Original Article

Investigation the performance of PV solar cells in extremely hot environments

Mohamed K. Hassan[1,2] · Ibrahim M. Alqurashi[1] · Ahmed E. Salama[3] · Ahmed F. Mohamed[1,4]

Received: 1 August 2022 / Accepted: 6 September 2022
Published online: 19 September 2022

Abstract

Manufacturers typically define photovoltaic (PV) modules under conventional test settings of 1000 W/m^2 at 25 °C, which may not be possible anywhere in the globe, because high ambient temperature is one of the most critical factors affecting photovoltaic solar cell efficiency. In this study, we will investigate the ambient temperature as well as the open circuit voltage, output power, short circuit current, and efficiency in hot regions such as Mecca (Makkah). It also discusses the correlations between PV efficiency, solar radiation, and ambient temperature. On the other hand, the addition of a layer of copper sulphate at a concentration of 1% is investigated. The use of a copper sulphate layer enhanced the PV characteristic in cases where the PV cell temperature was reduced by around (0.3–34.6 °C), while also increasing the open circuit voltage, output power, efficiency, and fill factor.

Keywords Photovoltaic (PV) · Solar radiation · Ambient temperature · Efficiency (η) · Fill factor (FF)

1 Introduction

The most important renewable energy source is solar power. Solar energy harvesting systems, such as rooftop water heating pipes, solar cells, and mirrors, are constantly improving and their efficiency grows with the advancement of technology [1].

Photovoltaic electricity from the sun it is a non-modern technology that is regarded the most effective and is the most widely utilized in solar energy technologies [2]. Solar photovoltaic energy is based on the use of sunlight without the use of heat. In the creation of energy, heat is a negative factor. The lesser the manufacturing efficiency, the higher the temperature of the unit. The ideal temperature for solar PV panel electricity production is 25 °C [3], while in some circumstances; high intensity radiation with a high degree affects the PV panel's efficiency [4]. Photovoltaic solar panels consist of many solar cells; these cells are made of semiconductors such as silicon, and are designed in two layers, a positive layer and a negative layer, which is what is known as the electric field [5].

The waves that are emitted by the sun stimulate the cell to make energy. When sunlight penetrates the solar cell, it generates a negative and positive voltage inside the p–n junction. Positive electrons travel to the top surface, while negative electrons travel to the lower surface. The two surfaces are connected to a battery to produce energy by drawing negative electrons. Photovoltaic cells are a promising technology and one of the most important alternative energy sources [6]. The major challenge for PV cell producers is the high

✉ Mohamed K. Hassan, mkibrahiem@uqu.edu.sa | [1]Mechanical Engineering Department, College of Engineering and Islamic Architecture, Umm Al-Qura University, Mecca, Saudi Arabia. [2]Production Engineering and Design Department, Faculty of Engineering, Minia University, El Minya 61111, Egypt. [3]Department of Mechanical Engineering, Faculty of Industrial Education, Sohag University, Sohâg, Egypt. [4]Mechanical Engineering Department, Faculty of Engineering, Sohag University, Sohâg, Egypt.

temperature [7]. The Kingdom of Saudi Arabia is a hotbed of solar installations and is one of the renewable energy objectives outlined in Vision 2030 [8].

The top conduction layer, the absorbent layer, and the rear layer are the three primary layers in a solar cell. The cell also has two positive and negative electrical layers. The electrical contact layer (positive), also known as p-type [9]. This layer is located on the cell's face and is made up of a slice taken from silicon monocrystals with some impurities added to it, and the background electrical contact layer (negative), which is made up of pure silicon with some impurities added to it, and both layers work together to transfer electrical current to and from the cell (Fig. 1).

There are three main common types of solar cells available in the market. Monocrystalline solar cells consist of a large mass of silicon and are produced in the form of a chip. Polycrystalline solar cells are made by melting multiple silicon crystals together, then re-merging them into one panel [11]. Polycrystalline solar cells are made by cutting silicon wafers for the ability to be attached to the solar panel [10]. Polycrystalline solar cells are made by melting multiple silicon crystals together, then re-merging them into one panel. The maximum current that can be delivered from the cell's edges is measured by shorting the cell's terminals at maximum output [12], and the current output in the solar cell is dependent on the intensity of the light coming from the sun or another source, as well as the angle at which the light is projected. When there is no load in the cell at the time of measurement, the voltage can be measured across the ends of the cell, and the voltage changes from one cell to the next due to differing manufacturing procedures and temperatures. The highest limit of the electrical energy output (P_m) to the radiative energy input can be described as the efficiency of a solar cell (P_{in}) [13]. The efficiency of a system is measured in terms of its impact on the environment [14]. PV module manufacturers use standard test conditions to measure three primary components: cell temperature, radiation, and air mass. These circumstances vary and mostly affect the power output of the modules [15].

