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Empirical Evaluation of Fixed and Single-Axis Tracking Photovoltaic System: Case of ASHRAE Solar Radiation Modelling for Medina, Saudi Arabia

Raed Alahmdi, Abdulrahman Alansari, Mohanad Abualkhair, and Abdulrahman Almoghamisi

***Abstract*—The main problem in studying the feasibility of solar systems is the enormous gap between theory and experimental radiation intensity, so to get accurate results there is a need for studying energy production in the site of the system empirically. In this study, the energy production of both fixed PV panel system and the system with single-axis tracking were empirically evaluated in Medina, Saudi Arabia. The two systems had the same 270 Wp PV panel. The fixed system was tilted by 23.5 degrees, and the single-axis tracker was tilted by 26 degrees. Both systems had an azimuth angle of zero degrees. A closed-loop three-points controller was used to control the tracker with 120 degrees rotation range. The two systems operated simultaneously in July, and the data were collected for 14 days. The empirical results showed that the tracker increased the generated energy by 48.5% during the testing period. As a comparing method, a modified ASHRAE model was used to estimate the increase in the panel's energy output with and without the single-axis tracker, and RMSE and MBE were calculated. It's been found that the experimental energy generation is 10%, 5% less than the estimation of the modified model for the fixed system and the tracking system, respectively. Finally, based on the analysis, it's been estimated that the single-axis tracker will increase the generated energy by 22.5% yearly in Medina.**

***Index Terms*—Empirical evaluation, solar tracking, photovoltaic system, solar radiation modelling.**

I. INTRODUCTION

The continuous use of fossil fuel as a primary energy source will cause fuel depletion, contaminate the environment, and adversely affect human health. Solar energy is a clean, reliable, and immense renewable energy resource, especially compared to other energy resources. Due to its availability and cleanability, solar energy became more popular in recent years than different clean energy types. Also, the increase in petroleum prices, environmental issues, etc., caused this attention to renewable energy resources. The power production of solar panels is greatly influenced by its orientation and the site of application. Saudi Arabia is one of the largest countries that have sunny weather. It is also considered one of the top fossil fuel consumers for electricity generation [1].

Although photovoltaic (PV) panels are considered the most reliable technology to harvest solar energy, the functionality of PV panels is affected by many factors like cloud cover, sun intensity, relative humidity, and heat buildup. On cloudy days, sunlight absorption reduces due to the clouds' reflection, limiting the panel's absorption of the sunlight. In summer days, the solar energy output is decreased by 10% to 25% due to the increase in temperature. More importantly, the panel's orientation has a significant effect on the system's energy production, and it varies with different locations. Solar collectors produce more power when it is oriented to the exact position of the Sun. Therefore, the use of a solar tracker system will increase the power output relatively [2].

A solar tracker is a device that traces the movement of the Sun from sunrise to sunset. Finster presented the first solar tracker device in 1962, and it was a purely mechanical device. One year later, Saavedra presented a tracking mechanism with electronic control and fully automatic [3]. In 1968, the first solar tracker was successfully built. Nonetheless, the tracker was passive. Within the 90s, researches and studies on solar trackers were completely engaged with electro-optical sensors [4]. From the late 90s, researchers focused on single-axis and dual-axis solar tracking. In the beginning, the focus was on the single-axis due to its simplicity. Later, the dual-axis was presented in the market. In the early 2000s, there was a dispute about whether a fixed/tilt solar tracker was a better solution for utilities, and it was found out that a tilt tracker was the best solution for utilities. Solar trackers have continually evolved since then to become more effective and more efficient. From single to dual-axis and from passive to active trackers, trackers in today's market are combined with features that generate better output [5].

The solar tracker's market worldwide is about 30 GW in 2020, and it is expected to grow at a CAGR of about 30% from the period 2020 to 2026 with an annual installation of over 35 GW [6]. Saudi Arabia in this case is expected to have the highest growth rate of solar trackers in the period 2020-2025 [7]. The gross value of solar trackers in 2019 was approximately 3.1 billion, and it is expected to grow more in the upcoming years [6]. The market has its share for both single-axis and dual-axis. However, the single-axis tracker takes about 64% of the solar trackers market. The single-axis tracker is mostly used due to its low initial cost, low maintenance, and simple design compared to the dual-axis tracker [8].

