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Research Article

Impact of Accumulated Dust on Performance of Two Types of Photovoltaic Cells: Evidence from the South of Jordan

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Abstract. This paper examines the impact of accumulated dust on two types of photovoltaic (PV) cells in the performance of solar panels facility located in the southern part of Jordan between January to August 2020. To determine the performance of the solar PV panel system, two elements have been considered: sun radiation total efficiency and output power generated from the two types of the PV panel. Results of the study revealed that the mass of dust accumulated on the polycrystalline panel accumulated faster than on the cadmium telluride panel at a rate of 10.5 g/m^2 for polycrystalline panels and 8.4g/m^2 for cadmium telluride panel. Furthermore, results indicated that the projected drop in the efficiency of washed and unwashed polycrystalline panels decreased monthly by 5% and 16% respectively, while the efficiency of washed and unwashed cadmium telluride panels decreased monthly by 5% and 11.5% respectively. In the same context, results indicated that the wind speed, concentration rate, and relative humidity increased by 3%, 5%, and 8% respectively whereas the ambient temperature decreased by 4% monthly. On the other hand, the size and charge of accumulated dust on the cadmium telluride panel surface were larger than the size and charge of dust on the polycrystalline panel surface with a high percent of (Si) and low percent of (Ca) and (Fe). This research contributes to the literature by providing empirical evidence for the impact of accumulated dust on PV panels applied on a dusty-weather such as the one in the southern part of Jordan.

Keywords: Photovoltaic; Solar Panels Performance; Renewable Energy; Jordan; Dust Charge.

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1. Introduction

Over recent years, the demand and use of renewable energy as a clean source have increased dramatically. It could be stated that solar power is a key source of renewable energy, and thus is considered a very promising technology worldwide. The Middle East and especially Jordan is a very proper area for solar radiation as the country is located in the Sunbelt zone. Ma'an region (south) is considered one of the best areas in terms of solar radiation, as the area has the highest annual solar radiation in Jordan at 5.9 kWh/m^2/day with 310 days of sunshine yearly (Baniyounes, 2017; MEMR, 2018). For this reason, the region has attracted tens of millions of US$ of investments in solar power fields during the last few years. Despite the high solar radiation, yet the region is considered one of the highest dusty areas in Jordan.

Meanwhile, the increased use of solar energy to generate electric power has several challenges. One of the main affecting factors in this regard is the environmental-related factors, such as temperature, humidity, intensity of solar radiation, wind speed, and accumulated dust (Kishor *et al*. 2010; Ahmed, 2016; Tripathi *et al*. 2017). Accumulated dust is considered the main factor for the reduced performance of the Photovoltaic (PV) cells since it reduces the amount of solar radiation absorption (especially in a dusty-region such as that in the southern part of Jordan). On average, the power generation efficiency is reduced by 15-35% for 20g/m2 of dust accumulated on the solar collector (Zaihidee *et al*. 2016). For example, in Saudi Arabia, the performance of solar cell decreased by about 32% during a period of eight months (Mani and Pillai, 2010). In the same context, a research conducted in Egypt for six-month using amorphous Silicon cells (without panel cleaning) indicated that the depression of Voc, Isc, and P is 58 %, 61 %, and 75 %, respectively. The presence of dust on the panel causes scratching in the surface glass and causes depression in η by 10% (Hassan *et al*., 2005). According to Walwil *et al*. (2017), the fouling dust has reduced output power by 40% after a period of 10 months without cleaning the surface of PV panel using monocrystalline in Dhahran, Saudi Arabia. However, the efficiency of the solar power generation system was

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reduced by nearly 10% due to the accumulation of dust in the North-eastern part of Jordan (Hammad *et al.* 2013). According to Kaldellis *et al.* (2010), the accumulation mass of dust particles deposition usually reduces the output power by about 5% and decreases efficiency by about 0.4%. These results were obtained from an experiment carried out under variable environmental situations (e.g. ambient temperature, solar irradiance) and different quantities of dust accumulated on the PV panels' surface for 70 days.

There are many factors affecting dust accumulation. Typically, the accumulated dust depends on dust properties (size, weight, density, and shape of particles), chemical characteristics, as well as the environmental and weather conditions of the site such as wind velocity, humidity, and outside temperature (Kaldellis *et al.* 2011; Mekhilef *et al.* 2012; Mustafa *et al.* 2020). Accordingly, the solar panels usually preserve the temperature of PV cell in the range (18-25°C), while the efficiency decrease by nearly 0.45% for each degree over 25°C (Rubab *et al.* 2017). The efficiency of the PV module decreases to 9.7% at 60% humidity and increases to 12.04% at 48% humidity (Katkar *et al.* 2011). In addition to the factors indicated above, particle size also affects the process of accumulating dust. Generally, fine dust particles decrease the efficiency of PV solar cells more than coarser particles (El-Shobokshy and Hussein, 1993). According to Yin and Wang (2014) fine particles have size of <10μm and coarser particles have size of >10μm.

