Eng. Sci., 2025, **37**, 1798

Engineered Science
DOI: https://dx.doi.org/10.30919/es1798

# Modeling, Simulation and Experimental Validation of Fixed and Tracking Bifacial Photovoltaic Systems

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## Abstract

There are considerable advancements in the photovoltaic (PV) industry, a promising alternative for the energy sector despite their low efficiency which necessitates thorough research. This is especially true for systems that incorporate the higher costs of tracking mechanisms used for increasing energy yields. This research aims to experimentally investigate the performances of fixed and tracking-based PV systems in Jordan by measuring and comparing them against the energy production of bifacial PV systems. This paper's method is to model and simulate the configurations and perform experimental validation of the selected systems which are fixed, single-axis and two-axis tracking. The models were simulated using the PVsyst simulation tool on which the models are calibrated and validated. The experimental results show a high energy yield in the two-axis tracking system, an improvement of 28.62% compared to the fixed system and 9.66% compared to the single-axis tracking system. The single axis tracking system also showed a 17.3% improvement in yield compared to the fixed system. The results show that the percentage error between the simulation and the experimental setups for the two-axis tracking, single-axis tracking, and fixed systems are 2.0%, 1.2% and 2.28% respectively. Thus, the developed models are applicable and can be generalized for similar climatic conditions.

*Keywords:* Bifacial photovoltaic; Tracking system; Energy yield; Jordan; PVsyst.

Received: 05 April 2025; Revised: 16 August 2025; Accepted: 10 October 2025.
Article type: Research article.

## 1. Introduction

Energy is the basis of civilization, and over the last decade, fossil fuels, which have been the primary energy source, have propagated the greenhouse effect and are believed to be causal factor of climate change. All the negative aspects of fossil fuels and the rise in modern alternative options raise the need for a new energy source to transition to that is sustainable and clean.[1] The growing global energy demand and energy consumption from conventional sources have led to the transition to solar and wind energies.[2]

Solar energy partially meets this demand with photovoltaics (PV), owing to its sustainable, clean, renewable, and high availability. The efficiency of PV panels varies between 15% and 22%, and development is still in progress.[3] The International Technology Roadmap for Photovoltaics (ITRPV) 2020 predicts that bifacial PV modules will dominate the solar energy landscape in the upcoming decade,[4] while a more recent publication highlights that the global solar capacity from 2012 to 2022 has risen from 100 GW to 1 TW and expects only another 3.5 years to double it again.[5] The goal of this research is to assess the comparative benefits of different bifacial solar PV systems by their non/tracking mechanism in MERGEFORMAT bifacial and tracking simulations conducted in Jordan (a growing solar PV adopter) and other climatically-similar locations.

A recent trend is the use of tracking systems with bifacial panel technologies. Previous research has compared the use of bifacial technology against mono-facial PV panel technologies. The results showed that the bifacial PV panels produced about 10%, 13% and 25% greater energy compared to the standard types (mono-facial, half-cut, polycrystalline) modules respectively. These results are an indicator that where the standard panels may produce a lackluster amount of energy,

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they can bridge the gap to improve the energy production of a utility-scale PV plant.[6] Getting the correct configuration is of paramount importance, and making sure it is site-specific is additionally vital. An example of this is a bifacial configuration in India that was optimized for that specific site's conditions which ended up boosting production by 30.54-34.93% compared to standard systems at the location. This was also achieved by implementing the simple method of bi-annual tracking.[7] There are even attempts to calculate the exact ground cover ratio of a bifacial system compared to a normal system given shading profiles, global positioning and site data.[8]

The remainder of this paper is organized as follows: Section 2 presents the literature review. Section 3 details the materials and methods, covering bifacial PV panels, panel configurations, the monitoring system, the PV pre design process, and model validation and calibration. Section 4 reports the results, both experimental and modelling, for the two axis tracking, single axis tracking, and fixed PV systems.

## 2. Literature review

Another study conducted by Gallegos *et al*. in Singapore in 2020 concluded that the single-axis bifacial tracking systems can improve the energy output by up to 35% and therein decrease the per unit cost (levelized cost of energy) by about 16% when compared to standard monofacial systems.[9] Rustemli *et al.*, who studied the effect of sun-tracking systems; the results indicated that the two-axis tracking system gives 10-20% more power than a single-axis tracking system.[10] Additionally, Russell *et al*. (2019) modelled a Bifacial single-axis tracking system, where the results showed that the bifacial tracking system efficiency had 14.0% higher efficiency than the fixed bifacial system.[11] Eke and Senturk in their research, designed and installed two 7.9 KWP PV systems: fixed and two-axis tracking surfaces, their analysis covered climate conditions in Turkey, and their results showed that unlike the 28° fixed tilt angle control, the double-axis tracking system obtained 30.79% more power output.[12] Burnham *et al*. also demonstrated that a two-axis tracking bifacial system gains 35-40% energy compared to a fixed-tilt system, and they also recommend using a two-axis tracking system in northern latitudes for a higher economic value.[13] One of the initial detractors of tracking other than the cost is the likelihood of maintenance, however, researchers are continuously working at that angle to make it more efficient, effective and reliable.[14]

Several other research publications have studied and provided results comparing simulation and experimental setups. Research conducted by K. R. McIntosh *et al*. on single-axis tracking bifacial systems focused on simulation and measurement, where the main results showed that on a clear summer day, the variability of bifacial gain falls within ±2% and does not exceed ±0.5.[15] In another study conducted by D. Berrian *et al*., the simulation data was compared with measured results for single-axis tracking bifacial PV; the accuracy of the simulation data varied from ±0.1% to ±4% depending on the tilt angle of the bifacial panels.[16] Previous research conducted by C. Deline *et al*. has documented and parameterized the difference in power loss in bifacial PV and concluded with three main points. Firstly, that the losses for a single-axis tracking system at a high ground-clearance were less than 0.5%, secondly, the panel orientation and the climate have a high impact on bifacial mismatch losses; and lastly that the bifaciality ratio and PV panel fill factor have a linear impact on mismatch losses.[17] Simulation and experimental data have not always been exact counterparts of each other. PVSyst is generally under 1% error for annual data, it fails up to 11% for granular sub-annual data (monthly, daily) for certain tilt combinations.[18] The general performance nowadays is highly accurate and has been reviewed and verified multiple times such as Buzra and Serdari and Ahmad *et al*.[19,20]

