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Energy, exergy, economical and environmental analysis of photovoltaic solar panel for fixed, single and dual axis tracking systems: An experimental and theoretical study

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A R T I C L E I N F O

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A B S T R A C T

This investigation focuses on energetic, exegetic, economical and environmental analysis of PV solar system using fixed, single- and dual-axes tracking systems under climatic weather of Zakho city/north of Iraq. Experiments are carried out on 5th September 2022. The energy and exergy analyses are used to predict the performance of three solar panels. The theoretical work includes technical, economical and environmental analysis of proposed 1 MW PV solar power plant are presented using similar characteristics of the experimental data of hourly meteorological climatic conditions during 2022. The findings display that the tracking systems have significant influences on 4–E performances. The experimental results displayed that electrical output power gain and thermal exergy output are increased when using tracking systems, where the exergy losses for single- and dual-axes tracking systems are decreased as compared to fixed solar plane. The maximum improvements in the electrical output power gain of PV solar panels using dual– and single–axes tracking systems are nearly reached to 40 % at 8 a.m., 13 % (for single) and 20 %(for dual) at 12 p.m. and 30 % at 17PM as compared to fixed solar panel. The theoretical results display that the yielded produced energy for single- and dual-axes are increased by 16.5 % and 25.5 %, respectively, as compared to fixed panel. The economic findings display that the cost of energy for single-axes, dual-axes and fixed tracking systems are 4.89, 4.41 and 8.26, respectively. Finally, the use of tracking systems reduces the CO_2 emission about 4000–4500 tCO2 annually.

1. Introduction

The limitation and reduction of the environmental degradation, the contribution in the green technologies development and their adoption is very necessary [1]. There are many renewable sources such as solar, hydro, wind and biomass which not make any pollution on the environment during their employment. These sources can be used instead of the fossil fuel sources of energy. The solar energy is one of the most available energy sources which have great possibility for green technologies due to its availability, inexhaustible energy source, clean and free cost [2–4]. The quantity of the solar radiation nearly about 1.2×10^5TW which reaches to the

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surface of the earth [2]. The effectiveness of solar systems using fixed panel is increased along with the utilizing tracking systems due the ability to follow the sun position during the day [1]. The using of tracking system can improve the performance of the extracted energy. Although there are several investigations in Iraq dealt with the PV solar system experimentally [3–13], most of these studies are not included the impacts of using tracking system.

Different studies dealt with solar tracking systems have been published. Molan et al. [14] experimentally investigated the PV solar energy via solar tracking system using exergy analysis. The outcomes show that the most solar radiation is lost and no benefit by PV panel. Neville [15] displayed that the solar energy system using dual–axes tracking system produced maximum energy output, while the energy output of single tracking reduces by 5%–10 % and without using tracking falls by 50 %. Arlikar et al. [16] proved that the triple tracking which uses with PV solar panel has been received energy greater than fixed PV panel. Qader et al. [17] theoretically displayed the feasibility analysis of 1 MW tie–grid connected PV power plant. In their study, an hourly meteorological data have been used to compare the system performance for three actual installed PV solar panels; without, single and dual tracking systems. The theoretical results displayed that the percentage increment in the annual yield factor for dual–axes and single–axes as compared to the fixed case are 25 % and 16 %, respectively. The findings showed that cost of energy (COE) for duel, single and fixed systems are 0.0441USD/kWh, 0.0489USD/kWh and 0.0826USD/kWh, respectively. The systems used for wide applications of solar energy such as Multiple-effect distillation MED. Gholinejad et al. [18] presented that the solar MED system along with polar axis, E–W, N–S, and full tracking systems produced more fresh water by 291 %, 246 %, 135 % and 341 %, respectively, as compared to without using tracking system.

The exergy analysis involves the useful energy which is used for solar energy. It depends on the irreversibilities sources and quantities that employed to modify the system efficiency. There are several investigations presented the PV performance of different cases [3,14,19,20]. Alomar and Ali [3] presented the energetic and exegetic analysis PV/T system using the experimental data of Dohok city/north of Iraq. The findings indicated that the environment conditions have an extremely actions on the energetic and exegetic outputs, where the range of thermal and electric exegetic performances have been found between 2 – 7 % and 10–18 %, respectively. Also, there are many studies conducted the environment, economic and technical analysis of solar energy systems. Ali et al. [13] investigated the environment, economic and energetic performances of a 1MWp photovoltaic power plant installed at Zakho city/Iraq using real data. The outcomes indicated that the investment of PV system is more feasible in Iraq in comparison with fossil fuels power plants. The economic outcomes show that the payback time is nearly 7 years to return the initial cost, whereas the payback energy time is nearly 2 years to return the embedded energy. The employment of PV plant can shrink the CO2 emissions between 600 and 2000 tCO2. Abdul-Ganiyu et al. [19] used the mono-Si photovoltaic-thermal (PV/T) panel installed in the Ghana using analytical methods to analyze the performances of these systems technically and economically through a 25-year period. The outcomes indicated that the annual total exergy to load from PV and PV/T sub-systems are 159.42 kWh/m2 and 330.15 kWh/m2 respectively. The exergy levelized cost (LCOEx) are US$ 0.45/kWh and US$ 0.33/kWh for PV and PV/T systems, respectively. Ali and Alomar [21] evaluated the technical and economic feasibility study for a grid connected photovoltaic solar system in a campus of University of Zakho, Iraq. The outcomes show that the system produces 5,205AC MWh during the year with a maximum power generated by the arrays 3.15AC MW. The yield and capacity factors of the system in 1st year are 1554 kWh/kW and 17.7 %, respectively. It has been found that the payback period to recover the cost of the government electrical energy without employing local electrical generators is 7 years.

A thoroughly review on previous investigations show that a considerable number of theoretical investigations have been dealt with energy, exergy, economic and environment analysis of PV solar in several cities in the world except the cities in Iraq due to the incomplete in the information on this issue. While most of these studies have been focused on the performances of technical and economical of different PV system applications without using tracking system, there is a lack in the experimental studies related with the energy, exergy, economic and environment analysis of PV solar systems by using tracking system in Iraq. In addition, the previous works reveal that there is no experimental investigation deal with the energy, exergy, economic and environment analysis of photovoltaic solar model using tracking system in Iraq. Most of the previous experimental studies related to this topic have been done without using tracking system. Based on the above details, the current study aims to perform an experimental work on the energy, exergy, economic and environment performance of PV solar energy using fixed, single– and dual–axes tracking systems. The systems have been installed in Zakho city/north of Iraq. In this work, the performances of energy and exergy analysis have been investigated to compare the electrical output power gain, electrical exergy, power of thermal exergy, outlet power exergy, exergy loss and energy production of these three cases for purpose of comparison. The work also implements an economic and environment feasibility study to compare the output between fixed and solar tracking systems which is based on the employment of the PV solar panel that used for experimental work.

The remnant paper is managed as follows: Experimental setup and uncertainty analysis are displayed in Section 2. The energetic and exegetic analysis are displayed in Section 3. The economic and environment feasibility test are presented in Section 4. The outcomes are displayed in Section 5. The findings are listed in Section 6.

