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Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment

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A B S T R A C T

The accumulation of dust particles deteriorates the performance of solar cells and results in appreciable losses in the generated power due to the sun irradiance scattering effects on the surface of the solar panel. This study investigates the impact of dust accumulation on photovoltaic solar modules in Baghdad city in Iraq. For this purpose an experiment has been conducted to quantify losses caused by the accumulation of dust on the surface of three identical photovoltaic solar modules. The modules have been installed with direct exposure to weather conditions, in a well controlled experimental setup. Subsequently, measurements of dust accumulation on modules have been taken on daily, weekly and monthly basis. The dust density and size distribution of aerosol particles and fibers have been also investigated and measured by a highly sensitive aerosols measuring system. The dusted module and another similar clean module have been then exposed to constant radiation and constant temperature using a solar simulator as light source. The deposition of the dust on the surface of the photovoltaic solar modules showed a reduction in both the short circuit current (I_{sc}) and the output power compared to the same parameters of the clean module. The average degradation rate of the efficiencies of the solar modules exposed to dust are; 6.24%, 11.8% and 18.74% calculated for exposure periods of one day, one week and one month. The experimental results are well compared with the calculations obtained by a theoretical model recently developed by the authors.

1. Introduction

The industry of photovoltaic solar modules has grown rapidly during the last decades. The photovoltaic technological innovations succeeded to transform from laboratories' prototypes to small size applications and to commercial production, with massive quantities of modules being produced and sold all over the world. Nowadays photovoltaics are not any longer limited to household or off-grid applications since they have been already used to create mega-scale power plants, generating electricity for districts and cities in many parts of the world. Actually, at the end of 2014, the installed capacity of PVs exceeds 175 GW [19], Fig. 1. In this context, the photovoltaic levelized cost of energy is almost in parity with the cost of conventional energy sources. Recent legislation and incentives released in many countries supported the photovoltaic solar energy in leading the integration mechanism of renewable energy technologies into the domestic electricity generation sector.

As it is well accepted, the photovoltaic based systems possess numerous advantages making them attractive for small and large scale investments [11]. More precisely, these systems are long lasting, require minimum operational control, they are almost maintenance free, especially in cases with no mechanical parts, and among all they offer maximum electricity yield during peak load demand periods (i.e. summer and noon). Despite all these benefits, dust accumulation [6,14,21] and limited tolerance to overheating [7,17] restrict the expected performance of the solar cells in hot and arid areas. Both factors mentioned lower the efficiency of the photovoltaic solar cells and consequently decrease the power output and the efficiency of the photovoltaic systems.

Iraq is one of the most affected countries in the Middle East concerning the occurrences of sand and dust storms. The frequency

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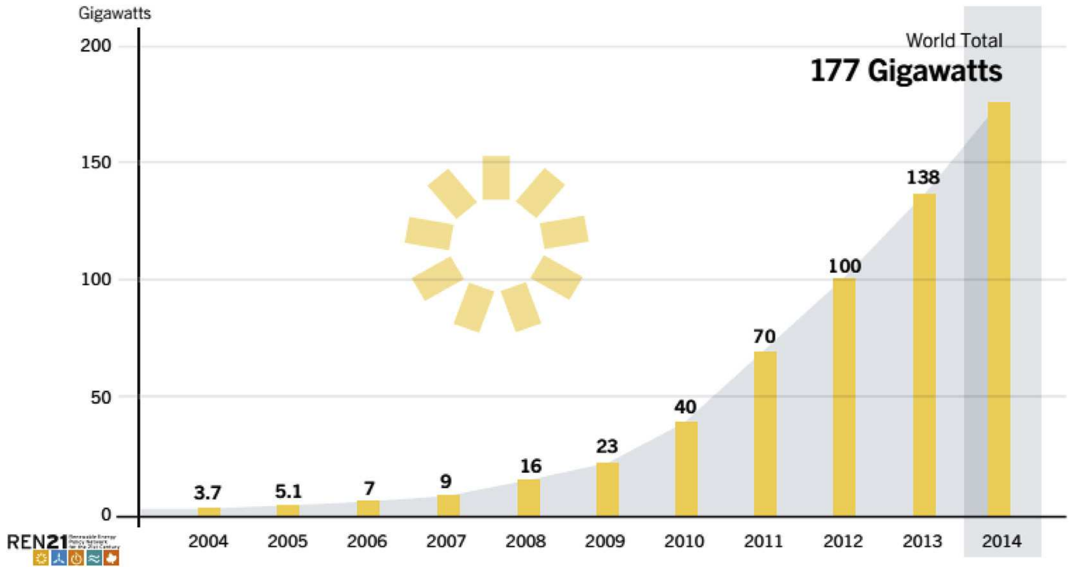

