Effect of pollution and cleaning on photovoltaic performance based on experimental study

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Abstract— A practical investigation carried out at outdoor conditions in Baghdad-Iraq winter months to evaluate the effect of traffic air pollution resulted from highways on the PV cells performance. I-V characteristics, cells' power, and efficiency assessed for three cells. The results indicate that the air pollution may deteriorate the PV cell performance, even with a short period of two months of the cells' outdoor exposure without cleaning. Also, the polluted PV cells' power reduced to about 12% while the naturally cleaned cell lost about 8% compared to the clean cell.

The assaying of collected pollutants revealed high rates of hydrocarbon particulate matters resulted from traffic exhausts. PV cells' cleaning methods results indicated that using sodium surfactant as well as alcohol preserves its performance with high rates. In the same time using portable or de-ionized distilled water reduced PV cell's performance by about 14% after six weeks exposure period. The study results show that a high satisfactory possibility for using PV modules in Iraq instead of diesel or gasoline generators.

Index Terms— cell performance, cleaning detergents, dust accumulation, particulate matters, photovoltaic cells, pollutants.

1 Introduction

During the last few decades Photovoltaic (PV) applications gained serious interest; it considered as a promising renewable energy solution for intense energy supply problems all over the world. PV modules can participate considerably in a central part of the increasing energy demand [1]. Till now, this technology usage is limited in Iraq due to many operational parameters related to the country topographic and environmental conditions. On the other hand, Iraq suffers from a high rate of population increments, rapid economic development of urban areas and acute shortage in electricity [2].

Iraq is bordered Iran to the east, Turkey to the north, to the southeast the Arabian Gulf, to the south Kuwait and Saudi Arabia, and Syria and Jordan to the west [3]. Iraq lies between latitudes 29° 5′ and 37° 22′ N and longitudes 38° 45′ and 48° 45′ E in southwest Asia. Fig. 1 shows Iraq map with a total area of 438,320 km2. Iraq estimated population in July 2011 was 30,399,572 persons with a growth rate of 2.399%. Baghdad is the capital city with a population of 5.751 million persons in 2011 [4].

Iraq's mainly climate characterized as a scorching and parched in general, and exposed to solar radiation frequently. It is mostly desert climate due to its mild to cold winters and dry, hot, and cloudless summers [5]. Iraq suffered from nearly two decades of drought accompanied with a decade of war resulted in a new dust bowl appears to be formed. Nowadays, Iraq is losing irrigation water to its upstream riparian neighbors—Turkey, Syria, and Iran [6]. As a result, dust storms are taking place with progressive frequency in Iraq. Iraq's climate has to be characterized by care. Kazem and Chaichan [7] studied in details the Iraqi dust specifications and its compounds according to the location and time of the year.

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The lack of electricity supply is the fundamental obstacle in Iraq today. The electricity supply is insufficient to meet demand, and the power severance is happening daily, that made Iraqi citizens coerced to use backup diesel generators [8]. As meeting electricity demand for a continuous supply is a crucial immediate issue for Iraq's electricity sector. Iraq has excellent solar resources as an example – Iraq's average solar irradiance is similar to that in North Africa. Today, the Ministry of Electricity starts to build a number of solar research stations with a few tens of megawatts (MW) capacity [9].

The wide diffusion of PV applications depends on variable limiting factors as its high initial investment cost [10] and the limited conversion efficiency of PV cells. The main factors affecting the PV-modules' output are the solar radiation intensity, the temperature increase, and the soil and dirt accumulation on the PV-panels surfaces (see Table 1) [11], [12]. In addition to, rain reiteration, wind velocity, air humidity, and the panels' inclination [13].

The high population density in Baghdad area accompanied by about two million cars and trucks in addition to millions of electric generators emit their pollutants into the air. Al these reasons can be considered as the main causes for the increased levels of atmospheric pollution. The vast amount of combustion engines operation resulted in high concentrations of particulate matter (PM) and smoke due to fossil fuels combustion [14]. Another considerable part of air pollution referred to fine particles transferring from some deserts surrounding Baghdad city. Baghdad topography, high solar irradiance, high temperatures, low wind speed and extensive drought periods germinate the air pollutants levels over the city. The driving question of this research is to determine the air pollution influences (i.e. dust accumulation) on the PV-panels performance in Iraq. An experimental investigation was undertaken to achieve some reliable data in this field. Results, discussion, analysis and conclusions have been given in this study.