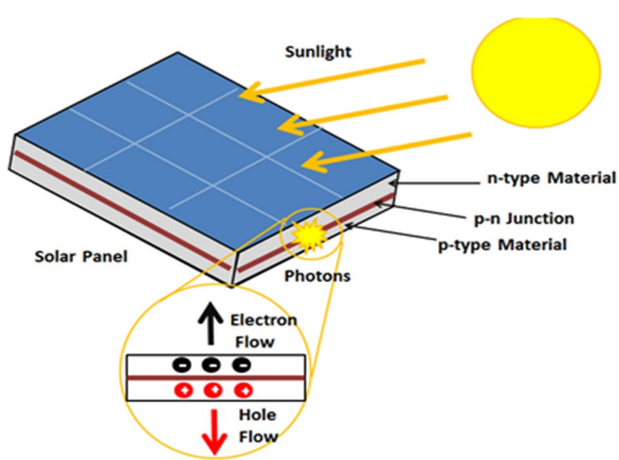

Fig. 1 Solar cell compound

As a result, this work provides a study to improve the efficiency of solar cells by describing the capacity of the cell during the cell cycle and recording the cell's characterization, and then studying ways to improve this performance by adding a layer of copper sulfate that absorbs the sun's heat and allows only sunlight to pass through the cell.

2 Experimental work

2.1 Investigation methodology

To achieve the purpose of this work, a study was conducted the characteristics of the PV under the different climate conditions at site Mecca (Makkah). The PV panel was installed and oriented to the south at a 21.5° angle to match the site direction of Mecca (Makkah) City, producing the most power. The experiments carried out on the Solar Energy Lab., Mechanical Engineering Department. On several days in June, from 7:00 a.m. to 18:00 p.m., measurements of the ambient temperature, sun intensity, and relative humidity are taken and recorded every hour to track the variation throughout the day. The various measurements are then recorded in the manner prescribed. The output power calculated [7], where

$$P = I \times V.$$

The PV efficiency is determined as following:

$$\eta = \left[\frac{P_{out}}{P_{in} \times A}\right] \times 100.$$

Also, the PV fill factor is determined using following equation:

$$FF = \left[\frac{(I \times V)}{\left(V_{os} \times I_{sc}\right)}\right] \times 100,$$

Where P_{out}: PV output power per (W), I: PV output current per unit ampere (A), V: PV output voltage per unit volt (V), P_{in}: Light input power (solar radiation) per unit (W/m^2), A: Solar cell area (m^2), V_{oc}: PV open circuit voltage per unit volt (V), I_{sc}: PV short circuit current per unit ampere (A) (Fig. 2).

Fig. 2 PV panel

2.2 Materials

This investigation makes use of the following materials: 10 W resistance, wire connections, copper sulphate powder from SPECIALITY CHEMICALS CO "$CuSO_4 \cdot 5H_2O$—M.W 249.68, Assay—not less than 99% maximum contaminant levels iron (Fe)—0.1%, chloride (Cl) —0.005%, a plastic layer of size: 365 × 275 mm and thickness of 0.1 mm, distiller water, some rubber in various thicknesses (5, 10, 20 mm), and GP silicone acetic.

2.3 Measurements

The suggested PV's output voltage and current were measured with a digital multimeter (KEW 1011) with the following accuracy: 0.5% in volts and 1.2% in current. While the ambient temperature and relative humidity are monitored using a "Temperature/Humidity Meter (TM-183) with accuracy: + %C in temperature." All temperature measurements were carried out on panel surface.

The Meteon Irradiance Meter Type (060501) "Sensor CM4" with an operational temperature range of – 40 °C to + 150 °C and measurement up to 4000 W/m^2 is used to measure solar radiation.

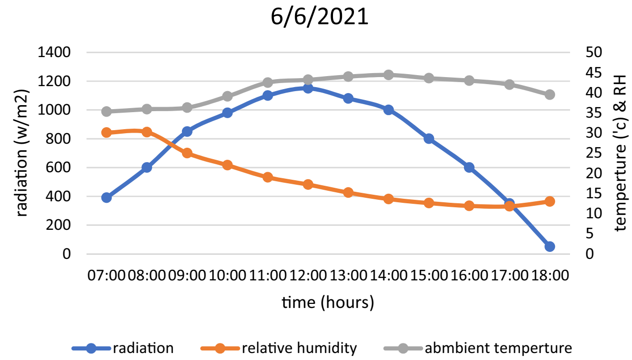

Fig. 3 Variation of ambient temperature, solar radiation and relative humidity during the day (9 June 2021)

3 Results and discussion

Many experiments have been carried out to investigate the characteristics of the PV cell in various weather circumstances such as ambient temperature, solar radiation, and relative humidity. In addition, the performance of the PV is improved employing substrate materials such as copper sulphate solution (CSS) at concentrations (1%) with and without a plastic layer. Furthermore, the upper surface of the PV is covered by a plastic layer without CSS, with the height from the upper surface changing from 0 to 5 mm, 10 mm, and 20 mm. The results presented here study the properties of the PV under various weather circumstances such as ambient temperature, solar radiation, and relative humidity. The results also indicate the performance of the PV employing various plastic layer and copper sulphate solution materials.