2. Experimental setup

2.1. Experimental rig

The complete test rig is set on the building at University of Zakho, where the university is located in Zakho city/Iraq. The test rig includes 3 PV solar panels as follows: the first panel is fixed which is used as a reference model; the second PV panel is employed single tracking system and the third PV panel is employed dual tracking system. The test rig also includes a data collection system, electrical accessories, measurement instruments and control systems. The real photo of test rig model is given in Fig. 1. Table 1 displays the PV solar system characteristics, where the panels are oriented towards south with a tilt angle of 37.1°.

In the present study, ten thermocouples of type K are used to measure the temperature of three PV panels and ambient temperature. Each PV solar panel is used 3 thermocouples, which is installed at the backside of the panels. One thermocouple is employed to measure the ambient temperature. The thermocouples are calibrated using a thermometer which is performed between two specified temperatures as shown in Fig. 2. The errors between the readings of thermocouple and thermometer have been found very small. The global solar irradiance has been measured using Pyranometer. The wind speed has been measured using a portable anemometer which is installed at the same height of the PV panels to ensure precise wind speed measurement data. The open circuit voltage and short circuit current have been measured every 10 min using special sensors (Arduino with micro-SD card) with 200 W light bulb load for each solar system. The linear actuators have been used to control the single- and dual-axes tracking systems. The control system of the linear actuator consists of the following electronic components: Arduino UNO microcontroller which is used to control various applications; light-depending resistor (LDR) which is made from photoresistor and a semiconductor and used to indicate the presence or absence of light; two channel 5 V Relay Module which is an automatic switch to control a high-current course with a low-current signal; micro limit switch that send an electric signal when an item physically contacts and moves the actuator and the power supply and voltage reducer. The data of the solar radiation, wind speed, voltage, current, and temperatures have been collected. A micro-SD card has been used as a data logger to collect the data of the real-time clock module (DS1302) and a power supply. Arduino is used as an essential part with electronic circuit for data collection.

2.2. Uncertainty analysis

The uncertainty of the electrical efficiency and power are analyzed, where the electrical power is assumed in terms of short circuit current I_{sc} and open circuit voltage V_{oc}. The V_{oc} and I_{sc} uncertainty values are equal 0.078 % and 0.16 %, respectively. So, the output electrical power uncertainty is estimated as [22]:

$$\frac{w_p}{P} = \left[\left(\frac{w_v}{V}\right)^2 + \left(\frac{w_I}{I}\right)^2\right]^{1/2} \tag{1}$$

In Eq. (1), w_v displays the uncertainty of V_{oc} , w_I displays the uncertainty of I_{oc} and w_p displays the uncertainty of P. The electrical efficiency is determined as [23]:

$$\frac{w_\eta}{\eta} = \left[\left(\frac{w_v}{V}\right)^2 + \left(\frac{w_I}{I}\right)^2 + \left(\frac{w_G}{G}\right)^2\right]^{1/2} \tag{2}$$

In Eq. (2), w_G displays the uncertainty in solar radiation, which is equal 0.1 %. The results display that the uncertainty in power output and electrical efficiency are equal 0.178 % and 0.245 % respectively.

3. Energetic and exegetic analysis

This section presents the energetic and exegetic analysis which is developed to investigate their performances. The present models are build based on the following assumptions: steady-state condition, the energy transfer through the PV solar panels is assumed to be 1D, the actions of dust above the panels is ignored and the surrounding conditions are time-dependent.

3.1. Energy analysis

The energetic performance of the tested panels cases are performed. The output electrical power can be calculated as [24]:

$$P_m = V_{oc} * I_{sc} * FF = V_m * I_m \tag{3}$$

In Eq. (3), FF displays the fill factor which represents the ratio between optimum power and V_{oc} and I_{sc} product. Hence, FF can be obtained as follows [24]:

Fig. 1. Solar PV panels for fixed, single tracking and dual tracking systems.

Table 1
PV panel characteristics.

Item	Specification
Power output warranty	Ten years over 90 %, 25 years over 80 %
Application Class	Class A
Lifespan	>20 years
Other certifications	IS09001:2008, RoHS
Product certifications/Standards	CE, IEC61215
Voltage temperature coefficient	-0.37 %/ $^{\circ}C$
Current temperature coefficient	0.08 %/ $^{\circ}C$
Power temperature coefficient	-0.43 %/ $^{\circ}C$
Operating temperature range	-40 $^{\circ}C$ $+85$ $^{\circ}C$
Max. hailstone impact (diameter/velocity)	25 mm; 23 m/s
Max. static load, back	2400Pa
Max. static load, front	5400Pa
Standard Testing Conditions	Solar radiation:1000 W/m^2, cell ambient temperature: 25 $^{\circ}C$, air mass:1.5.
Cable/Cable connector Model	900 mm solar cable with MC4 compatible connectors
Junction box protection degree	≥IP65
Frame(material/color)	Anodized aluminum alloy/Silver
Solar backsheet(material/color)	TPT/White – color (black color is optional)
Encapsulation(material)	Ethylene Vinyl Acetate(EVA)
Front cover(material/thickness)	Low-iron tempered glass/3.2 mm
Load conversion efficiency	Polycrystalline silicon,36-cell in series
Dimensions(L*W*T)	1480mm × 670mm × 35 mm (Panel area 0.9916m^2)
Grade of solar cells	A grade
Solar cells efficiency	around 19.0 % at STC
Short circuit current/Isc(A)	9.16A
Max. power current/Imp(A)	8.33A
Max. power voltage/Vmp(V)	18.0
Open circuit voltage/Voc(V)	21.6
Peak power *Pm*(W)	150 ± 5 %

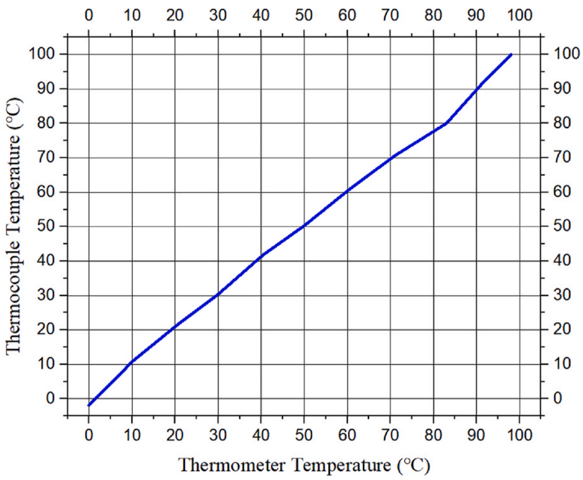

Fig. 2. Calibration of thermocouples.

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{4}$$

In Eq. (4), V_m and I_m display the optimum voltage and current, respectively. The electrical efficiency for three panels cases can be estimated as [24]:

$$\eta_{el} = \frac{P_m}{G A_{PV}} \tag{5}$$

where A_{PV} and G are the panel area and solar irradiance (W/m^2), respectively.