This research contribution provides empirical data about the impact of the accumulated dust on the performance of two types of PV in a region where a considerable investment is made in solar power mass projects. This paper proceeds as follows: Section 2 reviews the relevant literature, while Section 3 presents the research methodology. In Section 4, the research results and discussion are presented, whereas Section 5 concludes and makes some recommendations for future research

2. Previous Studies

Within the universal efforts to decarbonize the energy infrastructure, a considerable increase in the empirical research related to solar systems, PV efficiency, and dust accumulation impact on power generating has been noted in recent years. In this regard, attention in the current research is given to reviewing the most relevant research in this field (see for example: Adinoyi and Said 2013; Al-Shabaan *et al.* 2016; Kaldellis *et al.* 2011).

El-Shobokshy and Hussein (1993) examined the impact of accumulated particles in the reduction of power output. They used three different materials carbon (5μm diameter), cement (10μm diameter), and three different diameters of limestone particles (50, 60 and 80μm) deposited three different diameters of limestone particles on PV surfaces under the same density where the surface mass density was 25g/m^2 and measured the power output. Results of the study revealed that finer particles reduce output power more than coarser particles. Where the reduction was 90% for carbon and has fine particles more than cement material that has coarser particles on the surfaces where the reduction was 40%. In this context, previous research suggests that a high wind speed can remove coarser particles more than fine particles (El-Shobokshy *et al.* 1985).

Among very limited studies conducted in the MENA region, Al-Shabaan *et al.* (2016) examined the impact of mass deposition density (g/m^2) and particle size on the maximum output energy with an equal distribution (1/3) from different grain sizes using the monocrystalline panel. The study was conducted in the laboratory under steady conditions located at Al-Hussein Bin Talal University, in Ma'an region – south of Jordan. Results of the study showed that "fine" and "medium" sizes have positively affected the reduction of the transmitted light and decreased power output. Notably reductions were between 37.6% to 46.4% for 5g/m^2 and 5.6% to 20.0% for 1g/m^2 mass densities

Kaldellis *et al.* (2011) stated that particle chemical composition and their color are some of the dust characteristics that also affect PV efficiency through the effect on the deposition of dust on PV surfaces as reduction transmittance of surface and hence PV efficiency. In their study, Kaldellis *et al.* (2011) used three types of dust: (i) a commonly known urban air pollutant (i.e. limestone, which consists usually of Calcium Carbonate [CaCO3] which in turn, is usually used as a component of building materials); (ii) carbon-based ash, a by-product of incomplete hydrocarbons' combustion. It is usually discharged from thermal power generating stations or vehicular, and exhausts, and finally, (iii) a red soil that comes from dry terrain or is attributed to 'trans-boundary' spreading of dust from African deserts deposited on PV surfaces. Results of the study indicated that a large reduction in output power occurred by 7.5%, 4%, and 2.3% for red soils, limestone, and ash, respectively. In the same vein, it has been indicated that mud and talcum accumulation on PV modules reduces peak power by 18% and efficiency by up to 5% (Sulaiman *et al.* 2011).

According to Jiang *et al.* (2011) the output efficiency reduction from zero to 26% for dust-accumulated density increased from 0g/m^2 to 22 g/m^2 using different types of PV panel polycrystalline, mono-crystalline, and amorphous module and use the fine test dust (ISO 12103-1 A2). The dust under this test has a 'multi-distribution' sized from one μm to 100 μm, in which, dust with the size of 20 μm is about 20% and 74% of the dust less than 20 μm. The precise weight of the dust is 2.65 g/cm^3. The chemical components of dust are SiO2, Al2O3 and concluded that polycrystalline module covered by dust accumulated faster than other types under the same conditions (Jiang *et al.* 2011). It has been also indicated that the tilt angle of the PV panel also plays a major role in accumulated dust on the surface panel (Kaldellis *et al.* 2011). The accumulated dust on different tilts of PV glass surfaces decreased the transmittance of plates from 64% to 17% for 0° and 60° respectively, during 38 days in Kuwait City (Darwish *et al.* 2013). In the same context, a study has been carried out in the city of Tehran, and it has been concluded that the accumulated dust on different tilted (0°; 23°; 29°; 35°; and 42°) of PV surfaces decreases the output energy as a tilt angle decreased (Asl-Soleimani *et al.* 2001).

The accumulated dust depends also on the materials of PV surface modules. In this regard, it could be stated that the amount of accumulated dust on glass surfaces for PV with a 0° tilt angle is more than the amount of accumulated dust on glass surfaces for PV with a 90° tilt angle (El-Nashar, 2003). The use of glass covers with anti-reflective coating and textured PV surfaces in Dhahran, KSA reduced output power losses by 5% (Said and Walwil, 2014). Piliougine *et al.* (2013) used a thin-film module coated with self-cleaning properties and anti-reflective coating for PV surfaces in Malaga, Spain. The results indicated that the losses in output power due to uncoated modules was 3.3% while for coated was 2.5%. According to Appels *et al.* (2013), the use of coated glass samples (self-cleaning coating, an anti-reflection coating, and a multilayer coating) for PV surfaces in Heverlee, Belgium has caused the transmittance to be decreased by 1.75%, 1.3%, and 0.85% for anti-reflection coating, self-cleaning, and multilayer coating, respectively. In the same vein, the use of coated glass for PV surfaces in Minnesota, USA reduced glass transmittance by 20% after four months compared with 25% for traditional glass (Brown *et al.* 2012). It has been also indicated that superhydrophobic and superhydrophilic ESP coatings for PV surfaces in the laboratory decreased the dust particles-glass cover adhesion force from 90 to 12 nN (Kazmerski *et al.* 2016).

