Journal of Al-Azhar University Engineering Sector

Vol. 20, No. 74, January 2025, 193 - 210

ENERGY, EXERGY, ENVIRONMENTAL AND ECONOMIC (4E) ANALYSIS OF PV, CPV AND CCPV PANELS AT DIFFERENT CLIMATE CONDITIONS

M. Salah Mansour[1], H. Yahya[1,*], M. Halawa[2], M. A. Eid[1], Moataz. M. Abdel-Raouf[1]

[1]Mechanical Engineering Dept. Higher Technological Institute, 10th of Ramadan city 44629, Egypt.
[2]Faculty of Engineering, Mech. Department, Al Azhar University, Cairo, Egypt.

***Correspondence:** hany.yahya@hti.edu.eg

Citation:

M . S. Mansour, H. Yahya, M. Halawa, M. A. Eid and M. M. Abdel-Raouf, "Energy, exergy, environmental and economic (4E) analysis of PV, CPV and CCPV panels at different climate conditions", Journal of Al-Azhar University Engineering Sector, vol. 20, pp. 193- 210, 2025.

Received: 21 July 2024

Revised: 30 September 2024

Accepted: 28 October 2024

Doi:10.21608/auej.2024.306080.1688

ABSTRACT

In recent years, there has been a marked increase in interest in renewable energy sources, largely driven by environmental issues. Among these sources, solar energy has gained prominence as a key area of research. Advances in the efficiency of photovoltaic (PV) panels have significantly enhanced their appeal relative to other solar technologies. However, rising surface temperatures negatively impact the performance of PV panels, hindering the expected improvements in energy capture associated with the use of solar reflectors. This study investigates the year-round performance of cooling PV panels enhanced by reflective mirrors to assess the efficiency of solar reflector integration. This study examines the year-round efficiency of cooling PV panels augmented by reflective mirrors to evaluate the success of solar reflector integration. The objective of this investigation is to evaluate the efficiencies of a traditional PV panel, a CPV (cooled photovoltaic panel), and a CCPV (concentrated cooled photovoltaic panel) by directly comparing their performance and assessing their individual efficiencies. The investigation of output energy and exergy was conducted in the environmental conditions of 10th of Ramadan City, Egypt, during both the winter and summer seasons of 2023. The current study performs a comprehensive 4E analysis, encompassing energy, exergy, environmental, and economic analysis with life cycle assessment, in order to investigate the effects of incorporating reflecting mirrors and evaporative cooling pads on the efficiency of PV systems. The results show that CPV panels increase energy generation by approximately 5.62% and 6.34% during the winter and summer months, respectively. In contrast, CCPV panels enhance energy output by higher percentages of around 9.07% and 8.65% in the winter and summer seasons, respectively. This is despite the fact that the CPV configuration exhibits higher exergy values than the CCPV. The findings suggest that incorporating heat loss utilization is critical for maximizing the benefits of the CCPV system configuration.

KEYWORDS: PV performance, PV enhancement, Concentrated PV, PV cooling, Evaporative cooling, PV energy analysis, PV exergy analysis, 4E analysis.

تحليل أداء الطاقة ودراسة العوامل البيئية و الاقتصادية المؤثرة على إنتاجية الكهرباء من الألواح الشمسية والألواح الشمسية المركزة

محمد صلاح منصور[1]، هانى ابراهيم يحيى[1*]، محمد على حلاوة [2]، محمد أشرف عيد [1] ، معتز عبدالرؤوف [1]

[1] قسم الهندسة الميكانيكية، المعهد التكنولوجى العالى بالعاشر من رمضان 44629 ، مصر.
[2] قسم الهندسة الميكانيكية ، كلية الهندسة، جامعة الأزهر، مدينة نصر، 11884، القاهرة، مصر.

***البريد الاليكتروني للباحث الرئيسي :** hany.yahya@hti.edu.eg

الملخص

في السنوات الأخيرة، كان هناك ارتفاع كبير في الاهتمام بمصادر الطاقة المتجددة، ويرجع ذلك في المقام الأول إلى المخاوف البيئية. ومن بين هذه المصادر، برزت الطاقة الشمسية كموضوع هام للبحث. أدى التحسن في فعالية الألواح الكهروضوئية إلى

زيادة كبيرة في تفضيلها مقارنة بتقنيات الطاقة الشمسية الأخرى. الهدف من هذا البحث هو تقييم كفاءات الألواح الكهروضوئية التقليدية، وCPV (الألواح الكهروضوئية المبردة)، وCCPV (الألواح الكهروضوئية المركزة المبردة) من خلال مقارنة أدائها بشكل مباشر وتقييم كفاءاتها الفردية. تم تحليل نتائج الطاقة المنتجة والطاقة المتاحة في الظروف البيئية لمدينة العاشر من رمضان، مصر، خلال فصلي الشتاء والصيف لعام 2023. وتقوم الدراسة الحالية باجراء تحليلاً شاملاً (4E)، يشمل تحليل الطاقة المنتجة والطاقة المتاحة والتحليل البيئي والاقتصادي من أجل دراسة آثار دمج المرايا العاكسة ومنصات التبريد بالتبخير على كفاءة الأنظمة الكهروضوئية. أظهرت النتائج أن الألواح الكهروضوئية المبردة تزيد من توليد الطاقة بحوالي 5.62% و6.34% خلال أشهر الشتاء والصيف، على التوالي. في المقابل، تعمل الألواح الشمسية المركزة والمبردة على تعزيز إنتاج الطاقة بنسب أعلى تبلغ حوالي 9.07% و8.65% في فصلي الشتاء والصيف على التوالي. هذا على الرغم من حقيقة أن الألواح الكهروضوئية المبردة (CPV) أظهرت قيم طاقة متاحة (exergy) أعلى من CCPV. تشير النتائج إلى أن دمج استخدام فقدان الحرارة أمر بالغ الأهمية لتحقيق الاستفادة القصوى من أنظمة CCPV.

الكلمات المفتاحية : تحليل أداء أنظمة الطاقة الكهروضوئية، تحسين كفاءة الأوراح الكهروضوئية، الأوراح الكهروضوئية المركزة، تبريد الأوراح الكهروضوئية، التبريد بالتبخير، تحليل الطاقة واللطاقة المتاحة للألواح الكهروضوئية، التحليل الشامل للألواح الكهروضوئية (4E).