Fig. 1. Accumulated word-wide PV installed capacity time evolution [REN21].

of the occurrence has increased drastically in the last decade and it is increasing continuously. The events of sand and dust storms are either regional or local [22]. Unfortunately, the resulting dust deposition on the surface of the photovoltaic modules reduces the amount of incident radiation on the panel and creates shadow effect. More precisely, the radiation decrease leads to PV power reduction. Hence, if the dust deposition increases, the corresponding electricity generation reduces. This attenuation depends upon the dust characteristics, e.g. size of dust particle and density of the dust deposited [3,8,9,12,13,16]. Previous studies [18] and [10] showed that in dry areas, these losses could reach 15%. In such cases the only solution is to clean the modules with water. In large-scale photovoltaic plants this task is often expensive, especially in areas with water shortage [24].

One of the main problems affecting the performance of photovoltaic solar modules in Iraq and all the countries embracing the Sun Belt is the dust which accumulates on the surface of solar modules due to dust storms all through the year. Different approaches to analyze and quantify the effect of dust on photovoltaic modules have been studied by researchers investigating the impact of the exterior conditions such as; solar radiation, temperature and dust on two main parameters I_{sc} and V_{oc} (short circuit current and open circuit voltage) [4,12,15,22,23]. Nevertheless, most of previous studies mainly concerned solar thermal collectors.

Because dust and dust storms is one of the main problems affecting the performance of photovoltaic panels, it is worthwhile investigating the effects of dust on photovoltaic panels' performance. The aim of the present paper is to study the effect of dust on the performance of PV panels under normal weather conditions and under severe dust storms often appearing in the Arabic area.

Iraq is one of the countries with great potential for installing photovoltaic power plants. The country appreciates one of the highest mean annual solar radiation values all over the world, in addition to the recent political interest and support concerning revision of the energy mix and attempts for investments to establish photovoltaic operating power plants in Iraq. However, Iraq is mostly a desert region and the weather impact is regarded as key in any decision. Results of this study are necessary in order to give indications about the need for systematic cleaning as well as the duration and frequencies of cleaning schedules.

1.1. *The dust effect*

Dust events appear in many countries, normally during the summer when large amounts of dust and sand are raised and carried by the dry fresh winds. The deterioration of visibility during dust days may be due to dust lifted locally by wind and non-local dust adverted from other sources, notably from dust storms from neighboring countries.

Deserts surround most of the Arabian Gulf countries, where lands' surfaces are covered with calcareous loose sediments, which are a mixture of gravel, sand, silt and clay. The lands of these countries lack protective cover of vegetation and besides that they are also subject to strong winds. Dust and dust storms occur in all these countries almost throughout the year, with higher frequency during the summer and the spring [20]. In Iraq, dust and dust storms are not unusual phenomena since they occur in any month of the year. Such events are, however, more frequent during spring and summer seasons (March to August). According to existing data, during these six months about 75% of total annual dust events occur [1].

The extent to which the accumulation of dust has the capacity to decrease the efficiency of photovoltaic panels is still under study. In this context it is necessary to obtain accurate predictions of possible dust accumulation variation and to calculate the resulting expected drop in performance. In all these situations it is obvious that the dust effect phenomena come with serious implications that might hold utilities and investors hesitant towards similar applications.

1.2. *Justification*

The two major inconveniences related to investments in photovoltaics have been classified consequently to; effects of dust and overheating. The problem is that these two major reduction factors appear more severe in the most advantageous locations, where the highest radiation exists and thus photovoltaic modules can be installed. Typical cleaning mechanisms are not easily applicable in desert regions since they are mostly located distant from water sources. This might require transportation and storage capabilities that entail significant amounts of water in locations where water resources are scarce. Other types of water like brackish water, sea water, and waste water require treatment prior to utilization and this also increases costs. In order to facilitate analogous investments, one of the most important issues is to provide numerical evidence of the energy losses versus the amount of dust accumulated.