1.1 Problem statements

The annual performance of PV modules depends on its performance parameters that are the information available from

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manufacturers. This information is limited to temperature coefficients; short circuit current (Isc), open circuit voltage (Voc), and the maximum power (Pmax), at standard conditions [15]. Although this data information useful for comparing PV performance at rating conditions, it is insufficient to ratiocinate its performance under typical operating conditions [16], [17]. Many valuable published papers approved that the PV modules performance at typical conditions does not agree with its standard performance [18]. The differences between standard and typical performance are attributed to the large variations experienced in the solar incident angle, solar spectrum, operating temperature, and solar irradiance as compared to the standard conditions of 25°C cell temperature, 1000 W/m2 irradiance level, 1.5 AM, and zero angle of incidence.

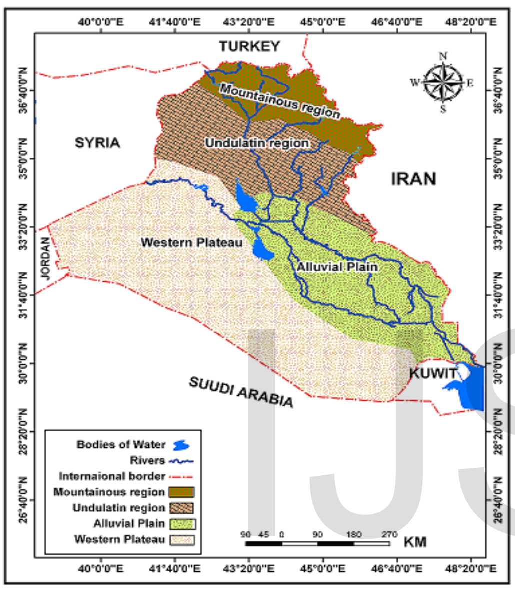

Fig. 1. Map of Iraq [2].

The PV modules as a start can be fixed on the building roofs, and many of these building dominate on streets and highways. Highways distinguished by high transportation density polluting the surrounding environment highly. If we consider that the majority of Iraq cars, buses and trucks have no permitted limits for emitted pollutants [19]. Also, million of the gasoline and diesel generators used to compensate electricity schedule cut without any emissions regulations. In addition, the Iraqi used petrol and diesel have the worst specifications. The gasoline has high levels of lead and sulfur [19]; and diesel has high levels of sulfur [20]. So, the air near highways is highly polluted and can affect the PV performance.

Concerning to the growing interest to install PV modules into the building sector, the primary aim of this study is to investigate the extent of the installation of PV modules in building near highways. The effects of dust, dirt and air pollution on the energy performance in Baghdad city region investigated too. The proposed analysis appreciates the reduction in PV performance due to the air pollution and dust accumulation on the surface of PV-panels.

As solar panels expose to ambient air; it is also exposed to the environmental condition, which may sometimes be very severe one (acid rain, pollution, snow). These parameters cause a gradual degradation in PV performance and can harm its structure. Many researchers determine the yield loss may hit up to 25% [21]. The best procedure to limit environmental effects is by proper cleaning of the PV panels to ensure their adequate operation and to increase their efficiency [22].

Many mechanical cleaning techniques are presently used to clean the PV panel service, like wiping and brushing. These methods most the time are not very efficient in removing minuscule particles and pollutants. Also, they may raise the corrosion and new impurities due to abrasion. Nowadays, there are many alternative methods that are much more suitable for cleaning PV panels [23]. As examples of the new PV panels cleaning methods: electrostatic and dielectrophoretic forces [24]; using a robotic device for cleaning PV panel arrays [25], and employing super hydrophobic nano-self cleaner [7].

The aim of the recent study is to evaluate the effect of intensive traffics carbon and vehicles exhaust emissions on PV cells performance. In the second part of this paper, the effect of cleaning method on the PV performance is studied. Of course, as the PV arrays are expected to be used to help the national grid during cut off periods for Iraqi citizens. The tested cleaning methods must be cheap and available in local markets.