1. INTRODUCTION

The rise in global population and growing concerns about the environment have led to an increased popularity of the use of renewable energy sources. Among these sources, solar energy has garnered significant attention from researchers worldwide. Solar energy can be harnessed in two forms: electrical energy and thermal energy. The conversion of solar irradiance into electricity is achieved using photovoltaic (PV) cells. These cells directly convert the incident solar irradiance into electrical energy. The most efficient and sustainable systems are the PV modules, which efficiently convert a portion of the solar irradiance into electricity. However, it is important to note that a significant portion of the solar irradiation is converted into heat, which in turn raises the temperature of the cells and diminishes the overall performance of the PV module. Using reflective mirrors in PV systems increases the intensity of solar radiation reflected on the panels, resulting in a higher output power from the PV panels, but it also causes an increase in the panel temperature. Higher module temperatures reduce the efficiency of photovoltaic solar cells, resulting in a reduction in output power and lifetime. Thus, proper cooling is needed to improve the panel's performance. Several studies have investigated enhancing PV panel efficiency through the implementation of passive cooling techniques [1–8]. Zuhur et al. [9] developed a concentrated photovoltaic cooling system prototype. The prototype was tested during hot summer days, and the experiments showed that using a concentrator did not impact the thermal energy gain significantly, with a total thermal energy gain of around 30 W in the system. However, with the use of a concentrator, the exercise efficiency improved. Despite this, the panel's backside temperature increased, resulting in lower electrical performance than systems without a concentrator. Zhe et al. [10] studied the effect of a water-cooling system on PV panels. The temperature distribution of the PV panels, both without and with a water cooling system, has been predicted. The results revealed that the average temperature distribution of the PV panel without the water-cooling system is higher than that of the panel with the cooling system. Specifically, the average temperature of the PV panel without the cooling system was recorded at 50.68 °C. On the other hand, for the water cooling system, it was observed that the PV panel with an inlet water temperature of 20°C could reduce the panel's temperature by 15.63°C compared to the panel with an inlet water temperature of 45°C. Gomaa et al. [11] introduced and experimentally assessed two innovative and cost-effective cooling methods aimed at improving the efficiency of solar photovoltaic (PV) systems. The results indicated an increase in daily energy yield of 10.2% for the backwater cooling system and 7% for the fins cooling system, in comparison to the non-cooling module. Hussien et al. [12] carried out an investigation on the cooling airflow characteristics and panel temperature distribution by utilizing computational fluid dynamics (CFD). The research included experimental measurements on three different configurations of PV panels, with the uncooled panel as the baseline case. Chan-Dzib et al. [13] presented a novel passive cooling technique that employs a distinctive configuration of curled aluminum fins to address the previously identified challenges. To assess the thermal efficiency of solar panels, CFD simulations were utilized, examining various geometric parameters of the newly designed curled fins. This analysis led to the identification of the most effective fin design for practical applications. Hossain et al. [14] investigated the application of nanofluids to enhance the efficiency of hybrid photovoltaic-thermal (PV/T) solar collectors. Their research identified several geometric configurations employed in PV/T systems, including serpentine, rectangular, microchannel, and sheet and tube designs. The findings indicate that the incorporation of nanofluids leads to a marked improvement in overall performance, including thermal and electrical efficiency, heat transfer characteristics, and exergy. This paper provides a thorough review of the various dimensions associated with the use of nanofluids, addressing aspects such as energy efficiency, exergy efficiency, overall efficiency, heat transfer coefficients, daily yield, power generation, entropy production, exergy loss, and temperature reduction in hybrid PV/T collectors. Gomaa et al. [15] conducted a study on an innovative economic design of a cooling cross-finned channel box, which included both thin (3 mm) and thick (15 mm) configurations. Their research focused on examining how different levels of irradiation and varying flow rates of cooling water influenced the temperature of the cells and the temperature of the cooling water at the outlet. The results indicated that increasing the flow rate of the cooling fluid resulted in a lower average surface temperature distribution within the photovoltaic/thermal (PV/T) system, as well as a decrease in the outlet temperature of the cooling water for both the thin and thick box heat exchangers, with the most efficient performance occurring at a cooling fluid flow rate of 3 L/min. Karim et al. [16] conducted an experimental investigation into a hybrid Photovoltaic/Thermal (PV/T) solar system, which integrates a photovoltaic module with devices designed for heat extraction from either water or air. The study explored the simultaneous circulation of both air and water, incorporating alterations to the air channel. The initial modification involved the insertion of a Thin Flat Metallic Sheet (TMS) within the air channel, while the second modification entailed the installation of Painted Black Ribbed surfaces at the base of the air channel. Bhakre et al. [17] conducted an environmental and economic analysis of the impact of photovoltaic (PV) cooling on CO2 emissions. The significance of PV cooling technology and various cooling techniques for PV cells are thoroughly examined to provide a comprehensive understanding. The study delves into how cooling PV cells affects the environmental cost of reducing CO2 emissions by analyzing different scenarios involving various cooling techniques. The eco-economic analysis showed that using hybrid nano-PCM, hybrid PCM, and hybrid PCM-water together was better at lowering the environmental cost of CO2 emissions than using each technique alone. Tahir et al. [18] presented a comprehensive review of 4E analysis known as energy, exergoeconomic, and exergoenvironment analysis of thermal power plants, intermittent renewable energy, and integrated energy systems. Shoaei et al. [19] conducted an analysis of energy, exergy, environmental, and economic (4E analysis) for a concentrating photovoltaic thermal (CPVT) system. The results indicated that CPVT had about 63% of the total energy efficiency and 9% of the total exergy efficiency. In the worst-case scenario, the system's CO_2 emissions resulted in an annual cost of up to 20 cents.

According to the literature review above, there is insufficient clarity about the impact of evaporative cooling on the efficiency of both standard PV and concentrated PV panels for different climate conditions throughout the year.

Therefore, the present work firstly investigates the relative performance and energy productivity of a standalone PV panel, a CPV (cooled PV panel), and a CCPV (concentrated cooled PV panel) in the environmental conditions of Tenth of Ramadan City, Egypt, across various seasonal conditions. Subsequently, a thorough 4E analysis in terms of energy, exergy, environment, and economic aspects was carried out to analyze the performance of both CPV and CCPV configurations during the summer and winter seasons. The assessment included a comparison of energy and exergy efficiencies, as well as an evaluation of generated CO2, taking into account the system's life-cycle assessment (LCA) and the cost associated with CO2 emissions. The present work aims to improve the efficiency of both photovoltaic and concentrated photovoltaic panels by implementing an affordable evaporative cooling method that requires minimal energy, whereas domestic water supply is available. Another important goal of this research is to develop a cost-effective approach to improving the efficiency of photovoltaic systems in high-temperature conditions by assessing different photovoltaic configurations.

2. EXPERIMENT SETUP

Monocrystalline PV solar modules were employed in the study to assess the improvement in solar panel efficiency. Data from three different configurations were collected to determine this enhancement. The experiment was carried out on the rooftop of the mechanical engineering department building at the Higher Technological Institute in 10th of Ramadan city, Elsharkia, Egypt. The geographical coordinates of the location are 30°18’21.7” latitude and 31°45’19.8” longitude, with a moderate and consistent climate experienced throughout the summer and winter seasons of 2023. Egypt has an annual average global horizontal irradiance duration of 2264 hours. The optimal tilt angle for photovoltaic (PV) panels at this site ranges from 11.8° in the summer to 41.8° in the winter. The experiments were carried out with a mean global horizontal irradiance of 565.2 and 862.9 W/m2 during the winter and summer seasons, respectively. The experimentation was carried out over multiple individual days in the winter and summer of 2023, and the mean data has been recorded. **Fig. 1** illustrates the basic schematic of the three tested experimental models.

Before conducting the tests on PV modules, the uncertainty of the tested PV modules was obtained by evaluating the output power of the PV panels in the same environment (standalone). Results show that the maximum relative percentage errors for CPV and CCPV power, based on typology, are ± 0.52% and ± 0.43%, respectively.

Before conducting the tests on PV modules, the uncertainty of the tested PV modules was obtained by evaluating the output power of the PV panels in the same environment (standalone). Results show that the maximum relative percentage errors for CPV and CCPV power, based on typology, are ± 0.52% and ± 0.43%, respectively.

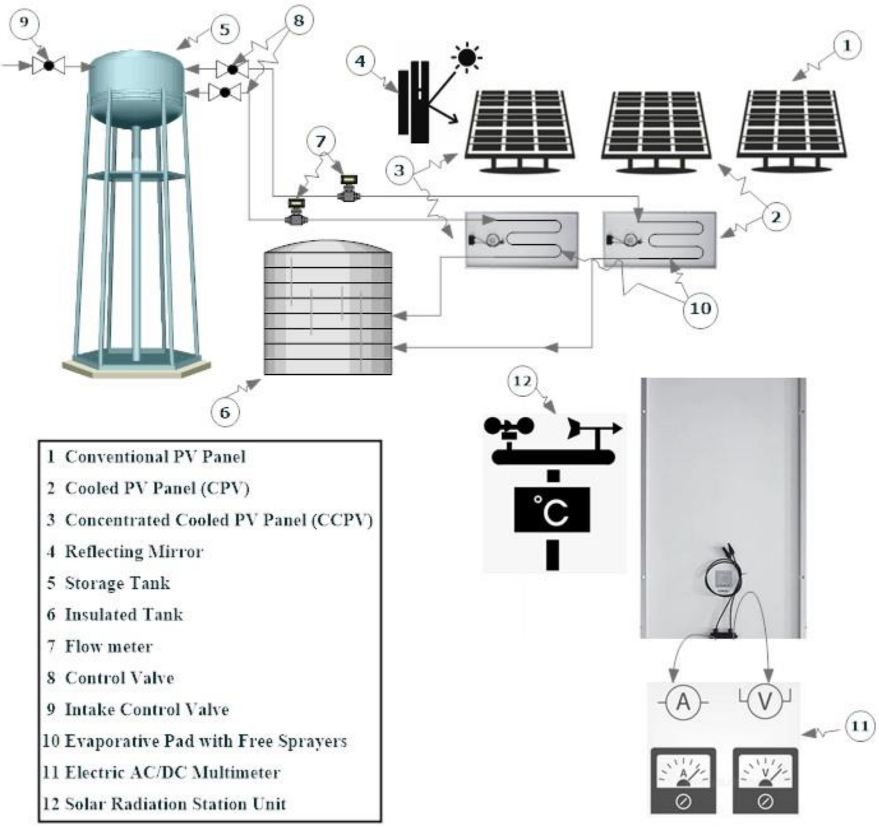


Fig. 1. Simple schematic of the experimental model.