3.2. Exergy analysis

The exegetic formulation is build according to 2nd law of thermodynamics due to the interactions of solar PV panel with the surrounding, which measures the various energy losses. In this analysis, the actual performance of PV system is investigated. The exergy balance of PV panel can be written as [20]:

$$Ex_{in} = Ex_{out} + Ex_{loss} + Ir \tag{6}$$

where, Ex_{in} represents the input exergy (W), Ex_{out} is the output exergy (W), Ex_{loss} is the losses in the exergy (W) and Ir is the module irreversibility. The input exergy to the PV module (Ex_{in}) can be determined by using Patela's equation, which is calculated as:

$$Ex_{in} = A_{PV} \times G \times \left[1 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right] \tag{7}$$

where A_{PV} is the PV module surface area (m^2), T_{amb} and T_{sun} represent the ambient (air temperature surrounding PV panel) and sun temperatures (K) which is assumed to be 5777 K. The output exergy is equal the difference between the electrical exergy by the PV panel and the thermal gains, which is dissipated to the surroundings:

$$Ex_{out} = Ex_{electrical} - Ex_{thermal} \tag{8}$$

where Ex_{ele} and $Ex_{thermal}$ are the electrical exergy (W) and the dissipated thermal exergy (W), respectively. The electrical exergy can be obtained as [20]:

$$Ex_{electrical} = \mathrm{V_{oc}} * \mathrm{I_{sc}} * \mathrm{FF} \tag{9}$$

The thermal exergy represents the amount of thermal energy lost from PV panel into the surrounding areas as [20]:

$$Ex_{thermal} = (h_{con} + h_{rad}) \times A_{PV} \times (T_{amb} - T_{PV}) \times \left(1 - \frac{T_{amb}}{T_{PV}}\right) \tag{10}$$

where h_{con} is the coefficient of convection heat transfer, h_{rad} is the radiation heat transfer coefficient, T_{PV} displays the panel temperature and T_{sky} displays the effective temperature of sky. These parameters are obtained as:

$$h_{con} = 2.8 + 3V \tag{11a}$$

$$h_{rad} = \varepsilon\sigma\left(T_{sky} + T_{PV}\right)\left(T_{sky}^2 + T_{PV}^2\right) \tag{11b}$$

$$T_{sky} = T_{amb} - 6 \tag{11c}$$

In Eq. (11), V represents the wind speed (m/s). The solar radiation income is the summation of the electrical energy and the thermal energy (loss energy). The energy loss is the thermal exergy which is dissipated from the PV module. The two forms of the energy is varied due to the local weather conditions. The exegetic is linked with the thermal energy losses of a PV module as:

$$Ex_{loss} = Ex_{in} - Ex_{out} \tag{12}$$

The PV panel exegetic efficiency is equal the exegetic output to the exegetic input ratio as [20]:.

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \tag{13}$$

4. Energetic, economic and environment feasibility analysis

The economic and environment feasibility analysis are based on 1 MW tie – grid connected PV power plant which is theoretically simulated in Zakho city. The SAM software is used which is based on hourly meteorological data for tested panels. This study is based on the actual solar panel that set in Zakho city (see Fig. 1). The Zakho city is a bordering region city located at north western part of Duhok Governorate (37.15° north latitude and 42.67° east longitude).

Due to the theoretical analysis, the output power of PV module is determined using solar radiation (G) and the ambient temperature (T_a). The PV output power can be obtained as [25]:

$$\mathrm{P_{mp}} = \mathrm{G}\eta_\mathrm{m}\mathrm{A_m}\left(\frac{\gamma_\mathrm{mp,ref}}{100}\right)(\mathrm{T_c} - 25) \tag{14}$$

In Eq. (14), G, η_m, $\gamma_{mp,ref}$ and T_c display the display solar intensity radiation, module efficiency, temperature coefficient of PV panel and cell temperature, respectively. The T_c can be found as:

$$\mathrm{T_c} = \mathrm{T_a} + \frac{\mathrm{G}}{800}\left(\mathrm{T_{NOCT,adj}} - 20\right)\left(1 - \frac{\eta_\mathrm{ref}}{\tau\alpha}\right)\frac{9.5}{5.7 + 3.8\mathrm{v_{w,adj}}} \tag{15}$$

The subscription "NOCT" in Eq. (15) represents the nominal operating cell temperature (experimentally recoded at 800 W/ m^2, 1.5 m/s and T_{amb} = 20 °C. The reference performance of PV is calculated as:

$$\eta_{ref} = \frac{I_{mp} V_{mp}}{1000 A_m} \quad (16)$$

In Eq. (16), I_{mp}, V_{mp} and Am are the optimum rating each of power current (Ampere), power voltage (Volt) and the module area (m^2). The inverter efficiency is evaluated as [26]:

$$\eta(t) = \frac{P_{in}(t) - P_{Loss}(t)}{P_{in}(t)} \quad (17)$$

In Eq. (17), P_{in} (t) and P_{Loss} (t) display the instantaneous input power and power loss, respectively. The input power (DC) can be written as:

$$P_{dc,0} = \frac{P_{ac,0}}{\eta_{inv,0}} \quad (18)$$

To obtain the output power of inverter, another equation of $\eta(t)$ is necessary to be formed. The efficiency distribution of inverter is obtained from datasheet displayed in Fig. 3. The behaviour of efficiency shows that the inverter efficiency depends on inverter rated power and $P_{in}(t)$. Thus, the curve of efficiency can be written as:

$$\left\{ \begin{array}{ll} \eta = C_1 \left(\frac{P_{PV,input}}{P_{INV,rated}} \right)^{C_T} + C_T & \frac{P_{PV,input}}{P_{INV,rated}} > 0 \\ \eta = 0 & \frac{P_{PV,input}}{P_{INV,rated}} = 0 \end{array} \right\} \quad (19)$$

where P_{PV} represents the output power, $P_{INV,rated}$ represents inverter's rated power and $C_1 - C_T$ represents the model coefficients. In SAM model, similar formulation are employed.

The evaluation criteria of economical and technical are used to emphasize the ability of PV system. Hence, the performance ratio (P_R), capacity factor (CF) and yield factor (YF) are assumed the technical criteria, where YF can be evaluated as the yearly electrical energy divided by the optimum output power that obtained under standard test conditions as [26]:

$$YF = \frac{E_{PV}(kWh/year)}{PV_{WP}(kWp)} \quad (20)$$

where E_{PV} and PV_{WP} display the system energy yield and the PV array's nominal power (P_{STC}). On the other hand, CF is evaluated as follows [27,28]:

$$CF = \frac{\text{YF}}{8760} = \frac{E_{PV}, annual}{8760 P_R^*} \quad (21)$$

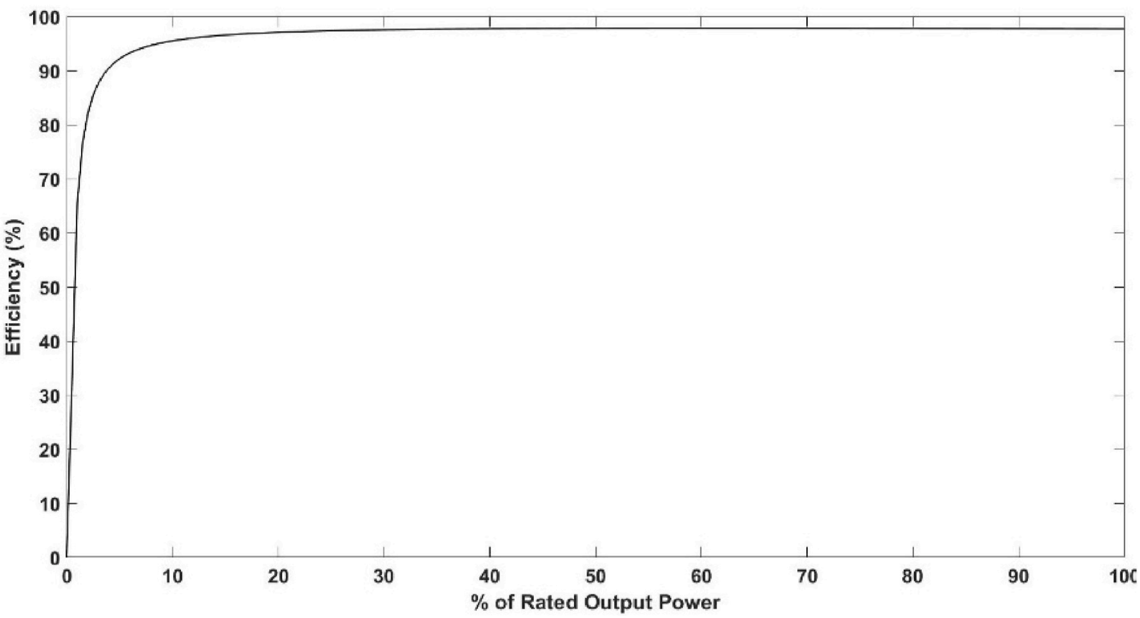

Fig. 3. Efficiency curve of inverter.

The CF determines the usage of PV array. Furthermore, P_R can be determined as follows:

$$P_R = YF \frac{G_{STC}}{\sum G_t} \tag{22}$$

In Eq. (22), $\sum G_t$ and G_{STC} display the accumulative irradiance and the amount of irradiance, respectively.

The economic factors of PV arrays such as cost factors, payback time and life cycle cost (LCC) are used for evaluation the economical analysis. Thus, LCC is obtained as [26]:

$$LCC = C_{capital} + \sum C_{O\&M} + \sum C_{replacement} - C_{salvage} \tag{23}$$

In Eq. (23), $C_{capital}$, $C_{O\&M}$, $C_{replacement}$ and $C_{salvage}$ are the project capital cost (includes initial costs of operating, system design and instruments), cost of maintenance (includes operators' income, local taxes, security and inspections), replacement cost and the net valuation in the final year of its life cycle, respectively. It can be usual practice to give a salvage rate of 20 % of the initial cost for devices that may be evacuated. After evaluating LCC, the unit price of the energy may be determined as follows [29]:

$$CoE = \frac{LCC}{\sum_{1}^{n} E_{PV}} \tag{24}$$

The net present value (NPV) represents the critical factor while evaluating the economic viability due to this factor considers as the net profit produced. When NPV has positive value, this means the project investing will be productive. The NPV can be calculated as [30]:

$$NPV = \sum_{t=0}^{N} \frac{Revenue_t}{(1+d)^t} - Cost_t \tag{25}$$

where N , t, i, $Cost_t$, $Revenue_t$, d represent the system lifecycle, year, interest rate, cost in year, PV system revenue in year and discount rate, respectively. The income during the year has been obtained as [31]:

$$\text{Revenue (year)} = \text{Energy price} \times \text{Energy produced} \tag{26}$$

To test the NPV for the present system, the payback period (PBP) has been determined, where PBP displays the amount of time that required to decrease NPV to 0. The determining of PBP depends on the value of NPV through lifecycle whether its negative or positive.

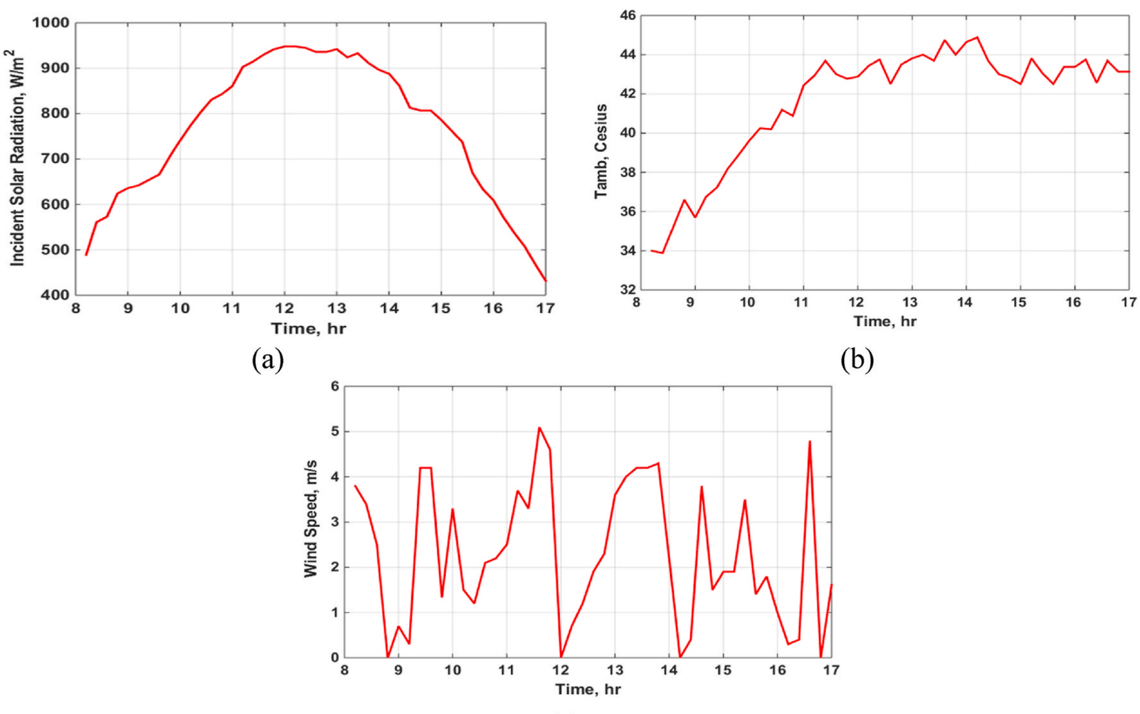

Fig. 4. Distribution of (a) solar radiation, (b) surrounding temperature and (c) wind velocity during 5th September 2022.

The negative value means that the system is not possible, whereas the positive value means that the N coefficient in Eq. (25) is obtained in 0.25-year stages and hence, NPV is obtained for each step until this value reach to zero. The PBP of PV panels is obtained as [31]:

$$PaybackPeriod = \frac{C_{capital}}{AnnulaPVRvenue - O\&M} \quad (27)$$

Finally, various greenhouse gases, particularly CO_2 is contributed to environmental contamination. The CO_2 emission considers as a main factor for global warming, where CO_2 is regarded as a pollution for the power plants employed fossil fuels for generating electricity [32]. The photovoltaic system is among the most environmentally friendly energy produced types. Thus, the environmental action is determined only by the embedded energy and CO_2 equivalent emissions. Based on this, the current research presents the possibility of shrinking CO_2 emissions while installing PV systems. The calculation of CO_2 emission is based on the simulation software which calls RETSCREEN for various fuels and power plants.