Summarizing, the main objective of this experimental work is to calculate the effect of dust on the performance of photovoltaic modules under the effect of severe dust storms and to compare the efficiency value with the one corresponding to normal weather conditions. For this purpose, high precision measurements of the dust parameters have been made using one high sensitive aerosol measuring system. Finally, indicative experimental data concerning the impact of the dust deposition density (g/m^2 at the panels' surface) on the panels' efficiency are favorably compared with the prediction results of a theoretical model recently developed by the authors.

2. Material and methods

The most reliable and direct way to calculate the dust impact on photovoltaic modules is by designing an experiment where the dust particles accumulated are collected on a regular basis. In the meantime, the power output of these (dust affected being in direct exposure to weather conditions) modules should be measured in comparison with the power output of exactly similar clean (without dust) panels.

2.1. Dust measuring system

In order to measure the dust density in an open air environment [5] one may use a specially scheduled measuring system. This sensitive aerosols' measuring system consists mainly of the dust photometer for continuous dust monitoring, measuring the dust density in mg/m^3 (with accuracy of 0.002 mg/m^3) and a Laser optical particle counter with fiber recognition. These two parts operate under computer control via a microprocessor control unit. Two portable dust photometers for field applications, connectable to the computer have been also used. This is in addition to the use of stationary dust sampler with programmable filter exchange, clean air box for filter handling, oven for filters drying, and sensitive scales for filter measurements. The microprocessor control unit is connected to the computer via IEEE interface which allows a full access to all addresses from the computer.

The dust photometer is used to ensure an automatic and continuous monitoring of dust density measured in mg/m^3. Laser optical photometer measures the shape and size distribution of dust particles (minimum diameter 0.3 μm, although measurements less than 0.4 μm have been neglected for increased reliability). The unit is located in the lab and it has a duct to the outside wall of the lab to suck and measure the dust particles, so the measurements are more accurate to avoid the effect of wind which leads to blow the dust particles and affect the measurement accuracy. The photometer is an advanced instrument designed for the on-spot measurements of the airborne concentration of fiber shaped and normal dust particles. The dust loaded air sample is sucked into an aerodynamic focusing system as shown in Fig. 2. By the action of the nozzle the dust particles are accelerated and arranged in line so that they can be carried across the laser beam one at a time. The output data from the laser photometer are detected through 10 main channels which are related to particle size ranges in 256 single channels in the microprocessor control unit.

In this study three identical photovoltaic solar panels (tilt angle of thirty degrees) have been installed in the Laboratory o Solar Physics (Solar Energy Research Center) Baghdad city in Iraq, latitude: 33°20′49.14″N, longitude: 44°22′34.05″E, elevation: 41.2 m above sea level. The average height of the panels was 1.8 m above ground level in order to obtain direct exposure to weather conditions. Measurements have been taken on daily, weekly and monthly basis. Each panel consisted of 33 mono-crystalline silicon solar cells; connected in series, with an active area of 70×10^{-4} m^2 per cell (Table 1). Module temperature, spectral distribution and solar radiation intensity are identical in all three panels, since a solar simulator has been used as light source. The study has been combined with dust density (mg/m^3) measurement, particle size distribution and analytical measurement of dust particles and fibers.

Measurements of voltage and current generated have been made by using a Kethly type multi-meter (RMS accuracy 99%) and the temperature of the module has also been measured using thermocouples connected to YSI 74 IC thermometer (accuracy ±0.2 °C), while the solar insulation has been recorded on Kip and Zonen (accuracy 99.5%) solar integrator connected to a printer and a sensor. The measurements have been made at constant radiation equal to 750 W/m^2 and constant temperature.

Measurements of mean dust density, total number of fibers, short circuit current, open circuit voltage, current and voltage in the maximum power point as well as the efficiency for daily, weekly and monthly exposed to dust modules are shown in Tables 2–4 respectively.

