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Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements

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ABSTRACT

One of the least analyzed side effects of atmospheric air pollution is the degradation of PV-panels' performance due to the deposition of solid particles varying in composition, size and type. In the current study, the experimental data concerning the effect of three representative air pollutants (i.e. red soil, limestone and carbonaceous fly-ash particles) on the energy performance of PV installations are analyzed. According to the results obtained, a considerable reduction of PVs' energy performance is recorded, depending strongly on particles' composition and source. Subsequently, a theoretical model has been developed in order to be used as an analytical tool for obtaining reliable results concerning the expected effect of regional air pollution on PVs' performance. Furthermore, experimental results concerning the dust effect on PVs' energy yield in an aggravated – from air pollution – urban environment are used to validate the proposed theoretical model.

1. Introduction

Photovoltaic (PV) technology is gaining worldwide interest during the last years and is intended to play a key role in creating a sustainable energy future by using an infinite and accessible to everyone energy source like the sun. Particularly, the cumulative installed PV capacity has more than doubled since 2007, reaching almost 21 GW in 2009 (see Fig. 1) [1]. Currently, PV systems operating all over the world are mostly met in central grid power stations and grid-connected roof-top or facade installations (i.e. Building Integrated Photovoltaics) [2,3] as well as in individual consumer applications and small scale stand-alone systems in remote areas (e.g. small solar water pumps) [4].

Nowadays air quality is considerably aggravated by infectious suspended particles [5–7] that may be directly emitted from both human and natural processes or formed in the atmosphere, i.e. sulphur oxides (SO_x), volatile organic compounds (VOCs), oxides of nitrogen (NO_x) and ammonia (NH_3) [8]. Despite the considerable number of measures [9] (e.g. introduction of natural gas into domestic and industrial sector, replacement of the old passenger cars, introduction of gas powered city buses, etc.) implemented in many urban areas such as the Greek capital, Athens, high concentration values of particulate matter (PM) consisting of finely subdivided solids or liquids such as dust (e.g. particles deriving from civil construction activities), fly-ash, smoke, aerosols and condensing vapors are measured at the downtown monitoring sites [10–12]. In this context, even though there are numerous scientific surveys concerning the photochemical and the PM air pollution, the problem still constitutes a vast and multilateral issue.

On top of the negative consequences on human health and on aquatic and terrestrial ecosystems, the air pollution may cause a wide range of damage to materials (e.g. cars, buildings, machines, etc.) due to dust deposition on their surfaces which may lead to erosion [13] and thus to surfaces' degradation. Furthermore, the presence of dust may negatively influence the energy performance of solar technologies such as PVs [14] and solar collectors [15]. This problem was first designated and analyzed some years ago in studies concerning the energy support of space missions. In this context, the reduction of the efficiency of PVs due to dust accumulation on their surfaces constitutes a subject of a number of studies [16,17].

In the current study, based on the results of previous experimental investigations [18,19] concerning the impact of urban air pollution on PVs' performance, an attempt is made to develop an appropriate theoretical model for simulating and displaying the major effects that the naturally deposited particles on PVs' surfaces have on the energy yield of PV generators. Usually, dust deposition on PVs' surfaces is washed out by the rain, but there are many places globally where the dry season lasts for remarkable time

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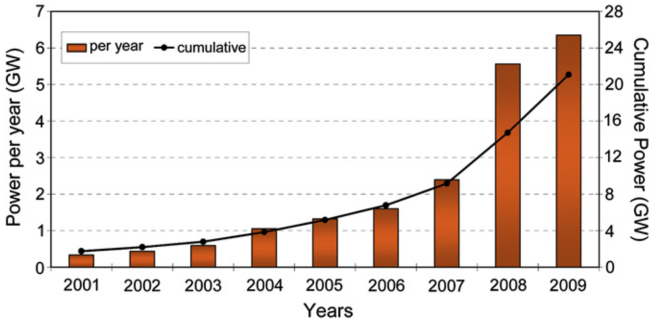

Fig. 1. Cumulative and annual PV installations globally.

periods. For instance, in Greece and particularly in the city of Athens, the dry season may last for about three to five months (including summer), and as it has already been experimentally investigated [20], the natural-urban dust deposition on the panels' surfaces may cause the PVs to operate at a lower performance, i.e. almost 0.5% efficiency reduction in absolute terms.

