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Evaluating Solar Tracking System Efficiency in Dusty and Humid Environments

Anwar H. Al-Assaf [1*], Mohammad Ismail[1], Mohamad I. Al-Widyan[2]

[1]*Department of Renewable Energy Engineering, Amman Arab University, Amman, Jordan*
[2]*Aircraft Maintenance Department, Amman Arab University, Amman, Jordan*

A R T I C L E I N F O

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A B S T R A C T

This paper will conduct an analysis and comparison of the efficiency of the fixed, single axis and dual axis solar tracking systems based on climate conditions in Jordan. An Altera Field-Programmable Gate Array (FPGA) kit was used to apply the solar tracking and showed a great increase in energy generation. The single-axis tracking system created 51.4 more Wh per day, which resulted in a total of 702.02 Wh generated, as opposed to 582.95 Wh generated by the fixed system. The fixed system showed a peak power output of 70 W, the single-axis tracker was 75 W and the dual-axis tracker at 80 W. The findings also emphasize the environmental factors which significantly affected the daily energy production with dust lowering it by about 40 % and humidity lowering it by up to 12 %. Although the dual-axis system was the most robust in operation, its sensitivity to the environment requires it to be cleaned and maintained on a regular basis. In general, the results show that solar tracking systems result in a substantial improvement of the photovoltaic performance, especially when the device is used in conjunction with proper management of the environment.

1. Introduction

Renewable energy plans depend on photovoltaic (PV) technology, but its ability to work well is extremely sensitive to its surroundings and the way it is set up. Tracking solar panels are often explored for improving how solar energy is collected, instead of using fixed installations. The use of solar trackers allows PV panels to follow the sun and therefore creates more energy each day. Previous research shows that both single-axis and dual-axis tracking systems are able to increase the energy output of PV panels by 20% to 50% more than fixed panels [1-4]. If a dual-axis tracker is used, energy generation can be raised by as much as 40% because it can alter both azimuth and elevation angles [5-11].

Nevertheless, performance of tracking systems is often affected by dust and high humidity in the air. Dust decreases the performance of PV panels by 20–40% in hot desert areas [12-15], and extra humidity also causes them to produce less energy by damaging the panels and making them dirtier [16-21]. New tools like nano-coatings and passive radiative cooling look very promising, but we don't yet have enough information about their use in the actual environment [22-27].

Researchers [1-4] found that solar panel orientation increases conversion efficiency by 20% to 50%, greatly improving energy output. Solar tracking system potential was examined in [28], with 42.57% of research discussing single-axis systems and 41.58% dual-axis systems. The study also examined azimuth and elevation (16.67%), horizontal (10%), and polar (16.67%) tracking methods. Studies on bi-axial solar trackers for PV plants [6, 7, 29] help to optimise the solar tracker systems. Easy-to-use software calculated the sun's orbit to maintain panels perpendicular to solar beams, boosting efficiency. In one research [6], a dual-axis tracker design tested at 27.5° latitude increased collecting efficiency by 24% over stationary devices. Further study [29] shown that double-axis trackers with polar-axis and azimuth/elevation models and closed-loop feedback control may increase energy return by 40% over fixed PV panels. Large systems save money since moving components use 2–5% of gathered energy.

Salim, et al. [12] found that long-term dust deposition on a solar PV system in Riyadh (Saudi Arabia) lowered performance by 32% after eight months compared to a daily-cleaned, 24.68°-tilted Kuwait City PV power output plummeted 17% following six days of sand deposition, according to Alshawaf, et al. [13]. Dust lowered PV efficiency by 20% over six months in spring and summer compared to autumn and winter. Sayigh [14] researched dust's effect on solar flat-plate collectors. Seven collectors were tilted at 0°, 30°, 60°, and 90°, with one from each pair cleaned regularly and the other left alone. Results indicate 2.5 g/m^2/day dust accumulation from April to June. Alshawaf, et al. [13] found that slanted glass panels in Kuwait decreased transmission by 64% to 17% after 38 days for tilt angles between 0° and 60°. Three days of dust deposition reduced horizontal collector energy gain by 30%. Since transmittance dropped, deserts should be cleansed daily after sandstorms.

The study by Alhajji, et al. [15] looked at how sandstorms in Saudi Arabia affect PV panel systems. There were about 25 sandstorms each year in Al-Ahsa region, leading to big energy losses due to dust.