When using solar trackers, financial and non-financial benefits are obtained. The financial benefits depend mainly on two factors. The first factor is the location of the system and its closeness to the equator of the earth. The other factor

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R. Alahmdi is with the Physical Sciences and Engineering Division at King Abdullah University of Science and Technology, 23955 Thuwal, Saudi Arabia (e-mail: raed.alahmdi@kasut.edu.sa).

A. Alansari is with the HSE Department at AMSteel LLC, 23425 Jeddah, Saudi Arabia (e-mail: Abdulrahman.alansari@amsteel.com).

M. Abualkhair is with the Mechanical Engineering Department at King Fahd University of Petroleum and Minerals, 31261 Dhahran, Saudi Arabia (e-mail: g202007760@kfupm.edu.sa).

A. Almoghamisi is with the Engineering Department M.M.Alharbi & Partners Co. Ltd, Jubail, Saudi Arabia (e-mail: dhami1.1997@gmail.com).

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is the initial and variable expenses of the tracking device itself. The non-financial benefits include the decrease in the number of used PV panels to generate the same amount of power. This decrease will lead to a reduction in the area occupied by the PV system. As a result, this will decrease the environmental impact of the chemical materials of the PV panels [9].

Solar tracking systems are categorized by the mode of their motion. Fig. 1 shows the different types of solar tracking systems.

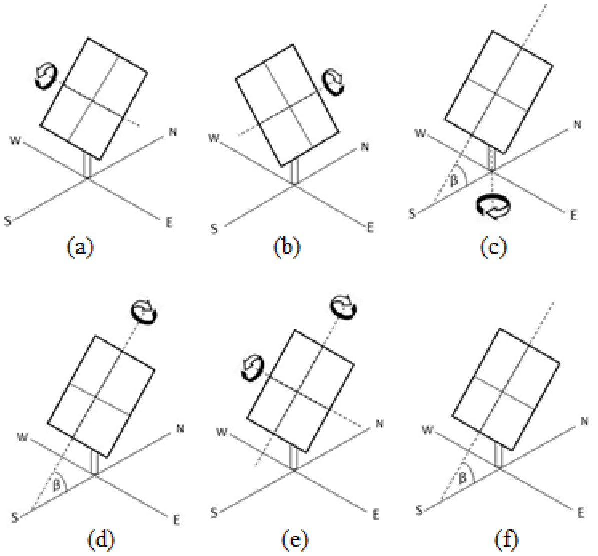

Fig. 1. Types of solar trackers.

Fig. 1 (a) shows a single horizontal east-west axis tracker. It rotates from north to south throughout the day on a fixed axis parallel to the ground. Fig. 1 (b) shows a single horizontal north-south axis tracker. It rotates from east to west on a fixed axis, which is parallel to the ground. Fig. 1 (c) shows a single vertical axis tracker; it rotates from east to west in a vertical axis following the Sun throughout the day. These systems are often installed in high-altitude or mountainous locations. Fig. 1 (d) shows an inclined axis tracker. This is similar to the horizontal tracker but with a tilted axis. Fig. 1 (e) shows a dual-axis tracker which allows full sun-tracking throughout the day and the year. Fig. 1 (f) shows a fixed PV panel that has no tracking system installed on it. As such, its power production is the lowest among the other cases [10].

Many experiments indicated that the single-axis solar tracker would increase the energy generation up to 28.4% compared to fixed PV systems [11]. On the other hand, a dual-axis solar tracker would increase the energy generation to 40% more than fixed PV systems. Nevertheless, dual-axis tracking systems commonly suffer from high energy losses while operation due to auxiliary units and moving joints. Also, dual-axis tracking systems tend to have high initial costs due to the need for more equipment to rotate the panels in both directions [12]. The increase in energy generation will differ from one site to another due to the location. In this study, the location is Medina city in Saudi Arabia, which is a low latitude city. All types of tracking systems are considered to be feasible in Medina according to a paper study on the feasibility of tracking systems in low latitude countries [13].