2 EXPERIMENTAL METHODOLOGIES

2.1 Photovoltaic Modules

The experimental tests conducted on the roof of the extension building of Mechanical Engineering Department, resided on the campus of the University of Technology near Mohamed Al-Qasem highway (see Fig. 2). The experimental installation used in the recent study (Fig. 3) is consisting of three panels' commercially available Polycrystalline photovoltaic cells. The cells type is AMP-P 110-12 (maximum power of each panel is 110 Wp, made by Allesun, Canada (Table 1). All the PV-panels are south oriented with a tilt-angle of 30o depending on Khalifa and Abdul-Jabbar [26], and Amori and Jabouri [27] results. The tests conducted in Dec.-2014 and Jan-2015 (winter time in Iraq). The first panel (the highest one) was left to be cleaned by natural conditions (wind and rain). The middle one was left to collect dust and bird dirt and pollutants and preserved in this condition by covering it in cloudy and rainy days. The third panel (the lowest one) kept clean all the time, and it cleaned with alcohol (purity 99.9%) before every measuring day.

TABLE 1

THE MAJOR EFFECTS ON THE PV MODULE'S PERFORMANCE [12]

Effect	Range
Temperature	1-10%
Angle of incidence	1-5%
Ageing	5% over the lifetime
Soil and dirt	0-15%
Snow	Location dependent
Partial shading	Location dependent
Diodes and wiring	3%

The performance of the three PV-panels tested; the I-V

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curve for the three panels depicted for various solar irradiance densities at cell temperature around 25^{o}C. It must be mentioned that particular attention paid to test day weather conditions so that rainfall and cloudy days were avoided. For this reason, three days of each week starting from Dec-2014 ending with Jan-2015 was dedicated to practical measurement.

2.2 Measured Parameters

The electrical output of Photovoltaic panel related to variable environmental and operating conditions measured. The input information required the influence of temperature, solar radiation and incident angle on the panel's electrical output.

s output.

Fig. 2. the tests location in University of Technology camp near Mohammed Al-Qasim highway as appeared by Google maps.

These parameters must be neutralized, so only the effect of dust and pollution effects dominate.

TABLE 2
THE USED PV MODULES SPECIFICATIONS

Solar module type	APM-P 110-12
Peak power	110 W
Max. Power voltage	17.2 V
Max. Power current	6.40 A
Open-circuit voltage	21.6 V
Short-circuit current	7.0 A
Weight	11.4 kg
Dimensions	1450x 720x35
Operating temperature	-40^{o}C to 90^{o}C
Wind resistance	2400 Pa

Standard Rating Conditions for PV performance

ASTM E 1036-02 has put standard rating conditions for measuring PV performance. These typical conditions are an irradiance level of 1000 W/m2, a solar cell temperature of 25°C, and a zero deg angle of irradiance. These conditions cannot be fulfilled in practical measures, but measurement can be approached with particular proportions. A brief description of each parameter neutralizing method used to obtain its effect on the PV performance illustrated in the following paragraphs.

Temperature effect

The optimum working temperature is around 25^{o}C as ASTM E 1036-02. For this reason, the choice pertained on winter days in Iraq where the radiation and air temperature preserve the panel temperature between 23 to 30^{o}C.

Solar radiation

Iraq distinguishes with high solar radiation intensity but at winter days it reduces to medium levels but still great compared to northern countries. Solar radiation varied between 296 to 417.5 W/m^2. These values must be taken into consideration when output power is measured compared to standard ASTM E 1036-02 values.

Incident Angle Function

The angle of incidence of the sun's irradiance must be normal to the photovoltaic module's surface. Under the clear sky conditions as in the recent experiments, the incident angle effect has a pronounced influence on the PV output. In this work, the angle of incidence was fixed as mentioned before on 30o toward south as claimed by reference [28].