* Corresponding author at: Department of Renewable Energy Engineering, Amman Arab University, Amman, Jordan.
E-mail addresses: anwar.assaf@aau.edu.jo (Anwar H. Al-Assaf)

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Nomenclature

Abbreviation
FPGA – Field-Programmable Gate Array
PV – photovoltaic
PDRC – passive daytime radiative cooling
PEC – Photoelectrochemical
LCOE – Levelized Cost of Electricity
DNI – Direct Normal Irradiance
IEA – International Energy Agency
LCA – Life Cycle Assessment
AI – Artificial Intelligence

Symbol
η – Efficiency [%]
I – Solar irradiance [W/m²]
P – Power output [W]

Space around Tabuk gets more sunlight since it experiences less storms (~5.5) every year. The records showed that productivity fell during sand events. It was advised that steps be taken to prevent dust at the site when selecting the September area.

Hayawi, et al. [30] constructed predictions for solar energy with ML using LSTM, GRU, and both of these together (LSTM-GRU hybrid models). Using the dust features made short-term forecasting of fine particles more accurate, with LSTM achieving a low MAE score of 0.018034. Determined that the highest chance of dust events is late in the afternoon and early spring, which results in big drops in the PV electricity output. Explained that dust forecasting is very important for maintaining grid stability.

The study by Elamim, et al. [16] carried out a study to measure how dust was accumulated on the panels during field tests in Morocco. The study revealed that PV power losses ranged from 7.4–12.35%, the maximum current was found to be reduced by 11.6–18%, and transmittance fell from 75% to 5%. The main particles found in dust were silica and calcite. Pointed out that dust reduces the amount of light passing through and leads to heat-related damage.

According to Shukla, et al. [31], PV output was estimated using ANN and SVR models under different types of dust. The solution with SVR did better: RMSE: 0.24, MAPE: 1.54%, R^2: 0.995 compared to ANN: RMSE: 1.41, MAPE: 11% and R^2: 0.983. These models make it easier to monitor equipment in real time and expect when it needs maintenance to prevent dust impacts. Shao, et al. [32] introduced the use of a Pytorch variant of Adam in detecting dust on solar panels through image processing. Model stability and the risk of overfitting were both reduced with the help of the Warmup and cosine annealing techniques. Using three neural networks (ResNet-18, VGG-16, MobileNetV2), the new approach has shown better accuracy when detecting dust. Shows great promise for the use of automated maintenance solutions.

Al-Sharafi, et al. [33] studied in detail the effects of dust on solar devices like PV, flat-plate collectors, concentrators, and chimneys. Dust results in a daily reduction of power, up to 80% loss each month, and up to 35% loss in annual revenue. The cost for cleaning was from $0.016 to $0.90 per square meter. Underlined that the right cleaning methods and a thorough knowledge of dust type play a key role in saving costs for solar operations. Ahmed, et al. [17] carried out an experiment to assess the nano-coating dust removal performance on PV panels in arid conditions. Short-circuit current and average power output of coated panels were about 65% and 77% higher than those without a coating. According to SEM findings, the coating protects the surface by preventing dust from attaching because it is uniform and features spherical shapes. Determined that nano-coating works very well to boost PV energy output in dusty areas.

Alatwi, et al. [18] introduced a deep learning approach to detect dust on solar panels at a low price. 20 pre-trained models and the SVM classifier were tested on public data; the result was 86.79% accuracy in finding dusty panels with DenseNet169 and linear SVM. The suggested process allows quick cleaning to avoid dust-related power losses and provides an eco-friendly and flexible approach to PV maintenance.

Alshammari, et al. [22] examined PET and PDMS polymeric films for cooling solar panels in a hot/humid environment in Saudi Arabia. At night, coatings reduced the temperature by 10 °C while from noon to dusk they reduced it by 1.15–1.35 °C, all without active cooling. Evidence that polymer-based coatings can be easily used for inexpensive coolings. Abdallah, et al. [34] examined the damage of PV module backsheets in the desert climate of Qatar. Discovered that the three conditions led to cracking, chalking, and deterioration of the backsheets of PA and PET, lowering the durability of the whole PV system. PET-2 exhibited better results because it avoided cracking by only showing chalking. The findings influence what materials are used for desert PV systems.

Mohammad Rafiei and Askarzadeh [35] analyzed the efficiency of a 2.5 kW grid-connected PV system in Iran using data for dust, humidity, temperature, and shading. Including dust reduced the accuracy of the trends found; exponential model performed the best (with RMSE 0.0018) when the dust was included. It is important to model how dust affects PV modules for correct prediction of how they will perform. In their research Hong, et al. [23] created a polymer coating suited to high humidity for use in passive daytime radiative cooling (PDRC). With >45% surrounding RH, the conventional coatings did not keep cool, but the modified ones could still keep the surface cool as high as 60% RH, which opens more doors for them in humid locations. Cooling in the daytime reached 7°C for a relative humidity of 30 percent. Listed one main restriction in the commercial use of PDRC coatings.

