.10	6.10	6.10	6.10
TEG generator	-	9.80	9.08	9.08
Heat sink	-	20	-	-
Water block cooling	-	-	10.03	10.03
Concentrator lens	-	139.32	139.32	139.32
DC pump	-	-	15.58	15.58
Tracker frame	320	320	320	320
Tank	-	-	32.80	32.80
Tube	-	-	21.04	21.04
Nanoparticle	-	-	-	38.31
Total cost (RM)	326.10	447.22	553.95	592.16
Year output (Wh)	410.6	3232.3	5001.7	5484.3
LCOE (RM/Wh)	0.7943	0.1384	0.1108	0.1080

4. CONCLUSION

In this work, a novel NCPV/T-TEG hybrid system was designed and tested to boost the solar energy conversion rate. The TEG acted as a second power generator to boost the overall electrical power of the hybrid system. The electrical and thermal performances of the hybrid system were investigated experimentally under three different cooling modes, i.e. natural cooling, water-based cooling, and CNT nanofluid based cooling. Based on the obtained experimental results, the proposed hybrid system confirmed the advantages of combining TEG technology with PV cells using CNT nanofluid as the cooling medium.

The conclusions based on the outcomes of the prevailing study are summarized as follows:

a) It was found that degradation in the overall performance of the PV cell was significant in the natural cooling mode compared to the water and nanofluid cooling modes. This was due to the limitation of the cooling performance of the heat sink and thermal barrier caused by the TEG module.

b) The total net electrical power generated for the CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG configurations was 1.731 W, 1.843 W, and 2.012 W, respectively. The majority of power was produced by the PV cell.

c) The TEG generator in CPV/TEG, WCPV/T-TEG, and NCPV/T-TEG respectively contributed ~1.58%, ~4.4% and ~4.6% from the total net electrical power generated.

d) It was found that the resulting amount of the electrical power for the NCPV/T-TEG configuration was ~88.98%, ~ 13.95%, and ~8.4% higher than the standard PV modules, CPV/TEG, and WCPV/T-TEG configurations, respectively. The NCPV/T-TEG produced ~4.98% of the overall thermal energy; higher than the WCPV/T-TEG hybrid system.

e) The NCPV/T-TEG generated 92.47% higher exergy than the standard PV cells, and 41.06%, and 8.8% higher than CPV/TEG and WCPV/T-TEG configurations, respectively.

Based on the outstanding performance of NCPV/T-TEG, it can be concluded that the proposed hybrid system could be one of the leading renewable vitality innovation arrangements to advance the concept of sustainable development and smart city, and be used to electrify regions in which their connection to grid is no longer economically possible.

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