Investigating the Effects of Solar Tracking Systems on Thermal Profile of Photovoltaic Modules

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Abstract- The world tends to rely more on solar photovoltaic energy as a reliable and affordable source of clean energy. The temperature of solar cells is one of the main factors affecting the efficiency of PV modules. The experimental study investigated the effects of solar tracking systems (STS) on their thermal profile under real-world harsh environmental conditions in Dammam city, Saudi Arabia, on a sunny day for different configurations of STS such as fixed-tilt PV module (FTPV), single-axis solar tracking system (SAST), and dual-axis solar tracking system (DAST), simultaneously. The experimental results proved that various STS have a noticeable effect on the temperature of PV modules. Differences in back-surfaces temperature between SAST and DAST compared to FTPV were recorded as 3.77% and 4.57%, respectively, while peak temperature differences of about 4.13 °C and 4.5 °C, respectively. In addition, differences in front-surfaces temperature of 2.59 °C and 5.1 °C were recorded between SAST and DAST compared to FTPV, respectively. Although the temperature profiles of the front-surfaces and back-surfaces of PV modules differed, both systems depicted similar thermal profiles. It was observed that during the solar noontime, the temperature differences were not significant, while differences in temperature profiles raised again toward the end of the day. The effect of wind speed on the temperature profiles of PV modules based on the STS was also investigated. The presented work contributes to the body of knowledge by providing insight into the effects of STS under real environmental conditions on the thermal performance of PV modules.

Keywords Thermal analysis; Solar tracking; Single-axis; Dual-axis; Photovoltaic; Wind; Renewable Energy.

1. Introduction

As the world's awareness of the drawbacks of high fossil fuel consumption increases, different sources of renewable energy offer sustainable and more effective solutions to compensate for current challenges with fossil fuel-based power generator systems [1-8]. One of the most dependable renewable energy sources is solar photovoltaic (PV) energy, especially since the prices have shown a considerable drop, while overall performance has improved during the past two decades [8-10]. One of the main factors that influenced the PV modules prices to drop is the increase in efficiency [11-12], while many other kinds of weather and installation-related factors affect a PV module's efficiency, such as irradiance, tilt angle, weather conditions, and cell's temperature [13-14]. Therefore, in order to enhance the efficiency of a PV module, each of these factors has to be studied. One approach to enhance PV modules' efficiency is by using PV solar tracking systems (PVST), these systems have multiple types based on many different elements like the system's degree of freedom, control scheme, and driving technique [15]. Although photovoltaic solar tracking systems are widely used nowadays, there are minimum studies regarding how tracing the sun affects the PV modules' temperature, one of the key factors in terms of the PV modules' efficiency.

One of the main reasons PV systems are popular nowadays is the massive drop in manufacturing prices for the past two decades. This price reduction is owed to many factors, which can be classified into two main categories according to a study highlighted by Kavlak, et al. [12]. Also, the study showed that the main changes in the prices of PV modules were made from 1980-2012. These categories are divided into high-level and low-level causes. High-level cases, such as research and development (R&D), learning-by-doing, and economies of scale, had the most contribution to the prices drop, where R&D, learning-by-doing, economies of scale, and other causes contributed about 60%, 7%, 22%, and 11% respectively [11]. Similarly, low-level causes like efficiency, non-silicon material cost, silicon prices, silicon usage, wafer area, plant size, and other causes contributed by 23%, 21%, 16%, 14%, 11%, 11%, and 3%, respectively [11]. According to this study, the leading low-level cause for the cost drop is the increase in efficiency of PV modules; thus, improving the efficiency of PV modules is crucial, where it was stated that an increase in efficiency causes an equivalent decrease in cost [11].