Dastoori *et al.* (2013) examined the effect of charging powder particles on PV efficiency. The results showed that the increased charged powder particles on the PV modules decrease the output voltage by using epoxy powder and charging processes of dust particles, which include: (i) corona charging and (ii) tribo charging. The results have also confirmed that decreasing the voltage leads directly to an increase in the net charge value of the powder.

Studying the effect of accumulated dust on the PV modules in outdoor environments could be a challenging task, thus, most researchers around the world used artificial dust. In this context, it could be stated that there have been few studies related to the physical and chemical characteristics of naturally accumulated dust in parts of the world. To improve the efficiency of PV cells and keep their efficient performance, there is a need to clean the surfaces of solar panels periodically. In this regard, there are several methods to clean and block accumulated dust like natural, manual, mechanical, automatic, Electrostatic Precipitator (ESP), and self-cleaning coating techniques. National Aeronautics and Space Administration (NASA) has developed electrostatic approaches for reducing the negative effects of dust on the lunar of solar panels. By attaching the electrodynamics screen to the PV module surface (He *et al.* 2011). The performance and the efficiency of the screen are dependent on many factors, including dust deposition rate, type of accumulated dust particle, method of operation, and the applied voltage (Sims *et al.* 2003).

Recently, a comparative study of various dust cleaning methods was conducted. Hudedmani *et al.* (2017) indicated that the Electrostatic Precipitator (ESP) method is efficient to clean solar panels and protect the top layer from physical damage or scratches using electrostatic charge force which utilized an Arduino-controller electrostatic precipitator and a weight sensor. Self-cleaning surfaces are manufactured in many ways like super-hydrophobic coating and super-hydrophilic coating. This method is modern and it depends on stopping depositing particles of dust on the surfaces of solar panels. In this regard, the dropped water will roll and slid or make the water layer and thus, leaves the outer surface of the solar panel portable the accumulated dust because it reduces the surface tension between the self-cleaning surface and water droplet (Sethi and Manik, 2018). There were no observed problems with shading or the effect of absorbed light using the coating methods because the coating layer is very thin (Maharjan *et al.* 2020).

Based on the previous studies indicated above, it could be stated that there are no empirical studies that examined the impact of accumulated dust on PV panels applied to dusty weather such as in the southern part of Jordan and consider at the same time particle properties. Therefore, this work investigates the behavior of the exposed PV modules under extremely dusty environments and provides an immediate efficient clean method that is suitable for dusty weather in the south of Jordan (i.e. Ma'an region). It also provides detailed information on the ratio of dust settlement, how it affects the PV module yield, and durability during the exposure period considering the electrostatic charge of accumulated dust. These aspects have not been previously examined and particularly in this region.

3. Research Methodology

The installation of the system was located in Ma'an, southern Jordan. This site is located less than 220 km to the Southwest of the capital Amman. Ma'an city located between ° 29 ′00 to ° 31 ′30 N latitude and ° 35 ′30 to ° 38 ′000 E longitude (Aymen *et al.* 2020). The location of the experiment is devoid of the population; therefore, the natural effect of dust alone can be carefully performed on solar panels. In this study, silicon crystalline (polycrystalline) and thin-film (Cadmium Telluride (CdTe)) are used. According to Richhariya *et al.* (2020), Cadmium Telluride (CdTe) are solar cells that contain thin-film layers of 'cadmium telluride' materials as a semiconductor to reconvert absorbed sunlight and then generate electricity. The Polycrystalline is also known as 'multi-crystalline'. In this type, many-crystal solar panels are made from pure solid silicon materials that consist of many small crystals (the grains. These grains are separated by 'grain boundaries' and usually have random crystallographic orientations) (Wang and Duan, 2019). In the current study, Polycrystalline with 1956mm×992mm×40mm dimensions and Cadmium Telluride (CdTe) with 1200mm×600mm×6.8mm dimensions were used. Photovoltaic modules were used under the same weather conditions. Notably, the systems operate by the tracking system.

The system is made by a combination and integration of a Microcontroller named *Arduino Microcontroller* and specific-purpose sensors (pyranometer, multimeter, voltmeter, anemometer, relative humidity sensor and temperature sensor). A connection of the PV modules was created to the Midi Data Logger, whereas a connection was created between the glass panels (with different probes underneath the surface) to the Arduino Microcontroller for processing data from sensors. The results were displayed on the computer and saved to a backup file that in turn; was recorded by Supervisory Control and Data Acquisition (SCADA) software. Figure (1) demonstrates the Midi Data Logger of the solar PV panel system.

Fig. 1 The Midi Data Logger of the Solar PV Panel System.

Two panels from each type were used to detect the relationship between the amount of the decreased output power and efficiency to the percentage of accumulated dust on its surface. These measures were depending on the concentration rate of dust calculations and connected it with changes in ambient temperature, wind speed, and humidity of the air. The results of voltage, current, and irradiation were displayed on the computer, and the daily tests were conducted over seven months, starting from the 1st Jan.2020 to 15th Aug.2020. The concentration rate is monitored by a particle matter device.