Power output data acquired from PV panels can be compared against many different models. The total radiation on a tilted surface is composed of the beam, reflected, and diffuse radiation. There are two types of solar radiation models, isotropic and anisotropic models. The diffuse radiation for the isotropic models is assumed to be uniform. Some of the wide models that are used in solar radiation estimation are ASHRAE clear sky model, Reindl et al. model, Perez et al model, Badescu model, Liu and Jordan model, Klucher model, Koronakis model, Hay and Davies model, and HDKR model [14]. In a study done in 2017, factors were been developed to modify ASHRAE clear sky model in a way to consider the effects of weather conditions in Saudi Arabia [15]. Thus, this modified ASHRAE model can be further investigated for Medina city.

Several studies proved that more energy would be incident on the panels' surface with a tracking system than the surfaces without tracking. According to a study done in Turkey, the PV panels have produced 32.5% more energy by a single-axis tracking system than the PV panels at a fixed position [16]. Another single-axis tracking system called "one axis three-position sun-tracking PV module" changes the PV orientation only at three fixed angles: morning, midday, and afternoon. As a result, the power output increased by 24.5% [17]. Another study in Iran indicated that a single axis solar tracker would increase power production by 35% than a fixed PV system [18]. In Jordan, a study was done by Mu'tah University indicated that a single tracker would increase power production by 20.4% more than a fixed system throughout the year [19]. As can be observed from the mentioned studies, a single solar tracker would increase the power production of PV panels but with a variation in the percentage of increase from one site to another.

This paper aims to specify the energy increase due to the use of a single-axis tracker (SAT) with PV panels through collecting experimental data of the PV system with and without tracking for Medina city. These collected data will be compared to the clear sky insolation ASHRAE model with the use of the correlation factors developed by Abouhashish for Medina city [15]. The comparison will be made using the actual data as a reference, and RMSE and MBE will be calculated with respect to the modified ASHRAE model. Finally, energy increase due to the use of SAT throughout the year will be estimated.

II. MATERIALS AND METHODS

The Single-axis tracker (SAT) shown in Fig. 1 (d) and a fixed mounting bracket are used in this experiment to hold PV panels. The fixed mount is tilted with the yearly optimum tilt angle suggested by M. Benghanem for Medina city, which is 23.5 degrees and zero azimuth angle as shown in Fig. 2 (a) [20]. The tracker is configured with an axis tilt angle of 26 degrees and zero azimuth angle as shown in Fig. 2 (b). These angles were found as optimum angles by the European Commission Joint Research Centre using PVGIS system [21]. The tracker has a closed-loop three-points controller and a linear actuator with a rotational range of 60 degrees to the east and similarly to the west. The controller sends the actuating signal based on the radiation difference of the two small PV sensors installed on the equilateral triangle.

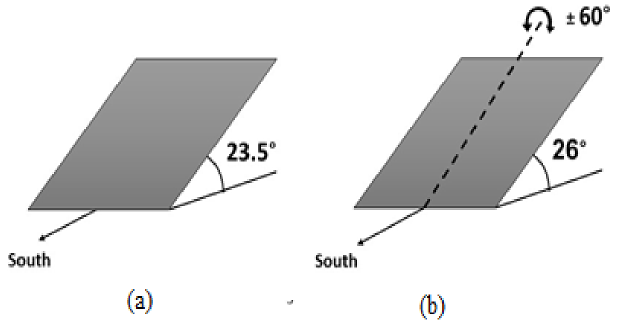

Fig. 2. Angle configurations of the experiment: (a) Fixed PV. (b) PV on the SAT.

To perform the experiment, two similar PV panels were used. One installed on the tracker, and the other one installed on the fixed mount. The panel's characteristics are shown in Table I.