PVST increases the efficiency of a PV system by detecting the sunrays and reorienting the modules, accordingly, leading to an increase in the output power [16-18]. There are two main types of STS: SAST and DAST, where each has its pros and cons [15,18-23]. For instance, although DAST is expected to collect more energy, it consumes more energy to trace the sun rays due to the additional actuation and control systems; therefore, it causes an increase in the initial and maintenance costs [23]. Even though STS might increase the energy yield up to 56%, as the previous studies concluded [15], it might sometimes burden the system for several reasons, such as the weather conditions [24]. Juliano da Rocha, et al. [25] studied the effect of different weather conditions on a DAST's energy, the results showed a net gain of 63.22%, 28.99%, and -19.47% in sunny, cloudy, and rainy weather conditions, respectively. In addition, Eldin, et al. [26] studied the effect of both cold and hot climates on an STS and noted a 39% increase in net energy of a PV system in a cold region. In comparison, the increase in net energy of a PV system in a hot region was about 8%. Another factor that has a significant effect on the efficiency of PV modules is the PV cell's temperature since the increase in temperature reduces the efficiency of the module, as mentioned by Siddiqui and Arif [27-28]. The bandgap for the solar cells decreases as the temperature rise; this reduction leads to a noticeable drop in the solar cells' open-circuit voltage (V_{oc}) and a minor increase in the short circuit current (I_{sc}). Since the voltage drop outstands the rise in current, the power output of the PV cells reduces according to Ohm's low (P= IV) as the temperature increase [29-31]. In addition, high temperature increases PV modules degrading rate, as mentioned by AlAmri, et al. [32]. Therefore, while studying the temperature effects on PV modules, ambient temperature and modules' temperature must be further investigated.

Al Hanai, et al. [33] explored the effect of different parameters on the efficiency of a 900 W thin-film module; one parameter is the ambient temperature, where it was recorded that VOC drops by 2.01V/°C and ISC decreases by 0.0413 A/°C when normalized via STC ratings. The study also concluded that the drop in current is due to the Staebler-Wronski effect (a chemical reaction reducing light to electricity conversion efficiency due to the increase in recombination current) and dust accumulation. In another study by Hammad, et al. [34], it is stated that the rise in ambient temperature led to a reduction in power and efficiency by 0.5%/°C and 0.05%/°C, respectively. In addition, Piliougine, et al. [35] explored the effect of a PV cell's temperature on VOC, ISC, and power. The outcome showed that the increase in the module temperature results in a significant decrease in the VOC and a slight increase in ISC; as a result, the power of the system drops in a range of 206 to 144 mW/°C. Baloch, et al. [36] studied the effect of "converging channel cooling" on PV modules. The study outcomes demonstrated how the PV module's temperature could vastly affect a PV module's power output, where a comparison between the monthly power output of cleaned and uncleaned PV modules was made. The comparison showed that the cleaned PV modules have higher power output each month of the year, especially during the spring season.

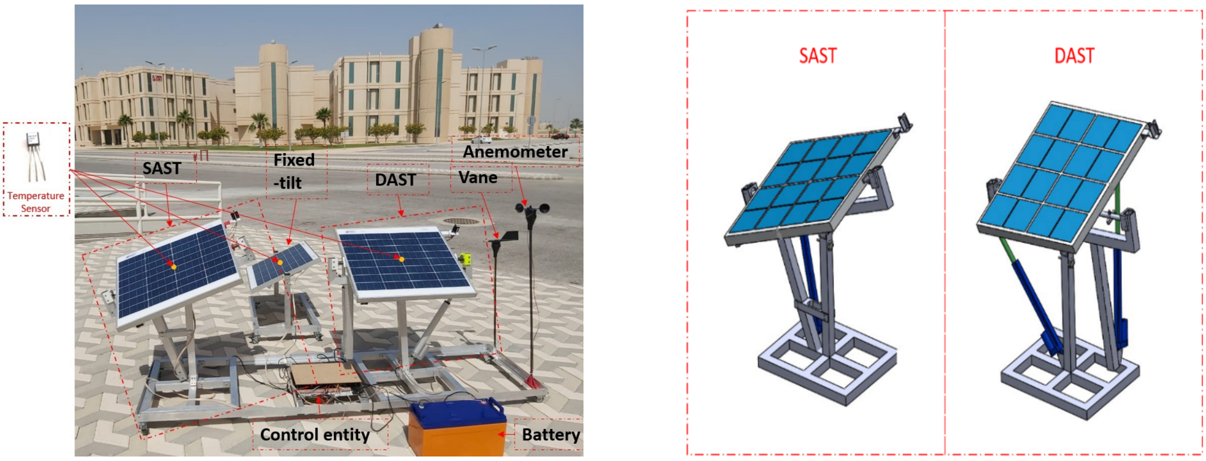
Wind speed and humidity play a significant role in the temperature of a PV module. Wind speed has an inverse relation with the modules' temperature since wind helps distribute the heat on PV modules' surface and increases the heat transfer between the modules and the ambient temperature [34, 37-38]. Kaushik, et al [30] has studied the relation between wind speed, ambient temperature, and modules' temperature, and the result demonstrated that wind speed has an inverse relationship with the modules' temperature. In contrast, the ambient temperature has a direct relation with the modules' temperature. Similarly, relative humidity directly relates to the temperature of PV modules since it affects the heat transfer negatively by reducing the thermal conductivity of the air [29, 39].