2.1. Case study 1: Standalone PV Panel

The experiment utilized a monocrystalline PV module measuring 670 x 540 x 25 mm, capable of producing up to 50 W under standard test conditions (STC) with a solar irradiance of 1000 W/m^2 and a temperature of 25°C. Positioned south-facing at an inclination angle of 29°, as recommended for optimal year-round tilt at this specific location [20], the module was oriented to capture the maximum available sunlight.

2.2. Case study 2: Cooled PV Panel (CPV)

A setup was designed to investigate the impact of water-based evaporative cooling on a PV panel's efficiency. The panel used in the experiment is identical to the reference one and is positioned at a 29° inclination angle, facing south, as shown in **Fig. 2**. An evaporative cooling pad is placed on the PV module's rear side, with a metal net 5 cm below the panel and the pad above it. The cooling pad is saturated with water using hoses with mounted nozzles distributed uniformly on them. A 200-liter well-insulated tank is installed at a height of 5 m to provide the cooling pad with sufficient coolant pressure without the need for a pump, with a flow rate of 1 l/min.

2.3. Case study 3: Concentrated Cooled PV Panel (CCPV)

A different configuration for the CPV was developed by incorporating a reflective mirror to focus sunlight onto the solar cells, aiming to enhance the efficiency of the setup. This configuration followed the same layout as the previous two models. The system's design prioritized cost-effectiveness, considering factors such as compact dimensions for portability, simple reflector adjustment, an inexpensive cooling system, and the use of readily available materials. The setup featured a singular mirror measuring 700 x 560 mm, which directed solar radiation towards the PV module. The mirror was affixed to a pivot axis to allow for optimal alignment to capture the maximum solar irradiance. This modified model's experimental setup is shown in **Fig. 3**.

Fig. 2. Typical case study 2 (CPV).

Fig. 3. Typical case study 3 (CCPV).

2.4. Measurements and Instruments

The system was equipped with precisely calibrated tools for measuring solar radiation, output current, output voltage, temperature, and water flow rate. The Solar Power Meter (SM206) was utilized to measure the global solar irradiance in W/m^2, typically within ± 10 W/m^2 ± 5%. Additionally, the digital multimeters (Uni-T UT33D) were employed to measure the PV module's output DC current and voltage with an accuracy of ±2% and ±0.8%, respectively. In order to operate the PV modules at their maximum power point at STC, the load resistance RL was determined using Ohm's law as follows:

$$R_L = \frac{V_{mpp}}{I_{mpp}} = 6.5\ \Omega \qquad \text{Eq. 1}$$

Furthermore, the Vantage Pro2 weather station unit is used to display and document weather data, including solar radiation, temperature, humidity, and wind speed. The weather station is tasked with measuring the other factors to authenticate the data obtained from the instrument mentioned earlier, excluding moist air relative humidity and wind speed, as both had an accuracy of approximately ±3%.

The maximum possible errors in power and other performance parameters were estimated by using the method proposed by [21]. The error estimation was based on the lowest output values and the accuracy of the measuring devices employed. This approach necessitates a careful identification of the uncertainties present in the different experimental measurements. The uncertainties associated with current (I), voltage (V), and global horizontal irradiance (GHI) are assessed at 2%, 0.8% and 5%, respectively. As a result, the uncertainty in power output, which is contingent upon the independent variables I and V, is computed to be 1.64%. In a similar manner, the uncertainty in electrical efficiency, which is affected by the independent variables I, V, and GHI, is also found to be 1.64%.

3. ENERGY ANALYSIS

Energy efficiency is a fundamental factor in PV power analysis, representing the percentage of sunlight energy that can be transformed into electricity by photovoltaic cells. The efficiency is determined by dividing the electrical power generated by the cells by the energy rate of the incident light, then multiplying by 100 to express it as a percentage.

$$\eta = \frac{P}{G \times A_{PV}} \times 100 \qquad \text{Eq. 2}$$

where, G is the intensity of global horizontal irradiance, which represents the intensity of solar irradiance over a horizontal surface in (W/m^2), A_{PV} is the PV module area in (m^2) and the PV module output power P can be determined by applying Equation 3:

$$P = V \times I \qquad \text{Eq. 3}$$

4. EXERGY ANALYSIS

Energy efficiency is concerned with the quantity of energy converted from one form to another without regard to its quality. Whereas exergy efficiency provides a qualitative measure of how nearly actual output energy approaches the maximum possible available energy and identifies system thermodynamic losses .The following analysis was performed only with cooled PV configurations.

For a PV module the exergy balance equation can be formulated as follows [22-25]:

$$Ex_{in} = Ex_{out} + Ex_{loss} + Ir \qquad \text{Eq. 4}$$

where, Ex_{in} is the amount of exergy received by the PV module, Ex_{out} represents the maximum useful energy utilized by the PV module undergoing a reversible process from the initial to the final state, Ex_{loss} is the exergy loss and Ir is the PV module exergy consumption due to irreversibilities.

The exergy input Ex_{in} can be calculated from Equation 5 using R. Petela [26-27] mathematical model.

$$Ex_{in} = A_{PV} \times G \times [1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4] \qquad \text{Eq. 5}$$

where T_{amb} and T_{sun} are the ambient and sun temperatures in °K, knowing that the sun temperature is about 5777 °K [22].

In addition to the electrical energy produced by the PV system, the PV modules also absorb thermal energy from solar radiation. This thermal energy is released from the surface of the PV panel to the environment, which can be viewed as a thermal loss. Therefore, the exergy output of the PV panel can be mathematically represented by Equation 6 [22–25].

$$Ex_{out} = P - Ex_{therm} \qquad \text{Eq. 6}$$

where Ex_{therm} is the PV thermal loss and is calculated from Equation 7 [22-25].

$$Ex_{therm} = Q \times \left[1 - \frac{T_{amb}}{T_m}\right] \qquad \text{Eq. 7}$$

where T_m is the panel average temperature.

$$Q = U \times A_{PV} \times [T_m - T_{amb}] + Q_{ev} \qquad \text{Eq. 8}$$

where U is the overall heat transfer coefficient due to convection and radiation.

$$U = h_C + h_R \qquad \text{Eq. 9}$$

The convection and radiation heat transfer coefficients are calculated from Equations 10 and 11 [22].

$$h_C = 2.8 + 3 \times \nu \qquad \text{Eq. 10}$$

$$h_R = \varepsilon \times \sigma \times (T_{sky} + T_m) \times ({T_{sky}}^2 + {T_m}^2) \qquad \text{Eq. 11}$$

The effective sky temperature is calculated from Equation 12 [25].

$$T_{sky} = T_{amb} - 6 \qquad \text{Eq. 12}$$

The evaluation of the heat dissipation rate from the cooling pad in the cooled PV panels is a crucial factor in analyzing the efficiency of the evaporative cooling method and its impact on the power output of the PV modules. Therefore, the heat dissipation rate can be determined using Equation 13.

$$Q_{rev} = m_{ev} \times \Delta H \qquad \text{Eq. 13}$$

Where, the amount of evaporated water per hour in kg/hr can be calculated from steam tables at the panel average temperature using the following formula [29]:

$$m_{ev} = (25 + 19 \times \nu) \times A \times (\omega_s - \omega_a) \qquad \text{Eq. 14}$$

Given that ν is the velocity of the air above the wetted cooling pad in m/s. The dry bulb temperature and relative humidity (RH) readings from the weather station, under Egyptian atmospheric pressure, utilized in conjunction with the standardized ASHRAE psychrometric chart to calculate the air humidity ratio (ω_a), and saturated air humidity ratio (ω_s).