The dust effect is considered site-dependent, i.e. it is strongly related to the local air pollution of the area where the PV system is installed, thus making it unreliable to apply a general model in all cases. For that reason, three, commonly met in urban and other environments, types of air pollutants (see Fig. 2) are selected and their effect on PVs' performance is determined based on experimental measurements [19]. Firstly, a common urban air pollutant, limestone, which is formed from the precipitation of calcium carbonate ($CaCO_3$) and is mainly used for civil construction activities, is examined [21]. Secondly, red soil, resulting from dry terrain or attributed to trans-boundary transfer of dust from African deserts [22], is investigated [23] and finally, carbonaceous fly-ash, mainly originating from the incomplete combustion of hydrocarbons (H/C) in thermal power stations or emitted from vehicular exhausts, is studied [24]. Note that the examined masses of the pollutants do not contain particles of particular size (only a diameter range is specified) so that the conditions of the experiment can better approximate the natural dust deposition on PVs' surfaces [18,20].

2. Position of the problem

According to already published results, a considerable impact of the air pollution on PV-panels' and solar collectors' normal operation is reported during the recent years [14,25,26]. PVs' performance may be considerably affected when dust particles are deposited on the panels' surfaces mainly because the presence of dust contributes to the reflection of the incident solar irradiance on the PV-cell, whereas, in several cases temperature dissimilarities due to cooling differences of the PVs' surfaces have been observed [14,27]. As a result of the above, a significant change of the PV-panels' current intensity and voltage output is expected, leading to a remarkable energy generation (or efficiency) reduction and a considerable annual loss in revenues [28].

The degradation of PV-cells' performance when solid micro-particles are deposited on their surfaces has been investigated by Letin et al. [29]. The equivalent shunt and series resistances of a PV-cell are strongly influenced under the impact of degradation, leading to a reduction of the PV-panel's Fill Factor (FF) [30]. In relation to the micro-particle structure and the effect of degradation, the decrease of the shunt-series resistances varies [29]. Accordingly, the efficiency of the PV-cell is also affected. The relation of natural dust deposition on PVs' surfaces with the corresponding voltage output under various PV-panels' tilt angles has been experimentally investigated by Kappos et al. [27]. The results showed that the particles' deposition is directly proportional to the inclination of the PV-panels.

In an attempt to quantify the impact of dust deposition on PVs' surfaces, values reaching up to 15% efficiency reduction have been reported [31], although it has been pointed out that the effect is site-specific [14,32], i.e. depending mostly on the local climate conditions as well as on topographical factors and the terrain's synthesis of the area where the PV installation exists [21]. Particularly, particle existence, humidity, rainfalls, ambient temperature and solar irradiance differ a lot from region to region and thus make it quite difficult to generalize the impact of air pollution on PVs' performance in a qualitative and quantitative manner. For instance, humidity causes the formation of a dew layer on the cover of the PV-panel, thus implying higher levels of adhesion for the dust being deposited on the PV-panels' surfaces [33]. In this context, in the heavily aggravated from air pollution urban areas, the dust and solid particles' (i.e. mainly by-products of fossil fuel combustion and construction related activities) deposition on panels' surfaces may cause up to 6.5% power output reduction even after a small period of time (i.e. two months) of PVs' exposure into the atmospheric air pollution without cleaning [20].

Based on the above, the current study is focused on the development of a relatively simple but reliable and easy to apply theoretical model for simulating and displaying the effects of the natural air pollution on PVs' performance by taking into consideration experimentally measured data concerning the impact of several – commonly met in urban and other environments – air pollutants (i.e. carbonaceous fly-ash, limestone and red soil particles) on the operational characteristics of a PV-panel.

More specifically, the energy conversion efficiency "η" of a PV-panel is expressed as the ratio between the generated power "P_{out}" and the incident solar power "P_{solar}" available on the collector's surface "A_c". Thus,

$$\eta = \frac{P_{out}}{P_{solar}} = \frac{P_{out}}{A_c \cdot G_T} = \frac{U \cdot I}{A_c \cdot G_T} \tag{1}$$

with "G_T" being the corresponding total solar radiation. In this context, one needs to measure the corresponding current "I" and voltage "U" output (normally comprising a function of time "t") in order to calculate the generated power of the installation.

Fig. 2. The three types of pollutants used in the experiment.