TABLE I. PV PANEL CHARACTERISTICS

Maximum Power (P_{max})	270 Wp
Voltage at Maximum Power (V_{mpp})	31.8 V
Current at Maximum Power (I_{mpp})	8.5 A
Open Circuit Voltage (V_{oc})	37.4 V
Short Circuit Current (I_{sc})	9.14 A
Panel Efficiency	0.165
Temperature Coefficient of P_{max}	-0.38001 %/ ℃
Temperature Coefficient of V_{oc} (K_V)	-0.110352 V/ ℃
Temperature Coefficient of I_{sc} (TCi)	0.08558 %/ ℃
Nominal panel temperature (T_N)	25 °C
Nominal operating temperature of the panel (N_{OT})	45 °C
Nominal solar irradiation (E_{iN})	1000 W/m^2
Panel Dimension (H/W/D)	1640x992x35 mm

In order to collect the data, Arduino Mega 2560 microcontroller is used with two ACS712 current sensors, DS3231 time module, potentiometer, tracker energy consumption meter, micro-SD card module, and set of resistors to find voltage using the voltage divider rule. The potentiometer is used to check the tracker's orientating error by comparing the angle of the tracker during the day with the theoretical optimum tracking angle found using the set of equations taken from the US National Renewable Energy Laboratory (NREL) [22]. In addition to the tracker's angle, the voltage and current of both panels were logged every nine seconds. Fig. 3 shows the schematic layout of both systems.

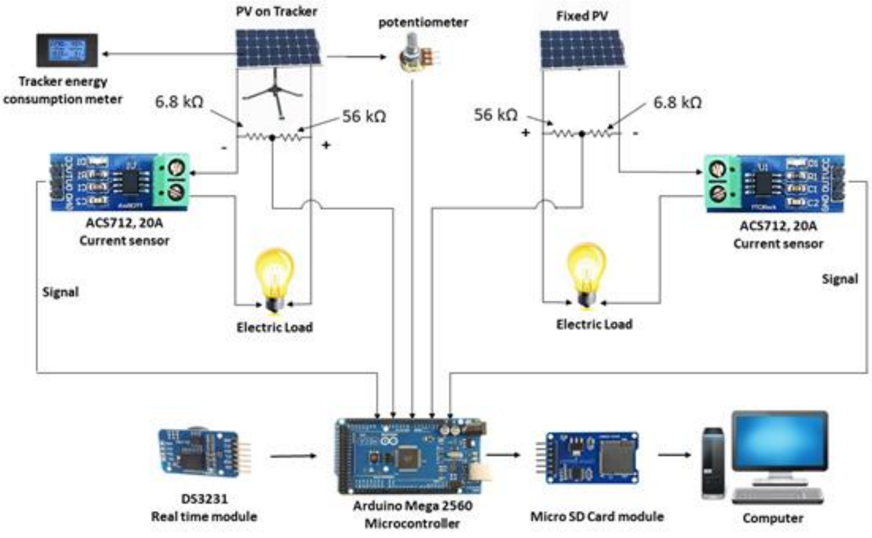

Fig. 3. Schematic layout.

The experiment took place in Medina city in Saudi Arabia (latitude: 24.47 and longitude: 39.61), and the data was collected from sunrise to sunset. The daily data was stored on micro-SD, and at the end of each day, it was transferred to the computer. The experiment was done in the summer for two weeks in the period 9-13 July and 15-23 July 2020.

After collecting the data, it was analyzed using MATLAB. The first stage of analysis was finding out the experimental power output of each panel by multiplying voltage and current. Then, averaging the power data of two weeks into one representative mean day data. After that, the theoretical insolation was computed using ASHRAE model of clear-sky solar radiation and multiplied by the clearness factors developed by Abouhashish for Medina city to adjust the calculated clear sky insolation to consider the effects of local weather conditions [15], [23]. To find the power output of PV, the ambient temperature was gotten from 'Time and Date AS' online platform, and cell temperature was calculated using Eq(1) [24]. PV panel characteristic in Table 1 was used to find the expected power output by using equations Eq(2)-Eq(7) [25]. These equations consider the ambient temperature, the panel's voltage, and radiation flux as independent variables. Considering voltage as an independent variable is highly important in this experiment as the voltage is inconstant, and Maximum power point tracking (MPPT) was not used.