The second part of this work is designed to measure and analyze the characteristics of particles accumulated on PV panels (i.e. an electrostatic charge, chemical composition, size of accumulated dust, and mineral percent of accumulated particles). Additionally, it should be indicated that improvement of the cleaning method or improvement of the manufacturing process of PV panels in this region depends on the electro charges of particles measured. It was indicated earlier that (ESP) clean method is considered the efficient cleaning method, thus to apply this method electrostatic charge of dust must be measured.

Empirically, there were two key steps performed in this study. The first step was to collect samples of accumulated dust using a fine brush from the PV surface for each type.* In the second step attention was given to measuring the mineral percent, chemical composition, and size of particles using X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), and sieves inside the laboratory of Al-Hussein Bin Talal University (hereafter, AHU) located in Ma'an, Jordan. Furthermore, in this step attention was also given to measuring the electrostatic charge of dust using a static meter inside the laboratory of Applied Science Private University (hereafter ASU), located in Amman, Jordan.

4. Results and Discussion

4.1 Performance of Polycrystalline and Cadmium Telluride Panels Measurement Results

To explore what kind of relationship exists between the output power, the absorbed solar radiation, and the efficiency of washed and unwashed polycrystalline panels and cadmium telluride panels with time, empirical tests were conducted. Results of this test are presented in Table 1 and Table 2.

The test was conducted daily but presented as an average monthly to ease reading for the reader. The reading was measured continuously during the day. From the obtained results, it could be observed that there was a difference between washed and unwashed for output power and radiation compared for each type. Overall, the average output power of the washed polycrystalline panel was about 50.44 W while radiation was about 379.56 W/m^2 and the average output power of the unwashed polycrystalline panel was about 41.12 W while radiation was about 371.82 W/m^2.

In Table 1 a summary of the average monthly radiation is presented. From the results, it was found that the difference in the value of radiation for the washed and unwashed panel for the months of January, February, March, April, May June, July, and mid-August was 3.26 W/m^2, 6.71 W/m^2, 11.79 W/m^2, 16.42 W/m^2, 14.01 W/m^2, 1.23 W/m^2, 6.03 W/m^2 and, 2.46 W/m^2, respectively. Overall, the average difference in radiation value for the washed and unwashed panel for all the months was 7.743 W/m^2. Notably, sun-tracking systems used have improved the radiation of PV plants dramatically.

Table 1
Average Monthly Results of the Output Power, Radiation, and Efficiency of Washed and Unwashed Polycrystalline Panel

Date	Output Power (P) W Washed Panel	Radiation (G) W/m^2 Washed Panel	Efficiency (η) % Washed Panel	Output Power (P) W Un-Washed	Radiation (G) W/m^2 Un-Washed	Efficiency (η) % Unwashed Panel
1-31/1/2020	24.76	200.69	6.36	18.85	197.43	4.92
1-29/2/2020	35.44	270.49	6.75	32.73	263.77	6.39
1-31/3/2020	43.76	330.85	6.82	35.25	319.05	5.69
1-30/4/2020	54.94	392.06	7.22	50.66	375.64	6.95
1-31/5/2020	65.12	434.33	7.73	49.79	420.31	6.10
1-30/6/2020	55.18	480.53	5.97	40.29	479.30	4.33
1-31/7/2020	68.77	461.09	7.69	53.32	455.06	6.04
1-15/8/2020	55.56	466.46	6.14	48.08	464.00	5.34

* In terms of the dust type, there was more than one type of dust used during this study. This includes topsoil and sand. Seasonally, south part of Jordan is faced by dry dust storms which impact amount of dust on the air.

A summary of the average monthly output power is also shown in Table 1. Based on these results, it was found that the difference between the washed and unwashed panels for the months of January, February, March, April, May, June, July, and until mid-August was 5.91W, 2.70W, 8.50W, 4.28W, 15.32W, 14.89W, 15.44W, and 7.47W, respectively. The overall average difference in output power value for the washed and unwashed panel for all the months was 9.32W.

As indicated in Table 1, the results showed that the average performance drop of the power output continuously over the period of seven months of the test was about 23%, while the irradiation's average performance drop over the same period of testing was about 2%. The power out performance's drop and irradiation are supposedly the same, however, low efficiency of used solar PV panels was noticed, which in turn; explains the gap between the two results.

In terms of efficiency, the results (as shown in Table 1) revealed that the difference between the washed and unwashed panels for the months of January, February, March, April, May, June, July, to mid-August was 1.44, 0.36, 1.12, 0.27, 1.62, 1.65, 1.65, and 0.79%, respectively. The average difference in efficiency value for the washed and unwashed panel during the whole investigated period of time was 1.11. In short, it could be concluded that the average performance drop in efficiency between washed and unwashed panels was about 21%.

Based on the results, it has been revealed that there was a difference between washed and unwashed for output power and radiation. Overall, the average output power of the washed solar PV panel was about 21.99W while radiation was about 394.61W/m^2, while the average output power of unwashed solar PV panel was about 20.12W whereas radiation was about 386.67W/m^2.

Table 2 illustrates the summary of the average monthly radiation of the washed and un-washed Cadmium Telluride Panel. Based on the presented results, it was found that the difference in the value of radiation for the washed and unwashed panel for the months of January, February, March, April, May, June, July, and until mid of August was 11.70W/m^2, 6.86W/m^2, 2.83W/m^2, 17.07W/m^2, 14.57W/m^2, 1.28W/m^2, 5.72W/m^2 and, 3.43W/m^2, respectively. Overall, the average difference in radiation value for the washed and unwashed panel for the whole investigated period of time was 7.93W/m^2. Notably, the sun-tracking system used has improved the radiation of PV plants dramatically.