3. Experimental data analysis

In order to determine the impact of the three selected air pollutants on PV-panels' performance, an experimental procedure is carried out in order to compare the energy yield and conversion efficiency of two statistically checked identical pairs of PV-panels (located at the same area) both being south oriented and adjusted at the same inclination. The experimental analysis is conducted in the Laboratory of Soft Energy Applications & Environmental Protection (SEALAB) located at the campus of the Technological Educational Institute of Piraeus (TEIP). On the basis of the experimental procedure the following parts of the laboratory's roof-top installation [34] are used:

- two pairs of PV-panels (maximum power of each pair 102 W_p and collectors' area 988 mm × 448 mm), of poly-Si, each one composed by two panels connected in series,
- a monitoring station,
- a control panel,
- a lead-acid battery storage system,
- a DC/DC charge controller (1 kW rated power),
- electrical loads (lighting and a water pump).

The experimental procedure is described in detail in previous works by the authors, see for example Refs. [19,21], thus a systematic and detailed series of measurements was taken from the two identical pairs of PV-panels, the one artificially polluted with the selected pollutant and the other kept clean. In this context, the dust deposition density "ΔM" is expressed (in g/m^2), via the PV collector area "A_c", as:

$$\Delta M = \frac{\Delta m}{A_c} \qquad (2)$$

where "Δm" is the total mass of dust layer on the surface of the polluted pair of PV-panels. The experimental procedure was carried out under clear sky conditions while at least 30 measurements were recorded within the time period examined (approx. 1 measurement per 120 s).

Based on the recorded measurements, the I and U values of both the polluted and clean pairs of PV-panels were first determined while at the same time the solar radiation (W/m^2) was recorded at the horizontal plane and at the PV-panels' surface by utilizing two Kipp & Zonnen pyranometers, LiCor type. During the experimental procedure the PV-panels remained south oriented and adjusted at 30° inclination. The pollutant's mass deposition density (g/m^2) on the polluted pair panel was specified for each examined case and its effect on the energy yield and the conversion efficiency of the two PV-pairs was determined. At this point, it is worth mentioning that the pollutant amounts were selected so that a variety of systematic measurements could be achieved. For that reason, based on the experimental measurements carried out, different pollutant mass depositions were selected, i.e. values being between 0.12 and 0.35 g/m^2 for red soil (I), 0.28 and 1.51 g/m^2 for limestone (II), 0.63 and 3.71 g/m^2 for ash (III) (see Table 1). Note that each time the panels were polluted uniformly with sprayed water containing sieved particles of a particular diameter range (see Table 2).

Table 1
Pollutant mass deposition densities in g/m^2.

Pollutant Class	Red soil (I)	Limestone (II)	Ash (III)
ΔM_1	0.12	0.28	0.63
ΔM_2	0.22	0.33	2.08
ΔM_3	0.26	0.77	3.11
ΔM_4	0.35	1.51	3.71

Table 2
Particles' diameter range.

Pollutant	Diameter (μm)
Ash	≤10
Limestone	≤60
Red soil	≤150

Proceeding to the results obtained, Figs. 3–5 illustrate the energy yield (Wh) of the clean "E_{cl}" and the polluted "E_{pol}" pair of PV-panels for the highest and the smallest recorded red soil, limestone and ash mass deposition density respectively. For instance, the smallest red soil mass deposition (i.e. $\Delta M_1^I = 0.12$ g/m^2) may cause the energy yield of a PV-panel to be reduced from almost 85 to 82 Wh within 1 h while if almost tripling the pollutant mass (i.e. $3 \times \Delta M_1^I \approx \Delta M_4^I$) the energy yield drops approximately from 63 to 58 Wh (see Fig. 3). Note that the measurements with different levels of dust on PVs' surfaces were not carried out simultaneously thus justifying the presence of different solar radiation values during the results analysis. Following, in Fig. 4 one may obtain the corresponding energy reduction due to limestone particles' deposition on PVs' surfaces, varying approximately from 3 to 7 Wh for particles' accumulation ranging from 0.28 g/m^2 to 1.51 g/m^2 respectively. Finally, as it is depicted in Fig. 5, the smallest recorded ash mass deposition density (i.e. $\Delta M_1^{III} = 0.63$ g/m^2) causes the energy yield to drop almost negligibly, i.e. from 44 to 43 Wh, while if considering six times the pollutant's recorded initial mass (i.e. $6 \times \Delta M_1^{III} \approx \Delta M_4^{III}$) the energy yield between the clean and the polluted pair panel within 1 h reduces by almost 12 Wh.