Testing the accumulated dust and pollutants

At the end of each month of the trial period, 10 grams of the accumulated dust and pollutants on the panel 1st and 2nd panels were collected and inspected in the laboratories of Science collage-Baghdad University. The pollutant collection procedure used to verify systematic measurements. Different pollutant mass deposi-

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tions were examined hydrocarbon ones mainly. Tessier Procedure was used to check the dust and pollutants constituents [29]. A 1g of each sample placed in a 50ml tube and was exposed to reagents and shaken well. The sediment rinsed with 8ml of distilled water and centrifuged again. Then, a 1g of the sample was exposed to 12ml of 5:1 HF-$HClO_4$ acid mixture and left to evaporate to near dryness. Another 10:1 HF-$HClO_4$ acid mixture was added again to the sample, and also the sample evaporated to near dryness. The process continued by adding 1ml of $HClO_4$ and evaporated the mixture until white fumes are visible. The resulting fume added to 12ml of NHCl and diluted with distilled water to 25ml [30], [31]. The digested solution was analyzed at Analyzing Department, Baghdad Environmental office as the following:

- PH measurement
- Ketones and ions in the sample.
- Calcium determination by EDTA method.
- Magnesium determination by calculating the difference between total scales and Calcium.
- Sulfurs determination by using scales equipment (turbidity meter).
- Sodium determination by using flame photometer.
- The heavy metals determination using atomic absorption device in the range of every wavelength for each element entering standard known lengths.
- Hydrocarbon emissions using GSP (Fuel laboratory, MED).

Cleaning detergents used in the study

As the study conducted for Iraq conditions, the cost must be taken into consideration for average income of most Iraqi peoples. For this reason, three available with suitable price level substances were used in the study. Deionized distilled water with 1/4 dollar price per bottle in the local markets. Alcohol (99.9% ethanol) with 3 dollars/ liter in the local markets, and finally cleaning detergent named Easy (glass cleaner) consist of water, isopropanol, sodium loraith sulfide, ammonia, odors and color (C.I. 42000). This detergent price is 1.5 dollars for the refill flask of 825 ml.

Test procedure

The study aimed to determine the impact of the location near highways on three mentioned PV panels. In addition to the dust accumulation, many hydrocarbons resulted from cars exhaust system as well as other components resulted from fossil fuel combustions, like sulfur and lead compounds were studied and analyzed.

The experimental procedure carried out to compare the energy yield and conversion efficiency of three panels (located in the same area) with three different conditions:

1- First one cleaned by natural factors as wind and rain.
2- Second one left to dust and pollutant accumulation and prevented from cleaning.
3- Third one cleaned before each test with alcohol.

The tests lasted for Dec-2014 and Jan-2015, and then the cleaning procedure effect was studied starting from 1/2/2015 till 15/3/2015. The three panels cleaned before every Sunday at the beginning of the measuring week. Each board cleaned with one type differs from the rest. The first one cleaned with distilled water, the second with alcohol and the third one with Easy detergent. The energy output of three panels measured, recorded and compared.

3 Results and Discussions

Fig 3 shows the PV modules group used in the study after two weeks from exposure to outdoor conditions. The select of the measurement time was due to it is the rain season in Iraq that gives useful indications of natural cleaning effect on PV performance.

Fig. 3, the used PV cells group.

Fig. 4 represent a photo of two modules the higher is the natural cleaning one after 24 hours of a rainy day, and the lower represents the dirty one. The figure reveals that after one day of rain there are many white precipitates. These white precipitates are traces of residue limestone.

Fig. 4, Natural cleaning cell (the higher one) and polluted cell (the lower one)

Fig. 5 manifests a photo of two modules the higher is the dirty one while the lowest is the clean one. The figure shows the effect of two weeks from exposure to ambient conditions. The dirty module colored with light black color resulted from

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hydrocarbon particulate matters participate.

Fig. 6 represents the I-V characteristics of the three used cells. The figure curves clarify that the cleaned cell produced the maximum current and voltage while the polluted one produced the minimum I-V. Leaving PV cell for natural cleaning caused a regain of a part of the lost I-V. The reduction in I-V characteristics measured was 7.62 and 11.87% for naturally cleaned and polluted cells respectively compared with cleaned cell.