3. Results and discussion

As already mentioned, it is absolutely necessary to have a good knowledge of the dust phenomena in order to investigate the problem of dust accumulation in a photovoltaic system. For this reason, analysis of the impacts of dust and dust storms are recorded during September. Actually, September belongs to the dry months of the year with total absence of rain, i.e. zero precipitation. During the investigation period five dust storms have been observed, two of them of high dust density, while one of them corresponds to a max daily dust density of 0.13 mg/m^3, as shown in Fig. 3, time average basis of 30 min, i.e. one gathers accumulated dust samples every 30 min.

Fig. 3 shows clearly the dust storm event which started at midnight and lasted till midday. The second storm event corresponds to mean (daily) dust density of 0.049 mg/m^3. Further dust storms of low density occurring are shown in Fig. 4, which shows that there have been five dust storms during the month of measurements.

One of the most interesting findings of our measurements is the difference encountered concerning the size of dust particles' deposition on the PV panels between normal days and storm events. More specifically, in the normal conditions the corresponding size distribution is based mainly on small particles, while the biggest ones are much rarer, Fig. 5. Actually, the existence order of the dust particles appearing during normal day conditions is from small (0.4–0.5) to big particles (1.1–1.2) μm. On the other hand, during dust storms (at this specific panels' tilt angle of thirty degrees) the size of the dust particles accumulated on the photovoltaic panels' surface is quite different. Actually, biggest dust particles appear more often (Fig. 5), thus the corresponding existence order is the following: (1.1–1.2), (1.0–1.1), (0.6–0.7), (0.5–0.6), (0.4–0.5), (0.7–0.8), (0.8–0.9), and (0.9–1.0) μm. The above comparison gives an indication that the large size particles (1.1–1.2 μm) are the most dominant ones in the case of dust storms in contrast to the most dominant particle size during normal days, being in the range of (0.4–0.5 μm). According to existing studies [8], even a small amount of dust on solar cells surfaces affects the sun light transmission to the solar cells. In this context, in case of heavy dust accumulation on solar modules, high reduction of PV panels' efficiency is expected.

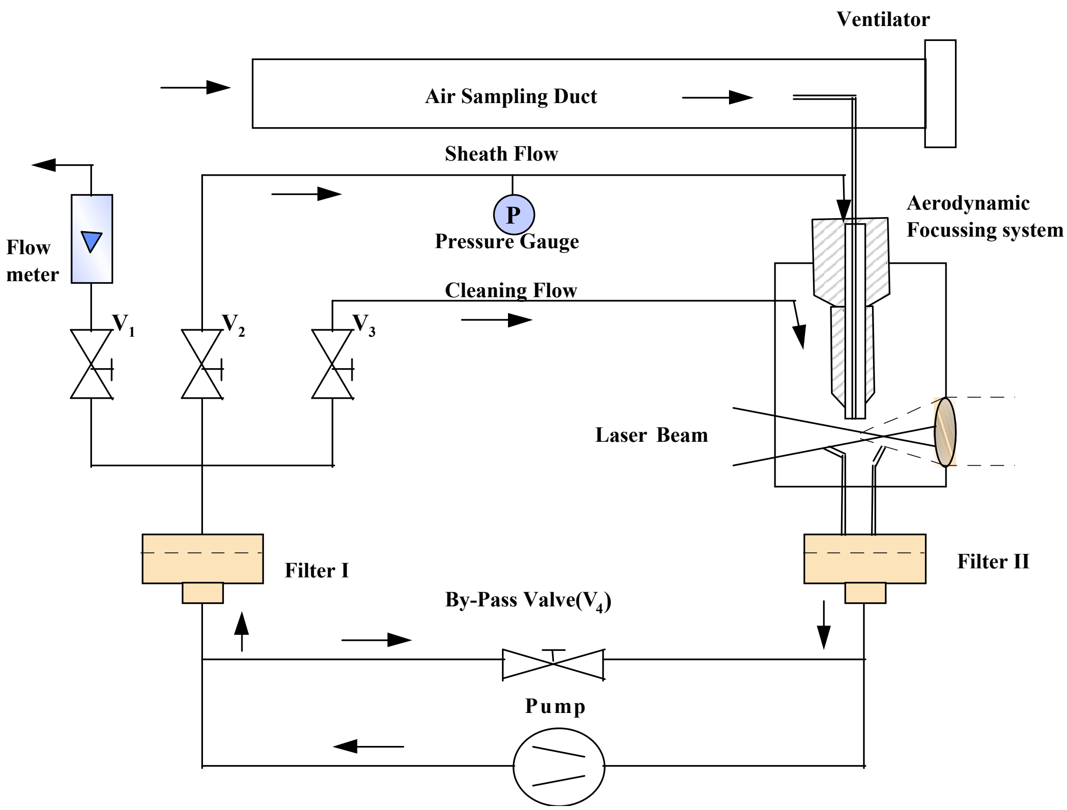

Fig. 2. Aerosol sampling system.