At this point it is important to mention that the utilization of the installation (peak power "P_p") capacity factor "CF" (i.e. the ratio between the actual and the rated output over a period of time), defined for a given time period "Δt" as:

$$CF = \frac{E_{\Delta t}}{P_p \cdot \Delta t} \qquad (3)$$

may be more convenient for further analysis, nevertheless the authors currently decide to present the energy yield distributions in order to improve the understanding of the physics of the problem.

According to the results, it is obvious that the presented reductions in the energy yield between the two pairs of PV-panels imply the deterioration of their performance when dust particles – of several compositions – are deposited on their surface. This performance deterioration is also statistically validated [19]. Furthermore, it is safe to say that the deposition of each pollutant causes quite different effects on PVs' performance. Fig. 6 summarises the

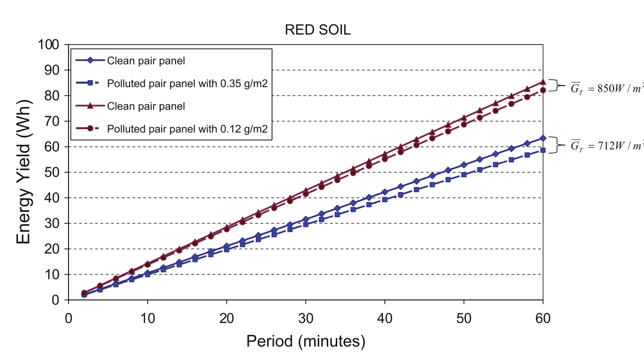

Fig. 3. Energy yield of the clean pair panel compared with the polluted one for the highest and the smallest recorded red soil mass deposition density.

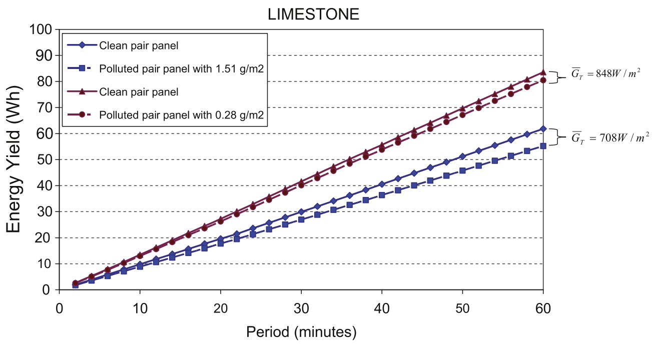

Fig. 4. Energy yield of the clean pair panel compared with the polluted one for the highest and the smallest recorded limestone mass deposition density.

resulting capacity factor (or energy yield) reduction percentages between the clean "CF_o" and the polluted "CF" pair panel as a function of different mass deposition densities of red soil, limestone and carbon-based ash. In this context, the corresponding capacity factor (or energy yield-see also Eq. (3)) reduction percentage for each examined case is expressed as:

$$\Delta(CF) = \frac{CF_o - CF}{CF_o} \times 100 = \frac{E_{cl} - E_{pol}}{E_{cl}} \times 100 = \Delta E \qquad (4)$$

Based on the results depicted in Fig. 6, there is a strong indication that in comparison to the other two pollutants, red soil (I) deposition on PV-panels' surfaces leads to a much greater capacity factor or energy yield decrease. In fact, it seems that the generated energy is significantly reduced by the red soil deposition, while the effect is slightly smaller for limestone (II) and considerably smaller for carbon-based ash (III). Particularly, mass $\Delta M_4^I = 0.35$ g/m^2 (red soil) causes almost the same impact (i.e. 7.5% energy reduction) with mass ΔM_2^{III} (ash) but ΔM_2^{III} is about six times greater than ΔM_4^I. Additionally, an amount of only 0.12 g/m^2 (ΔM_1^I) of red soil may cause the energy production to drop by almost 4% of its normal value under clean conditions, while almost the same energy reduction may be caused if 0.28 g/m^2 (ΔM_1^{II}) of limestone particles are deposited on PV-panels' surface. Red soil mass ΔM_3^I causes almost the same energy reduction (i.e. 6%) with mass ΔM_3^{II} (limestone), although ΔM_3^{II} is three times greater than ΔM_3^I. Finally, masses ΔM_4^I and ΔM_2^{II} are almost the same but ΔM_2^{II} causes about half the energy reduction that ΔM_4^I does.