$$T = T_A + E_i\left(\frac{N_{OT}-20}{0.8}\right) \tag{1}$$

$$\propto = \frac{E_i}{E_{iN}} \tag{2}$$

$$I_{max} = \frac{I_{SC}}{1-\exp\left(\frac{-1}{b}\right)} \tag{3}$$

$$\gamma = 1 - \frac{V_{min}}{V_{max}+\tau_V} \tag{4}$$

$$\tau_i = 1 + \frac{TCi}{100}(T - T_N) \tag{5}$$

$$\tau_V = K_V(T - T_N) \tag{6}$$

$$P(V) = \propto I_{max} V \tau_i * \left[1 - \exp\left(\frac{V}{b(\gamma \propto +1 - \gamma)(V_{max} + \tau_V)} - \frac{1}{b}\right)\right] \quad (7)$$

where,

T_A: Ambient temperature °C

T: Cell temperature °C

E_i: Solar irradiance W/m^2

b: Characteristic I-V Curve constant

V_{min},V_{max}: V_{oc} at 200 W/m^2 and at 1000 W/m^2

V: Panel voltage at specific time

P(V): Panel power output at the specific voltage

Finally, root mean square error (RMSE) and mean bias error (MBE) was calculated between experiment data and the modified ASHRAE model results using the following formulas [26]:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(I_{measured} - I_{estimated})^2}{N}} \quad (9)$$

$$\text{MBE} = \sum_{i=1}^{N}\frac{(I_{measured} - I_{estimated})}{N} \quad (10)$$

III. RESULTS AND DISCUSSION

According to the collected data, there is a significant difference in power production between fixed PV and PV on the SAT. The collected data of the 14 days have been averaged into two representative curves. The curves represent PV panel power output with and without SAT. The average standard deviation between representative day data and actual data has been found to be 11.4 W/m^2 and 21 W/m^2 for fixed PV and PV on SAT respectively. The power production was varying over the day, and it reached its maximum at the solar noon. The SAT shows an increase in power output during all day except for the solar noon hours. Fig. 4 shows the power production of both systems.

The power consumption of the motor that actuates the SAT has been found to be less than 1% of the power increase due to tracking. Thus, it was neglected, and the power production was considered as the net power. Fig. 5 shows the difference between the power outputs of the fixed PV and the PV on the SAT.

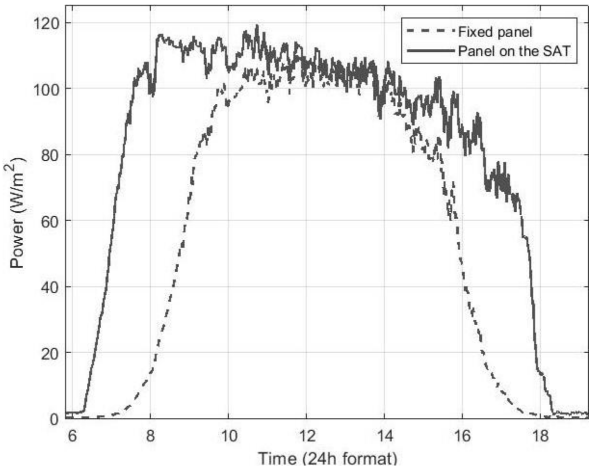

Fig. 4. PV power production

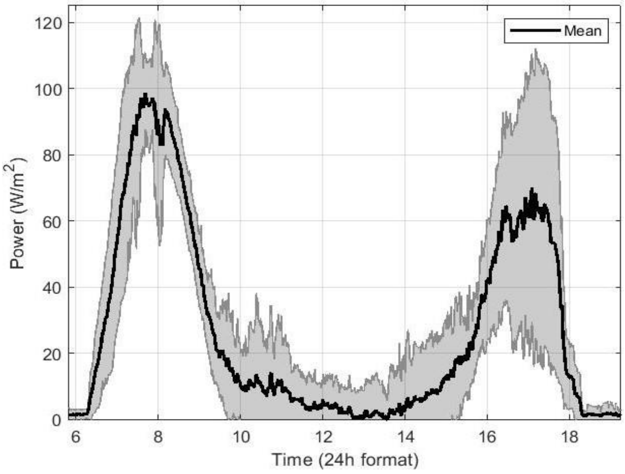

Fig. 5. Power difference between panels with and without SAT for the period 9-23 July. The power range is the shaded region.