Fig. 5, Polluted cell (the higher one) and polluted cell (the lower one)

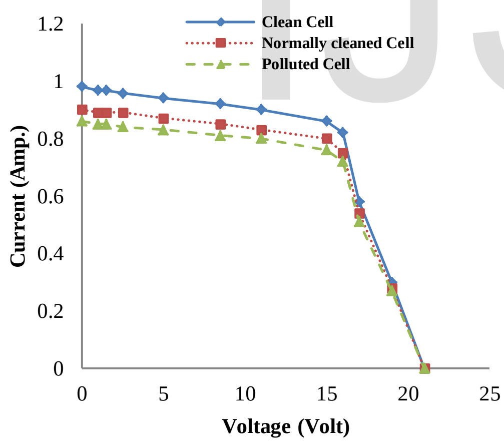

Fig. 6, I-V characteristics for the tested PV cells with load

The produced I and V results in the power, as Fig. 7 manifests. The cell power reduced with pollution accumulation as well as with naturally cleaned. The PV cell power obtained at variable irradiance intensities. At any given irradiance the power calculated and for a measured current and voltage the maximum power is obtained. The power reduction rates equal the rates mentioned above as it results from multiplying I with V.

Fig. 8 reveals the efficiency of the used cells. The cleaned cell had an average efficiency rate of 4.82%; the naturally cleaned cell had an average efficiency rate of 3.233%. The polluted cell average efficiency rate was 1.749%. An overall decrease in efficiency of 63.7% for polluted cell compared with the cleaned one. This decrement referred to one or a combination of factors that include pollutants accumulation; and increasing ambient temperature and solar irradiation. The tests time selected that the ambient temperature did not exceed 25ºC, but that did not curtail its effects especially at the end of February days.

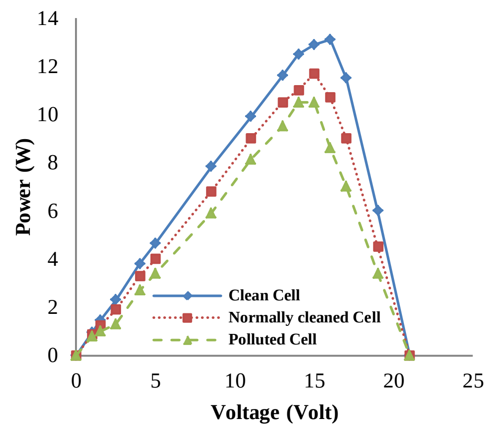

Fig. 7, the resulted power vs. voltage for the measured PV cells with load

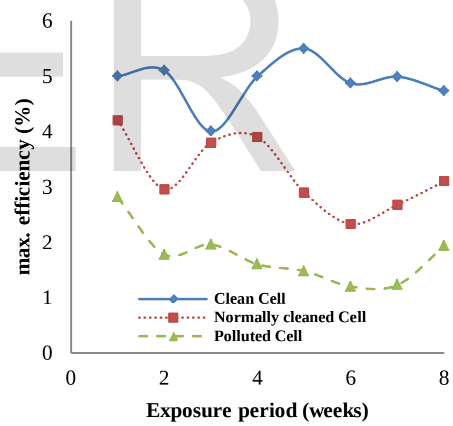

Fig. 8, I-V characteristics for the tested PV cells with load

The extreme points in Fig. 8 clarify the effect of the fluctuating in solar radiation hitting the cells. Since the cells tested at local weather fluctuation, the variation in solar radiations varied with time, as well as, the ambient temperature. In other hand, the equation (1) used to evaluate the maximum power values was using the calculation of efficiency as instantaneous values while the solar radiation values averaged for a period. These differences produce some of the inaccuracies in the effectiveness values where the sun radiation alters in few seconds and minutes.

$$\eta = \left(\frac{P_{max}}{(GHI \times Area)}\right) \times 100\% \quad (1)$$

Where Pmax, GHI, and area are the maximum power delivered, global horizontal irradiation, and PV panel area, respectively. Fig. 9 shows the effect of daytime in hours on Open-Circuit Voltage (Voc). The Voc is affected directly by the amount of solar radiation reaching the PV cell and its cleanness. Polluted cell Voc degraded highly compared with cleaned cell while natural cleaning by rain and wind recovered a part of the lost voltage.