Highly advanced computational techniques also exist to run through scenarios and parameter combinations comparable through sensitivity analyses such as Harris Hawks Optimization, Slime Mold Algorithm, Firefly Algorithm, Manta Ray Foraging Optimization, and Cuckoo Search Algorithm.[21] Other techniques for optimization focus on the accurate simulation of effects such as shade in large scale products and the row-to-row effect this may have or the estimation of albedo from largely available data such as the normalized difference vegetation index.[22,23] Even rudimentary approaches like mirror installations have achieved a production boost of up to 51% in bifacial configurations.[24]

Applying bifacial panels and trackers can garner a gain of 19.39%-27.39% but this hinges on the exact climatic conditions and on-site configuration, this in-turn supports the idea that representative on-site experiments are always required to accurately and efficiently extrapolate from.[25] Even the specific orientation is in question some areas such as deserts where a vertical system outperforms a standard tilted system by up to 9.2%.[26] In the domain of our research, the potential of three bifacial photovoltaic modules is examined to assess the performance of various solar tracking systems when compared with fixed photovoltaic modules, all under the identical climatic conditions of Jordan and identical module types. The power output of each panel is monitored in our experiment, with measurements recorded at 3-minute intervals using an I–V (current–voltage) characteristic checker. These empirical findings are then compared to the simulation models for validation.

## 3. Materials and methods

The experimental procedure for validating the effectiveness of bifacial tracking configurations in Jordan and the full process outline are shown in Fig. 1. The experimental work was done at the School of Engineering at the University of Jordan, Amman, (32°00'38.8"N 35°52'30.8"E), as shown in Figs. 2a and b show the sketch drawing of the rooftop location and the positionings of the various tracking devices.

Due to Jordan's high level of solar radiation (4-8 kWh /m2 per day), the country is considered one of the highest potential spots for the installation of solar energy systems, additionally owing to the moderate weather conditions and an annual average temperature range between 23.5 °C and 12.5 °C.[27] Accurate solar radiation and ambient temperature measurements with good resolution are required for this study, and the University of Jordan hosts its own weather station that measures global and diffuse solar radiation in addition to ambient temperatures with a resolution of 5 minutes. Fig. 3 shows the solar radiation, and Fig. 4 shows the ambient temperature during the measuring period.