3.1 Effect of weather conditions during the daytime

The following results are acquired under various weather circumstances, including solar radiation, ambient temperature, and relative humidity, on the PV's behaviour. Figures 3, 4, 5, 6, 7 and 8 depict the change in solar radiation, ambient temperature, and relative humidity over time. On June 6, 9, 11, 15, 19, and 20, 2021. It is observed from the behaviour of solar radiation on different days that solar radiation has a low value at first and then steadily grows until it reaches its maximum value about 12:00 pm. These numbers also demonstrate that solar radiation has a value greater than 1000 W/m^2 between 9:00 a.m. and 14:00 p.m., and a value greater than 800 W/m^2 between 8:00 a.m. and 15:00 p.m., after which it gradually drops (Table 1).

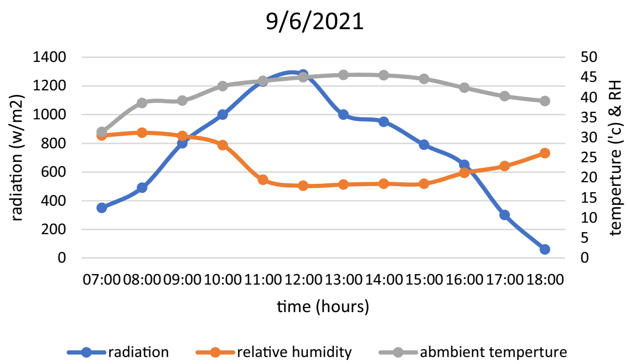

Fig. 4 Variation of ambient temperature, solar radiation and relative humidity during the day (9 June 2021)

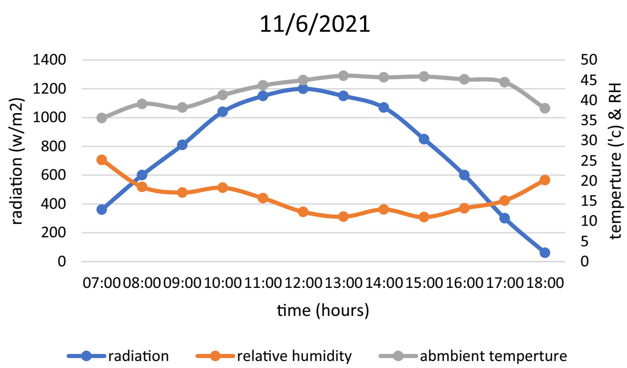

Fig. 5 Variation of ambient temperature, solar radiation and relative humidity during the day (11 June 2021)

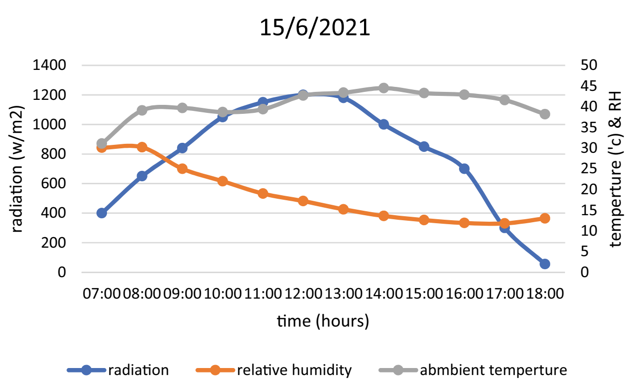

Fig. 6 Variation of ambient temperature, solar radiation and relative humidity during the day (15 June 2021)

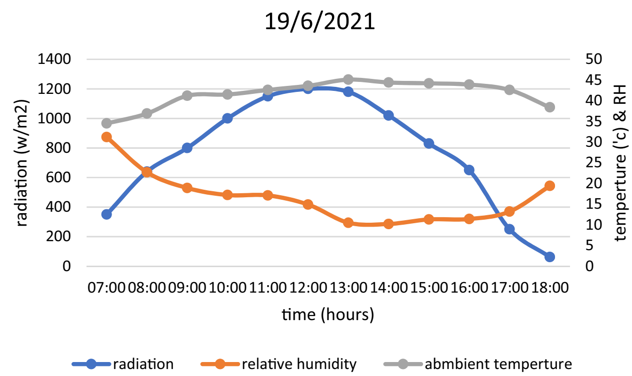

Fig. 7 Variation of ambient temperature, solar radiation and relative humidity during the day (19 June 2021)

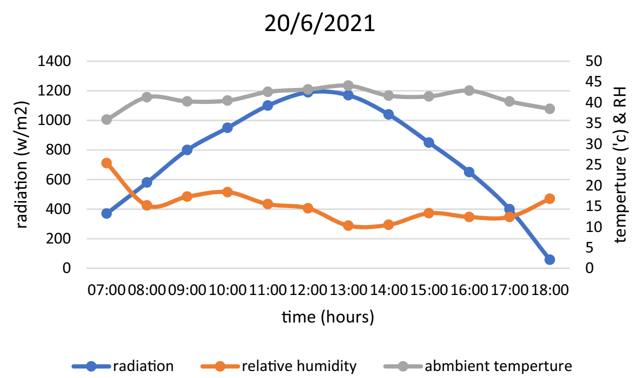

Fig. 8 Variation of ambient temperature, solar radiation and relative humidity during the day (20 June 2021)