Hence, the exergy efficiency is calculated applying Equation 15.

$$\eta_{Ex} = \frac{Ex_{out}}{Ex_{in}} \times 100 \qquad \text{Eq. 15}$$

5. ENVIRONMENTAL ANALYSIS

This analysis may be considered an extension of the previous energy and exergy analysis. Hakan Caliskan [30] presented an energy and exergy environmental analysis based on the life-cycle assessment method, a method that identifies the environmental impact of a process based on its life cycle from extraction to disposal. This LCA method is based on ISO 14040 through 14044 standards. The amount of CO_2 emissions in kg CO_2/kWh is considered the environmental analysis parameter for this investigation. Different values related to CO_2 emissions from the electricity generation source are presented in **Table 1**.

Table 1. Estimated CO_2 emissions for electricity generation sources [30].

System	CO_2 emission value (kg CO_2/kWh)
Hydro	0.010-0.013
Wind	0.009-0.010
Solar thermal	0.013
Nuclear	0.066
Biomass	0.015-0.041
Solar PV	0.032
Oil	--
Coal	0.778
Biogas	0.960-1.050
Natural gas	0.443
Geothermal	0.038
Fuel cell	0.664

In the present analysis, the equivalent CO_2 emissions for solar PV systems are assumed to be 0.032 kg CO_2/kWh, as estimated by Sovacool [31]. The present work investigates the environmental impact of the tested PV modules using energy and exergy environmental.

5.1. Energy-Environmental Analysis

For energy-environmental analysis, the amount of released CO_2 emissions in kg CO_2/time, χ_{CO_2}, is expressed in Equation 16 [32].

$$\chi_{CO_2} = Y_{CO_2} \times P \times t_w \quad \text{Eq. 16}$$

where Y_{CO_2} is the CO_2 emissions for solar PV modules obtained from LCA and t_w is the system working time.

5.2. Exergy-Environmental Analysis

While, for exergy-environmental analysis, the amount of released CO_2 emissions in kg CO_2/time, χ_{ex,CO_2}, may be obtained from Equation 17 [32].

$$\chi_{ex,CO_2} = Y_{CO_2} \times Ex_{out} \times t_w \quad \text{Eq. 17}$$

6. ENVIRO-ECONOMIC ANALYSIS

The cost of carbon dioxide emissions may be considered a critical parameter in the analysis. This parameter, which relates to energy, environment, and economics, is connected to the earlier environmental analysis and is determined by the quantity of CO_2 emissions released, as shown in Equations 18 and 19 [29].

6.1. Energy-Enviro-Economic Analysis

The energy-enviro-economic parameter is calculated from Equation 18.

$$C_{CO_2} = \chi_{CO_2} \times C \quad \text{Eq. 18}$$

where C is the social cost of CO_2 emissions in \$/ton. According to the US federal government's Interagency Working Group (IWG), the estimated social cost of CO_2, which is applied in the present work, is around 51 \$/ton CO_2 during the years from 2020 to 2025 [33].

6.2. Exergy-Enviro-Economic Analysis

Whereas the exergy-enviro-economic parameter is expressed in Equation 19.

$$C_{ex,CO_2} = \chi_{ex,CO_2} \times C \quad \text{Eq. 19}$$

The determination of the energy, exergy, environmental and economic parameters may be considered a distinct method to understand and analyze the performance of the tested PV modules in this study.

7. RESULTS AND DISCUSSION

The study was conducted over several days, encompassing both the winter and summer seasons of 2023. The experimental results were recorded, and the average results in the winter and summer were utilized in the subsequent analysis.

Figs. 4 and **5** illustrate the relation between the output voltage and electric current of the tested PV throughout the day during the winter and summer seasons, respectively. These figures also illustrate a correlation between the variation in solar irradiance throughout the day and significant changes in the behavior of the PV-tested modules' output electric current and voltage. Therefore, throughout all the experiments conducted, it was observed that the modified panels showed an increase in both voltage and electric current when compared to the standalone panel. The data presented in **Fig. 4** illustrates the findings of winter studies, indicating an average rise of 2.83% in CPV voltage and 3% in electric current. While the corresponding findings for CCPV are 3.87% and 5%, respectively. As for the summer readings, as shown in Fig. 5, it indicates an average rise of 2.85% and 3.39% in CPV voltage and electric current, respectively. While the corresponding readings for the CCPV in summer are 4.12%, 4.35%. Elevated temperatures of PV cells can lead to a decrease in the conversion efficiency of the PV modules. Without proper cooling, the temperature of the PV module rises, impacting the output voltage and current, as shown in **Figs. 4** and **5**, ultimately resulting in a reduction of the output power of the PV module.

Figs. 4 and **5** also illustrate the impact of the reflecting mirrors in the CCPV configuration on PV panels' performance. CCPV configuration increases the amount of solar intensity on PV panels, and as the light intensity increases, the open circuit voltage, short-circuit current, and maximum output power of solar cells also increase. The prescribed figures also indicate that the CPV and CCPV configurations have a higher impact on the electric current and voltage in the summer compared to the winter. This phenomenon can be attributed to the disparity in solar irradiance and cooling effects between the summer and winter seasons.

Before conducting the tests on PV modules, the uncertainty of the tested PV modules was obtained by evaluating the output power of the PV panels in the same environment (standalone). Results show that the maximum relative percentage errors for CPV and CCPV power, based on typology, are ± 0.52% and ± 0.43%, respectively.

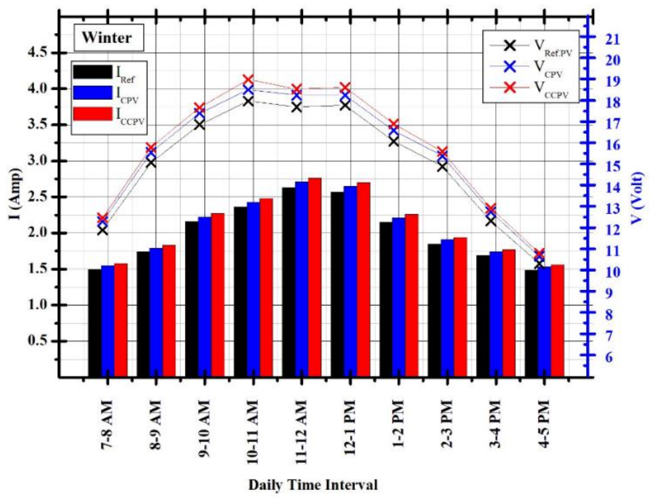


Fig. 4. The relation between panels output voltage and current versus daily time intervals during winter season.

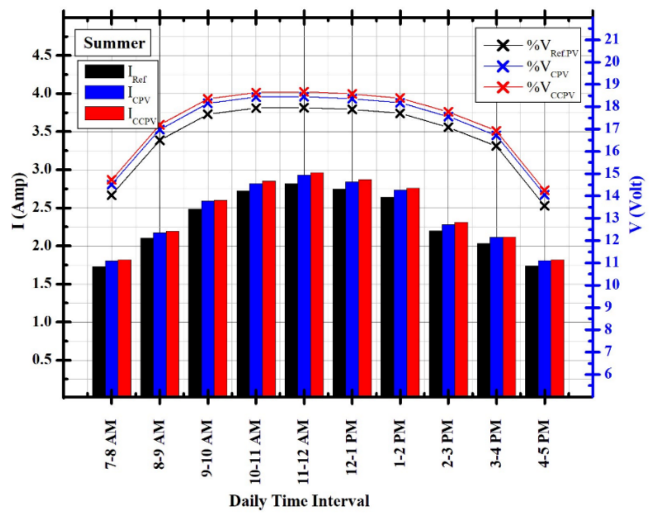


Fig. 5. The relation between panels output voltage and current versus daily time intervals during summer season.

Figs. 6 and **7** exhibit the results for the output energy and exergy from the tested PV modules throughout the day during the winter and summer seasons, respectively. As shown in **Fig. 6**, throughout the winter season, CPV panels yield energy values ranging from 14.96 to 48.12 Wh during the day. On the other hand, CCPV panels produce energy outputs varying from 15.44 to 49.57 Wh. **Fig. 6** also illustrates the CPV and CCPV exergy variation throughout the day during winter season, ranging from 13.59 to 44.49 W.hr and 12.69 to 36.97 Wh, respectively. In contrast, the results of the summer experiments, as depicted in **Fig. 7**, indicate increased energy and exergy output levels, varying from 26.09 to 55.47 Wh and 24.07 to 50.29 Wh, respectively, throughout the day, for the CPV configuration. On the other hand, the CCPV configuration exhibited output levels ranging from 26.62 to 56.67 Wh for output energy and 20.79 to 36.93 Wh for output exergy throughout the day.