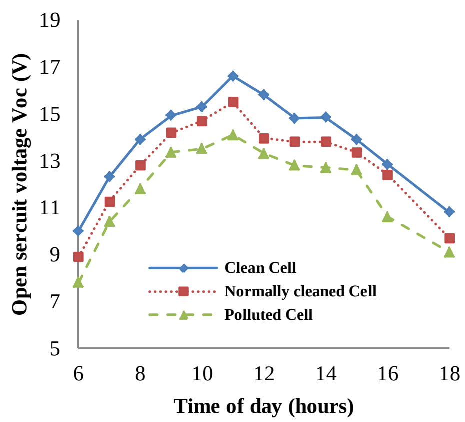

Fig. 9, the effect of daytime on the resulted open circuit voltage for the tested PV cells with load

The same condition can be said about the resulted short circuit current (Isc) with days progression, as Fig. 10 states. The high reduction in Isc amperes weather for polluted or naturally cleaned with time confirm the necessity for proper cleaning to retrieval the required I-V.

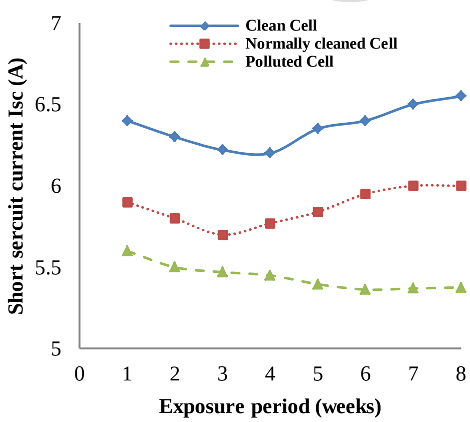

Fig. 10, the effect of the exposure period on the short circuit current for the tested PV cells with load

Fig. 11 illustrates the effect of day's progression on the tested PV cell weekly average maximum power. For the cleaned cell, the maximum power/week increased apparently at February weeks due to higher solar radiation. February higher solar radiation did not benefit the polluted and naturally cleaned cells.

Dust accumulation in the tested cells expected in a dusty weather like Baghdad city. Pollutant accumulation in the established cells was in general uniform, formalized a thin dark gray pollutant layer by the end of the week. It affects the cells efficiency by reducing the solar radiation intensity that reaches it. The problem studied in the recent article is not the dust accumulation effect as well as pollutants accumulation on PV cells surfaces. Pollution includes in addition to the dust all the suspended particles that include metallic, hydrocarbon particles in addition to sulfur. Table 3 represents the result of checking the accumulated pollutants on the polluted cell. The table shows that a significant value of particulate matters accumulated on the cell surface. PM accumulation confirms that highways traffic pollutants affect the PV cell performance. The problem lies in the size of the accumulated PM. The large particle sizes can be cleaned while the nano-sized ones are difficult cleaning.

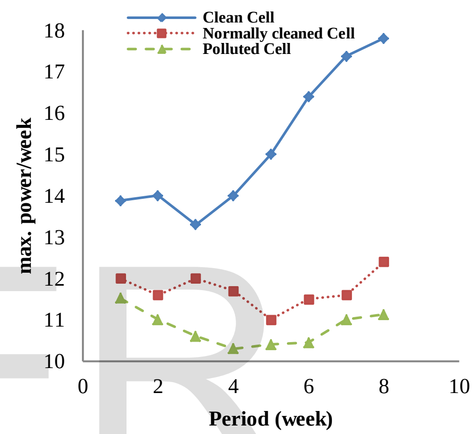

Fig. 11, the effect of the daytime on the resulted open circuit voltage for the tested PV cells with load

Fig. 12 illustrates a photo for dry anointing with white paper enlarged using electronic microscope. The silica particles appeared in white color while the particulate matters in black one. The yellow and green colored particles represent metallic particles.

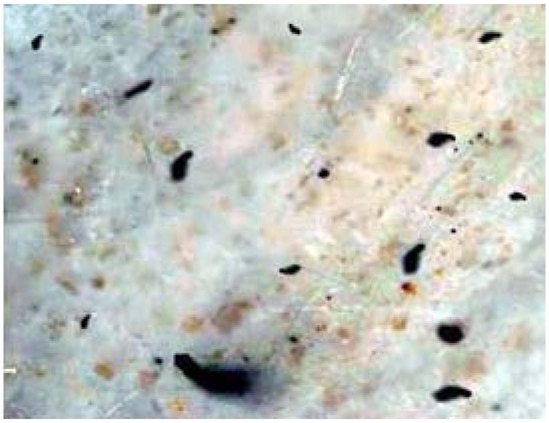

Fig. 12, a photo of microscopic enlargement of a dry wiped paper to check the accumulated pollutants