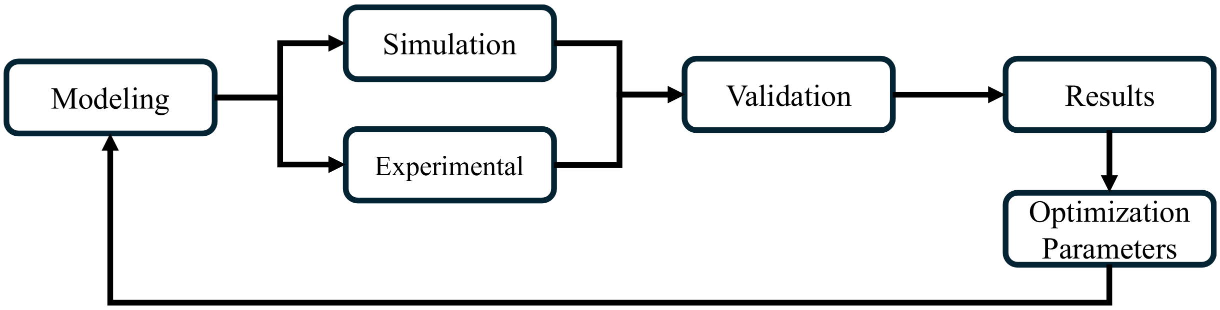

**Fig. 1:** Experimental procedure for validating the effectiveness of bifacial tracking configurations in Jordan.

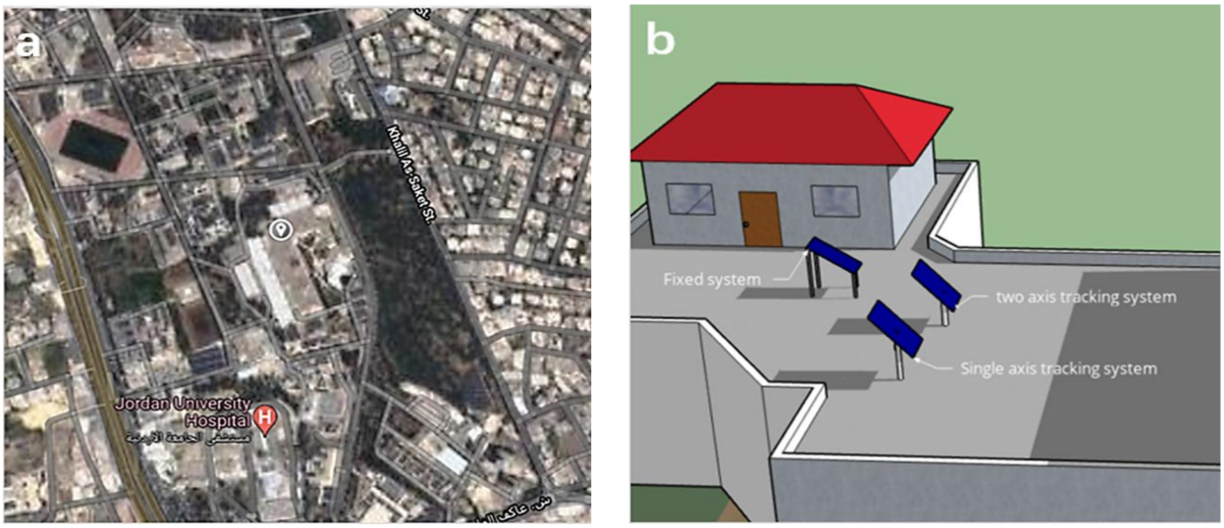

**Fig. 2:** (a) System's location (Image source: © Google Maps, Map data © 2025 Google); (b) Systems drawing.

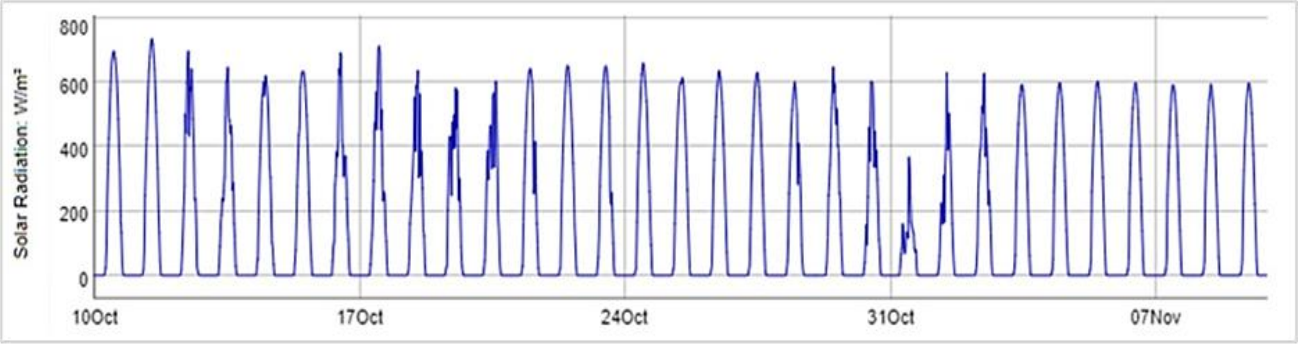

**Fig. 3:** Solar radiation in the installation site is measured during the period from the nearest weather station.

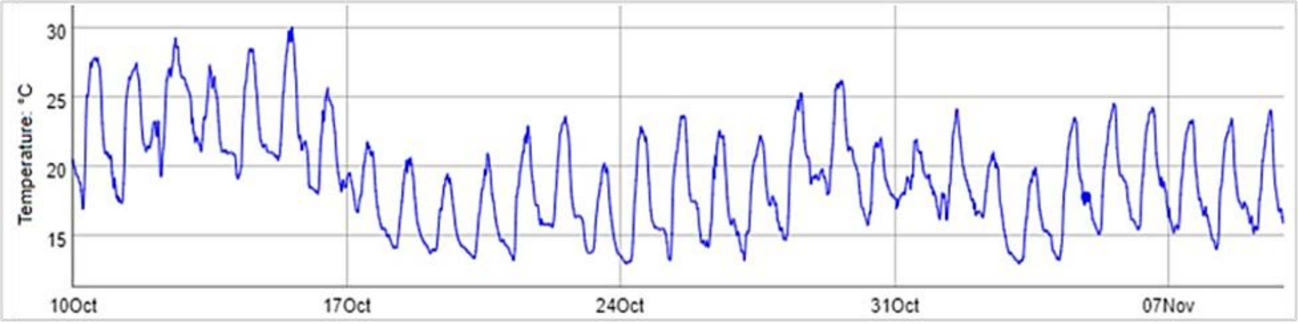

**Fig. 4:** The ambient temperature at the installation site during the measuring period is determined from the nearest weather station.

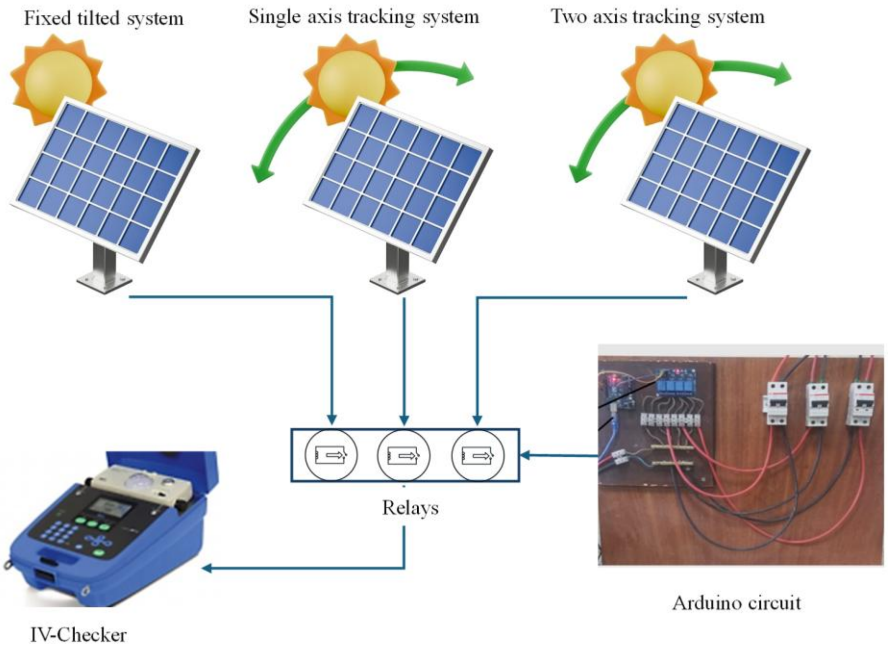

**Fig. 5:** Experimental system diagram.

Fig. 5 shows a general sketch of the main unit of the experimental setup used in this work. This setup consists of the following main parts: Three Bifacial Monocrystalline types, Monitoring system, Arduino, I-V Checker and DC Motor.

### 3.1 Bifacial PV panels

Three bifacial monocrystalline half-cut panels, each with 370 Wp nominal power, have been installed. Every module is a set of 72 Monocrystalline cells connected in series. The panel for each tracking setup is separately positioned. Table 1 presents the characteristics of these panels under the standard test conditions.

### 3.2 Panels configurations

Each of the 3 systems has its own support structure and tolerance as shown in Table 2. The setups for the tracking systems total 4.9 m$^2$ of solar panel surface. The two axis and single axis trackers utilize two actuators and one actuator respectively which are used to change the position horizontally and vertically. and the DC motor used is the SM4S510M2, which has a torque of 1400 Nm., an input voltage of 24 V, current of 2 A, and speed of 1.5 mm/s. The structures are shown in Fig. S1 for the 2-axis, 1-axis and fixed systems respectively.

### 3.3 Monitoring system

An IV checker is used to monitor the panels. One of the limitations is that it is only capable of monitoring a single panel at a time using the standard connections. The limitation is overcome by an Arduino microcontroller with relay circuits to facilitate the monitoring of 3 panels simultaneously. It achieves this by switching the input measurement from panel to panel at 1-minute intervals. The IV Checker used is an MP-170 I-V checker, and its specifications are presented in Table 3.