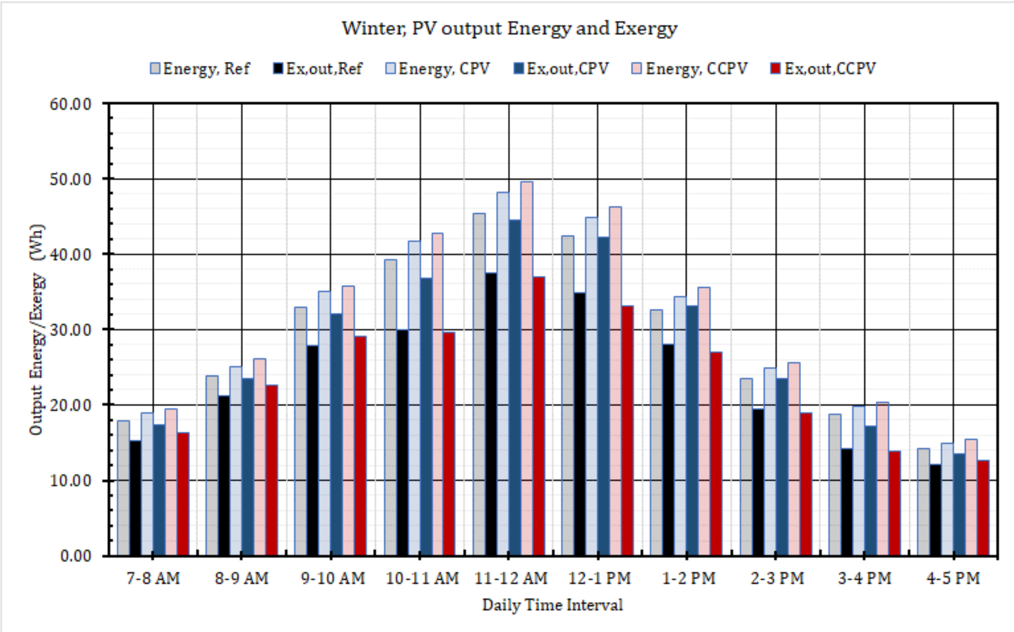


Fig. 6. Reference PV, CPV and CCPV output energy and exergy throughout the day during winter season.

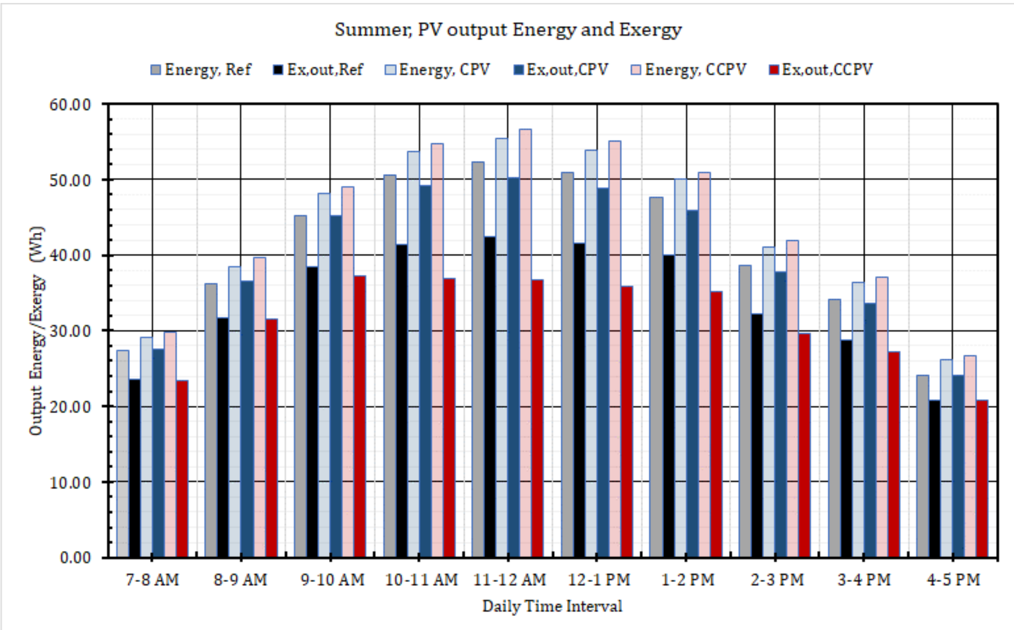


Fig. 7. Reference PV, CPV and CCPV output energy and exergy throughout the day during summer season.

Figs. 8 and **9** display the findings regarding the energy and exergy efficiencies of the investigated PV modules at various time intervals of the day in both the winter and summer seasons, respectively. In winter, the average energy efficiencies for the reference PV, CPV, and CCPV were found to be about 15.24, 16.14, and 16.62%, respectively. Where the corresponding findings for the exergy efficiencies are 13.56, 15.59 and 13.47%, respectively. On the other hand, **Fig. 9** illustrates the lower summer readings for both the energy and exergy efficiencies. the average energy efficiencies for the reference PV, CPV and CCPV were found to be about 13.29, 14.14 and 14.45%, respectively, in summer season. **Fig. 9** also demonstrates lower values for the exergy efficiencies in summer season compared to winter season. The values for the average exergy efficiencies for summer season for reference PV, CPV and CCPV panels are 12.05, 13.82 and 11.08%, respectively.

Based on the energy analysis, the findings from the winter and summer seasons illustrate a more significant improvement in CCPV panel energy efficiency compared to CPV. A notable enhancement in CPV panel exergy efficiency was identified when compared to CCPV through exergy analysis. The values for the energy and exergy efficiencies are related to the corresponding results for the output energy and exergy, shown in **Fig. 6** and **7**. The variations in energy and exergy analyses suggest that the output energy and exergy values fluctuate while the amount of power received by the PV module stays constant. This could be interpreted as an indication of the changing energy and exergy values. The CCPV panel's findings on exergy efficiency validate prior recognition of the importance of capturing heat losses in the CCPV system in order to maximize the benefits derived from this particular configuration.

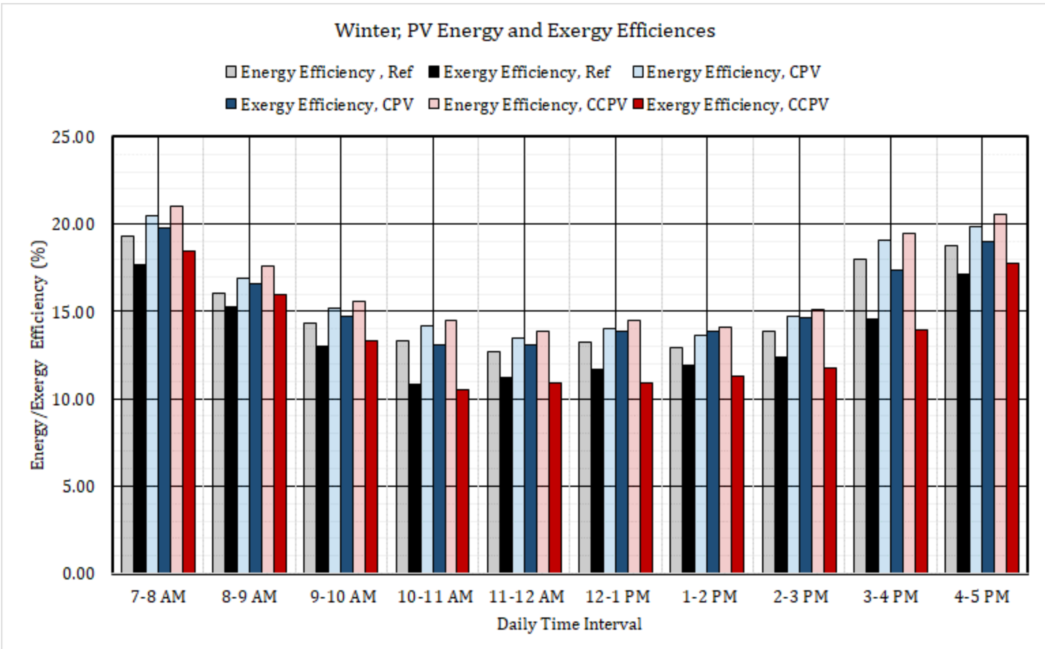


Fig. 8. Reference PV, CPV and CCPV energy and exergy efficiencies throughout the day during winter season.