3.2 Effect of air gap on the performance of photovoltaic

Two identical PV panels are employed, with one PV covered by a plastic layer on the upper surface at a spacing ranging from 5.10 to 20 mm. Figure 9 depicts the output power of two PVs without and with a 5 mm air gap during the daytime hours of 20 June 2021. This graph shows that the PV output power without surpassing (0.015–7.066 W) was 6.747 W at 12:00 pm. Figure 10 depicts solar radiation and efficiency of two PV without and with a 5 mm air gap, while Fig. 11 depicts ambient temperature, relative humidity, and efficiency of two PV without and with a 5 mm air gap during the day.

Figure 12 depicts the output power of two PV without and with a 10 mm air gap during the daytime hours of June 19, 2021. We can see from this graph that the PV output power without reaching (0.016–7.169 W) was 6.751 W at 12:00 pm. Whereas Fig. 13 depicts solar radiation and the PV efficiency of two PV without and with a 10 mm air gap, Fig. 14 depicts ambient temperature, relative humidity, and the PV efficiency of two PV without and with a 10 mm air gap during the day.

Figure 15 depicts the output power of two PVs without and with a 20 mm air gap during the day on June 15, 2021. This figure shows that the PV output power was 7.22 W at 12:00 pm till it reached (0.018–7.37 W). Figure 16 depicts solar radiation and efficiency of two PV

Table 1 Values of ambient temperature, solar radiation and relative humidity

Day		Min	Max	At 12:00 PM	Maximum values
06/06/21	Ambient temperature °C	35.6	47.1	46.9	8:30–17:30 > 35
	Solar radiation, W/m^2	51	1190	1190	10:00–14:00 > 1000
	Relative humidity %	8.1	32	13.5	11:00–18:00 < 20%
09/06/21	Ambient temperature °C	33.2	43.1	43.3	7:30–17:30 > 35
	Solar radiation, W/m^2	60	1180	1180	10:00–14:00 > 1000
	Relative humidity %	15.1	39	17	10:30–16:00 < 20%
11/06/21	Ambient temperature °C	33.8	44.2	43.1	7:30–18:00 > 35
	Solar radiation, W/m^2	60	1175	1175	10:00–14:00 > 1000
	Relative humidity %	10.2	25.5	12.1	8:00–18:00 < 20%
15/06/21	Ambient temperature °C	30.2	46.1	45.3	9:00–18:00 > 35
	Solar radiation, W/m^2	75	1240	1240	9:30–14:30 > 1000
	Relative humidity %	10.9	38.1	16	12:00–17:00 < 20%
19/06/21	Ambient temperature °C	34.5	47.1	44.1	7:30–18:00 > 35
	Solar radiation, W/m^2	52	1225	1225	10:00–14:00 > 1000
	Relative humidity %	8.6	29.3	15.1	9:00–17:30 < 20%
20/06/21	Ambient temperature °C	32.9	47.4	46.1	7:00–18:00 > 35
	Solar radiation, W/m^2	46	1212	1212	10:00–14:00 > 1000
	Relative humidity %	8	25.5	13.1	7:30–18:00 < 20%

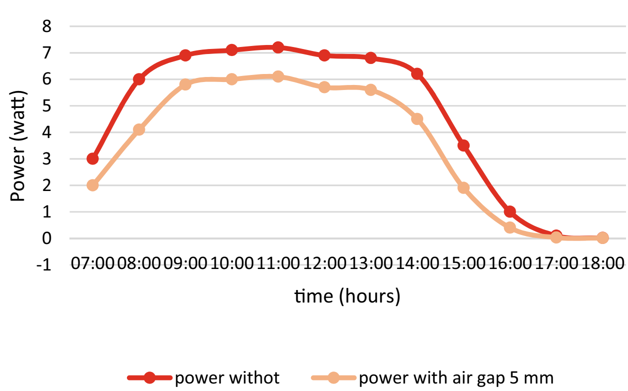

Fig. 9 Output power of two PV without and with air gap 5 mm during the day

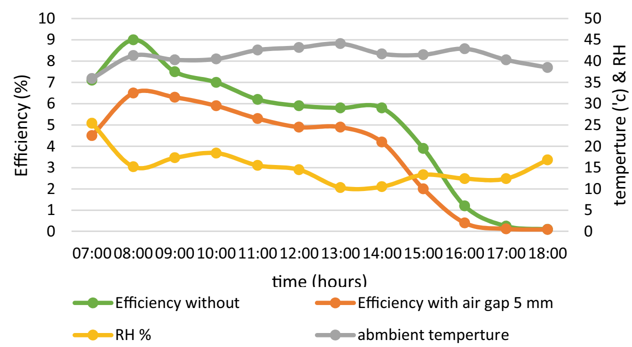

Fig. 11 Ambient temperature, relative humidity and PV efficiency without and with air gap 5 mm daytime