4. Theoretical simulation model

As a result of the aforementioned analysis, the presence of dust particles on the surface of PV-panels surcharges their energy performance, the rate of which depends strongly on the type of the pollutant. At this point, an attempt is made to simulate the PV-panels' energy yield (or capacity factor) drop on the basis of the air pollutant type (i.e. red soil, limestone and flying ash) and the corresponding specific mass deposition "ΔM". In order to develop a reliable and practical relation an exponential function of the general form:

$$CF_j = CF_o \cdot e^{-A_j \cdot \Delta M_j} \qquad (5)$$

is selected as the most appropriate among other analytical distributions tested. In this context, the available experimental data have been statistically elaborated and the resulting exponential curves (along with their 95% confidence curves) have been drawn separately for each pollutant concerning the capacity factor (energy yield) ratio (i.e. $CF_j/CF_o = E_{pol}/E_{cl}$) against different amounts of mass depositions (see Fig. 7). Even though the range of mass depositions used in the experiment is relatively narrow, the trend lines calculated may provide useful information about how intensively is the energy ratio between the polluted and the clean pair panel reduced for several types of pollutant mass depositions, appearing in most applications. The correlation of the exponential trend line with the results is deemed to be sufficiently reliable with the R-squared value being close to 1. Note that CF_o expresses the case of no pollution deposition ($E = E_{cl}$). At this point, it should be noted that by examining the experimental results drawn from other relevant studies [32,35,36], one could state that the degradation of PVs' performance due to dust deposition could be sufficiently described by an exponential trend line for low and moderate dust concentrations (e.g. ≤ 5 g/m^2). Nevertheless, based on the corresponding experimental procedures carried out in these studies, higher amounts of dust deposition had been mainly dispersed artificially on the panels' surfaces, since such high values are seldom met in the real world. Actually, it would be almost impossible to obtain these quantities naturally (due to PVs' exposure to aggravated from air pollution environments) since PVs' surfaces would be normally washed out by the rain. Thus, the proposed model is more appropriate for dust concentrations up to 5 g/m^2, which can be naturally deposited on PV s' surfaces.

According to the calculation results, coefficient "A_j" ranges between 0.06 and 0.24 depending on the type of the pollutant "j"

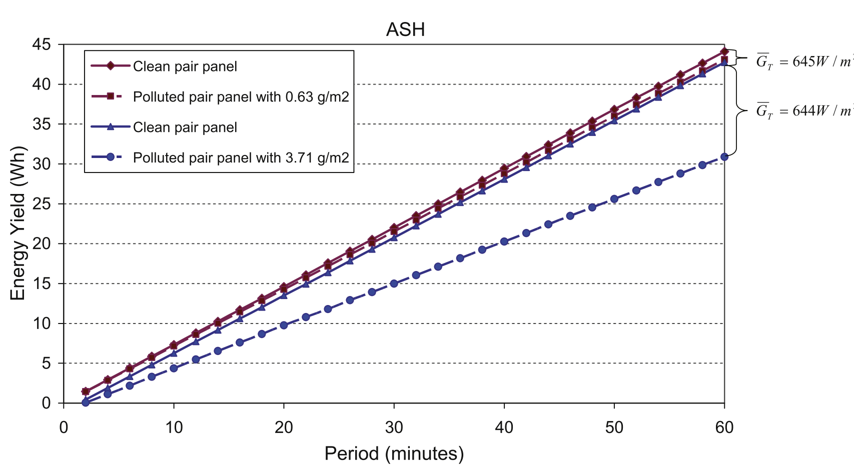

Fig. 5. Energy yield of the clean pair panel compared with the polluted one for the highest and the smallest recorded ash mass deposition density.