The kingdom of Saudi Arabia has set a goal to install 57 GW worth of renewable energy by the year 2032, which would represent 30% of the total energy generation of the kingdom, where 41 GW worth of renewable energy would be extracted from solar PV farms [40]. Dammam is a major industrial city with a promising future for solar energy, according to a study made by Awan, et al. [41] on 44 different regions in the kingdom to measure the global horizontal irradiance (GHI). Dammam city has an average daily GHI of about 5.89 kWh/m2, proving the city's high potential in the solar industry. In spite of the fact that some studies in the kingdom of Saudi Arabia are conducted to examine the effect of temperature on PV modules such as [42], minimum studies locally and internationally have investigated the impact of PVST on the temperature of PV modules. Since it is common knowledge that an increase in temperature reduces the operational performance of PV modules, this study aims to investigate the temperature variance of PV modules caused by STS accompanied by the wind velocity effect. It is important to accurately estimate the energy of PV modules [43]. The importance of the study is to facilitate better evaluation for STS energy analytics, which provides the chance for better financial analysis, therefore, better feasibility studies. In addition, the study opens the door for further studies regarding the STS effect over PV modules' temperatures at different weather conditions. The objective is to ascertain the suitability of relevant tracking systems by comparing their thermal performance in comparison to operational losses.

2. Methodology

2.1. Mechanical design

This experiment has three systems: FTPV, SAST, and DAST. A computer-aided design (CAD) is primarily made for each system structure in order to ensure the flexibility of the trackers' design. After that, the mechanical design went through many optimization processes to increase its strength and stability. The complete model is assembled at the mechanical workshop at Imam Abdulrahman bin Faisal University (IAU) and shown in Fig. 1.



(a) (b)

Fig. 1. (a) Fixed-tilt, SAST, and DAST Models: (b) SAST and DAST CAD Model

2.2. Electrical setup

After finishing the mechanical setup, an electrical setup was established for the system to operate. Linear actuators were added to each system to provide the necessary movements, where they are controlled according to control signals received from an embedded controller (Arduino Mega). Light-dependent resistors (LDRs) were used and compared to determine the location with the highest light intensity. Different sensors are used with the aim of measuring multiple parameters (i.e.: temperature, wind speed, wind direction, light intensity, and humidity), where all the data from the sensors is saved at an SD card using an SD card adaptor connected to the embedded controller as shown in Fig. 2. Linear actuators, sensors, and the control unit were powered via a 12 V battery. All sensors are singularly calibrated to ensure the proper acquisition of data and best performance.