Table 1
Photovoltaic modules specifications.

Parameter	Photovoltaic modules specification
Orientation	South-west
Inclination	30°
Solar radiation	750 W/m^2

Table 2
Module (1) for daily measurements.

Module (1): Daily measurements		
Parameter	Module without dust	Module with dust
Mean dust density (mg/m^3)		0.412
Total number of particles		1820542
Total number of fibers		459859
I_{sc} (A)	2.22	2.14
V_{oc} (V)	17.81	17.68
I_m (A)	2.02	1.88
V_m (V)	13.21	13.37
Efficiency (%)	10.22	9.62

Table 3
Module (2) for weekly measurements.

Module (2): Weekly measurements		
Parameter	Module without dust	Module with dust
Mean dust density (mg/m^3)		0.072
I_{sc} (A)	2.20	2.0
V_{oc} (V)	17.70	17.65
I_m (A)	2.02	1.76
V_m (V)	13.21	13.56
Efficiency (%)	10.22	9.14

Table 4
: Module (3) for monthly measurements.

Module (3): Monthly measurements		
Parameter	Module without dust	Module with dust
Mean dust density (mg/m^3)		0.030
I_{sc} (A)	2.20	1.89
V_{oc} (V)	17.81	17.70
I_m (A)	1.95	1.63
V_m (V)	13.64	14.04
Efficiency (%)	10.39	8.75

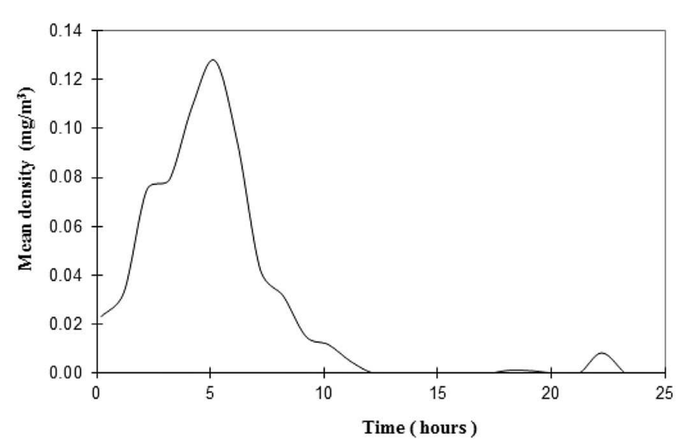

Fig. 3. Mean density in (mg/m^3) as a function time (hours) for one day measurements.

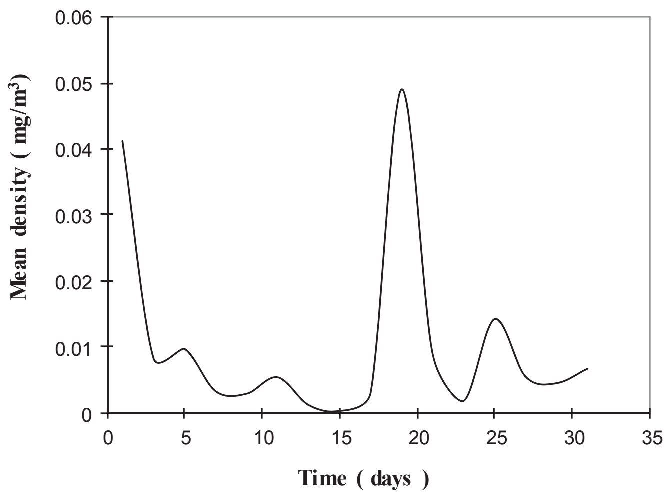

Fig. 4. Mean density in (mg/m^3) as a function of time (days) for monthly measurements.