TABLE 3

ACCUMULATED POLLUTANT COMPOUNDS SPECIFICATIONS

Pollutant type	Testing method or device	Naturally cleaned Percentage	Polluted percentage
Silica	atomic absorption device	95.472	95.87%
Cement	atomic absorption device	1.4	2.12%
Hydrocarbon	GSP device	1.11	1.38%
Sulfur	scales equipment (turbidity meter)	0.078	0.186%
Limestone	EDTA method	0.91	0.39%
Sodium	flame photometer	1.03	0.054%

Fig. 13 shows the effect of cleaning method on the tested PV cells. Cleaning the cell with the sodium surfactant stabilized its efficiency significantly with efficiency loss less than 1% for two months exposure for environmental conditions. The same thing said on cleaning the cell with alcohol except about 0.1% reduction in the cell efficiency. Using the water as cleaning detergent reduced the cell efficiency with the exposure period progression with about 14% for two-month operation. Water failed in cleaning the small particles (that are in nano scales) especially carbon ones. Author of reference [31] claimed that greater reduction in the short circuit current (Isc) of a PV cell caused by smaller particles than larger particles when the pollutants coverage measured in g/m^2.

Some of the accumulated pollutants bonded intensively on the PV cell surface that requires some pressure accompanied with a soft wet cloth material on the cell surface depending on the amount of accumulated pollutants. The exposure period progression caused higher accumulations on the cell surface that reduced the reception of the incident solar radiation. The cleaning with alcohol and sodium surfactants weekly proved the ability on preserving the PV cell performance at near maximum performance region.

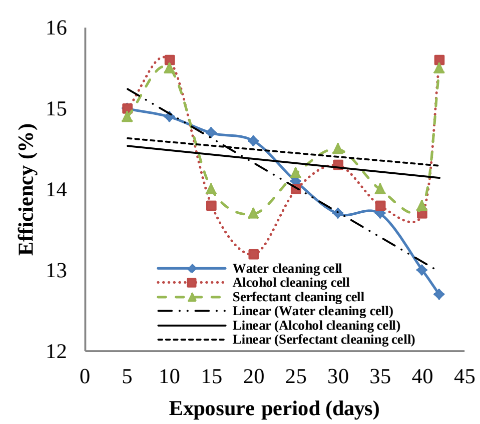

Fig. 13, the effect of the exposure period on the tested PV cells efficiency for variable cleaning detergents

Indeed, using PV modules in Iraqi citizen houses or in government buildings considered as quality prosperity in using alternative energies for electricity generation. The recent study results indicate that the high environmental pollution has a moderate effect on the PV arrays performance. Excluding the PV arrays parts and assembling costs, cleaning costs such as detergents and cloth are tiny for weekly or two weeks period cleaning. The possibilities of using PV cells on the domestic level seem very favorable to Iraq.

4 CONCLUSIONS

An experimental investigation was carried out during a period of four months (i.e. starting from December 2014 to the end of March 2015) to evaluate the effect of traffic air pollution resulted from highways in the PV cells performance. The tests conducted in University of Technology camp near a high dense traffic Mohammed Al-Qasim highway in Baghdad city. The performance of three PV cells, all south oriented and adjusted at 30o inclination, was investigated. The effect of air pollution and cell cleaning were tested. The obtained results indicate that the air pollution may deteriorate the PV cell performance, even with a short period of two months of the cells' outdoor exposure without cleaning. The polluted PV cells produced power reduced to approximately 12% compared to the clean cell. While the naturally cleaned cell lost about 8% compared to the clean cell. The maximum power/week increased for the cleaned cell, compared to the polluted and naturally cleaned cells. The collected pollutants inspections clarified high rates of hydrocarbon particulate matters that resulted from cars exhausts.

PV cells' cleaning methods results indicated that using sodium surfactant as well as alcohol preserves its performance with high rates. In the same time using portable or de-ionized distilled water reduced PV cell's performance by about 14% after six weeks exposure period. The study results give optimistic picture for the possibilities of using PV modules in Iraq instead of diesel or gasoline generators.

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