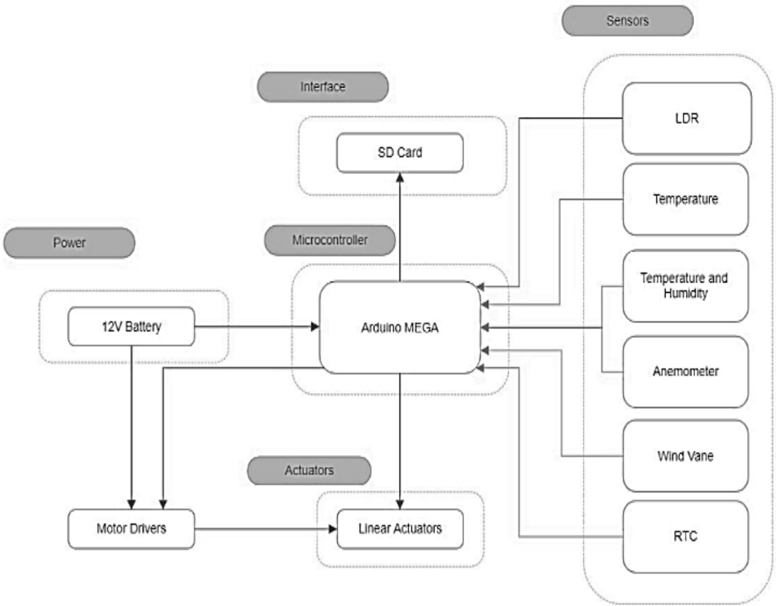


Fig. 2. Electrical Block Diagram

2.3. *Control scheme*

A PID controller was implemented to manipulate both the SAST and the DAST modules' direction and movement speed to minimize power consumption used by the actuators.

Fig. 3. shows a block diagram of the developed feedback-controlled system. To ensure the accuracy of the trackers and prevent overshooting and unnecessary power consumption, an anti-windup mechanism was used for the controller's integral term, limiting the integral factor's accumulation over long periods on which the system is unable to move. In addition, the maximum output signal from the PID controller is determined along with a threshold to prevent damaging behavior. In addition, it was avoiding an output command via the PID that might be too high that it damages the actuators or too low that it does not provide sufficient power to activate the actuators.

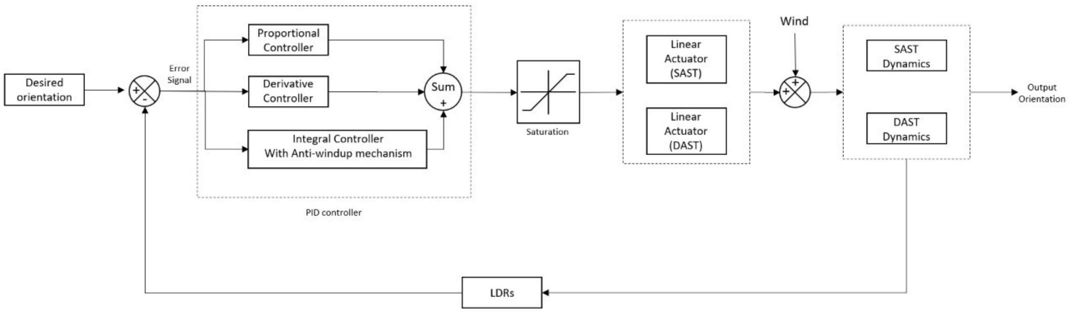


Fig. 3. Block Diagram for SAST and DAST Controllers

The feedback signals given to the PID controller are from the LDRs' values, upon which the micro-controller (Arduino Mega) commands the actuators to reorient the PV modules to the direction with the highest light intensity accordingly. An experiment was made in order to determine the error margin; as a result, the error margin was found to be 0.35°. Fig. 4. demonstrates how the PID controller function on different STS.