**Table 1:** Panel characteristics.

| Symbol | | Value |
|---|---|---|
| Open circuit voltage ($V_{oc}$) | $V_{oc}$ | 48.66 |
| Short circuit current ($I_{sc}$) | $I_{sc}$ | 9.7 |
| Rated voltage at maximum power | $V_{mp}$ | 39.96 |
| Rated current at maximum power | $I_{mp}$ | 9.26 |
| Rated maximum power at STC | $P_{max}$ | 370 |
| Cell efficiency (%) | $\eta$ | 19.0 |

**Table 2:** System and support structure specifications.

| System | Fixed | Single-axis tracking | Two-axis tracking |
|---|---|---|---|
| Supported structure | 0.99m × 1.960m (32 kg) | 0.99m × 1.960m (60 kg) | 0.99m × 1.960m (60 kg) |
| Wind speed tolerance | 160 kmh | 144 kmh | 144 kmh |
| Tracker accuracy | - | 0.5 degrees | 0.5 degrees |
| Elevation angle | - | - | 0-90 degrees |
| Hour angle | - | -50-50 degrees | -50-50 degrees |

**Table 3:** IV Checker specifications.

| IV checker | Value |
|---|---|
| Voltage range | 10 - 1000 V |
| Current range | 0.1 - 10 A |
| Measurement interval | 5 s |
| Sensor unit | Si-sensor / T-Type thermocouple |
| Communication t | RS-422 / 232C |

### 3.4 Pre-design process for PV system

In the design of any PV system, data requirements should include the geographic location, PV panel data sheets, weather data for the intended location, and any other data that can help the simulation to surmise all the influences of the physical counterpart. In a study conducted by Surabhi Sharma *et al.*[28] PVsyst is the recommended simulation software due to its accurate results and insights about PV module conditions. Based on the recommendation, the simulation tool used for this study is PVSyst. The simulation model was built to mimic the experimental setup. Of the challenges that emerged was that the PVsyst could not simulate a system without an inverter in an on-grid configuration or charge controller in an off-grid configuration. The simulation was therefore modified to an on-grid configuration where the inverter losses will be eliminated and only the Maximum Power Point (MPP), $I_{sc}$ and $V_{oc}$ values are collected. Fig. 6 shows an overall view of the simulation system's components.

The simulation consists of three modelling systems that are all simulated in identical conditions. A fixed module was selected with a 26° tilt angle and oriented to face south, as shown in Fig. 7. A vertical single-axis tracking module was selected with a 30° tilt angle and an azimuth range between -50° and 50° as shown in Fig. 8. A two-axis tracking module was selected with a tilt angle range between 0° and 90° and an azimuth range between -50° and 50° as shown in Fig. 9. Table 4 shows the overview and parameters of the system used for two-axis tracking, single-axis tracking and fixed systems.