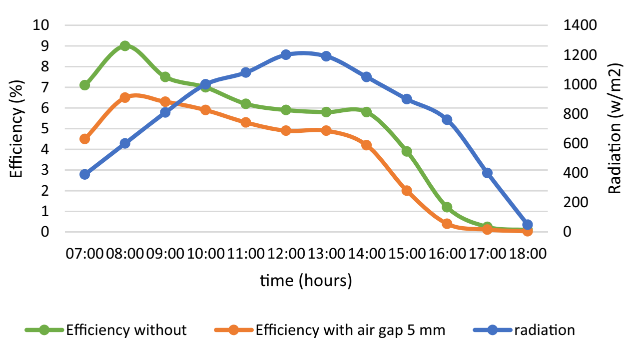

Fig. 10 Solar radiation and PV efficiency without and with air gap 5 mm during daytime

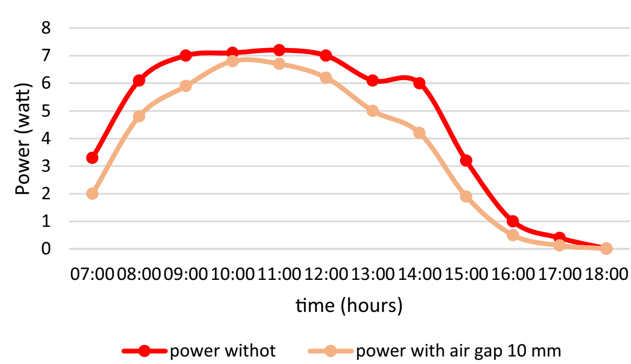

Fig. 12 Output power of two PV without and with air gap 5 mm during the day

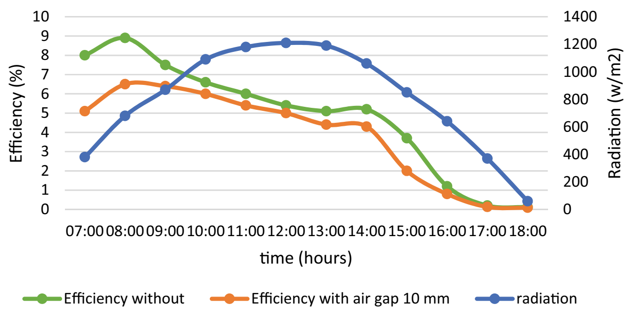

Fig. 13 Solar radiation and PV efficiency without and with air gap 5 mm during daytime

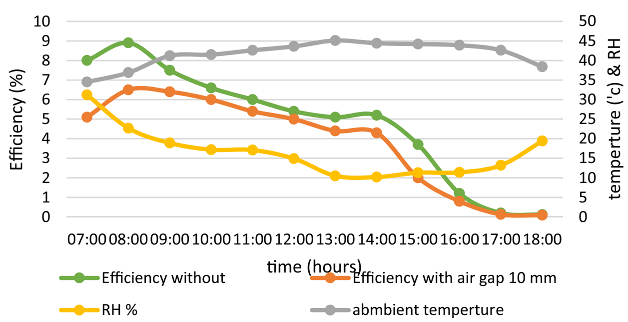

Fig. 14 Ambient temperature, relative humidity and PV efficiency without and with air gap 5 mm daytime

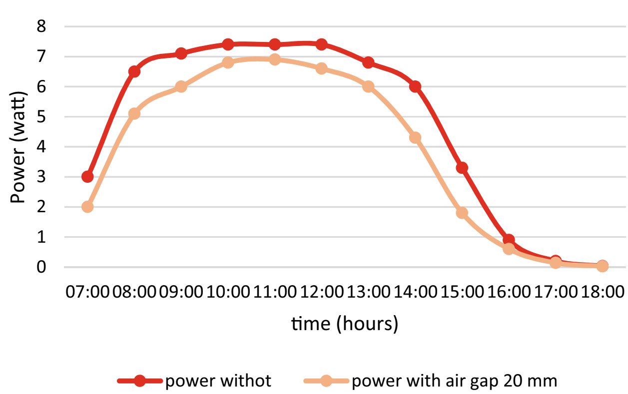

Fig. 15 Output power of two PV without and with air gap 5 mm during the day

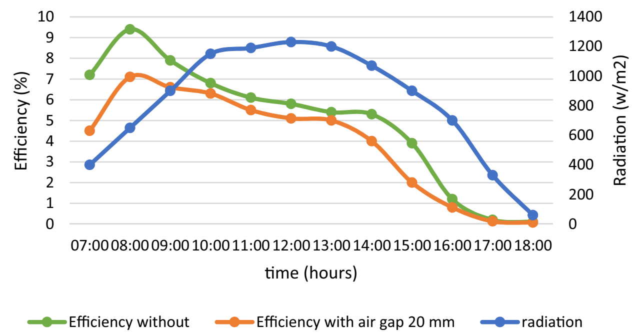

Fig. 16 Solar radiation and PV efficiency without and with air gap 5 mm during daytime