5. Results and discussion

5.1. Experimental results

The current study deals with the experimental investigation to compare the performance of three PV solar panels (fixed without tracking, single-axis tracking and dual-axis tracking) using energy and exergy analyses. The three panels were set on the one building at University of Zakho and the experimental tests have been obtained on the sunny day at 5th September 2022. The distribution of the wind speed, surrounding temperature and solar irradiance for 5th September 2022 are displayed in Fig. 4. The solar radiation intensity progresses gradually from low value at 7AM to maximum value ≈ 950 W/m2 at range between 11AM and 13PM, then the irradiance decreases gradually and it maintains a minimum value at 19PM. The ambient temperature increases gradually and maintains maximum value with about 45 °C at about 12 noon, then it remains with the temperature range of 42–45 until the sunset.

Fig. 5(a) illustrates the variations of the cell temperature during the day. The outcomes indicate that the temperature for three cases increments gradually from 7AM until the noon, then it remains relatively constant for 3 h and then, it decreases gradually by about 10 °C–15 °C. In general, the panel temperature that used tracking systems greater than the fixed panel and the cell temperature for dual tracking system (DATS) slightly larger than those of single tracking system (SATS) due to the continuous exposure to the solar radiation. Fig. 5(b) includes the electrical output power for three cases throughout the day using Eq. (3). The outcomes displayed that the panels power that uses tracking way is higher than those for fixed panel. The SAST and DAST output power for the periods between

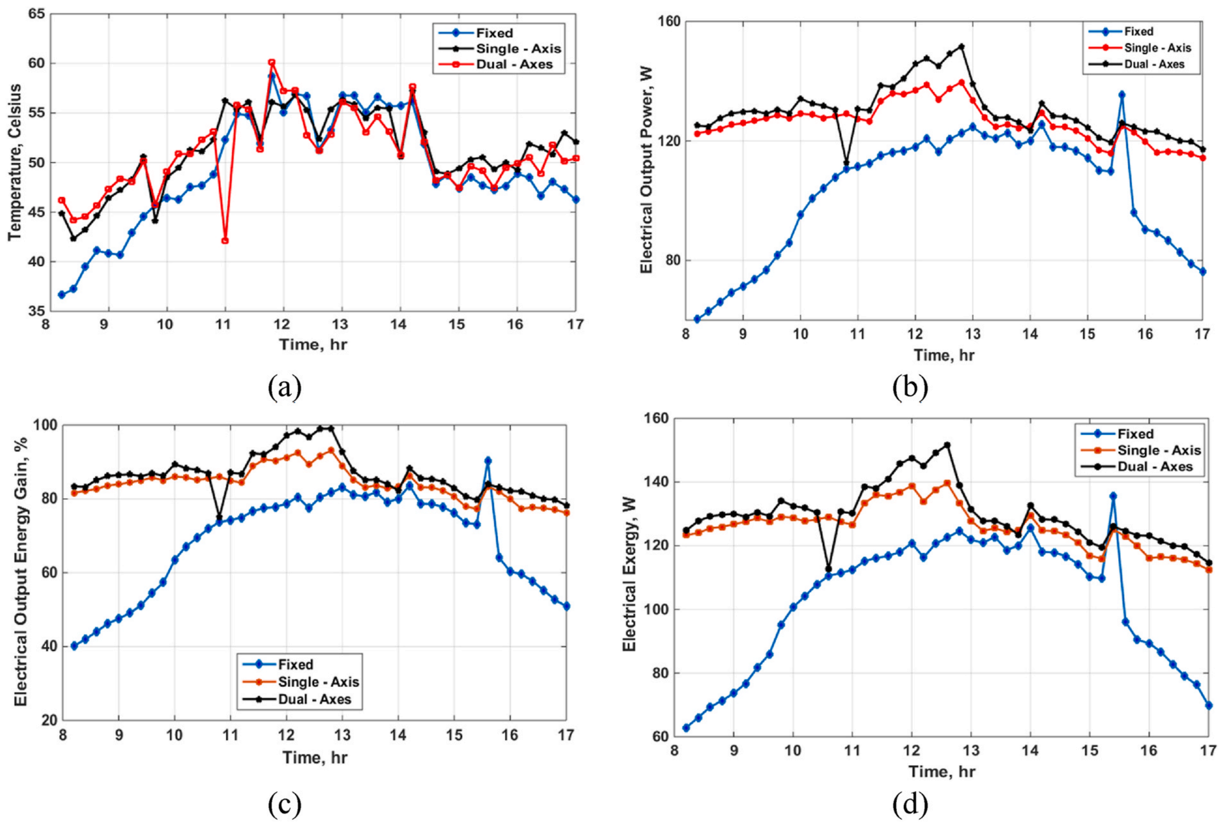

Fig. 5. Distribution of (a) Cell temperature, (b) Electrical output power, (c) Electrical output energy gain and (d) electrical exergy for without tracking, single tracking and dual tracking at 5th September 2022.

8AM and 10 a.m. and between 15PM and 17 p.m. become very large as compared to the fixed system. Maximum enhancement in the output power is obtained at 8 a.m. Fig. 5(c) displays the output electrical power gain for PV solar panel using fixed, single-axis and dual axes tracking system during the day of 5th September. This value has been obtained as a ratio of output power to the peak power of panel (150 W). The results indicated that the improvement in the energy has been observed during the time particularly in the morning and before the sunset. Also, the maximum enhancement in the output electrical for solar modules with tracking systems is more than those of fixed solar module. The maximum improvements in the electrical output power of PV solar panels using dual– and single–axes tracking systems are nearly reached to 40 % at 8 a.m., between 13 %(single) and 20 % (dual) at 12 p.m. and 30 % at 17PM as compared to fixed solar panel. The electrical exergy for tested solar panels are presented in Fig. 5(d). The findings indicated that the electrical exergy increases for the cases SAST and DAST as compared to those of fixed panel. Also, the maximum enhancement in the electrical exergy for solar modules with tracking system is more than those of fixed panel. The electrical exergy is less than electrical energy.

Fig. 6(a) represents the thermal exergy variations obtained using Eq. (10) from the panels. The outcomes show that thermal exergy for fixed panel is less than the tracking systems particularly during the time between 8 a.m. and 10 a.m. and between 15PM and 17PM. Fig. 6(b) displays the outlet exergy variations obtained using Eq. (8) from the panels for three cases due to the electrical and thermal energy. The outlet exergy for fixed panel increases from low value at the morning to maximum value at 12 noon which remains relatively unchanged about 3–4 h and then, the outlet exergy is decreased. This phenomenon can be explained by fact the exposure of the fixed panel to the direct solar radiation is low at the morning and before sunset. The outlet exergy for the panels which uses tracking systems shown a large increase at the morning and before the sunset. Fig. 6(c) illustrates the exergy loss variations obtained using Eq. (12) throughout a day of 5th September for tested panels, where the outcomes displayed that the three cases have similar trends as solar irradiance variation through the day. The exergy loss for fixed panel is larger than those of the panels which is employed tracking systems.