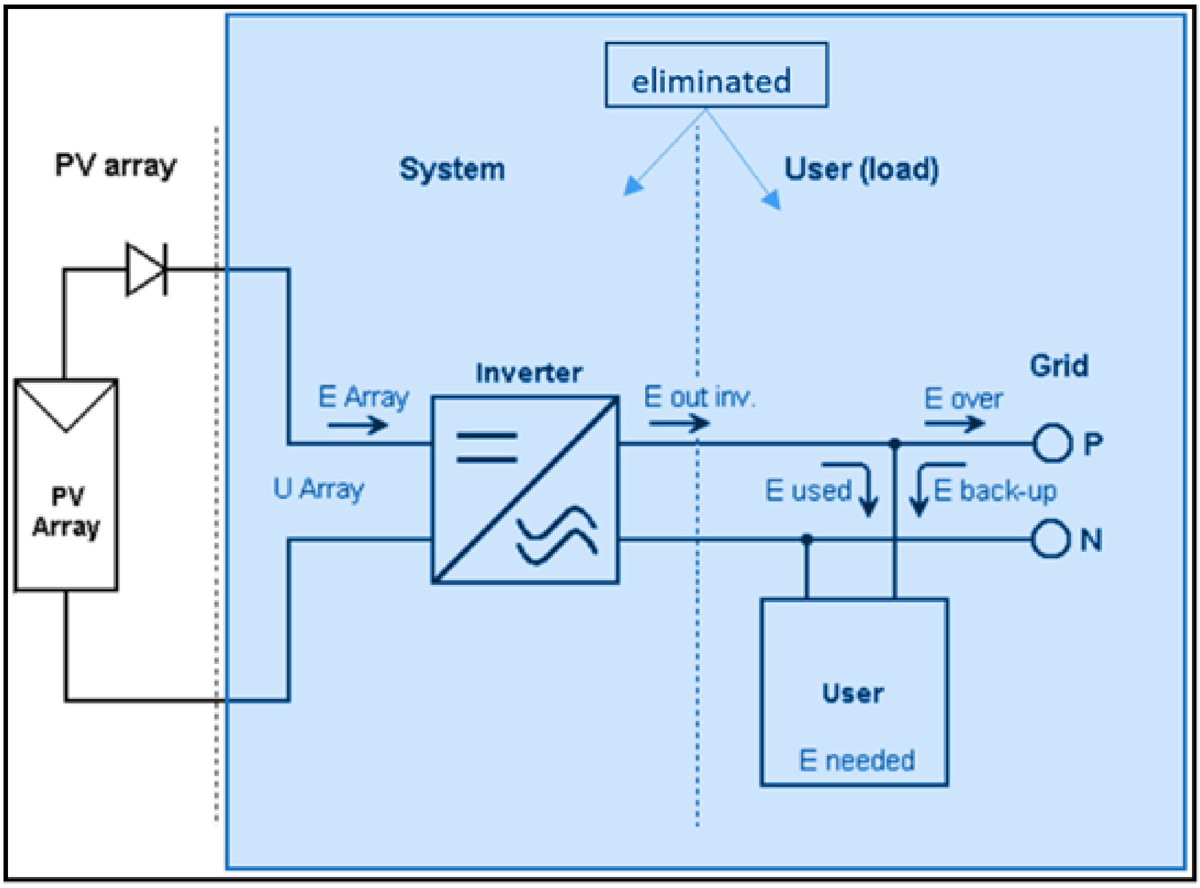

**Fig. 6:** Overall view of the simulation system’s components.

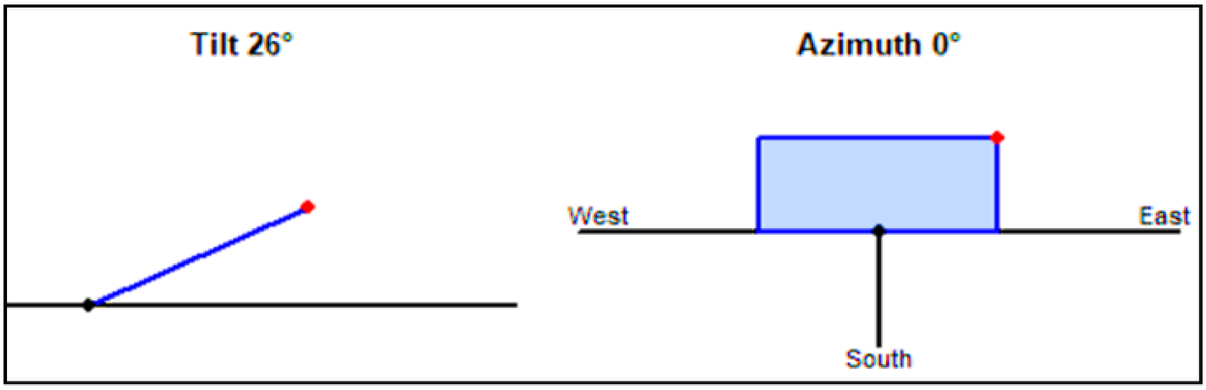

**Fig. 7:** Orientation of fixed system.

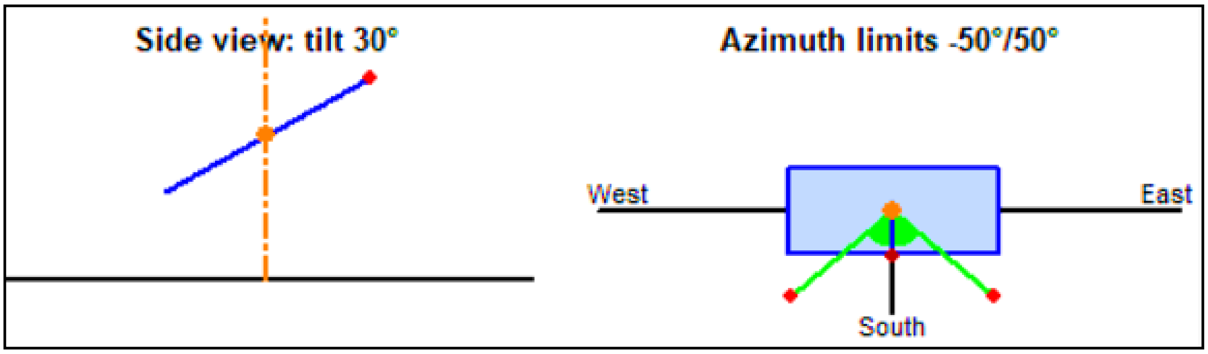

**Fig. 8:** Orientation of single axis tracking system.

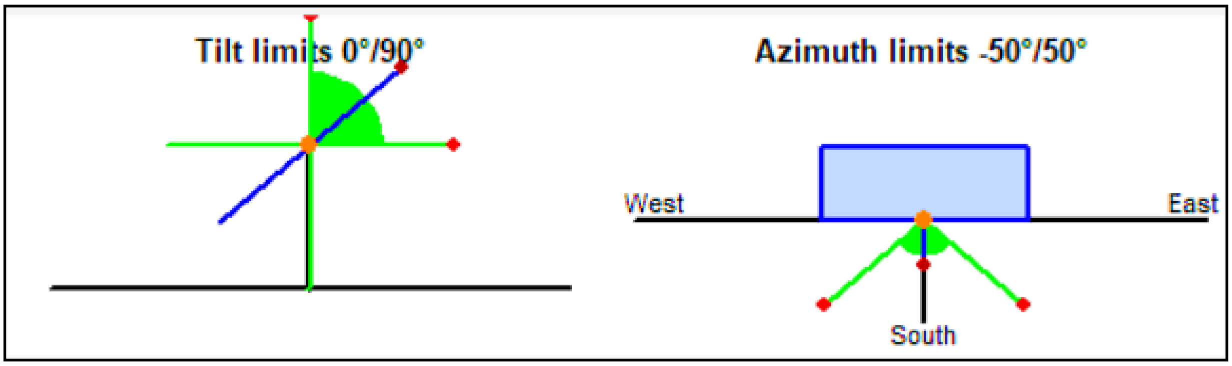

**Fig. 9:** Orientation of two-axis tracking system.

**Table 4:** Overview of the two-axis tracking system's parameters.

| Orientation parameters | | | |
|---|---|---|---|
| Field type | Fixed tilted plane | Tracking, the vertical axis | Tracking, two axes |
| Plane tilt | 26° | 30° | 0°, 90° |
| Plane azimuth | 0° | 50°, -50° | 50°, -50° |
| Compatibility between system definitions | | | |
| 1 Sub-array | $P_{nom}$= 370 Wp<br>modules area = 2 m² | $P_{nom}$= 370 Wp<br>modules area= 2 m² | $P_{nom}$= 370 Wp<br>modules area = 2 m² |
| System parameters | | | |
| Sub-array #1 | PV array | PV array | PV array |
| PV modules: | 1 string of 1 module in series<br>1 total | 1 string of 1 module in series<br>1 total | 1 string of 1 module in series<br>1 total |
| $P_{nom}$ = 370 Wp | 370 Wp | 370 Wp | 370 Wp |

### 3.5 Model validation and calibration

Data readers and output plotters were used to track and validate the data connection between the components. Many factors can influence the PV simulation result, such as ambient temperature, dust, shunt and series resistances, shading, and more. In the case of this study, it was observed that the three most important influencing factors for the arid Jordanian climate, namely the thermal losses, were the effect of dust accumulation on solar radiation, the wiring losses, and the degradation ratio effect. Each of these factors is considered individually and as a total combination for the given systems.

The validation procedure is shown in Fig. 10 begins with application of the input, e(t), to the system, which is the set of values representing latitude, tilt-angle, albedo, height, and bifacial PV modules. The voltage, current, and power are measured and stored. All the gathered parameters and data are fed into the model. Measurement data for output voltage and current is available as a data file created by the measurement program. The measured output ($y_{meas}$) is compared to the simulated output ($y_{sim}$) for a given parameter-set p. The output power rates can either be measured directly - if present - or be calculated using the measured output voltage and current in the data file. On PVsyst, these measurements are generated as part of the simulation. The deviation value (r(t)) is passed through operations to filter (F) "noise" in the data, then square it and integrate it (SI), and the resulting signal is a measurement of the integrity of the fit. Through optimization (minimizing r(t) and hence C(p)), the best parameter-set p, the values for $y_{meas}$ and $y_{sim}$ can be based on any parameter but is usually based on power output.[29] After collecting weather data from the nearest weather station, the data was prepared and inserted into PVsyst.

## 4. Results and discussion

In this study, three Bifacial photovoltaic modules undergo a trial of performance built with different solar tracking systems alongside a fixed-tilt system under identical conditions: the same type of modules, loads, and solar radiation conditions concurrently. At 3-minute intervals, the power output of each panel is measured with an IV Checker and then compared with a simulation model to validate the output against the simulation.

### 4.1 Experimental results

The average generated power by all systems is measured by the IV Checker. The IV Checker recorded the power output of all systems continuously. Fig. 11 shows a sample of the power generated by each system on a clear sky and cloudy day.