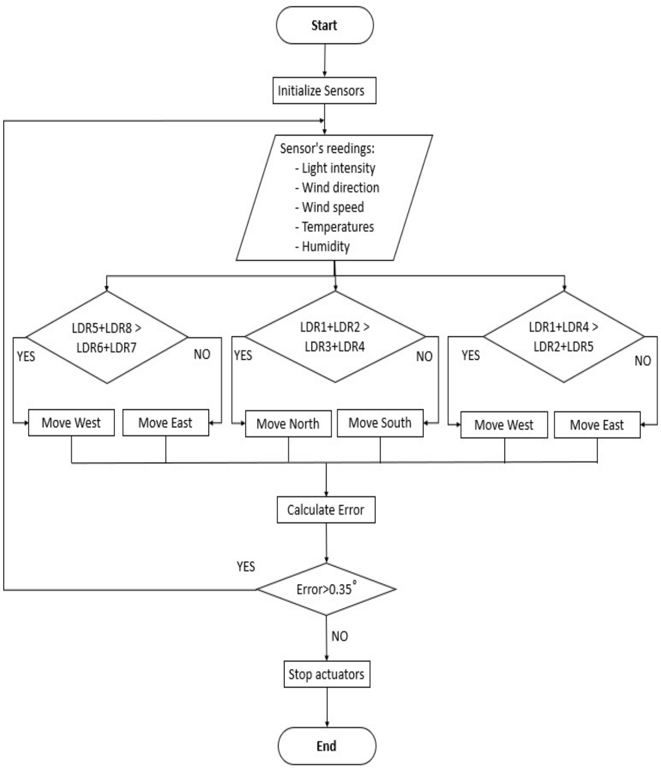


Fig. 4. PID Process Flowchart

2.4. Experimental setup

The experiment was conducted on June 10, 2021, on a sunny day with a relative humidity of about 17% throughout the day. The investigation took place at IAU in Dammam city (latitude (φ): 26.4°). All three systems were tested at the same time, aiming to increase the accuracy of the comparison. Both FTPV and SAST were fixed toward the south (since Saudi Arabia is located in the northern hemisphere) at the yearly optimum tilt angle ($\beta_{OY} = 23°$) according to equation 1 [44].

$$\beta_{OY} = \varphi * 0.76 + 3.1 \qquad (1)$$

Where β_{OY} is the yearly optimum tilt angle, and φ is the latitude, where the relation is applicable if φ is between 25 and 50. Three 50 W PV modules were used to perform the experiment. Fig. 5. shows the PV modules' specifications (where P_m is the maximum power, I_m is the maximum power point current, and V_m is the maximum power point voltage).

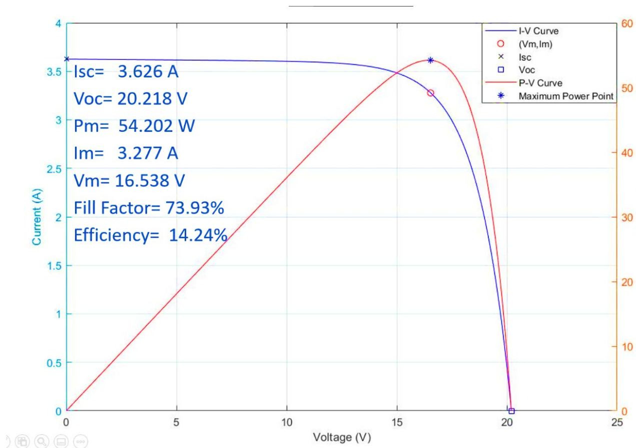


Fig. 5. PV modules specifications, IV and PV curve

The main focus of this paper is to study the temperature behavior for different PV tracking systems, where three methods were used to determine the temperature of the modules. The first method is by mounting a temperature sensor (LM35) on the back-surface of each module. The output data from the temperature sensor is recorded with a frequency of 29 Hz. The second method uses an infrared thermometer and a thermal imaging camera, where the second method is used to record the front-surface temperature of the PV modules each hour. Table 1 shows all the different measuring instruments used for recording the temperature of the PV modules.

Table 1. Different Temperature Measuring Instruments.

Instrument	Model #	Thermal sensitivity
Thermal Imaging Camera	HT02	0.15 °C
Infrared Thermometer	GM550	1.5 °C
Temperature Sensor	LM35	0.5 °C

3. Results and Discussion

The experiment was implemented by exposing the different STS along with a FTPV simultaneously to the sun rays in order to accurately measure the effects of STS on the temperature of a PV module since the STS receive more sun radiation due to the fact that they are perpendicular to sun rays it is to be predicted that STS modules would have a higher temperature than the FTPV.

3.1. Back-surface temperature.

The study has shown an expected outcome, where SAST and DAST PV modules underwent an increase in temperature

compared to the FTPV, and all modules have greater temperature than the ambient, as shown in Fig. 6. Although many factors affect the temperature of the PV modules, the temperatures increase of STS modules compared to the FTPV is mainly owed to the rise in solar irradiance received from the sun due to tracing the sunrays since all modules were tested simultaneously in the exact location.