5.2. Theoretical results

The proposed power plant has been tested during a year to predict the energy, economic and environmental feasibility analysis due to the use of the simulation method. Similar characteristics of the experimental PV solar panels are employed to present the economical and technical analysis results. The distribution of the ambient temperature, wind velocity and solar irradiation during the entire year are presented in Fig. 7. The values of tilt angle is presented in Fig. 8(a) since its considered a necessary coefficient in determining the amount of power formed by panel. The best tilt angle nearly equal to the latitude of Zakho city for five months which is selected as a tilt

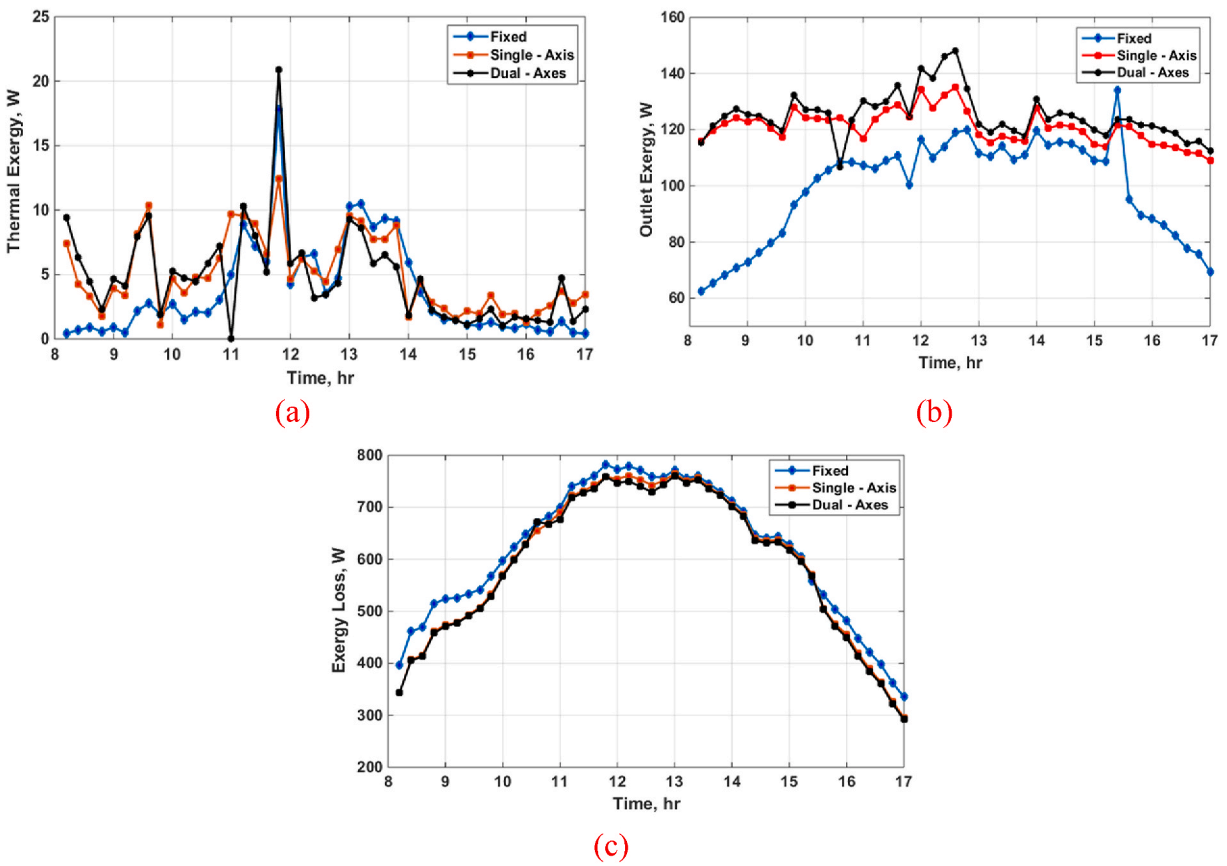

Fig. 6. Distribution of (a) Thermal exergy, (b) Outlet exergy and (c) exergy loss for fixed, single tracking and dual tracking at 5th September 2022.

angle for the panel that operated without tracking. The cell temperature obtained from Eq. (15) affects the panel efficiency, where its distributions throughout a year is shown in Fig. 8(b). The outcomes show that the cell temperature increases with the surrounding temperature and solar radiation intensity.

The monthly generated energy, yield factor and Net Present Value for PV power plant (1 MW) for three different tracking systems are illustrated in Fig. 9. As seen from Fig. 9(a), the energy production ranges for fixed, single-axis, and dual-axis systems are (62 MWh – 150 MWh), (50 MWh – 220 MWh) and (80 MWh – 230 MWh), respectively. The peak energy production for the three systems is around 150 MWh, 220 MWh and 230 MWh, respectively, showing an enhancement percentage of 31 % for single-axis and 34.7 % for dual-axis as compared to fixed panel system. The maximum enhancement for three systems has been obtained in May and July, whereas the lowest energy output for these systems has been found in January and December. Fig. 9(b) displays the yield factor distribution obtained using Eq. (20) for three tracking systems during 12 months data. The highest results are reached for intended systems within the summer months of May–September due to the high ambient temperature and solar insolation. For some winter months, the yield factor for the PV power plant of a single-axis is more than those of a dual-axis. The fixed PV solar panel cost includes the support structure and other accessories. In contrast, the single-axis and dual axes tracking systems include the cost of the fixed panel plus additional costs due to the tracking systems. The results in Fig. 9(c) demonstrates that the PV power plant income (obtained from Eq. (25)) increases and the cost of the intended power plant (obtained from Eq. (27)) will be recovered after 9 years for a fixed system and about 15 years for the other two systems (single-axis and dual-axis).

Table 2 briefly compares the economical and technical outcomes for the three tested panels, where the solutions confirm that the yearly energy generated are 1428466 kWh (for fixed panel), 1709710 kWh (for single tracking) and 1919613 kWh (for duel tracking). The findings indicated that there is an increment in the generating energy by 34 % (for duel tracking) and 19.6 % (for single tracking) as compared to the panel without tracking. For the first year, the outcomes display that the annual yielded energy obtained using Eq. (20) are 1,416 kWh/kWp (for fixed panel), 1,694 kWh/kWp (for single tracking) and 1,902 kWh/kWp (for dual tracking). The solutions confirm that the using tracking system acts to progress the generated energy by 19.6 % (for single tracking) and 26 % (for dual tracking) in comparison with the fixed panel. On the other hand, the effectiveness coefficients of the tested system are nearly 0.71 (for fixed panel), 0.71 (for single tracking) and 0.69 (for duel tracking). Moreover, the annual capacity coefficient obtained using Eq. (21) are found equal 16.2 % (for fixed panel), 19.3 % (for single tracking) and 21.70 % (for duel tracking). The outcomes show that the employment tracking system has a positive action on the generated energy, where the COE of system obtained using Eq. (24) has been found equal 0.083 USD/kWh (for fixed panel), 0.049 USD/kWh (for single tracking) and 0.044USD/kWh (for dual tracking). Hence,