1 day PV panels' exposure up to 16.5% for one month continuous operation in this dust affected environment, see Figs. 6–8. In the same figures one may also see the (I–V) curve of the corresponding clean panels.

On the basis of the measurements taken, see also equation (1):

$$\eta = \frac{P_{out}}{A_c \cdot G_T} = \frac{V_m \cdot I_m}{A_c \cdot G_T} \tag{1}$$

where "P_{out}", "V_m" and "I_m" is the power output, voltage and current of the solar panel at the maximum power point respectively, "A_c" is the panel's area and "G_T" is the corresponding solar irradiance (taken 750 W/m^2) in the current experiment, the power output "P_{out}" of the dust affected panels is quite lower than the clean ones for the entire operational range of the PV panels. The corresponding efficiency drop ranges from 6% up to 16.5%, leading to an analogous reduction of the expected energy yield of the dust affected panels.

Almost similar results have been reported by Ref. [8] concerning the dust impact on PV panels in a heavy polluted urban environment of Athens Greece. Of course in urban areas the air pollutants composition is rather different, since ash and limestone are also present on top of red soil mainly appearing in Baghdad, thus the energy efficiency reduction is more modest.

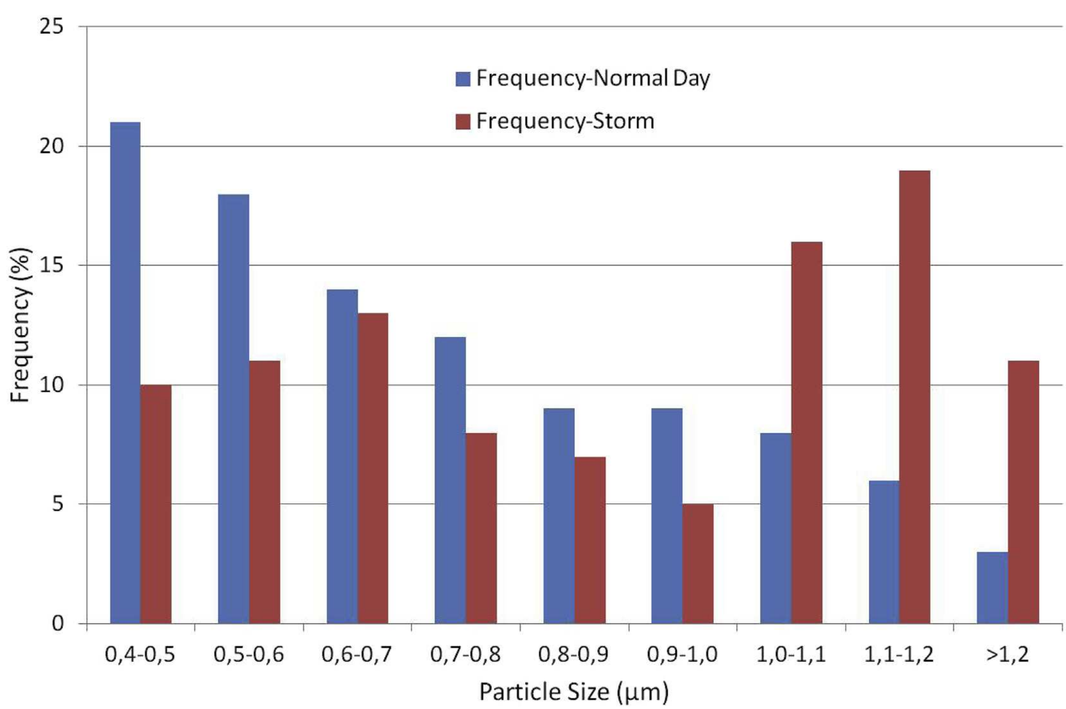

Fig. 5. Frequency of dust particles during normal days and wind storm events.

More specifically, taking into consideration the dust storm events that occurred during the measurements' period, one may investigate the Current–Voltage (I–V) relation for PV panels influenced by daily, weekly and monthly operation in the above described dust storm affected environment. For every period examined, the dusted module, which has been exposed directly to weather conditions for the entire period, and another similar clean module have been then exposed in the Laboratory to constant radiation equal to 750 W/m^2 and constant temperature equal to 27 °C, using the KX-150 solar simulator as light source (Table 1).