Fig. 5 clearly shows that weather conditions greatly impact the power output difference with and without SAT. Ten days of the experiment were sunny, while four days were partly sunny. In one way or another, the representative curves showed a good fit with the stander deviation stated earlier in this section. It has been found that the increased energy output of PV due to tracking for the study period is 48.5%, and Fig. 6 shows it for individual days.

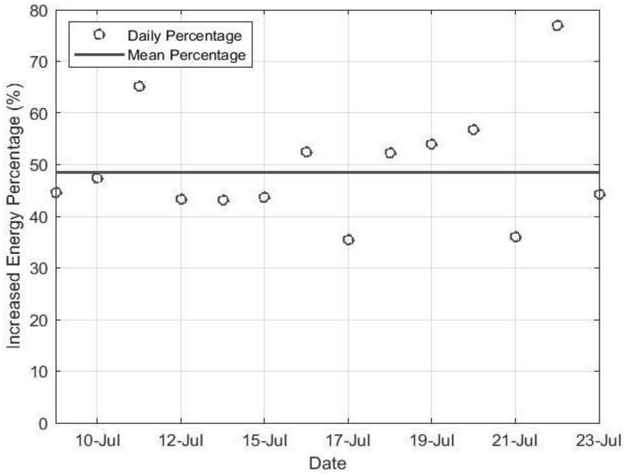

Fig. 6. Daily energy increase percentage due to the use of SAT.

By comparing the result of the modified ASHRAE model and the actual power output of the panel, it has been found that the model is a good fit for the fixed panel case with an average RMSE of 10.5 W/m^2 and MBE of 6.1 W/m^2. On the other hand, for the panel on SAT, the average RMSE is 14.1 W/m^2 and the MBE is 3.5 W/m^2. The results of the modified model and the experimental results of fixed panel and panel on SAT are shown in Fig. 7 and Fig. 8 respectively. The actual total energy generated by the panel is 10% less than the predicted by the modified model for the fixed panel case while it is 5% less for the panel on SAT case. Thus, the modified ASHREA model showed a good result for Medina city during the study period with a maximum error of 10% in total energy.

Using the same modification of ASHRAE model by Abouhashish, and by assuming constant load voltage of 29 volts and the ambient temperature of previous years, it has been found that the use of the SAT in Medina will approximately increase the generated energy of the panel by 22.5% yearly. This percentage reaches its maximum in spring with 24%, and in summer, autumn, and winter, the percentages of increase are 22%, 21.5%, and 22.5%, respectively. The yearly in-plane irradiation calculated by the modified model on the fixed panel configuration is 1741 kWh/m^2, while It is been estimated to be 2561 kWh/m^2 using Photovoltaic Geographical Information System (PVGIS) of the European Commission Joint Research Centre [21]. This significant difference raises doubts about the reliability of uses Abouhashish's clearness factors for yearly calculation especially that those factors were developed based on one-year data only.

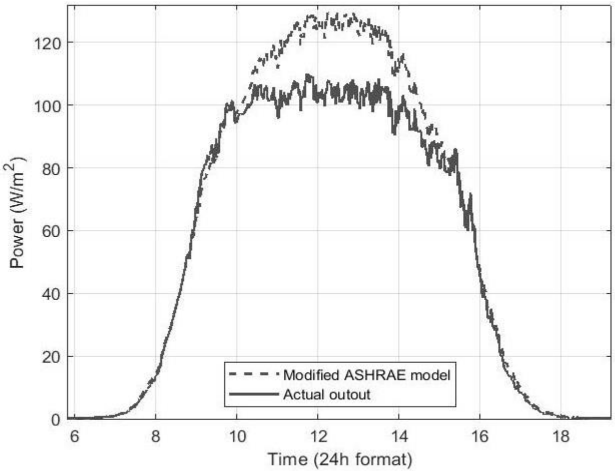

Fig. 7. Power output of the mean day of the fixed configuration.