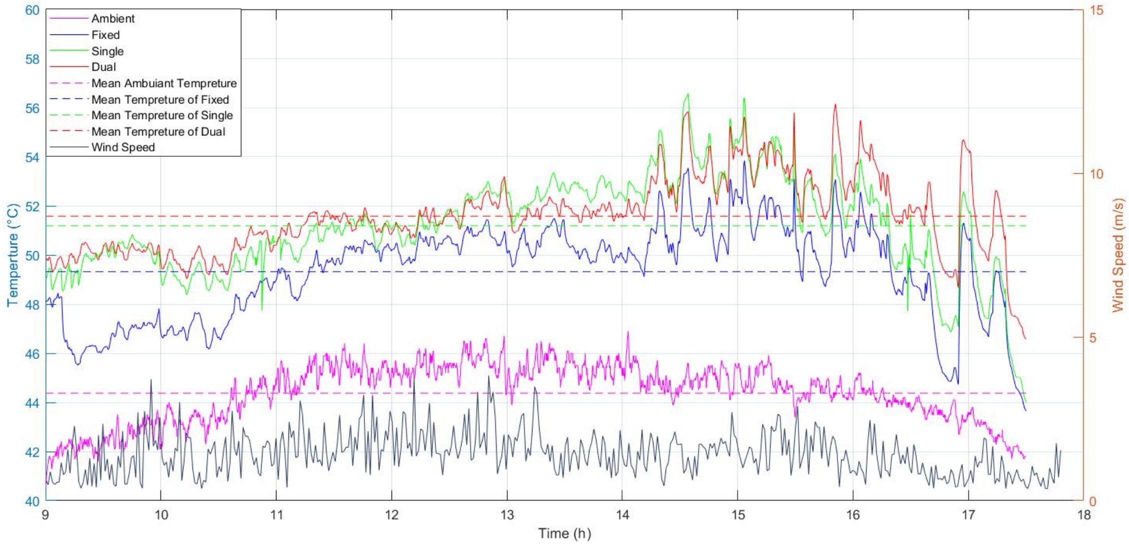


Fig. 6. Fixe-Tilt, SAST, and DAST PV Modules' Back-Surface Temperature.

Table 2. represents various statistical information for the different systems. The table shows that the maximum, minimum, mean, and median temperature of the STS modules is higher than the FTPV, which supports the claim that the increase in temperature is mainly owed to the photovoltaic solar tracking systems.

Table 2. Statistical Information for Fixed-tilt, SAST, and DAST Modules.

Statistical Parameter	System	Value (°C)	Statistical Parameter	System	Value (°C)
Maximum	Dual	56.1593	Median	Dual	51.5623
	Single	56.5778		Single	51.2083
	Fixed	53.8419		Fixed	49.8717
Minimum	Dual	46.5728	Range	Dual	9.5864
	Single	43.9961		Single	12.5817
	Fixed	43.6524		Fixed	10.1895
Mean	Dual	51.5864	Standard Deviation	Dual	1.5582
	Single	51.1935		Single	1.9888
	Fixed	49.3317		Fixed	1.9243

The maximum increase in temperature for the STS modules in respect to the FTPV was recorded at the beginning and end of the day due to the high solar irradiance difference between STS and FTPV. The maximum temperature difference between the FTPV and the SAST PV modules is 4.13 °C, and between the FTPV and the DAST PV module is 4.5 °C. On the other hand, the minimum difference was approximately recorded at the solar noon, as Fig. **7**. demonstrates. The mean differences in temperatures between SAST, DAST modules, and FTPV are 1.86 °C and 2.25 °C, respectively, which accommodate an increase in mean temperature by 3.77% and 4.57% increase with respect to FTPV. As for the mean difference between DAST and SAST PV modules' back-surface temperature was measured to be 0.39°C. This accommodated to 0.77% increase in DAST with respect to SAST, which shows that the difference between the SAST and DAST back-surface temperature is minimal due to its insignificance. It can be concluded via Fig. **7**. that the thermal losses due to the increase in temperature are higher in STS since the rise in temperature causes a drop in PV modules' efficiency.

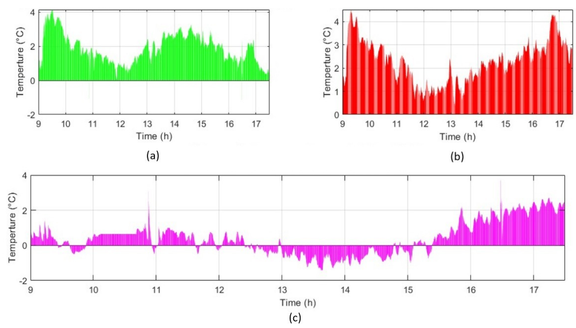


Fig. 7. Differences in Back-Surface Modules' Temperatures for (a) SAST and fixes-tilt, (b) DAST and fixed-tilt, and (c) DAST and SAST.