According to the data gathered there is a remarkable current decrease. This happens obviously due to the decrease in number of photons generating the photocurrent in view of dust accumulation [2]. More specifically, the decrease encountered starts from 6% for

Finally, in order to check qualitatively the measurements reliability, the above described data have been compared with the calculation results of the well established analytical model by Ref. [6] concerning the dust impact on PV panels' energy performance. Actually this model estimates the efficiency drop "$\Delta\eta$" of a PV panel due to the deposition of dust particles in comparison with a similar clean one operating under the same ambient conditions, taking into account the dust concentration and the dust characteristics. More precisely "$\Delta\eta$" depends on the efficiency of the clean panels "η_o", the dust concentration "ΔM" (in g/m^2) on each panel

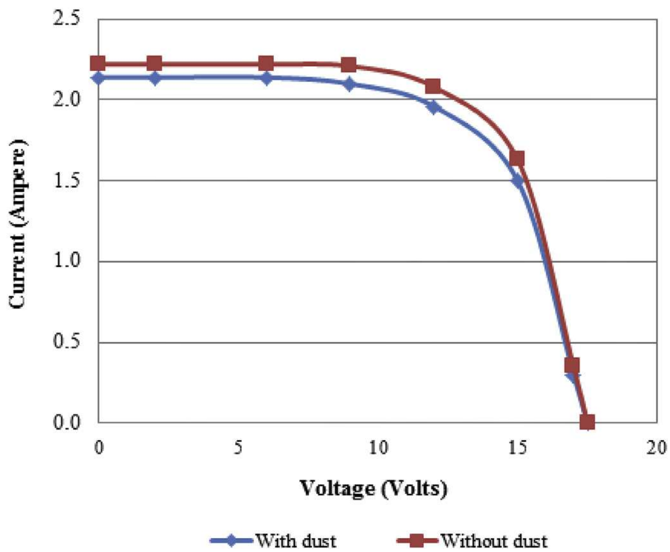

Fig. 6. Photovoltaic module Current–Voltage (expressed in amp vs. volt) variations with dust for daily panels' exposure.

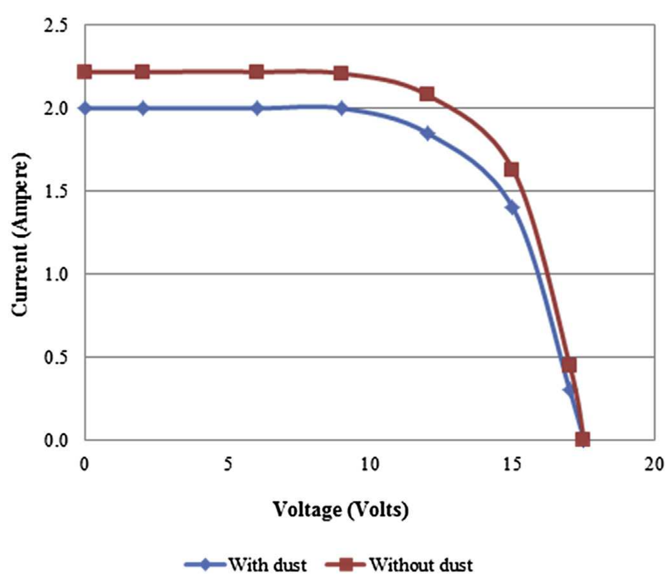

Fig. 7. Photovoltaic module Current–Voltage (expressed in amp vs. volt) variations with dust for weekly panels' exposure.

and an empirical coefficient "A" depending on the dust characteristics [6]. For Baghdad test case the red soil semi-empirical coefficient has been adopted, i.e. $A = 0.24 \pm 0.085$ (m^2/g). Furthermore, the efficiency of the clean panels is taken from Tables 2–4, while the dust deposition density (as collected from the dusted panels) is also provided in Table 5. More specifically the values of "ΔM" given in the sixth column of Table 5 correspond to dust deposition of one day, one week and one month outdoor exposure respectively.

$$\Delta\eta = \eta_o \cdot \left(1 - e^{-A \cdot \Delta M}\right) \tag{2}$$

In this context, by applying this analytical model the efficiency drop estimated is comparable with the one resulting by the measurements (Table 5). More specifically the analytical model slightly underestimates the PV panels' efficiency, although the maximum discrepancy does not exceed 15%. Moreover, the estimated