The data was used to determine the percentage difference in power output between the different tracking systems and the fixed system on different days. The average power results favor a two-axis tracking system over the single-axis tracking and fixed systems. The maximum power produced was in October between 11:00 am and 12:00 am during the day, exactly at solar noon. The percentage difference is described by Eq. (1). This equation shows the calculation of the power difference based on the comparison of two-axis tracking, single-axis tracking, and fixed-system.

$$\text{Percentage Difference }\% = \left[\frac{\text{power of tracking system} - \mathrm{P_{fix}}}{\text{power of the fixed system}}\right] \times 100\% \qquad (1)$$

where $P_{fix}$ is the power of the fixed system.

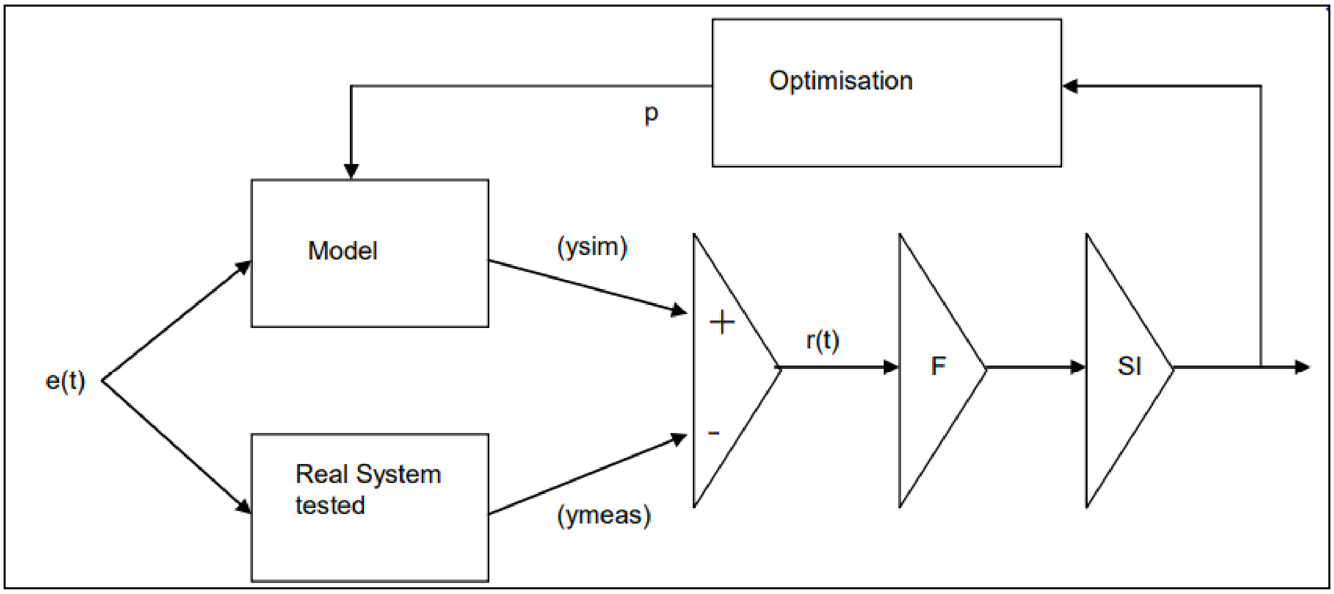

**Fig. 10:** Validation procedure.[29]

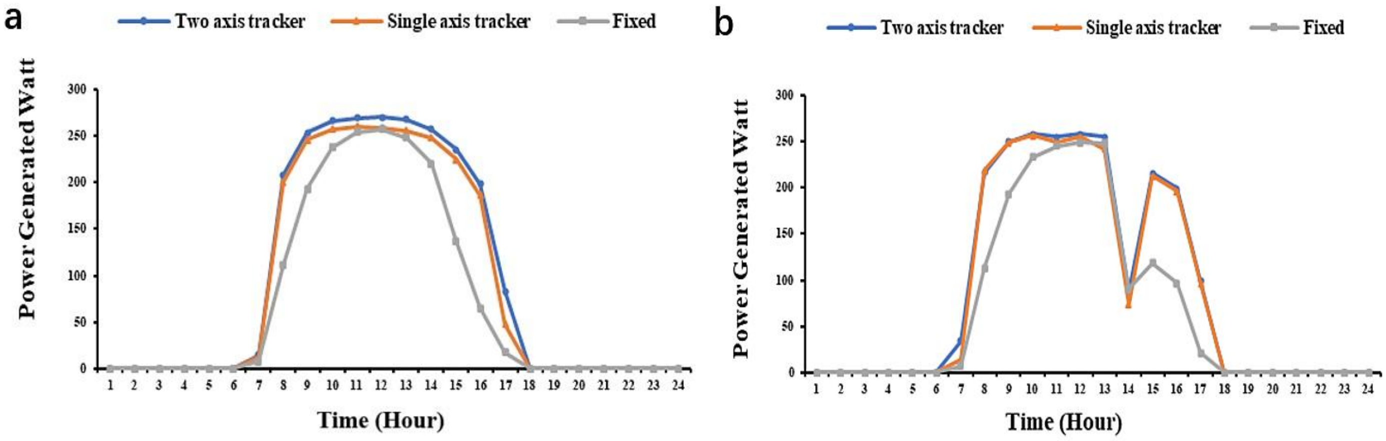

**Fig. 11:** (a) The power output for all systems on a clear sky day, (b) The power output for all systems on a cloudy day.

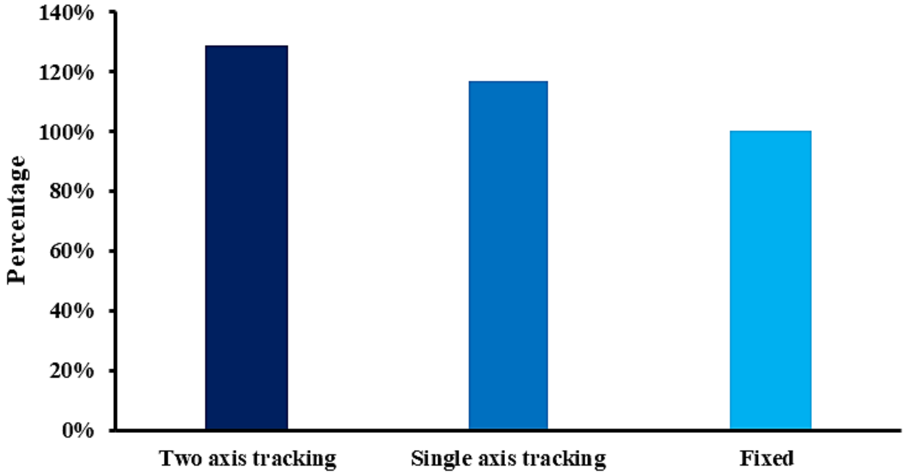

**Fig. 12:** The total output energy collected for all systems in October, the measuring period.

On a clear sky day, the percentage difference between the the fixed system which stood at 28%. On a cloudy day, the percentage difference between the two tracking systems was 11.85%, and the difference to the fixed system was about 25.46%. The two-axis tracking system has been found to produce the highest amount of energy in total, up to 13,464.8 Wh, for the period from October 21 to 27, as shown in Fig. 12.