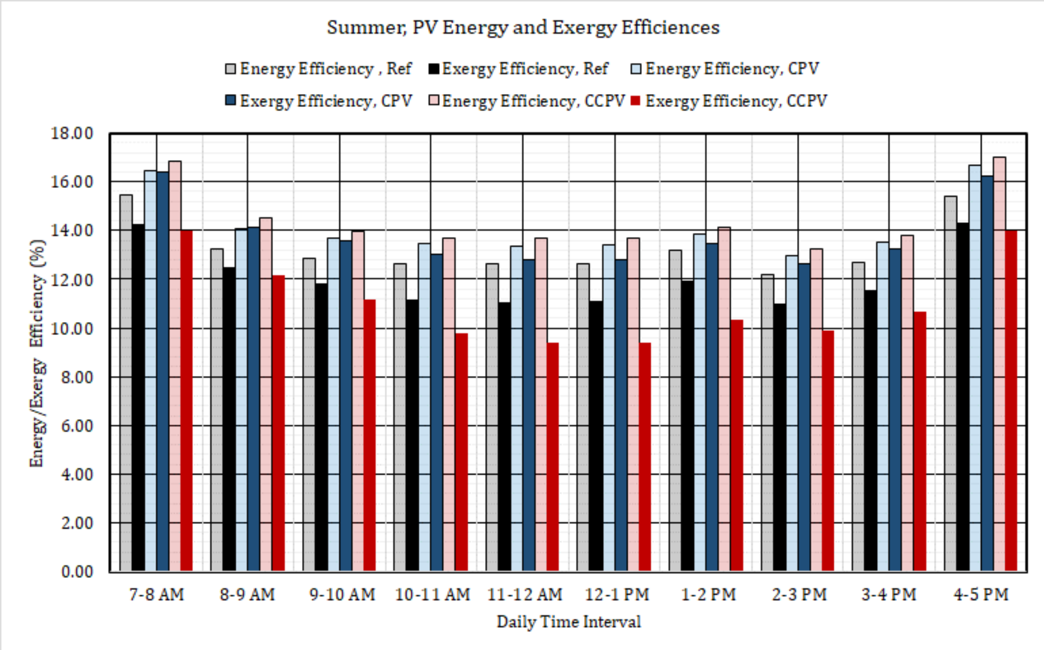
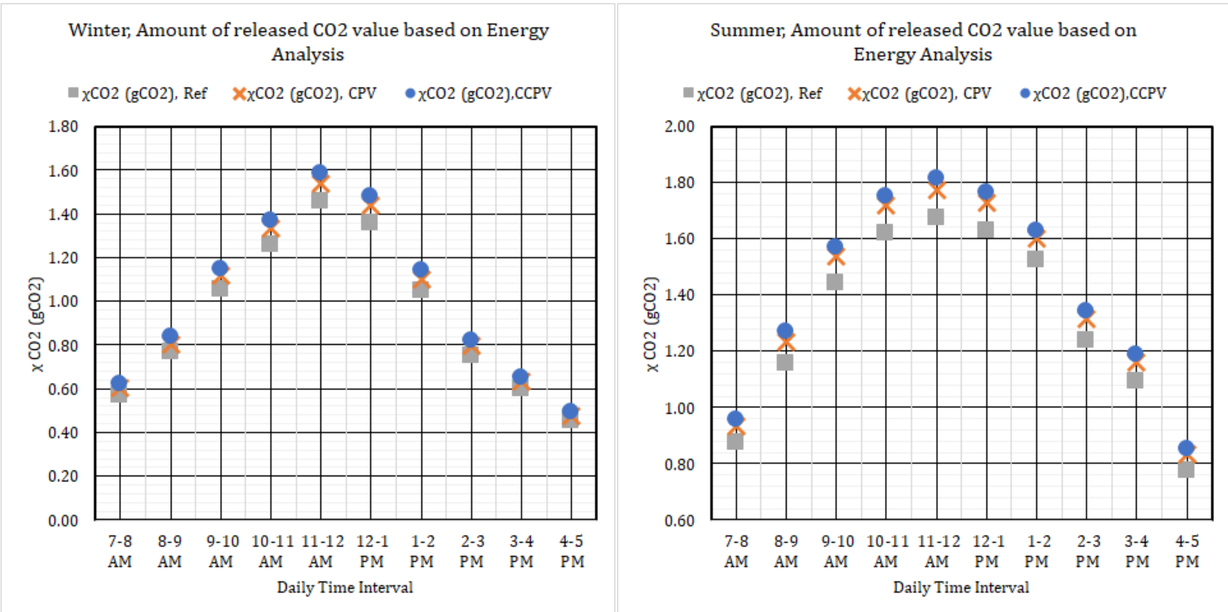


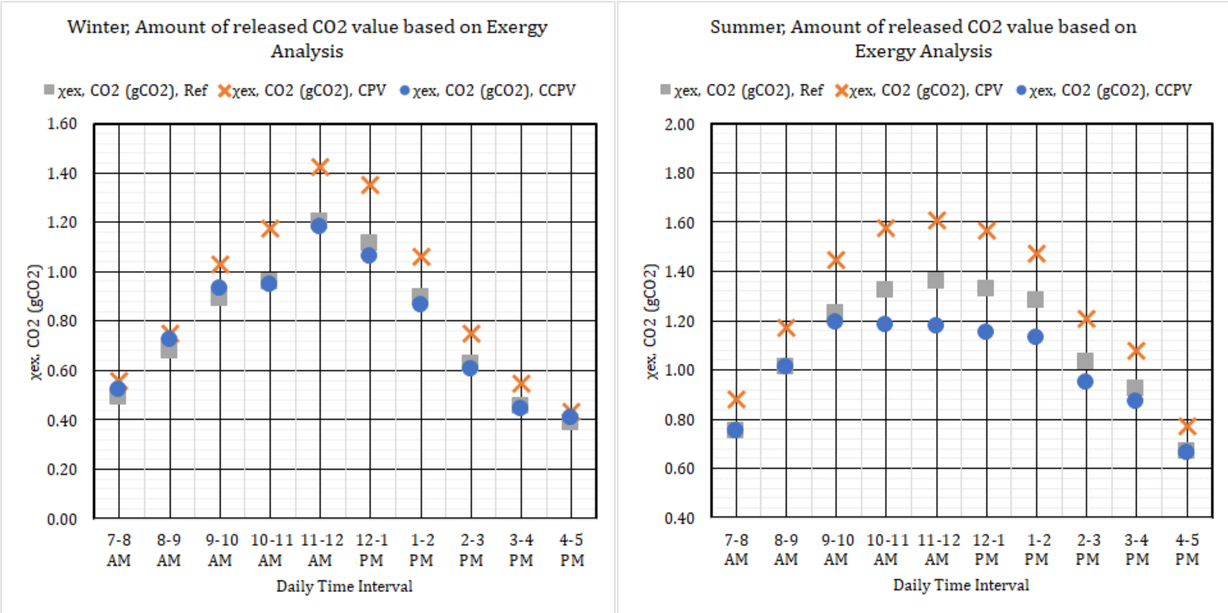
Fig. 9. Reference PV, CPV and CCPV energy and exergy efficiencies throughout the day during summer season.

Figs. 10 (a) and **(b)** display the outcomes of the energy-environmental assessment during the winter and summer seasons, respectively, as previously discussed in this document. The amount of CO_2 emissions released in grams, as determined by energy analysis, is correlated with the preceding energy assessment. **Fig. 11 (a)** and **(b)** illustrate the amount of CO_2 emissions released in grams, based on exergy-environmental analysis, throughout the day during the winter and summer seasons. The findings suggest that CCPV demonstrates higher levels of released CO_2 emissions compared to CPV, as illustrated by the energy-environmental assessment. In contrast, the results suggest that CCPV shows lower levels of CO_2 emissions when compared with CPV, as depicted by the exergy-environmental analysis.