In terms of the monthly average of the output power, the results (as shown in Table 2) indicated that the difference between the washed and unwashed panels for the months of January, February, March, April, May, June, July, and until mid-August was 1.22W, 2.93W, 0.16W, 1.39W, 2.57W, 3.00W, 3.38W, and 0.30W, respectively. The overall results indicate that the average difference in output power value for the washed and unwashed panel for the whole examined period of time was 1.87W.

Regarding the difference between washed and unwashed panels for output power and irradiation, the results (see Table 2) showed that the average performance drop of output power continuously over seven months' test was about 9%, while the average performance drop of irradiation continuously for the same period was about 2%. Theoretically, the performance drop of power output and irradiation was supposed to be the same, however, the efficiency of solar PV panels used was low, that is why there was a gap between the two results.

In terms of the monthly average efficiency, the results (based on data introduced in Table 2) indicated that the difference between the washed and unwashed panels for the months of January, February, March, April, May, June, July, and until mid of August was 0.45, 1.28, 0.004, 0.13, 0.51, 0.82, 0.89, and 0.04, respectively. Notably, in March, the efficiency of washed panels and unwashed panels was almost equal due to rainfall during this period of the year. The average difference in efficiency value for the washed and unwashed panel for all months was 52%. In summary, the average performance drop in efficiency between washed and unwashed panels was about 7%.

4.2 Concentration Rate with Efficiency of Unwashed Polycrystalline and Cadmium Telluride Panels Measurements Results

To explore what relationship may exist between the efficiency of unwashed polycrystalline and cadmium telluride panels and the distribution, concentration rate with time starting from July 15th, 2020 to August 12th 2020 was measured. Results of this measurement are presented in Table 3

Table 2

Average Monthly Results of the Output Power, Radiation, and Efficiency of Washed and Un-Washed Cadmium Telluride Panel.

Date	Output Power (P) W Washed panel	Radiation (G) W/m^2 washed panel	Efficiency (η) % Washed Panel	Output Power (P) W Unwashed Panel	Radiation (G) W/m^2 Unwashed Panel	Efficiency (η) % Unwashed Panel
1-31/1/2020	10.46	217.03	6.69	9.23	205.32	6.24
1-29/2/2020	16.97	281.19	8.38	14.03	274.32	7.10
1-31/3/2020	18.66	334.65	7.74	18.49	331.81	7.74
1-30/4/2020	24.21	407.74	8.24	23.82	390.66	8.11
1-31/5/2020	29.59	451.70	9.10	27.02	437.12	8.58
1-30/6/2020	22.54	499.75	6.54	20.53	498.47	5.72
1-31/7/2020	29.05	479.26	8.42	25.67	473.54	7.53
1-15/8/2020	23.47	485.56	6.75	23.17	482.12	6.67

Table 3
The Average Weekly Changes in Concentration Rate Values with Efficiency of Unwashed Polycrystalline and Cadmium Telluride Panels

Time Period	Mass of Filter Paper with Collected Particles (g)	Concentration Rate×10^{-5} (g/m^3)	The efficiency of Unwashed Polycrystalline Panels (%)	The efficiency of Unwashed Cadmium Telluride Panels (%)
15-22/7/2020	3.75	8.41	6.95	7.83
23-30/7/2020	3.87	9.46	5.53	6.75
31/7-7/8/2020	3.85	9.28	5.44	6.90
8-15/8/2020	3.90	9.77	4.50	5.71

From the obtained results, it has been shown that the average concentration rate of dust on the monthly test was about 2.308×10-5 g/m^3. The highest performance drop of the efficiency occurred in the final week while the highest performance rise of the concentration rate occurred in the same week, (as the highest concentration rate of dust occurred during the period of 5th-12th/Aug/2020). The speedy wind contributed to accumulating the dust on the filter paper of particle matter and thus, decreased the efficiency of unwashed polycrystalline and cadmium telluride panels. In the same context, the efficiency of the unwashed polycrystalline panel decreased by 16% while the unwashed cadmium telluride panel decreased by 11.5% with an increased concentration rate of 5% during the monthly test. Furthermore, the mass of dust collected from polycrystalline and cadmium telluride surfaces after over seven months was 10.5g/m^2 and 8.4g/m^2 respectively.

4.3 Weather Conditions effect on the Performance of Polycrystalline Cadmium Telluride Panels Results

In comparison with the other parts of Jordan, the investigated area (south – Ma'an region) has its own weather conditions. In average, the southern and eastern parts of Jordan are generally dusty with high temperatures in summer. Generally, August is the hottest month of the year at Ma'an, with an average high of 34°C and low of 19°C. In average, the cool season lasts for 3.1 months, from December 1 to March 5, with an average daily high temperature below 17°c. The coldest month of the year at Ma'an is January, with an average low of 2.5°C and high of 13°C (Weatherspark, 2022). Seasonal storms usually occur in the months of April and October. The average monthly change in the weather conditions' values is presented in Table (4).

To explore the relationship that may exist between the performance of washed, unwashed polycrystalline and cadmium telluride panels with the concentration rate and weather condition changes (i.e. wind-speed, ambient temperature, and relative humidity) over the period of study, an analytical chart was used as shown in Figure (2), whereas the detailed results are presented in Table (5).