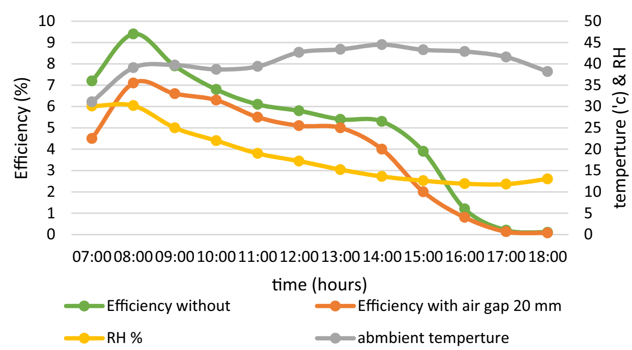

Fig. 17 Ambient temperature, relative humidity and PV efficiency without and with air gap 5 mm daytime

without and with a 20 mm air gap, while Fig. 17 depicts ambient temperature, relative humidity, and the PV efficiency of two PV without and with a 20 mm air gap during the day.

Table 2 explains the effect of an air gap (5, 10, 20 mm) on power and efficiency. The air gap reduces power and efficiency while protecting the PV from dust.

Table 2 Reduction in power and efficiency between with and without and with air gap

Reduced		Reduced Min	Reduced Max	Reduced at peck time 10:00	Reduced at 12:00 p.m.
Air gap 5 mm	*P* (W)	0.004 18:00	1.81 14:30	0.83–1.52	0.987
	η (%)	0.07 17:00	3.11 07:30	0.7–1.4	0.813
Air gap 10 mm	*P*(W)	0.004 18:00	1.80 14:30	0.71_1.44	0.728
	η (%)	0.08 17:00	2.8 07:00	0.58–1.36	0.585
Air gap 20 mm	*P* (W)	0.003 18:00	2.49 14:30	0.7–1.62	0.88
	η (%)	0.037 18:00	3.09 07:30	0.57–1.48	0.712

3.3 Effect of adding copper sulphate solution

Two PV panels are utilized in this portion. The PV upper surface is covered by a plastic covering on one of the two cells, which is well pasted to avoid permeability, and the

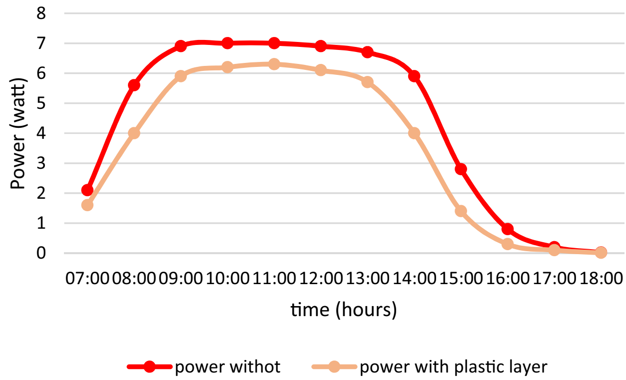

Fig. 18 Output power of two PV without and with plastic layer during daytime

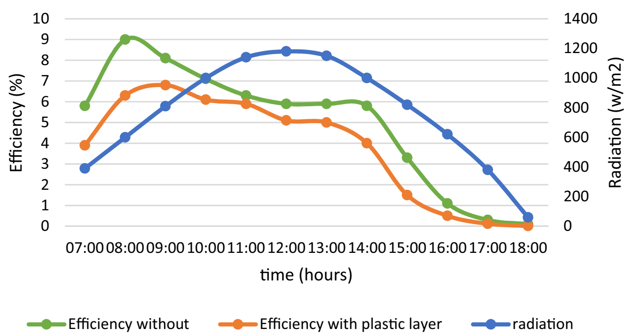

Fig. 19 Solar radiation and PV efficiency without and with plastic layer during daytime

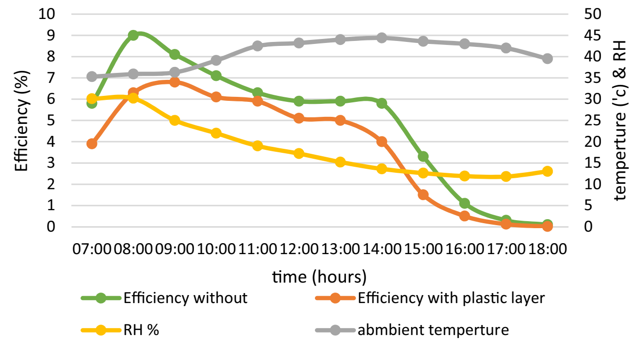

Fig. 20 Ambient temperature, relative humidity and PV efficiency without and with plastic layer during daytime