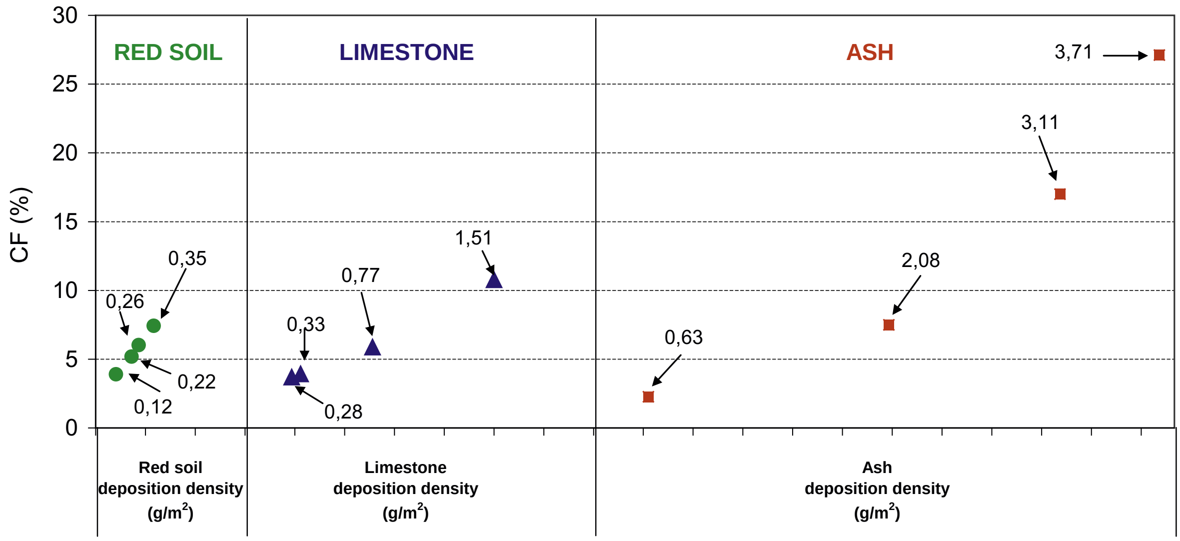

Fig. 6. Capacity factor reduction (in %) of the polluted pair panel due to different pollutant mass depositions (in g/m^2).

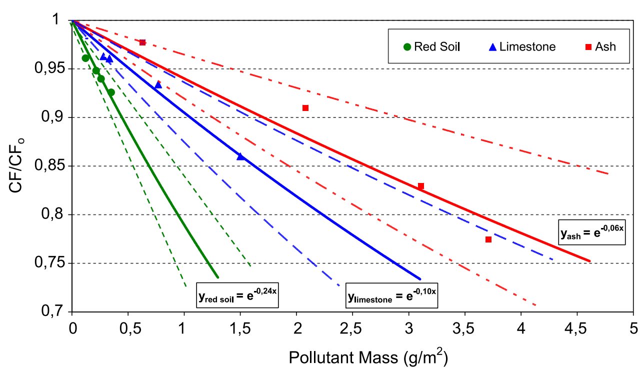

Fig. 7. Capacity factor ratios as a function of different mass depositions for each pollutant.

(see Table 3), while "CF_j" is the capacity factor of the polluted pair of panels for the specific pollutant mass deposition "ΔM_j" (in g/m^2). Also in Table 3 one may find the corresponding standard deviation of "A_j" for the three pollutants investigated.

Consequently, as a theoretical case study and for comparison purposes, the energy yield of the clean pair of PV-panels within 1 h is plotted in Fig. 8, and compared with the corresponding one of the polluted pair panel when 1 g/m^2 of each pollutant is deposited on its surface, see Eq. (3), thus $E_j = CF_j \cdot P_p \cdot \Delta t$. The illustrated reductions imply a non-negligible deterioration of PVs' energy performance in all cases. Obviously, the worst deterioration is caused by the deposition of red soil, i.e. approximately 16 Wh energy decrease per hour, representing almost 19% of the respective energy produced by the clean pair panel. The effect is smaller for limestone and ash, i.e. approximately 10% and 6% reduction of the energy produced by the clean pair panel respectively, always assuming the same air pollution disposal.

Table 3
Coefficient "A" and standard deviation.