The findings of Li, et al. [36] HPDA was used to strengthen the flexible perovskite solar cells (FPSCs) in extreme humidity. After 10,000 bending cycles in an environment with 65% RH, FPSCs with HPDA kept a PCE of 94.1%, ending up with a PCE of 24.43%. The adhesion and humidity resistance of the film are highly developed for use in flexible solar panels. Wang, et al. [37] designed a deep artificial network that mixes many models for predicting short-term power output of a high-humidity island PV station. In most cases, RMSE from the model was 34 to 64% lower than from the baseline systems (CNN-BIGRU and LSTM) in every weather state. Continued to function well despite working in complicated, high-humidity environments found in islands.

It is shown in the literature that 20%–50% more energy can be produced by tracking sunlight, with dual-axis trackers achieving the biggest improvement. However, there are not many studies that systematically examine how performance on the track ties to real environmental damages.

The unique part of this work is that it compares three different solar tracking systems experimentally in a field study using both dust and high humidity. Unlike studies done before, this one measure both the influence of dust and humidity on PV energy yield and how tracking setups respond to them under real-world conditions, uniquely comparing fixed, single-axis, and dual-axis configurations while quantifying their energy gains

2. Methodology

In order to analyze performance, the setup was set up to assess three solar systems; a fixed system and two tracking ones, with axes using single or dual movement. The systems were put together and tested in the same place and under identical conditions in Amman, Jordan. Each system was designed with the same PV modules, all rated at the same capacity, to separate the impact of tracking angle on efficiency.

The fixed system was attached at an angle aligned with the best position for its latitude. The single-axis tracking system rotates only on the horizontal (azimuthal) axis, guiding the panel to face the sun from east to west as it moves in sky. Having a dual-axis system meant the tracking system could change the azimuth and elevation angles together, assisting the device in staying aligned with the sun at any time.

Automatic tracking for movable systems used LDRs and microcontrollers, so that changes could be made instantaneously based on the light intensity outside. To make the robot stable, changes in the sun's angle were detected by sensors that then caused the robot to move. A digital data collection system was used to track the power output (W) and voltage-current data every half hour from sunrise to sunset.

Besides measuring performance without dust, the impact of light (10%), moderate (25%) and heavy (40%) dust on the PV cells was examined by manually applying dust to the panels. Just as with heat, humidity was tested by following standardized reductions (2%, 5% and 12%) that were based on references and local climate, applied to the clean system's output.

The total Wh output and peak W were measured and compared for each configuration and condition tested. Performance trends were drawn using power vs. time plots to determine which system did best in various situations.

3. Results

In this section, the power of fixed, single-axis and dual-axis solar tracking systems are compared using real environmental data. Systems were checked every day to see if they worked well and if they were sensitive to dust and humidity changes. Operational data is shown in the form of power plots and checked against daily energy totals to determine if the systems function properly and reliably.

Figure 1 shows that throughout the day, the power output of the fixed, single-axis, and dual-axis tracking systems varies significantly. Total daily power output is 582.946 W, with the fixed tracking system—which does not change in response to the sun's movement—showing a slow rise in power output, reaching a peak of about 70 W at midday and then steadily declining throughout the afternoon. However, the power output is consistently higher with the single-axis tracking system, which can adapt to the sun's horizontal position. This is especially true in the morning and late afternoon, when the system reaches its peak values of approximately 75 W. A 20% improvement over the fixed system, this system produces a total daily power output of 702.017 W.

Consistently outperforming the other systems, the dual-axis tracking system provides a higher power output from morning until late afternoon, with peak values reaching around 80 W. This is done by adjusting to the sun's horizontal and vertical position. The total daily power output is 821.089 W, which is about 41% higher than the fixed system because it can follow the sun's trajectory more precisely.

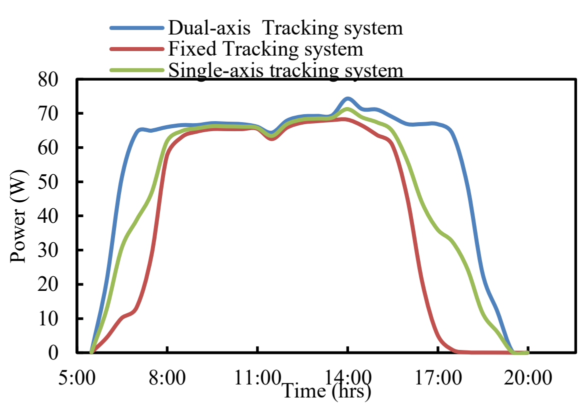

Fig.1. Solar tracking systems.