3.2. Efficiency Drop

The efficiency of a PV module is affected by the change in cell's temperature, as Hammad, et al. mentioned [23], efficiency drops by 0.05%/°C, when the efficiency drop was measured for the modules used in this study a noticeable drop occurs, as represented in Fig. 8. The mean reductions in efficiency for each FTPV, SAST, and DAST module are 1.22%, 1.31%, and 1.33%, respectively. The drop in efficiency leads to a significant effect on the power production of each module, where according to Hammad, et al [23], the power drop coefficient is 0.5%/°C, which is ten times greater than the efficiency drop coefficient. Although the drop in efficiency of both STS modules is higher than the FTPV, usually the energy generated by STS exceeds the potential losses in the module's efficiency due to the continuous tracking of the solar radiation.

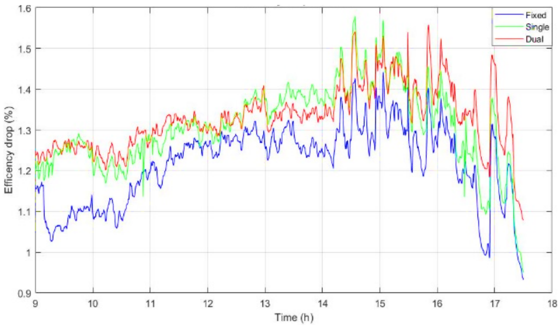


Fig. 8. Efficiency Drop Due to The Temperature Increase.

3.3. Front-surface temperature.

As for the front-surface temperature for the different PV modules, a thermal imaging camera along with an IR thermometer were used to measure the temperatures of the various PV modules at different times of the day. As Fig. 9. shows the temperature of the PV modules' front-surface is different from the PV modules' back-surface throughout the day, although the temperature profile for both surfaces is similar and expected. The mean temperature difference between the FTPV and the SAST PV module was recorded as 2.56°C, which accommodates a 4.76% increase in SAST front-surface temperature compared to the FTPV according to equation 2. In addition, the mean temperature difference between the FTPV and the DAST PV module was recorded as 5.1°C, which accommodates a 9.71% increase in DAST front-surface temperature compared to the FTPV according to equation 3. Also, the mean temperature difference between the SAST PV module and the DAST PV module was recorded as 2.6°C, which accommodates a 4.72% increase in DAST front-surface temperature compared to the SAST according to equation 4. Temperature increase calculations (%):

$$TSF = \frac{TS - TF}{TF} \quad (2)$$

$$TDF = \frac{TD - TF}{TF} \quad (3)$$

$$TDS = \frac{TD - TS}{TS} \quad (4)$$

Where, TSF is the increase in SAST module temperature in comparison to FTPV, TS is the SAST module temperature, TF is the FTPV temperature, TDF is the increase in DAST module temperature in comparison to FTPV, TD is the DAST module temperature, and TDS is the increase in DAST module temperature in comparison to SAST module temperature.

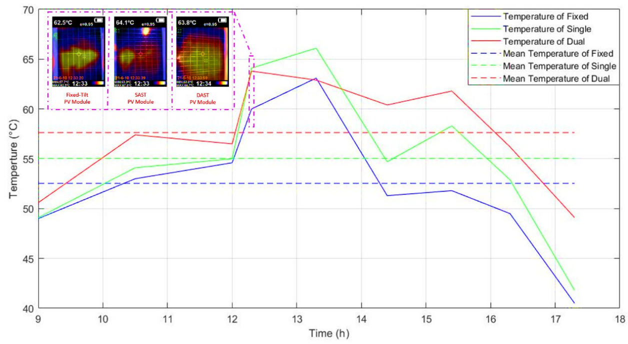


Fig. 9. Fixe-Tilt, SAST, and DAST PV Modules' Front-Surface Temperature.