Pollutant	A_j
Ash	0.06 ± 0.024
Limestone	0.10 ± 0.034
Red soil	0.24 ± 0.085

Following, Fig. 9 shows the PV-panels' conversion efficiency for the theoretical case of 1 g/m^2 and mean solar radiation "$\overline{G}_T$" being equal to 800 W/m^2 under clean and polluted panels' conditions. In this context, the efficiency difference "$\Delta\eta_j$" between the polluted and the clean (almost identical and nearby located at the same tilt angle) pair of PV-panels is defined as:

$$\Delta\eta_j = \frac{P_o}{G_T \cdot A_c} - \frac{P_j}{G_T \cdot A_c} = \frac{E_o - E_j}{G_T \cdot A_c \cdot \Delta t} = \frac{(CF_o - CF_j) \cdot P_p}{G_T \cdot A_c} = \frac{CF_o \cdot P_p \cdot \left(1 - e^{-A_j \cdot \Delta M_j}\right)}{G_T \cdot A_c} \quad (6)$$

or equivalently:

$$\Delta\eta_j = \eta_o \cdot \left(1 - e^{-A_j \cdot \Delta M_j}\right) \quad (6a)$$

As one may conclude there is a remarkable efficiency drop of the artificially polluted panels (compared with the clean ones) in all cases (Fig. 9). It is obvious that the highest decrease occurs when red soil particles are deposited in PV-panels' surfaces, causing an efficiency reduction of almost 2.3% while 1.2% and 0.7% are the respective decrease percentages (in absolute terms) for limestone and ash.

Following, an attempt is made to check the reliability of the proposed theoretical model by using the results of a previous

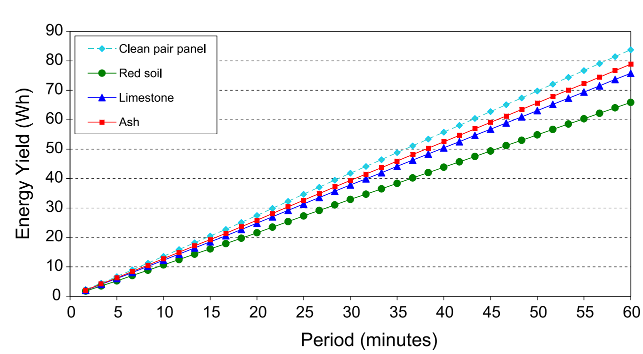

Fig. 8. Energy yield of the clean pair of PV-panels compared with the polluted ones in case of 1 g/m^2 pollutant mass deposition.

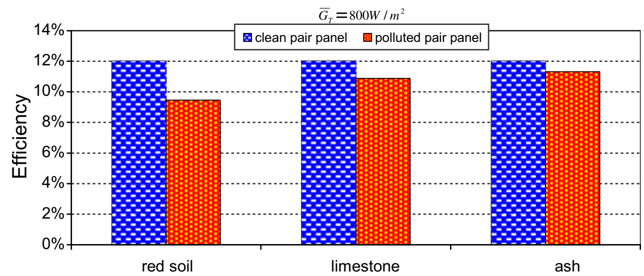

Fig. 9. Conversion efficiency between the clean and the polluted pairs of PV-panels, within 1 h, in case of 1 g/m^2 pollutant mass deposition and $\overline{G}_T = 800$ W/m^2.

experimental study [20] conducted in the aggravated – from air pollution – urban environment of Athens, where high concentrations of PM are observed, consisting in a large extent of carbonaceous fly-ash particles and derivatives from civil construction activities. As a part of that experiment, the energy performance of a clean pair of PV-panels was compared with the corresponding of a polluted one under different natural air pollution quantities accumulated on the PVs' surfaces over a certain time period (i.e. from 2 to 8 weeks). Specifically, the pairs under comparison remained exposed to the atmospheric air pollution over a certain time period being both south oriented and adjusted at 30° inclination. After a specific number of days and before the starting of rainfalls a considerable number of measurements were taken from both the polluted and clean pairs of PV-panels in order for the effect of dust deposition on PVs' energy performance to be evaluated. Special attention was paid on the weather forecast in order for any cases of rainfall to be avoided. Throughout the time period of two dry months, on the basis of the experimental procedure, four different values of specific dust deposition were recorded. More specifically, the values varied from 0.1 to 1 g/m^2, amounts which correspond to the shortest (2 weeks) and the longest period (8 weeks) of the polluted PV-pairs' exposure into atmospheric air pollution.

In Fig. 10, one may find the capacity factor ratio (CF/CF_o) values concerning the artificially polluted panels with red soil, limestone and ash, against different pollutant mass depositions. In the same figure one may also include the corresponding values of the naturally polluted PV-panels. At this point, one may see that if the natural polluted panels' capacity factor ratio is compared separately with each one of the three artificial pollutants (see also Fig. 7), considerable differences may arise. Actually, in case of natural pollution deposition, the total capacity factor (and energy reduction) percentage ranges from 1.7% to 6.5%, amounts which correspond to the smallest (i.e. 0.1 g/m^2) and the highest (i.e. 1 g/m^2) recorded dust deposition density within the time period of the experiment (see Fig. 11).