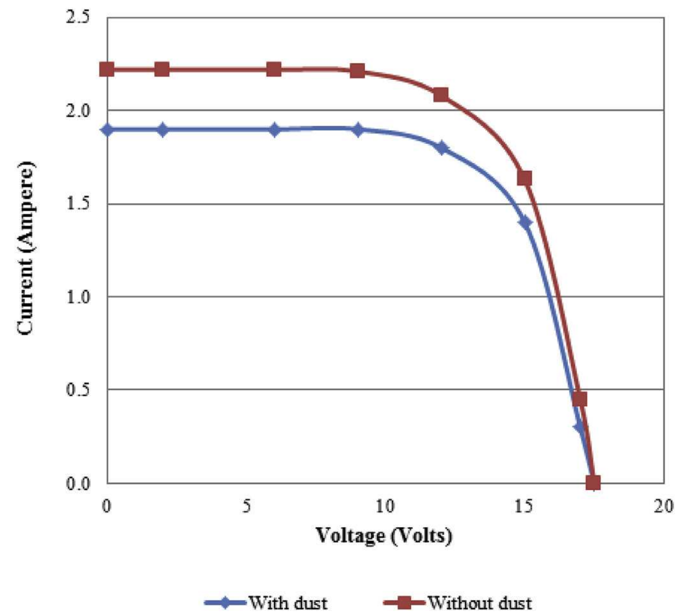

Fig. 8. Photovoltaic module Current–Voltage (expressed in amp vs. volt) variations with dust for monthly panels' exposure.

efficiency drop for the dust affected panels in Iraq is much higher (more than double) than the one encountered in urban areas (Athens, cases of natural deposition), underlining the severity of the dust impact in near desert PV installations.

Finally, similar efficiency drop has been encountered by a similar experimental analysis in Cyprus environment, where the PV panels have been exposed to dust episodes due to the dust transfer from the Sahara desert [10]. More specifically, the polycrystalline PV panels' efficiency reduction mentioned by Kalogirou during the dry period of study varies between 10% and 15% for four weeks to twelve weeks outdoor exposure, respectively. According to the results given in Table 5 the efficiency reduction of the dusted panel in Iraq (fifth column, last line) is slightly above 15% for one month outdoor exposure in the dust storms.

4. Conclusions

The negative impact of dust accumulation on photovoltaic panels implies a drop in energy efficiency of photovoltaic modules and thus a decrease of the corresponding energy yield. Using extensive and detailed real world measurements, it is concluded that the expected power output of any photovoltaic power plant is largely influenced by the accumulation of dust, especially over long time periods. If this influence is ignored, it is almost definite that strong difference will appear between the actual and the estimated energy yield of these power systems.

More specifically, the experimental results show that dust considerably reduces the maximum current from 6.9% to 16.4% depending on the time period of PV panels' exposure in dust affected environment (i.e. from one day to one month). Moreover, the experimental measurements are in accordance with the results of existing analytical models. Based on these conclusions, scheduled cleaning is recommended as an essential solution for minimizing the dust impact on photovoltaic solar panels. Otherwise, the magnitude of dust effect may be very high especially for large scale solar power plants. Choosing the right cleaning mechanism is vital in maintaining the same power output all through the life span of these solar panels. In this direction, further research should

Table 5
Decrease in short circuit current, maximum current, and efficiency of the modules.

Time of measurement	Decrease in I_{sc} (%)	Decrease in I_m (%)	Efficiency of clean panel η_o (%)	Decrease in efficiency (%)		
				Experimental data	Dust deposition density "ΔM" (g/m^2)	Calculation results
Daily	3.60	6.93	10.22	5.87	0.21	4.81
Weekly	9.09	12.87	10.22	10.57	0.40	9.23
Monthly	14	16.41	10.39	15.78	0.64	14.26

investigate the most appropriate cleaning system that might vary widely depending on the frequency, scale and cost of the cleaning mechanism proposed. Similar experiments are also recommended in potential photovoltaic installation locations. Such studies are very helpful in order to determine the extent of the dust impact in every specific location and accordingly to determine the proper cleaning schedules and mechanisms.

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