(a) **(b)**

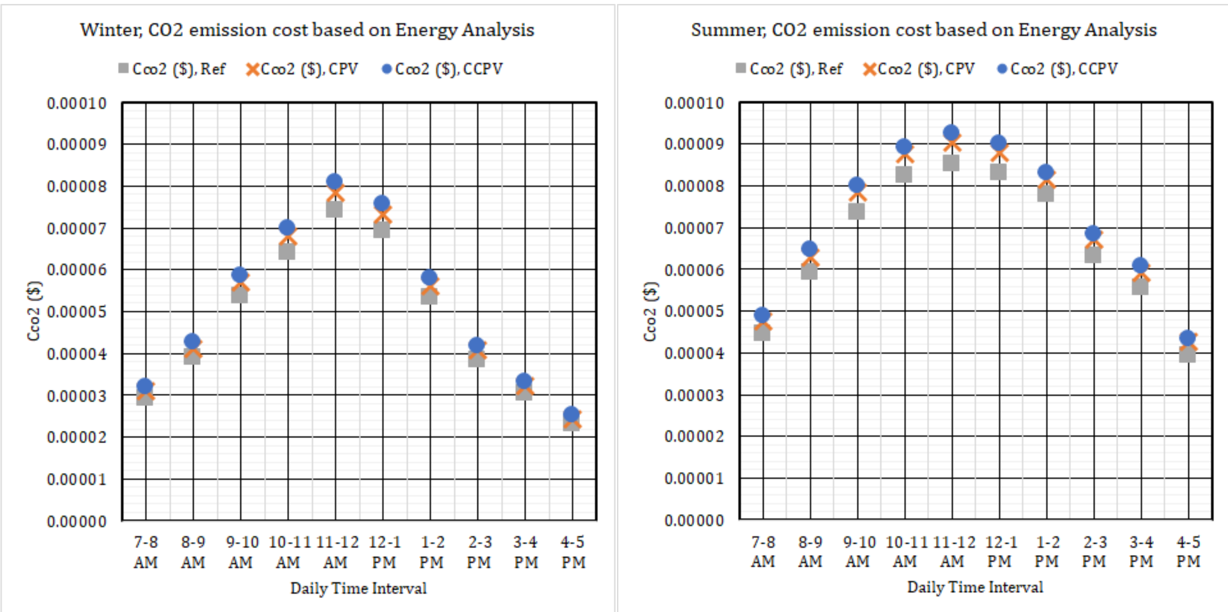
Fig. 10. The relation between the amount of released CO_2 emissions (based on energy analysis) versus daily time intervals during winter and summer seasons.



(a) **(b)**

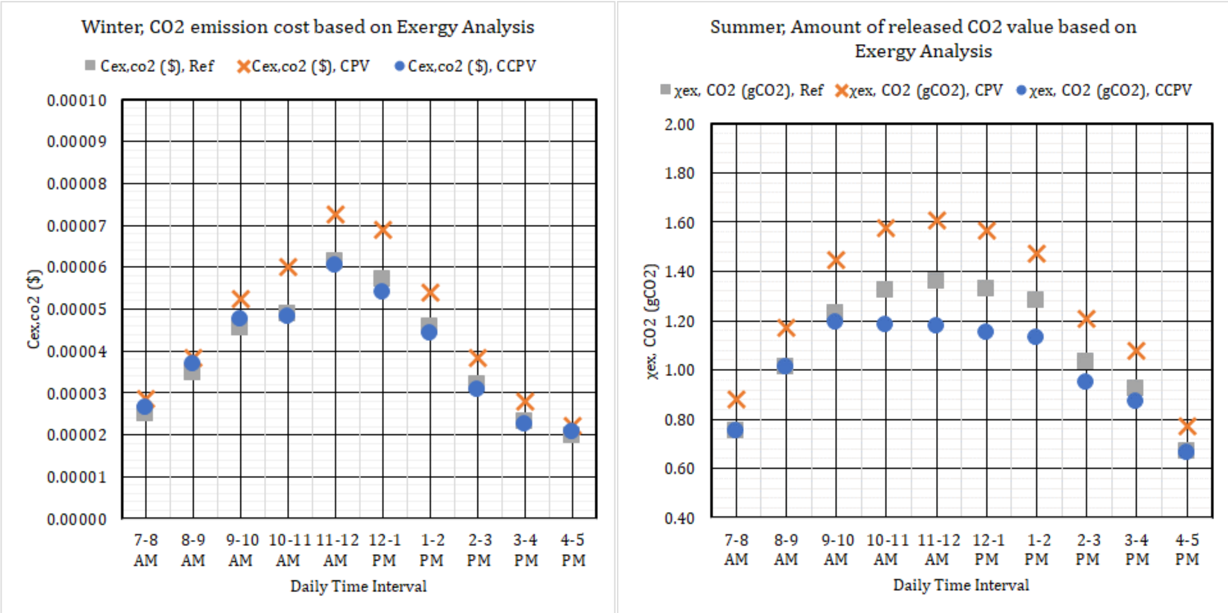
Figs. 11. The relation between the amount of released CO_2 emissions (based on exergy analysis) versus daily time intervals during winter and summer seasons.

Fig. 12 (a) and **(b)** illustrate the results of the energy-enviro-economic analysis during the winter and summer seasons, respectively. The energy-enviro-economic parameter in $, as determined by energy-enviro-economic, is associated with the earlier energy and energy-environmental assessments. On the other hand, **Fig. 13 (a)** and **(b)** show exergy-enviro-economic parameters in dollars throughout the day, during the winter and summer seasons. The findings reveal that CCPV has higher energy-environment-economic parameter values than CPV. In contrast, the results suggest that when compared to CPV, CCPV exhibits exergy-enviro-economic parameter values.



(a) **(b)**

Fig. 12. The relation between the energy-enviro-economic parameter versus daily time intervals during winter and summer seasons.



(a) **(b)**

Fig. 13. The relation between the exergy-enviro-economic parameter versus daily time intervals during winter and summer seasons.

CONCLUSIONS

The present work conducts an in-depth examination encompassing energy, exergy, environmental, and economic aspects to explore the consequences of shifting from conventional photovoltaic systems to either CPV or CCPV. The study investigated the improved performance of CPV and CCPV configurations in comparison to conventional PV panels by integrating evaporative cooling pads into the modified configurations (CPV and CCPV) and utilizing reflective mirrors for the CCPV setup. The following conclusions can be drawn:

a. During the winter season, there was an average increase of 2.83% in CPV voltage and 3% in electric current. In contrast, the results for CCPV showed a higher increase, with 3.87% in voltage and 5% in electric current.
b. The summer data shows a typical increase of 2.85% in CPV voltage and 3.39% in electric current. In contrast, the corresponding CCPV measurements for summer show a rise of 4.12% and 4.35%, respectively.
c. The integration of the evaporative cooling method into PV systems leads to a decrease in the temperature of the PV module, which affects the output voltage and current, ultimately resulting in an increase in the output power of the PV panels.
d. Utilizing reflective mirrors enhances the solar irradiance incident on photovoltaic panels, leading to a rise in light intensity and subsequently boosting the power output.
e. The CPV and CCPV configurations demonstrate a greater impact on the electric current and voltage in the summer season compared to the winter months.
f. During the winter season, the CPV setup exhibits energy and exergy values between 14.96 to 48.12 W.h and 13.59 to 44.49 W.h, respectively, throughout daylight hours, while the CCPV arrangement demonstrates elevated energy and exergy ranges from 15.44 to 49.57 W.h and 12.69 to 36.97 W.h, respectively.

g. During the summer season, the CPV system demonstrates energy and exergy levels between 26.09 to 55.47 W.h and 24.07 to 50.29 W.h, respectively, throughout the day. In contrast, the CCPV configuration exhibits higher energy and exergy values ranging from 26.62 to 56.67 W.h and 20.79 to 36.93 W.h, respectively.
h. While CCPV yields greater output energy than CPV in winter and summer, the results reveal that CCPV has a lower output exergy than CPV.
i. PV panels demonstrate lower exergy efficiencies during the summer months compared to the winter months.
j. CPV panels increase output energy by around 5.62% and 6.34% in the winter and summer seasons, while CCPV panels boost energy by about 9.07% and 8.65% during the winter and summer seasons, respectively.
k. The CCPV showed higher levels of CO_2 emissions compared to CPV based on the energy-environmental assessment. In contrast, the CCPV displayed lower CO_2 emissions levels than CPV according to the exergy-environmental analysis.
l. The present work indicates that CCPV shows superior energy-environmental-economic parameter values in comparison to CPV. Conversely, when compared with CPV, the findings imply that CCPV displays exergy-environmental-economic parameter values.
m. It is crucial to integrate heat loss utilization into the CCPV system in order to optimize the advantages of the CCPV configuration, as highlighted through the conduction of exergy, exergy-environmental, and exergy-enviro-economic analyses.
n. The current study suggests that hybrid photovoltaic/thermal solar systems have the potential to be a cost-efficient method and an effective solution for maximizing the benefits of PV systems while also harnessing untapped thermal losses from such systems.