The results revealed that the highest wind speed occurred in the last week (6.82 m/s) of the experiment, whereas the highest relative humidity, concentration rate, and the highest drop in the average performance of washed as well as unwashed polycrystalline and cadmium telluride panels took place at the same week – despite the decrease in the temperatures. In summary, the wind speed, concentration rate, and relative humidity increased by 3%, 5%, and 8%, respectively, whereas the efficiency of washed and unwashed polycrystalline panels decreased by 5%, 16%, respectively. In the same vein, the efficiency of washed and unwashed cadmium telluride panels decreased by 5%, 11.5%, respectively, whereas ambient temperature decreased by 4%.

Table 4
Average Monthly Results of Changes in Weather Conditions

Date	Ambient-Temperature (℃)	Wind-Speed (m/s)	Relative Humidity (%)
1-31/1/2020	7.040	6.90	63.32
1-29/2/2020	9.60	6.46	57.33
1-31/3/2020	13.70	7.59	48.10
1-30/4/2020	17.05	6.71	43.26
1-31/5/2020	23.15	6.78	28.27
1-30/6/2020	25.06	6.36	26.66
1-31/7/2020	28.63	6.58	26.74
1-15/8/2020	26.40	6.60	33.33

Table 5
The Efficiency of Washed, Unwashed Polycrystalline and Cadmium Telluride Panels with the Concentration Rate and with the Changes in Weather Conditions

$\eta_{PolyWashed}$ (%)	$\eta_{PolyUnwashed}$ (%)	$\eta_{CadWashed}$ (%)	$\eta_{CadUnwashed}$ (%)	C.R*10^{-5} g/m^3	$T_{\circ}$ (°C)	Vw (m/s)	R.H (%)
6.95	6.95	8.80	7.83	8.40	29.14	6.14	26.14
7.02	5.53	9.72	6.75	9.46	30.71	6.43	24.14
7.28	5.44	9.24	6.91	9.28	29.71	6.14	25.00
6.10	4.50	7.75	5.71	9.77	26.00	6.81	35.72

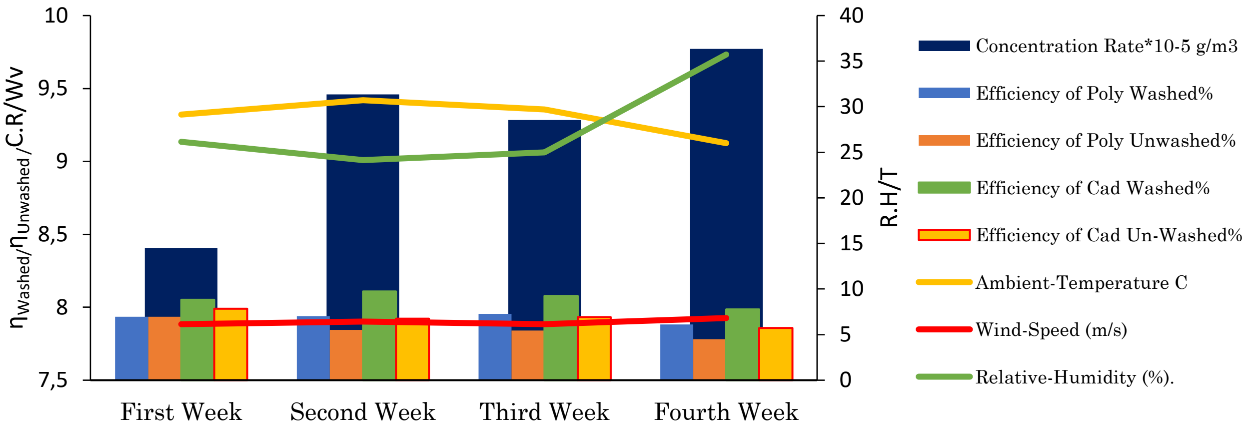

Fig. 2 Variation of the Concentration Rate and the Efficiency of Polycrystalline and Cadmium Telluride Panels with Changes of the Weather Condition

Overall, it could be stated that the efficiency of the polycrystalline and cadmium telluride washed and unwashed panels are low in comparison to their amounts at STC. This is attributed to an increased ambient temperature where the efficiency is decreased by almost 0.45% for each degree over 25℃ and decreased to 9.7% at 60% humidity (as the relative humidity in January month usually reaches 60%). It could be also stated that the accumulated dust has negatively affected the efficiency of the PV panel by decreasing 15-35% for 20g/m^2 of accumulated dust. Furthermore, it has been noted that the amount of absorbed solar radiation is ranged between 200 to 500 W/m2. These results are consistent with (Katkar *et al.* 2011; Rubab *et al.* 2017; and Zaihidee *et al.* 2016).

4.4 Properties of Accumulated Particles Measurements Results

This section consists of four parts that are vital for analyzing the characteristics of particles accumulated on the PV panels in Ma'an region. These characteristics include: chemical composition, minerals percent of accumulated particles, size of particles, and electrostatic charge. The overall objective of this analysis is to examine the accumulated dust problem on PV panels; in order to improve cleaning methods and the manufacturing process of PV panels specifically designed for this region (or similar environment).