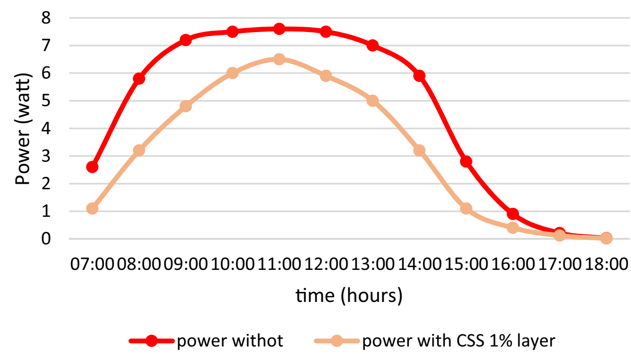

Fig. 21 Output power of two PV without and with CSS 1% during daytime

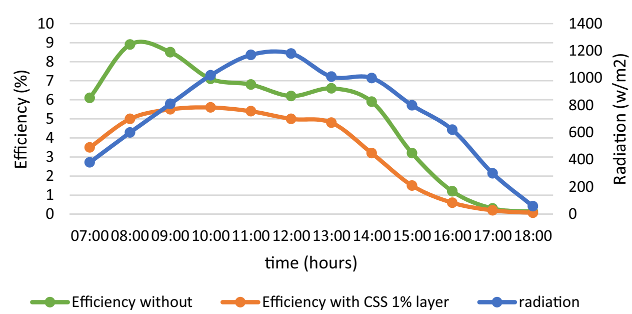

Fig. 22 Solar radiation and PV efficiency without and with CSS 1% during daytime

other is free. The two PV panels' output power and efficiency, as well as solar radiation, ambient temperature, and relative humidity, are all measured. Following that, CSS was injected at a concentration of 1% and the same parameters were recorded as before. Figure 18 depicts the output power of two PV systems with and without a plastic coating during the day on June 6, 2021. This graph shows that the PV output power without a plastic coating climbs gradually until 9:00 a.m., after which the value of output power remains nearly constant until 13:30. At 12:00 p.m., it registered 6.93 W. During the day, Fig. 19 depicts the variation in solar radiation and efficiency of two PV systems without and with a plastic layer. Figure 20 depicts the variation of ambient temperature, relative humidity, and efficiency of two PV systems without and with a plastic layer over the course of a day.

Figure 21 depicts the output power of two PV systems without and with CSS 1 percent daylight during the hours of 9 June 2021. This graphic shows that the output power of free PV starts low and gradually grows as solar radiation increases until it reaches (0.019–7.61 W). At 12:00 p.m., it measured 7.46 W. Figure 22 depicts solar radiation and PV efficiency without and with 1% CSS during the day. Figure 23 depicts the ambient temperature, relative humidity, and efficiency of two PV systems with and without a 1% CSS and a layer of plastic during the day.

Table 3 compares output power and PV efficiency without and with CSS and a layer of plastic at various concentrations.

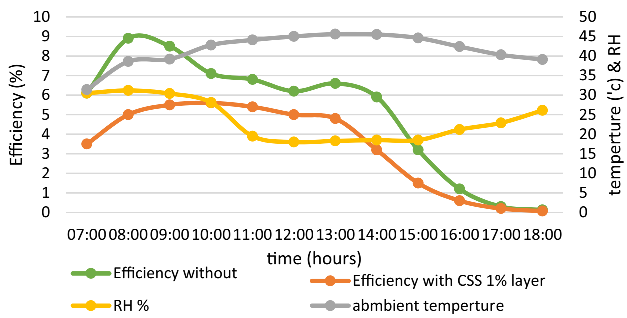

Fig. 23 Ambient temperature, relative humidity and PV efficiency without and with CSS 1% during daytime

4 Conclusion

Photovoltaic (PV) energy is regarded as one of the most essential options. Renewable energy is free, clean, and available most of the time. The performance of solar cells is externally dependent on environmental conditions, with changes in ambient temperature and solar radiation affecting output parameters such as output voltage, current, power, efficiency, and fill factor. The current thesis portrayed Makkah city's climate parameters like as sun intensity, ambient temperature, and relative humidity on various days in June. This was done to investigate the features of the PV in various weather conditions. This study suggests that:

1. Solar radiation begins low and gradually increases until it reaches its peak at 12:00 p.m. between 9:00 a.m. and 14:00 p.m., solar radiation is greater than 1000 W/m^2, and between 8:00 a.m. and 15:00 p.m., it gradually decreases.
2. 2.The ambient temperature has initially small values of around (30–35 °C), then gradually increases to a high of more than 40 °C between 9:00 a.m. and 17:00 p.m., and then gradually lowers again to values of around (33–38 °C) at time 18:00 p.m.
3. Relative humidity has initially high values (24–39%) and then steadily drops until it reaches its minimal values (7–16%). The relative humidity drops as the temperature rises.
4. The PV output power reaches its peak between 9:30 a.m. and 1:30 p.m., and hence the output power drops as solar radiation increases.5. The maximum value of the PV efficiency at the period between 7:30 and 8:30 a.m. and then gradually decreases with increasing of the ambient temperature although increasing in solar radiation.
5. In Makkah, relative humidity has no effect on the performance of photovoltaic solar cells.
6. Air gaps (5, 10, 20 mm) generated by a plastic layer from the upper surface of the PV diminish the PV output power by 1.52 W, 1.44 W, and 1.62 W, respectively. Furthermore, it affects PV efficiency by 1.4%, 1.36%, and 1.48%, respectively. However, the air gap of 10 mm has the smallest drop in output power and efficiency.
7. The obtained results show that using a layer of plastic with a 1% concentration of copper sulphate solution (CSS) leads to a 2.55 W reduction in output power, while the efficiency of the PV with CSS concentrations continues to increase after 8:30 a.m. despite increasing ambient temperature, but CSS leads to a 2.47% reduction in efficiency at the peak time compared to the free PV.