The two-axis tracking configuration, compared to the single-axis tracking and fixed systems, achieved a bifacial gain of 9.66% and 28.62% greater generation, respectively. Additionally, the single-axis tracking system gains 17.3% more power compared to the fixed system, as shown in Table 5. The result of this experiment is also compared against other studies in other locations to highlight the importance of conducting such experiments in different locations as the results can differ greatly, this comparison is show in Table 6.

**Table 5:** A summary of the improvements in system output compared against single axis tracking and fixed systems.

| Installation Type | Improvement of the tracking systems compared with the fixed system | Improvement of the tracking systems compared with the single-axis tracking system |
|---|---|---|
| Single-axis tracking system | 17.30% | ------- |
| Two-axis tracking system | 28.62% | 9.66% |

**Table 6:** Comparison of results from different experiments of fixed vs. tracking configurations.

| Single axis tracking systems compared with the fixed system | Two axis tracking systems compared with the fixed system | Two axis tracking systems compared with the single-axis tracking system | Reference |
|---|---|---|---|
| 17.30% | 28.62% | 9.66% | This study |
| 14.0% | ------- | ------- | [11] |
| ------- | 30.79% | ------- | [12] |
| ------- | 35%-40% | ------- | [13] |
| 31.8% | ------- | ------- | [30] |
| 27.3% to 30% | 31.2% to 34.62% | ------- | [31] |
| **-------** | 19.62% | ------- | [32] |

After validating the simulation model by calibrating the losses and inserting the weather data to PVsyst, the results were compared with the experimental results. The equation that describes the Percentage error is as follows Eq. (2):

$$\delta = \left|\frac{v_A - v_E}{v_E}\right| \times 100\% \tag{2}$$

where $\delta$ is the percentage error, $v_A$ is the actual value observed, and $v_E$ is the expected value.

As an indicator, the Root Mean Square Error (RMSE) can be computed using Eq. (3):[33]

$$RMSE = \sqrt{\left(\frac{\sum_{i=1}^{n}(O_i - E_i)^2}{n}\right)} \tag{3}$$

where $O_i$: is the $i^{th}$ observed data, $E_i$: is the $i^{th}$ estimated data, and $n$ is the total number of observations.

### 4.2 Two-axis tracking system

Fig. 13a shows the experimental power values and simulation power values achieved by the two-axis tracking system on a clear-sky day. Fig. 13b presents the experimental and simulation power generated on a cloudy day.

### 4.3 Single-axis system

Fig. 14a shows the experimental and simulation power generated by the single-axis tracking system on a clear-sky day. Fig. 14b shows the experimental and simulation power generated on a cloudy day. The calculated error was 1.2% on average for the measured period, where the highest error was 2.6%, while RMSE was 20.67 on the same day.

### 4.4 Fixed system

Fig. 15a shows the experimental and simulation power generated by the fixed system on a clear-sky day. Fig. 15b shows the experimental and simulation power generated on a cloudy day. The calculated error was 2.28% on average for the measured period, and the highest error was 4.48% on a cloudy day. For this fixed system, the RMSE reached 91.35.

The energy uplifts measured for the three bifacial arrays; +28.6 % for dual axis, +17.3 % for single axis, and an additional +9.7 % dual over single fall squarely within the performance envelopes reported internationally. International Energy Agency Photovoltaic Power Systems Program (I IEA PVPS) Task 13 lists typical tracker gains of 15–20 % for single axis systems, with bifacial modules adding a further 2–10 % absolute benefit.[34] Best Practices for Bifacial Tracking report and confirmed by National Renewable Energy Laboratory (NREL) validation work which showed 15–25 % tracker gain for monofacial systems plus a further 4–15 % bifacial bonus.[35] Li *et al*. showed, through optical modelling, that an inclined south–north single axis tracker recovers 97 % of the radiation captured by a dual axis tracker and produces about 30 % more energy than a fixed array in high insolation regions and <20 % in low insolation regions.[36]

Site specific factors, however, can modulate both energy yield and economic preference. Hammad *et al*.[37] reported a 31.3 % annual yield benefit for dual axis tracking in Jordan, yet, found virtually identical module conversion efficiencies for tracked and fixed arrays (≈13.8 %) because the tracker's continuous motion mitigated dust accumulation. Their 20 years techno economic analysis nonetheless favored the fixed system, as the added capital and maintenance costs of dual axis hardware outweighed the energy premium under local pricing. Together with Li *et al*.[36] evidence that well optimized single axis designs can harvest most of the dual axis benefit at lower complexity, these findings emphasize that tracker selection should balance energy gain against soiling environment, component pricing, and long term O&M costs. The present results therefore reinforce the global consensus: while dual axis trackers maximize output, single axis tracking often provides a cost effective compromise, and fixed tilt systems remain competitive where tracker premiums or maintenance burdens are high.

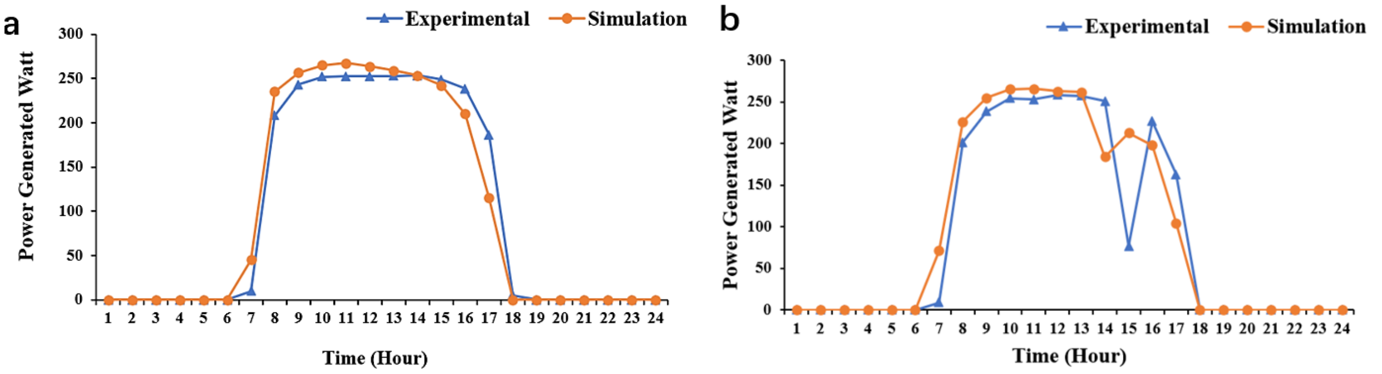

**Fig. 13:** (a) Power output of the experimental setup and simulation, two-axis tracking system on a clear sky day, (b) Power output of the experimental setup and simulation, two-axis tracking system on a cloudy day.