4.4.1 Particles Chemical Composition Measurement Results

The chemical structure of the accumulated dust layers on the polycrystalline and cadmium telluride panels surface – using X-Ray Fluorescence (XRF) – has been analyzed. The dust particles are mostly composed of calcium (Ca) followed by silicon (Si), with smaller amounts of Iron (Fe), aluminum (Al), Potassium (K), and Titanium (Ti) for polycrystalline and cadmium telluride panels with different percentage.

On the polycrystalline PV surfaces, it was found that the output power and the efficiency of washed and unwashed declined by 11%, 5%, and 16%, respectively, during the period 15th/July/2020 to 12th/August/2020 with dust composition Ca (57.33%), Si (20.62%), and Fe (11.17%), respectively. For the cadmium telluride, it was found that the produced power and the efficiency of washed and unwashed panels decreased by 5%, 5%, and 11.5%, respectively, for the same period with Ca (54.20%), Si(28.12%), and Fe(7.12%) content of particles, respectively. Based on these results, it could be stated that the total efficiency and output power of polycrystalline panels are further decreased the total efficiency and produced output power of cadmium telluride at a high percent of (Ca) and low percent of (Si). The detailed readings of the chemical composition of accumulated dust on the polycrystalline panel and the cadmium telluride panel are available upon request.

4.4.2 Particles Mineral Percent in Dust Measurement Results

In this section, attention is given to analyzing the mineral intensity of the dust accumulated on the layers of the polycrystalline and cadmium telluride panels' surface. The dust particles have many minerals with different intensities for each surface where the intensity of the main minerals on the cadmium telluride surface is more than the polycrystalline surface panel.

For the polycrystalline PV surfaces, it was found that the output power and efficiency of the washed and unwashed decreased by 11%, 5%, and 16%, respectively. At the test time, there were forty-eight minerals with different intensities. These minerals can be classified under four main types – as illustrated in Table (6).

Table 6
X-Ray Diffraction Result of Dust on Polycrystalline Panel

Chemical Formula	Mineral Name	Intensity (Peak Area)
Calcium Carbonate ($CaCO_3$)	Calcite, Syn	1138
Calcium Oxide (CaO)	Burnt lime	960
Silicon Oxide (SiO_2)	Quartz, Syn	468
Copper Iron Sulfide ($CuFeS_2$)	Putoranite	438

For Cadmium telluride PV surfaces, it was found that the output power and the efficiency of washed and unwashed decreased by 5%, 5%, and 11.5%, respectively. During the period of the tests (from 15th/July/2020 to 12th/August/2020), there were fifty-four minerals identified with different intensities under nine main minerals as distributed in Table 7.

Based on the results, it has been shown that the cadmium telluride panel has more intensity of mineral than the polycrystalline panel. Moreover, the overall efficiency and the produced output power of the polycrystalline panel decreased further the overall efficiency and produced power of cadmium telluride at a low intensity of the main mineral. The detailed readings of the mineral intensity patterns of accumulated dust on the polycrystalline panel and cadmium telluride panel are available upon request

4.4.3 Particles Size Measurement Procedures Results

Measurements of the size of accumulated particles on the polycrystalline and cadmium telluride panels' surface within the investigated location have been carried out by using sieves. The dust particles are distributed in different sizes as illustrated in Table 8.

Table 7
X-Ray Diffraction Result of Dust on Cadmium Telluride Panel

Chemical Formula	Mineral Name	Intensity (Peak Area)
Calcium Carbonate ($CaCO_3$)	Calcite, Syn	1375
Silicon Oxide (SiO_2)	Quartz, Syn	1214
Calcium Oxide (CaO)	Burnt lime	1126
Magnesium Sulphate Hydroxide ($Mg_3(SO_4)_2(OH)_2$)	Caminite	816
Iron Silicate ($FeSiO_3$)	Clinoferrosilite, Syn	425
Iron Manganese Fluoride Phosphate $(Fe, Mn)_2PO_4F$	Zwiese	385
Calcium Aluminium Silicate Hydrate ($CaAL_2Si_2O_8$)	Gismon	337
Sodium Calcium Oxide Fluoride Phosphate (Ca6Na4 (PO_3F) $6O_2$)	NA	269
Calcium Manganese Sulfate Hydroxide Hydrate ($Ca_3Mn+4(SO_4)_2(OH)_6$ $.3H_2O$	NA	259

Table 8
Particle Sizes Distributed on Polycrystalline and Cadmium Telluride Panels

Sizes (μm)	Weight (%)	
	Polycrystalline Panel	Cadmium Telluride Panel
200	NA	42.77
150	45.88	14.26
106	45.05	7.80
75	5.75	16.65
45	3.16	15.49
38	0.15	3.03

Table 9
Electrostatic Charge Measurement Results

Panel Type	Static Meter Reading
Dust collected from Polycrystalline Panel	-1.73 kV/cm
Dust collected from Cadmium Telluride Panel	+1.34 kV/cm

Based on the results, it has been shown that the cadmium telluride panel has larger particles than the polycrystalline panel. Under the Cadmium Telluride panel, it has been found that the produced power and the washed and unwashed cadmium telluride efficiency decreased by 5%, 5%, and 16%, respectively, with particle size, almost >200μm. When it comes to the Polycrystalline panel, it was found that the produced power and the washed and unwashed efficiency decreased by 11%, 5%, and 16%, respectively, with particles size, almost >150μm. The fine dust of the polycrystalline panel decreased the transmittance of panels, and thus, decreased the total efficiency and output power more than large dust.