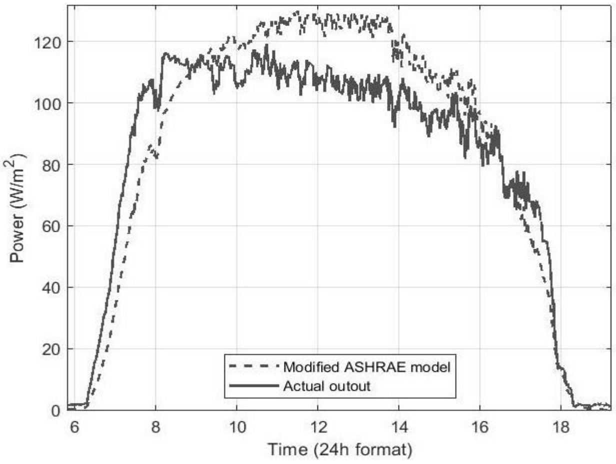

Fig. 8. Power output of the mean day of the SAT configuration.

IV. CONCLUSION

The study specified the energy increase due to the use of a single-axis tracker (SAT) with PV panels through collecting experimental data of the PV system with and without tracking in Medina, Saudi Arabia. The data of both panels' voltage and current were logged every nine seconds during the experiment period. The results showed a significant increase in energy generation due to tracking except at noon when both systems had almost the same energy generation. The test results showed that the tracker increased the energy generation by 48.5% for the 14 days of testing. The average standard deviation between representative day data and actual data has been found to be 11.4 W/m2 and 21 W/m2 for fixed PV and PV on SAT respectively. Nonetheless, the representative curve showed a good fit. The average RMSE was found to be 10.5 W/m2 and MBE 6.1 W/m2 for the fixed panel and an average RMSE of 14.1 W/m2 and MBE of 3.5 W/m2 for the panel on SAT. The modified ASHRAE model showed a good result for Medina city during the study period with a maximum error of 10% in total energy. By extending the modified model for the whole year period, it has been found that the use of the SAT in Medina will increase the energy generation of the panel by 22.5% yearly. One potential future research work is in the direction of analyzing the impact of adding SAT for longer periods and economical evaluation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors took apart on each stage and but on the individual level, R. Alahmdi was responsible for setting the methodologies, following up with the practical experiment and managing the project, while A. Alansari was responsible for drafting the manuscript and proofreading. M. Abulkhair compared and analyzed the data from the actual and theoretical sets. A. Almoghamisi was the one who led the fabrication of the tracker used in this experiment.

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R. Alahmadi graduated from Taibah University in 2020 with a bachelor's degree in mechanical engineering with first-class honor. Previously, he completed internships at Tokai University in Japan; SAR company in Saudi Arabia. Currently, he is taking a master's degree in mechanical engineering at King Abdullah University of Science and Technology (KAUST) specialized in Micro-electromechanical systems (MEMS). He is a fellow of Qimam Fellowship and CoCreate Fellowship.

Abdulrahman Alansari graduated from Taibah University in 2020 with a bachelor's degree in mechanical engineering, Previously, he participated on a research and development project at the university of science and technology in Pakistan. Currently, he is working at the HSE department in AMSteel LLC operating in King Abdullah port in KAEC, Saudi Arabia.

Mohannad Abulkhair graduated from Taibah University in 2020 with a bachelor's degree in mechanical engineering with first-class honor. Currently, he is taking a master's degree in mechanical engineering at King Fahd University of Petroleum and Minerals (KFUPM) specialized in thermal sciences.

Abdulrahman Almoghamisi graduated from Taibah University in 2020 with a bachelor's degree in mechanical engineering. Currently, he is working as a mechanical engineer at the Engineering Department at M.M.Alharbi & Partners Co. Ltd.