3.4. Effect of Wind and ambient temperature.

Some important factors affecting the temperature of the PV modules are wind and ambient temperature. Fig. 6 shows the ambient temperature in addition to the wind speed with the different PV modules' temperatures throughout the day. In this study, the wind data were collected and shown in Fig. 10. The trend for the temperature of the different systems and the ambient temperature is similar from the beginning of the day until the afternoon; after that, the trend of the temperature of the modules differs from the ambient temperature. The change in the trend of the PV modules temperatures can be related to the change in the wind speed and direction. After the solar noon, a noticeable drop in the wind speed accrued, which was one of the causes of the change in the temperature behavior for the different PV modules. Therefore, there is an inverse relationship between the wind speed and the modules' temperature as expected. It is noted that the wind has a different effect on the PV modules used due to the different orientations of each module.

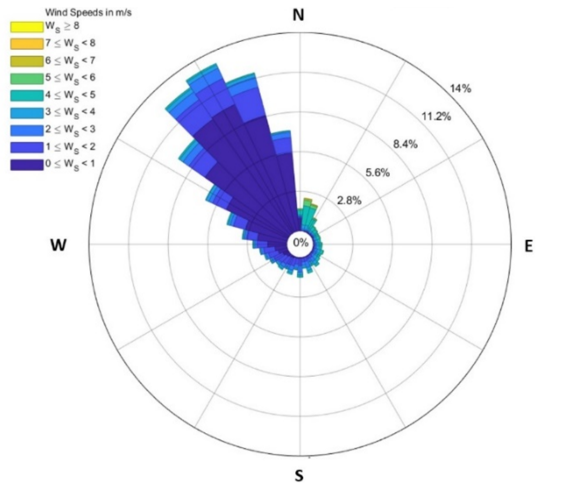


Fig. 10. Wind Rose for Dammam City on June 10, 2021.

4. Conclusion

An experimental study detailing the effect of different photovoltaic solar tracking systems on the temperature profile of PV modules was conducted. The results of the various types of solar tracking systems were compared to the FTPV. Furthermore, the effects of ambient temperature and wind speed were also investigated. The following conclusions can be drawn from the presented research work:

- STS modules have a higher temperature than the FTPV. Therefore, although the energy generation of the PV STS used increased, the temperature increased as well, which led to a drop in PV modules' efficiency by approximately 0.05%/°C. This drop in efficiency causes more energy losses that are dissipated in the form of heat, increasing the PV modules' degradation rate. In this regard, the drop in efficiency due to the increase in the modules' temperature of the SAST and DAST was very close, which demonstrates that the effect of the modules' temperature on STS is almost the same. Furthermore, the energy increase due to STS can compensate for the potential thermal losses. With that said, so as to determine the most suitable solar system many other factors (such as financial analysis and PV modules degradation rate) should be investigated.

- The temperature profile for both the PV module's back-surface and front-surface is similar and correlates with the ambient temperature profile until afternoon. Afterward, the temperature profile of the PV modules changes, which can be related to the increase in wind velocity and shows that the relation between wind speed and the temperature of STS PV modules is an inverse relation.

- The experimental study conducted highlights the effect of STS on the temperature profile. Furthermore, it connected it to the efficiency of the PV modules, contributing to enhancing further analytics and feasibility studies for STS for future STS applications.

The objective of this section is to highlight to the readers various avenues of further research and development. Since the Kingdom of Saudi Arabia aims to be a leader in the renewable energy section as stipulated in the 2030 Vision of the government, significant investment and infrastructure development are being conducted in KSA regarding the renewable energy sector. The presented experimental work aims to be a pioneering work for assessing the suitability of relevant types of solar tracking systems for implementation in the renewable energy market. Other researchers and engineers can utilize the data presented in the manuscript to develop further and test tracking systems that can be adopted for harsh desert environments. As with any experimental pioneering research work, further studies must be conducted to study the effect of STS under varying climatic conditions and longer duration in various regions of the kingdom. It is also recommended to study the impact of cooling coupled with STS in order to demonstrate how cooling can change the thermal profile and the output power of different STS. These areas can be treated as avenues of further research and development.

Abbreviations:

P_m	=	Maximum power point
I_m	=	Maximum power point current
V_m	=	Maximum power point voltage
STS	=	Solar tracking systems
FTPV	=	Fixed-tilit PV modules
SAST	=	Single-axis solar tracking system
DAST	=	Dual-axis solar tracking system
V_{OC}	=	Open Circuit Voltage
I_{SC}	=	Short Circuit Current
LDR	=	Light-dependent Resistors

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