4.4.4 Particle Electrostatic Charge Measurement Results

A static meter is used to measure the electrostatic charge of dust for polycrystalline and cadmium telluride panels located on the investigated site (i.e. Ma'an). Results of this measurement are presented in Table (9).

The results showed that the developed cleaning method is simple by AC voltage supply (multiple-or single-phase) connected to the electrodes with the same electrostatic charge of dust measured for each type, which in turn; repulse the dust particles and avoid the accumulation of dust problems in the tested location. And thus, improving the output power production and the efficiency of panels.

On the other hand, under the large charge-dust, the panel's performed was improved where the efficiency of cadmium telluride decreased by 11.5% at +1.34 kV/cm but polycrystalline decreased by 16% at -1.73 kV/cm in the same conditions.

4.5 The Economical Study

The economic analysis is a vital tool that helps researchers and decision-makers to have a holistic view of the study conducted. The current financial analysis focuses on the effect of the accumulated dust in the PV system and its overall impact on decreasing output energy.

In this study, the calculation of the economic feasibility is based on several assumptions. This includes: the nominal power rating of the polycrystalline module=310 W from the datasheet; the nominal power rating of the cadmium telluride module=117.5 W from the datasheet; the average annual amount of sun hours in the investigated region (i.e. Ma'an) = 3510 h/year (Weather and climate average monthly, 2020). Production for one year of polycrystalline module = the nominal power rating × the average annual amount of sun hours in the investigated region = 310 W×3510 h/year =1088.1 kWh/year.

In the same way, the production for one year of cadmium telluride module = 412.42 kWh/year. A current feed-in tariff in Jordan =42 Fils/kWh per month (National Electric Power Company, 2020). Then a current feed-in tariff in Jordan per year = 504 Fils/kWh. Yearly revenue of polycrystalline module= a current feed-in tariff in Jordan per year × Production for one year of polycrystalline module=504 Fils/kWh×1088.1 kWh = 548402.4Fils, this equals JOD 548.40.

Performance drop for one month of polycrystalline module = 11% =1.32 % for one year. Cost of performance drop of polycrystalline module per year= Yearly revenue of polycrystalline module× Performance drop of polycrystalline module for one year= 548.40 JOD×1.32 = JOD723.89/module. Under this approach, the cost of the performance drop of the cadmium telluride module per year=124.71JOD/module, as the performance drop for one month of cadmium telluride module= 5%. Based on these results, it could be stated that the cost of the performance drop of the polycrystalline module per year without cleaning is larger than the cost of the performance drop of the cadmium telluride module per year without cleaning.

In major solar power projects, where large-scale PVs are installed, washing techniques can play a critical role in the overall performance and operation of the PV plants. In the case of Jordan, the country is considered among the three poorest countries worldwide in water resources, thus, innovative and environmentally-friendly washing methods (such as ESP) are required. In this context, relying on technologies that do not require the use of water will be the preferred option, which in turn; would reduce the water drain in the PVs cleaning operations and eliminate the environmental impact resulting from the cleaning operations as well. However, the technical and economic feasibility of the washing options should be intensively studied within any major solar project. In this regard, the availability of water, the environmental impact of disposing of wastewater, and the impact of the used power to operate the Electrostatic Precipitator (ESP) on the total performance of the PV plant are all among the crucial factors that should be examined. Nonetheless, investigating these factors is beyond the scope of the current research.

5. Conclusion and Recommendations

This research examined the influence of physical and chemical properties and the electric charge of the accumulated dust on the efficiency of two models of PV cells. The research provides a shred of empirical evidence from a dusty area located in the heart of the MENA region. The results of the empirical tests show a high reduction in output power and solar radiation and thus, decreasing the total efficiency. The tests were conducted over a month period of time.

The research also revealed that the polycrystalline panel is more affected by the changing weather conditions (within the investigated region) in comparison with the cadmium telluride panel. Over a month of testing, the researchers found that the high wind speed and relative humidity have more effect on the panels.

In addition, the polycrystalline panel covered by dust accumulated faster than the cadmium telluride panel. In terms of the accumulated minerals in the tested region, it has been concluded that the dust on a polycrystalline panel has a high percentage of (Ca) and (Fe) and a low percentage of (Si) whereas the cadmium telluride panel accumulated with a low percent of (Ca) and (Fe) and high percent of (Si). On the other hand, the dust on a polycrystalline panel is finer than the dust on a cadmium telluride panel. This is explained by the decreased total efficiency and output power on the polycrystalline panel more than the cadmium telluride panel. Furthermore, it was found that a large particle size has a large charge and a small particle size has a small charge.

In light of the findings, the researchers recommend collecting extra types of dust from other wide-reaching locations which, in turn, would offer a well-established database for concentration rate factors. A further collection of accumulated dust through utilizing new technologies of PV panels could provide a better database for the impact of accumulated dust on different types of PV in the investigated region. Finally, the effect of rain and frost conditions are another significant factors that require further investigation on the cleaning mechanisms and how such factors would affect the creation of several dust outlines on the PV's surface. In the long term, studying the impact of 'non-uniform' accumulated dust on different modules of PV can provide more accurate results.

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