REFERENCES

[1] Mohamed R. Gomaa, Waleed Hammad, Mujahed Al-Dhaifallah, Hegazy Rezk, Performance enhancement of grid-tied PV system through proposed design, cooling techniques: An experimental study and comparative analysis, Solar Energy 211 (2020) 1110–1127.
[2] Hafiz Muhammad Ali, Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems – A comprehensive review, Solar Energy 197 (2020) 163–198.
[3] Saeed Siah Chehreh Ghadikolaei, An enviroeconomic review of the solar PV cells cooling technology effect on the CO2 emission reduction, Solar Energy 216 (2021) 468–492.
[4] Ramkiran B, Sundarabalan CK, K. Sudhakar, Sustainable passive cooling strategy for PV module: A comparative analysis, Case Studies in Thermal Engineering 27 (2021) 101317.
[5] Karthikeyan Velmurugan, Sunilkumar Kumarasamy, Review of PCM types and suggestions for an applicable cascaded PCM or passive PV module cooling under tropical climate conditions, Journal of Cleaner Production 293 (2021) 126065.
[6] Mohammed Sanad Raja, Ahmed J. Abid, Zuhair S. Al-Sagar, "A Systematic Review for Enhancing Solar Photovoltaic System Efficiency by Reducing the Panel Temperature", 2023 IEEE 3rd International Conference in Power Engineering Applications (ICPEA), pp.77-81, 2023.
[7] Krishna Kant Dixit, Indresh Yadav, Gaurav Kumar Gupta, Sanjay Kumar Maurya, "A Review on Cooling Techniques Used For Photovoltaic Panels", 2020 International Conference on

Power Electronics & IoT Applications in Renewable Energy and its Control (PARC), pp.360-364, 2020.

[8] Saurabh Mehrotra, Pratish Rawat, Mary Debbarma, K. Sudhakar, Performance of a solar panel with water immersion cooling technique, International Journal of Science, Environment and Technology, ISSN 2278-3687, Vol. 3, No 3, 2014, 1161 – 1172.

[9] Sadık Zuhur, İlhan Ceylan, Alper Ergün, Energy, exergy and environmental impact analysis of concentrated PV/ cooling system in Turkey, Solar Energy 180 (2019) 567–574.

[10] Leow Wai Zhe, Mohd. Irwan Yusoff1, Amelia Abd Razak, Muhammad Irwanto Misrun, Safwati Ibrahim, Muhammad Izuan Fahmi, Afifah Shuhada Rosmi, Effect of Water Cooling Temperature on Photovoltaic Panel Performance by Using Computational Fluid Dynamics (CFD), Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 56, Issue 1 (2019) 133-146.

[11] Gomaa, M.R.; Al-Dhaifallah, M.; Alahmer, A.; Rezk, H. Design, Modeling, and Experimental Investigation of Active Water Cooling Concentrating Photovoltaic System. *Sustainability* **2020**, *12*, 5392. https://doi.org/10.3390/su12135392

[12] Ahmed Hussien, Abdelgalil Eltayesh, Hesham M. El-Batsh, Experimental and numerical investigation for PV cooling by forced convection, Alexandria Engineering Journal (2023) 64, 427–440.

[13] E. Chan-Dzib, A. Bassam, J.G. Carrillo, Novel curled cooler to enhance the efficiency of a photovoltaic panel system, Applied Thermal Engineering Volume 249 , 15 July 2024, 123317.

[14] Hossain, Farzad & Karim, Md.Rezwanul & Bhuiyan, Arafat A.. (2022). A review on recent advancements of the usage of nano fluid in hybrid photovoltaic/thermal (PV/T) solar systems. Renewable Energy. 188. 114-131. 10.1016/j.renene.2022.01.116.

[15] Gomaa, Mohamed & Ahmed, Mohsen & Rezk, Hegazy. (2021). Temperature distribution modeling of PV and cooling water PV/T collectors through thin and thick cooling cross-fined channel box. Energy Reports. 8. 10.1016/j.egyr.2021.11.061.

[16] Karim, Md.Rezwanul & Akhanda, M.. (2011). Study of a hybrid photovoltaic thermal (PVT) solar systems using different ribbed surfaces opposite to absorber plate. Journal of Engineering and Technology. 9. 17-30.

[17] Someshwar S. Bhakre, Pravin D. Sawarkar, Vilas R. Kalamkar, Performance evaluation of PV panel surfaces exposed to hydraulic cooling –A review, Solar Energy 224 (2021) 1193–1209.

[18] Muhammad Faizan Tahir, Chen Haoyong, Han Guangze, A comprehensive review of 4E analysis of thermal power plants, intermittent renewable energy and integrated energy systems, Energy Reports, Volume 7, November 2021, Pages 3517-3534.

[19] Mersad Shoaei, Seyed Farhan Moosavian, Ahmad Hajinezhad, 4E analysis of a concentrating photovoltaic thermal system (CPVT) with examining the effects of flow regime and concentration ratio, Energy Reports, Volume 8, November 2022, Pages 14753-14770.

[20] Global Solar Atlas. 2017. 10th of Ramadan city solar data [accessed Jan 2022]; https://globalsolaratlas.info/map.

[21] R. J. Moffat, "Using Uncertainty Analysis in the Planning of an Experiment," ASME. J. Fluids Eng, vol. 107(2), pp. 173–178.

[22] Anand S. Joshi, Ibrahim Dincer, Bale V. Reddy, Thermodynamic assessment of photovoltaic systems, Solar Energy 83 (2009) 1139–1149.

[23] Nallapaneni Manoj Kumar, Umashankar Subramaniam, Mobi Mathew, A. Ajitha, Dhafer J. Almakhles, Exergy analysis of thin-film solar PV module in ground-mount, floating and submerged installation methods, Case Studies in Thermal Engineering 21 (2020) 100686.

[24] Dheya Ghanim Mutasher, Mohammed Fowzi Mohammed, Zaid Salman Obaid, Energy and Exergy Performance Calculation of Solar Photovoltaic/ Thermal Hybrid System under the Baghdad Environment, Journal of University of Babylon for Engineering Sciences, Vol. (27), No. (1): 2019.

[25] K. Sudhakar & Tulika Srivastava (2014) Energy and exergy analysis of 36 W solar photovoltaic module, International Journal of Ambient Energy, 35:1, 51-57, DOI: 10.1080/01430750.2013.770799.

[26] Petela, R. (1961) Exergy of Heat Radiation. Ph.D. Thesis, Faculty of Mechanical Energy Technology, Silesian Technical University, Gliwice. (in Polish).

[27] Petela, R., Exergy of heat radiation, Solar Energy, Volume 74, Issue 6, June 2003, Pages 469-488.

[28] Wattmuff, J.H., Charters, W.W.S., Proctor, D., 1977. Solar and wind induced external coefficients for solar collectors. Internationale Revue d'Heliotechnique 2, 56.

[29] http://www.engineeringtoolbox.com/evaporation-water-surface-d_690.html.

[30] Hakan Caliskan, Novel approaches to exergy and economy based enhanced environmental analyses for energy systems, Energy Conversion and Management 89 (2015) 156–161.

[31] Benjamin K. Sovacool, Valuing the greenhouse gas emissions from nuclear power: A critical survey, Energy Policy 36 (2008) 2950– 2963.

[32] Seyed Farhan Moosavian, Daryoosh Borzuei, Abolfazl Ahmadi, Energy, exergy, environmental and economic analysis of the parabolic solar collector with life cycle assessment for different climate, Renewable Energy 165 (2021) 301e320.

[33] Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990 (2020).