Figure 2 demonstrates how accumulating dust on fixed solar tracking systems reduces their performance. Under perfect cleaning, the system reaches a maximum power output of about 68.2 W and produces 1165.94 Wh of energy daily. With just 10% dust, solar modules' output is markedly reduced through the day and the peak values lower from 68.1 W to 61.4 W, while the daily energy drops around 10% from 1171.55 Wh. Once dust levels are at a moderate level (reduction of about 25%), there is greater impact, as peak power falls to 51.2 W and the system uses ~874.46 Wh of energy. If dust exposure reaches 40% (reduction), the system's peak power and daily energy drop by 40% to 40.9 W and ~699.56 Wh, respectively.

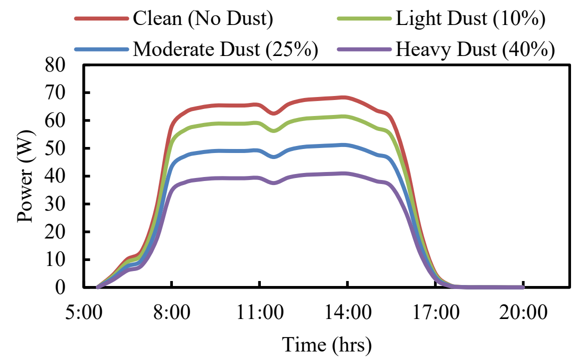

Fig. 2. Performance of fixed solar system with dust.

Figure 3 illustrates the effects of dust on the single-axis solar tracking system. If tidy, the system reaches an optimum power of 71W and produces over 1400 Wh a day. Slight dust reduces efficiency to ~64 W and 1263.70 Wh, but heavy dust cuts output to just ~53.2 W and 1053.08 Wh. Maximum power decreases to 42.6 W when dust is thick (40%) and the total energy output declines to 842.47 Wh. Although tracking well, its efficiency is reduced by dust, showing how important it is to regularly remove dust.

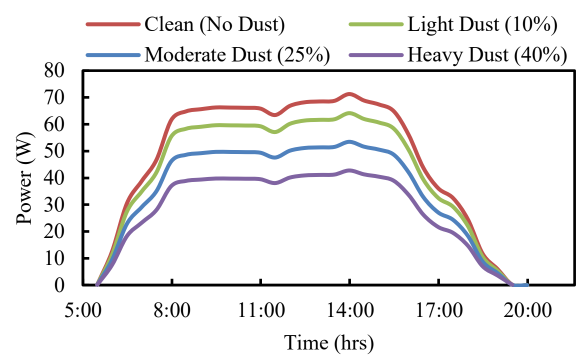

Fig. 3. Performance of single tracking solar system with dust.

Figure 4 shows how dust affects the dual-axis solar tracking system. The system produces its maximum power of ~74.3 W and gives 1642.29 Wh each day in a healthy state. If the panels are just lightly dusty (10%), output is reduced to 66.9 W and 1478.06 Wh, but moderate dusting (25%) will drop that to 55.7 W and 1231.72 Wh. Under heavy dust, the maximum power produced is about 44.6 W and the total energy decreases to 985.37 Wh. Though the dual-axis system is the most powerful, it is easily affected by dust and should therefore be cleaned often to maintain its best results.

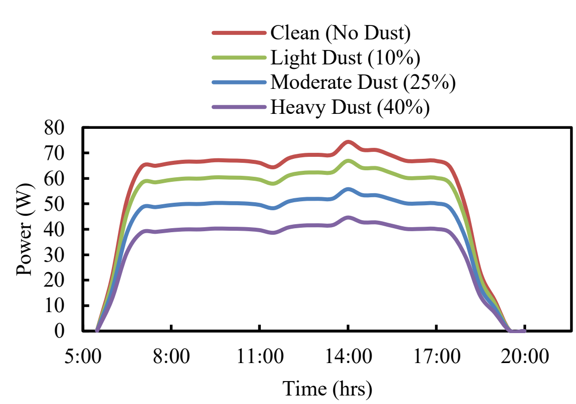

Fig. 4. Performance of dual tracking solar system with dust.

Figure 5 depicts the effects of humidity upon the fixed solar system. In clean and dry conditions, the system efficiently reaches its highest power of ~68.2 W and creates 1165.94 Wh every day. When humidity drops to 2%, it still has little effect and cuts the peak slightly, to about 66.8 W. Peak power and energy values are reduced to 64.8 W and 1108 Wh respectively, if the air's humidity is low (5%). When the air is very humid (12%), peak output drops by 30% to ~60 W and the total daily energy used by the panel is ~1025 Wh.