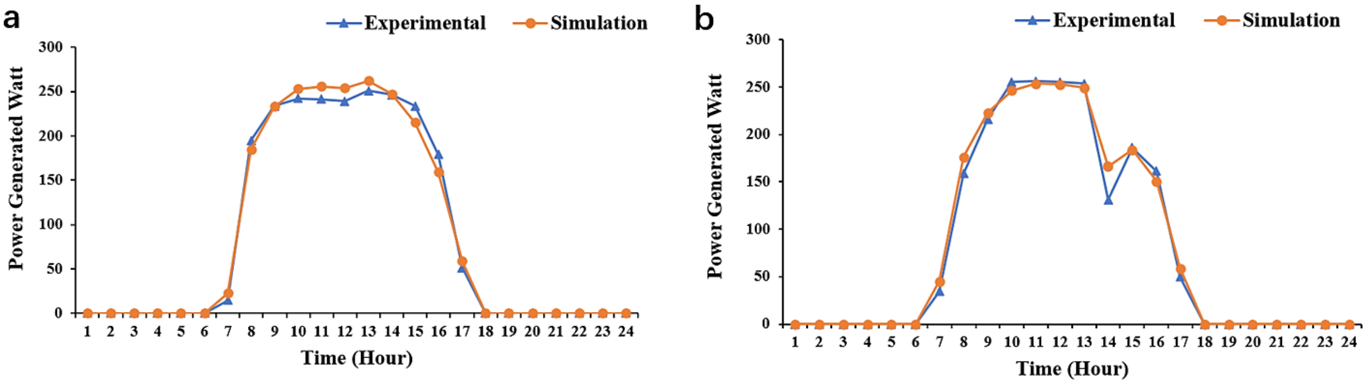

**Fig. 14:** (a) Power output of the experimental setup and simulation, single-axis tracking system in a clear sky, (b) Power output of the experimental setup and simulation, single-axis tracking system in a cloudy day.

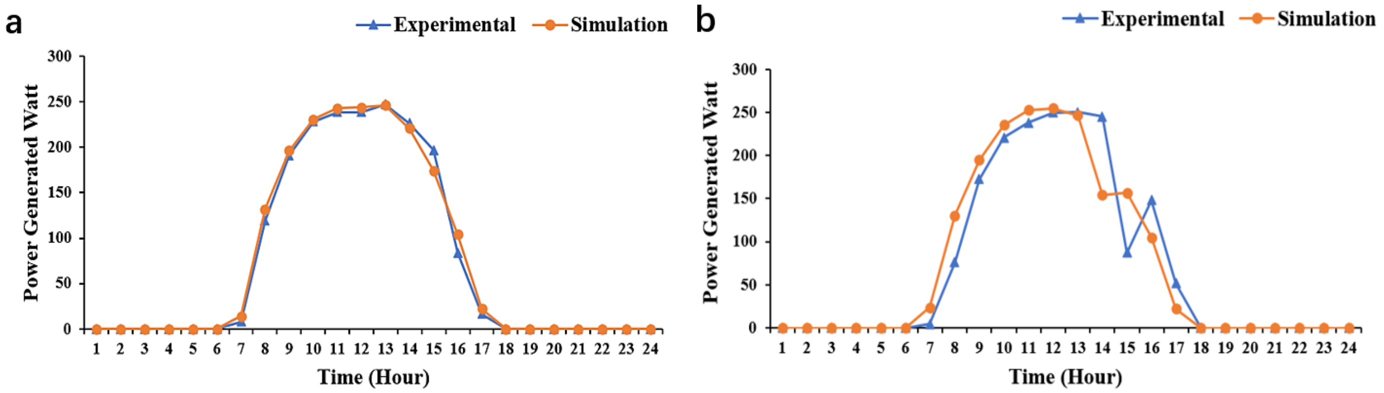

**Fig. 15:** (a) Power output of the experimental setup and simulation, fixed system on a clear sky day, (b) Power output of the experimental setup and simulation, fixed system on a cloudy day.

## 5. Conclusion

In this study, three bifacial PV modules were installed using different tracking mechanisms and a fixed non-tracking system, and they were all measured, compared and validated using simulation software. The inclusion of tracking mechanisms clearly increases the total energy yields of the systems, the highest being that of the bifacial PV module with the two-axis tracking. The tracking systems generated a greater amount of output power compared to the fixed system, where the measured difference is about 28.62% greater energy yield from the two-axis tracking compared with the fixed system and about 17.3% greater energy yield from the single-axis tracking compared to the fixed system. The two-axis tracking system provides about 9.66% greater energy yield compared with the single-axis tracking system.

The results show that the simulation models are fairly and accurately representative of real-world output and can be generalized for similar climatic conditions. The results showed a low error percentage in the two-axis tracking (2.0%) and the single-axis tracking (1.2%) systems as opposed to the fixed system (2.28%) which showed the greatest error. One of the major factors affecting and increasing the errors in the model is the weather data, which cannot be predicted accurately, especially on semi-cloudy days. A decent mitigating step is inserting weather data into the software and implementing the calibration criteria, forcing the mismatch to decrease and to reach an error of less than 1.2%.

## Conflict of Interest

There is no conflict of interest.

## Supporting Information

Applicable.

## CRediT Statement

**Qasim Aburumman:** Conceptualization, Supervision, Writing – review & editing, Resources, Data analysis, Visualization, Validation, Software, Data curation. **Osama Ayadi:** Conceptualization, Methodology, Supervision, Writing – review & editing, Investigation, Project administration. **Otaeeb Al-Oran:** Formal analysis, Data curation, Visualization, Investigation, Review & editing. **Mohammed E. B. Abdalla:** Writing – original draft, Methodology, Formal analysis, Review & editing, Visualization. **Mohammed Al-Mahmodi:** Writing – original draft, Methodology, Simulation, Review & editing, Visualization.

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