5 Recommendations

Based on the findings, it is possible to recommend that the upper surface of the PV cell be covered with a layer of plastic at a height of 10 mm to protect it from dust and achieve the greatest performance.

Table 3 Reduction in output power and PV efficiency between without and with adding CSS and a layer of plastic at different concentration

Reduced		Reduced		Reduced at peck time 10:00–14:00	Reduced at 12:00 p.m.
		Min	Max		
Closed without solution	*P* (W)	0.003 18:00	2.07 14:30	0.88–1.82	0.948
	η (%)	0.07 18:00	2.76 08:00	0.78–1.77	0.8
Concentration 1%	*P* (W)	0.007 18:00	2.72 14:30	1.35–2.51	1.72
	η (%)	0.1	4.05	1.12–2.48	1.44

Acknowledgments Not applicable.

Author contributions All authors contributed equally to the following items of the manuscript: Conceptualization, methodology, validation, formal analysis, investigation, resources, writing original draft preparation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding Not applicable.

Availability of data and materials Not applicable.

Declarations

Conflict of interest Not applicable.

References

1. Ebhota WS, Jen TC (2020) Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system. Int J Precis Eng Manuf Green Technol 7(1):97–117
2. Bosch JS (2017) Investigation of the performance of a large PV system, Doctoral dissertation. Universitat Politècnica de Catalunya. Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.
3. Hassan MK, Aldughmi AN (2021) Measurement of current-voltage characteristics, energy yield and the efficiency of the photovoltaic solar cell, as well as its applications in Saudi Arabia. Mech Eng Res Dev 44(11):186–196
4. Lanzafame R, Nachtmann S, Rosa-Clot M, Rosa-Clot P, Scandura PF, Taddei S, Tina GM (2010) Field experience with performances evaluation of a single-crystalline photovoltaic panel in an underwater environment. IEEE Trans Ind Electron 57:2492–2498
5. Rauschenbach HS (2012) Solar cell array design handbook: the principles and technology of photovoltaic energy conversion. Springer Science & Business Media, Berlin
6. Ono LK, Liu S, Qi Y (2020) Reducing detrimental defects for high-performance metal halide perovskite solar cells. Angew Chem Int Ed 59(17):6676–6698
7. Sajjad U, Amer M, Ali HM, Dahiya A, Abbas N (2019) Cost effective cooling of photovoltaic modules to improve efficiency. Case Stud Therm Eng 14:100420
8. AlOtaibi ZS, Khonkar HI, AlAmoudi AO, Alqahtani SH (2020) Current status and future perspectives for localizing the solar photovoltaic industry in the Kingdom of Saudi Arabia. Energy Transit 4(1):1–9
9. Tabrizi AA, Saghaei H, Mehranpour MA, Jahangiri M (2021) Enhancement of absorption and effectiveness of a perovskite thin-film solar cell embedded with gold nanospheres. Plasmonics 16(3):747–760
10. Li M, Dai Y, Ma W, Yang B, Chu Q (2017) Review of new technology for preparing crystalline Silicon solar cell materials by metallurgical method. In: IOP conference series: earth and environmental science, vol 94, no 1, p 012016. IOP Publishing.
11. Zhao J, Ghannam R, Htet KO, Liu Y, Law MK, Roy VA et al (2020) Self-Powered implantable medical devices: photovoltaic energy harvesting review. Adv Healthc Mater 9(17):2000779
12. Maka AO, O'Donovan TS (2022) Effect of thermal load on performance parameters of solar concentrating photovoltaic: high-efficiency solar cells. Energy Built Environ 3(2):201–209
13. Jeong SH, Park J, Han TH, Zhang F, Zhu K, Kim JS et al (2020) Characterizing the efficiency of perovskite solar cells and light-emitting diodes. Joule 4(6):1206–1235
14. Malik P, Chandel SS (2021) A new integrated single-diode solar cell model for photovoltaic power prediction with experimental validation under real outdoor conditions. Int J Energy Res 45(1):759–771
15. Mustafa RJ, Gomaa MR, Al-Dhaifallah M, Rezk H (2020) Environmental impacts on the performance of solar photovoltaic systems. Sustainability 12(2):608