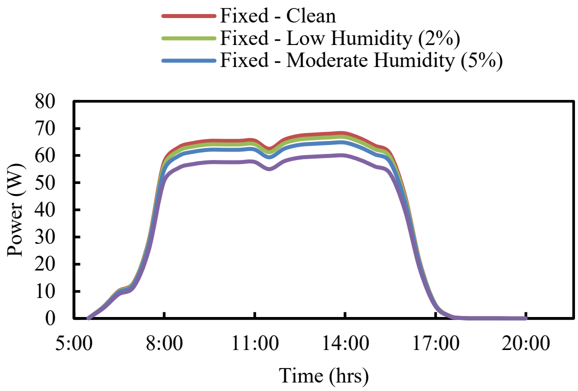

Fig. 5. Performance of fixed tracking solar system with humidity.

Figure 6 demonstrates the changes in humidity on a single-axis tracking system. With clean solar panels, it can provide a peak output of 71 W and produces about 1404.11 Wh each day. At 2% humidity, the device gives out ~69.6 W of power. When humidity rises to 5%, peak power drops to 67.5 W and the energy produced is 1333.9 Wh. When humidity is high (12%), efficiency goes down and the unit reaches a maximum output of ~62.5 W daily and consumes 1235.6 Wh. As irradiance is better tracked, moisture in the air does result in some dropped power.

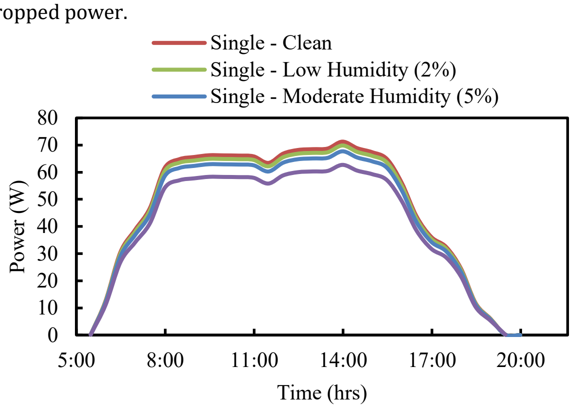

Fig. 6. Performance of single tracking solar system with humidity.

Figure 7 reveals the impact of humidity on the two-axis tracking system. When it is clean, its maximum power is 74.3 W and it delivers 1642.29 Wh each day. With only 2% humidity, the performance drops to 72.8 W and 1609.44 Wh.

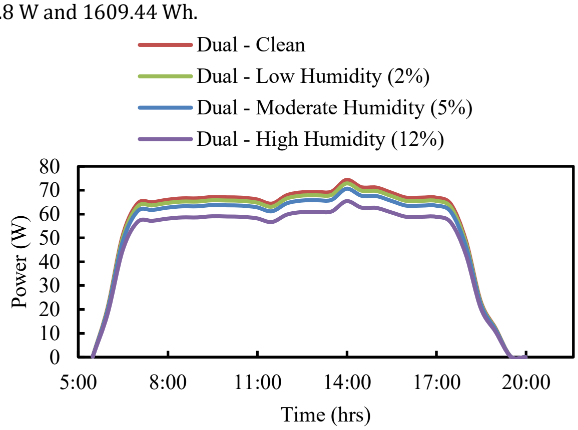

Fig. 7. Performance of dual tracking solar system with humidity.

4. Conclusion

With moderate humidity at 5%, the device outputs about 70.6 W and 1560.18 Wh. In high humidity at 12%, its top power is drained to about 65.3 W with a low energy output of 1444.22 Wh. Even though it has precise tracking, the system can be easily influenced by humidity, so it needs special care in damp climates.

The study found that solar tracking greatly improves the daily production of solar energy under Jordanian conditions. According to the findings, the dual-axis tracker worked most efficiently, supplying 821.09 Wh daily, about 41% more than what was recorded from the fixed design (582.95 Wh). The one-axis system improved results by about 20% when compared to a fixed station. However, the tests showed that environmental conditions played a major role in how the system performed. Dust created daily energy loss of 40% and also led to peak power reductions. Similarly, a rise in humidity to 12% caused a lowering of daily energy generation. In all conditions, the dual-axis tracker showed the highest energy output, except that it was sensitive to tiny particles and humidity. The research reveals that increasing PV energy relies on monitoring but depends more on frequent cleaning to keep the system reliable..

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