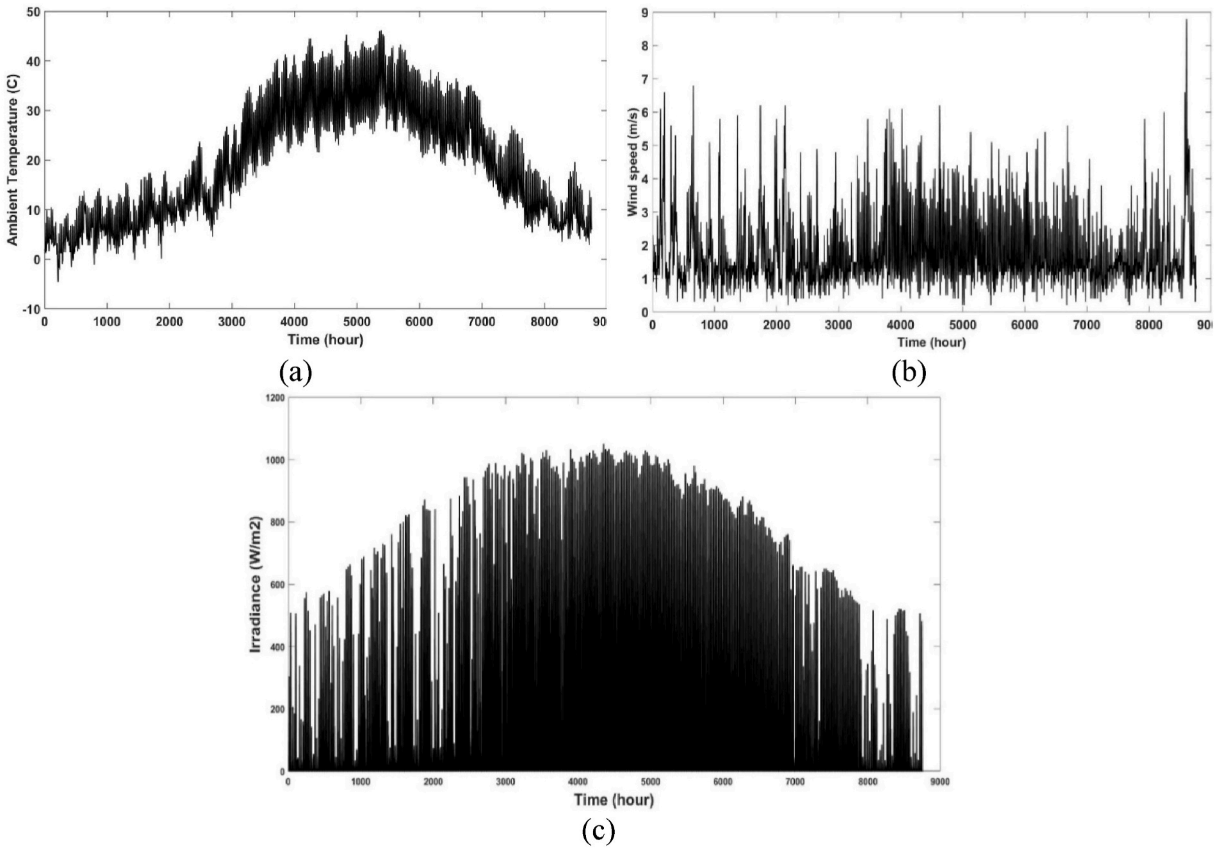

Fig. 7. (a) Ambient temperature (b) Wind speed in m/s and (c) Hourly Solar insolation in W/m^2 for an entire year.

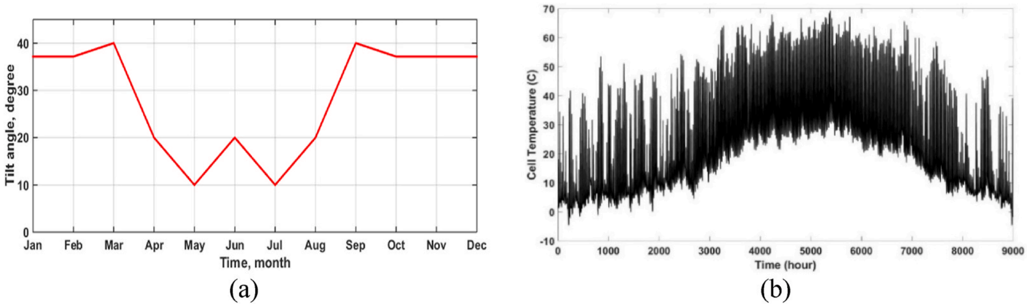

Fig. 8. Distribution of (a) Monthly optimum tilt angle and (b) Hourly cell temperature in.

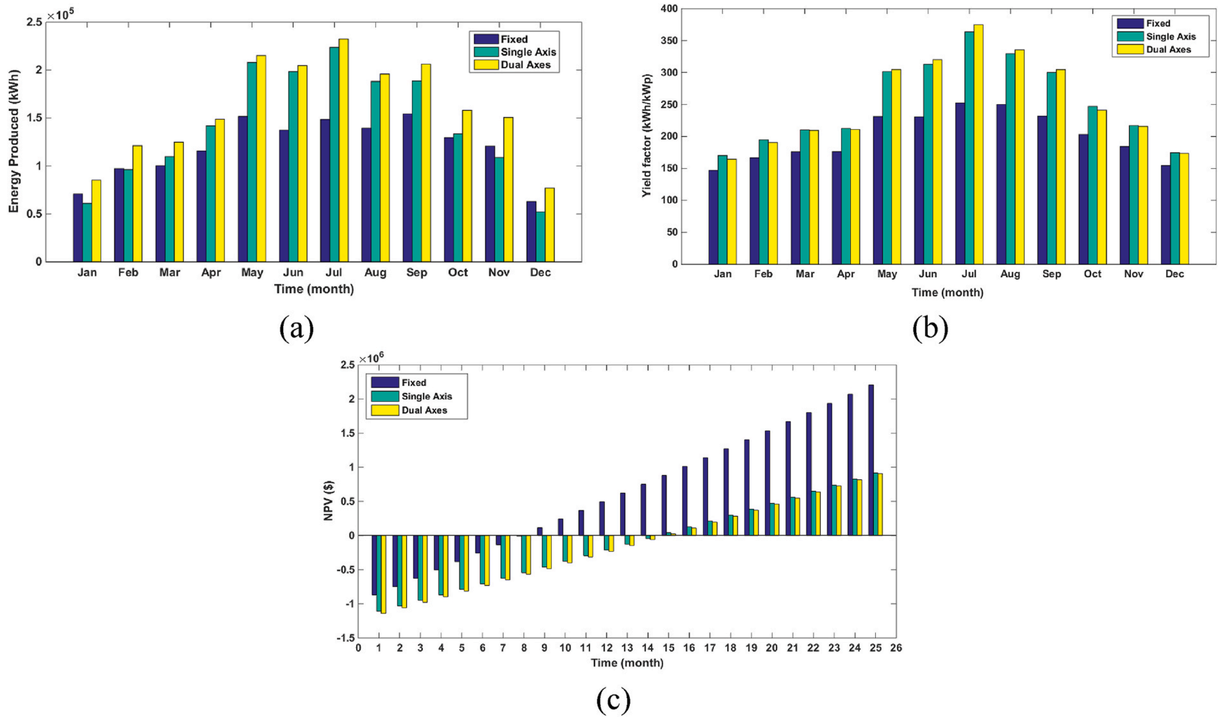

Fig. 9. Results of (a) Monthly Energy production, kWh, (b) Monthly yield factor, kWh/kWp and (c) Net Present Value through the lifetime.

Table 2
Economical and Technical factors outcomes.

Item	Value		
	Fixed	Single Axis	Dual Axes
Total Initial Cost for PV panels and Installation	756,756.00 USD	908,107.19 USD	938,377.44 USD
Salvage Value (20 %)	19,372.95 USD	27,243.22 USD	28,151.32 USD
Operation and maintenance	13 USD/KW-yr	15 USD/KW-yr	16.5 USD/KW-yr
Modules total area	8736 m^2	8736 m^2	8736 m^2
Land area	87360 m^2	17470 m^2	17470 m^2
Yielded Energy	1,416 kWh/kWp	1,694 kWh/kWp	1,902 kWh/kWp
System Lifetime	25 Years		
Yearly energy produced	1,428,466 kWh	1,709,710 kWh	1,919,613 kWh
Annual Capacity factor	16.2 %	19.3 %	21.70 %
Annual Performance ratio	0.71	0.71	0.69
COE	8.26 cents/kWh	4.89 cents/kWh	4.41 cents/kWh
NPV	120,334 USD	22,354 USD	22,860 USD
IRR	11 %		
Power purchase agreement(PPA price)	9.15 cents/kWh	5.03 cents/kWh	4.53 cents/kWh
Simple Payback period (PBP)	9 years	15 years	15 years

the using tracking system acts to rise the energy production although it has highly installation costs. On the other hand, the results demonstrate that NPV for single and dual tracking systems is lower than without tracking panel and thus, the payback period for the single and dual tracking systems are longer than without tracking system. Owing to the government supporting in Iraq through reducing the taxation, the cost of energy is lower than other countries [27].

Table 3 presents the comparison of the CO_2 emission between PV solar system and fossil fuels power plants used in Zakho city for local and central power plants that calculated using simulation software, where the outcomes confirm that the CO_2 emission produced by PV system is very small in comparison other fossil fuels power plants. The CO_2 emission is reduced when using PV system instead of either natural gas or gasoline by 472.8tCO_2 and 3292.6tCO_2 (for fixed panel), 565.9tCO_2 and 3940.8tCO_2 (for single-axis) and 635.4tCO_2 and 4424.7tCO_2 (for Dual-axis). Table 4 gives the costs of social, O&M, fuel, installation and generated energy for different power plants. The outcomes display that the energy generated by employing gas and steam turbines systems are nearly four times PV system. Thus, the cost of fossil fuel and maintenance are extremely high as compared to PV system, whereas the running cost of PV system is very low. It can be noted here that the community social cost of tCO_2 is 50 USD resulting from effect of CO_2 emission. It can be dedicated that the PV system has no action on the CO_2 emission.

6. Conclusions

This article implements an experimental and theoretical study on energy, exergy, economic and environment performance of PV panel using fixed, single tracking and dual tracking systems. The experimental data are recorded for a sunny day on 5th September 2022 using a test rig installed on the building at University of Zakho located in Zakho city, Iraq. The experimental analysis of the current study has been performed based on the metrological data such as ambient temperature, solar irradiation and wind speed. The theoretical energy and exergy analyses have been performed based on the yield factor, net present value, payback period, energy cost, capacity factor, annual energy and performance ratio. The following findings are listed:

1. The outcomes display that the electrical, thermal and outlet exergy performances for PV solar panel using single- or dual tracking systems are better than fixed panel. The thermal exergy losses are decreased when the tracking system is used.
2. The findings indicated that the cell temperature for solar panels with tracking systems is higher than the fixed panel owing to the direct exposure to the solar radiation.
3. The maximum enhancement in the electrical energy gain is obtained at 8 a.m. and 17 p.m. by using tracking system as compared to fixed panel, where the peak improvements in the electrical output power of PV solar panels using dual– and single–axes tracking systems are nearly reached to 40 % at 8 a.m. and 30 % at 17PM as compared to fixed solar panel.
4. The theoretical results display that the produced energy and the yielded energy for the proposed model with using tracking systems are increased for all months as compared to fixed panel. The average enhancement percentage has been found equal 31 % for single-axis and 34.7 % for dual-axis in comparison with fixed panel.
5. The findings demonstrate that the annual yielded energy has been raised by using tracking systems as compared to fixed panel by 19.6 % (for single tracking) and 26 % (for dual tracking).
6. The total initial and installation costs for the tracking solar energy systems are increased as compared to the fixed system due to the employment of the control systems for the tracking systems. The cost of energy for the tracking systems is decreased as compared to the fixed panel, where the values are obtained equal 0.083 USD/kWh (for fixed panel), 0.049 USD/kWh (for single tracking) and 0.044USD/kWh (for dual tracking). Also, the total costs of PV solar power plant are reduced as compared to the same power plant that using either steam or gas turbine.
7. When using PV model with either fixed or solar tracking system instead of Natural gas and gasoline, the CO_2 emission is reduced about 473 tCO_2 and 3293 tCO_2 (for fixed panel), 566 tCO_2 and 3941 tCO_2 (for single-axis) and 635 tCO_2 and 4425 tCO_2 (for Dual-axis).

Author statement

Omar Rafae Alomar, Omar Mohammed Ali and Bashar Mahmood Ali: Conceptualization, Methodology, Software. Omar Rafae Alomar and Veen S. Qader: Data curation, Writing- Original draft preparation. Omar Rafae Alomar: Visualization, Investigation. Omar Rafae Alomar and Omar Mohammed Ali: Supervision. Omar Rafae Alomar and Obed M. Ali: Software, Validation: Omar Rafae Alomar and Omar Mohammed Ali: Writing- Reviewing and Editing.

Declaration of competing interest

I, on behalf of my co-authors, Omar Mohammed Ali, Bashar Mahmood Ali, Veen S.Qader and Obed M. Ali, of the manuscript

Table 3
Comparison of CO_2 emission and annual energy for different power plants factors.

System	CO2 Emission Factor, tCO2/MWh		Annual Energy produced, MWh	Reduction in CO2 Emission, tCO2	
	Natural gas	Gasoline		Natural gas	Gasoline
Fixed	0.331	2.305	1428.466	472.8	3292.6
Single-Axis			1709.71	565.9	3940.8
Dual-Axis			1919.613	635.4	4424.7

Table 4
Comparative between PV system and various plants that using fossil fuels.

Costs (USD/year)	Power Source		
	Steam turbine	Gas turbine	PV
Fuel	279,000	235,725	0
Social	100,850	44,350	0
O&M	396,500	133,000	18000
Initial	10,063,000	2,200,000	1800000
Total	10,839,350	2,613,075	1818000

entitled, "**Energy, Exergy, Economical and Environmental Analysis of Photovoltaic Solar Panel for Fixed, Single and Dual Axis Tracking Systems: An Experimental and Theoretical Study**", hereby declare that there is no conflict of interest regarding the publication of this article in the Case Studies in Thermal Engineering.

Dr.-Ing. Omar Rafae Mahmood Alomar.

Data availability

No data was used for the research described in the article.

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