In an attempt to estimate the total capacity factor (or energy) reduction percentage "$\Delta(CF)$" due to the deposition of dust particles on PVs' surfaces one may use – in view of Eqs. (4) and (5) – the following approach:

$$\Delta(CF) = \frac{CF_o - CF}{CF_o} \times 100 = \left(1 - e^{-A_{eq} \cdot \Delta M}\right) \times 100 = \Delta E \qquad (7)$$

with "ΔM" (in g/m^2) being the total mass of dust accumulated on the PV-panel's surface and coefficient "A_{eq}" depending on the mass content of dust for each pollutant "ΔM_j", i.e.:

$$A_{eq} = \sum w_j \cdot A_j \qquad (8)$$

with

$$w_j = \frac{\Delta M_j}{\Delta M} \qquad (9)$$

and

$$\sum w_j = 1.0 \qquad (10)$$

According to the experimental measurements carried out, the coefficient A_{eq}, in the case of natural-urban pollution deposition on PVs' surfaces, should range between 0.06 and 0.24. As it has already been mentioned above, the natural pollution effect is site-specific/dependent and in that case the depicted energy reduction is a result of PVs' outdoor exposure (without being cleaned or washed out by the rain) to the atmospheric pollution met in the region where the experiment was conducted. For example, in the specific situation the pollution is deriving primarily from vehicular exhausts ($w_{ash} \approx 75\%$) and secondly from civil construction activities ($w_{limestone} \approx 20\%$) in the nearby location, while the mass content of dust in red soil is almost negligible ($w_{red\ soil} \approx 5\%$). Therefore, by setting the above percentages in Eq. (8), the coefficient A_{eq} is found equal to 0.077 ± 0.019. Thus, by applying Eqs. (5) and (7) one may draw the corresponding curves of Figs. 10 and 11. In both figures one may see that the analytical curves coincide to a large extent with the experimental points concerning the naturally polluted PV-panels, indicating the validity of the above described methodology.

Finally, one may check the validity of the proposed analysis on the conversion efficiency of the naturally polluted PV-panels, see Fig. 12. Using the predicted "A_{eq}" value, one may successfully simulate the efficiency reduction experimental values due to several natural dust deposition masses on PVs' surfaces. As

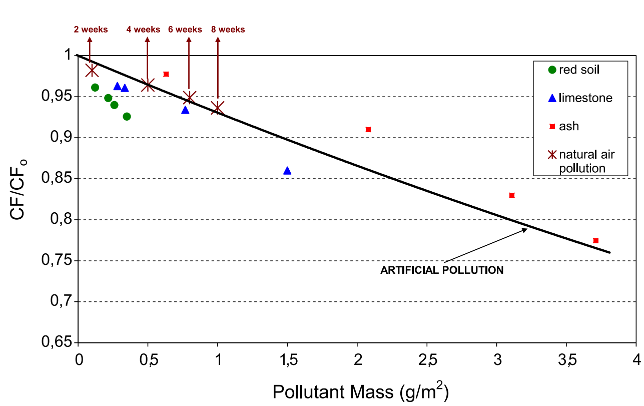

Fig. 10. Capacity factor ratio as a function of different pollutant mass depositions for artificially polluted PV-panels.

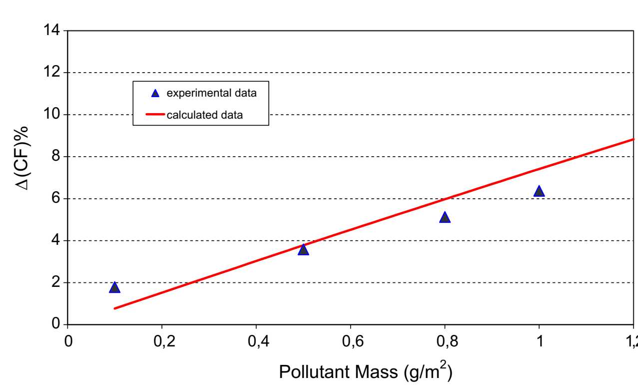

Fig. 11. Capacity factor reduction percentage based on experimental and calculated data as a function of different pollutant mass depositions for naturally polluted PV-panels.

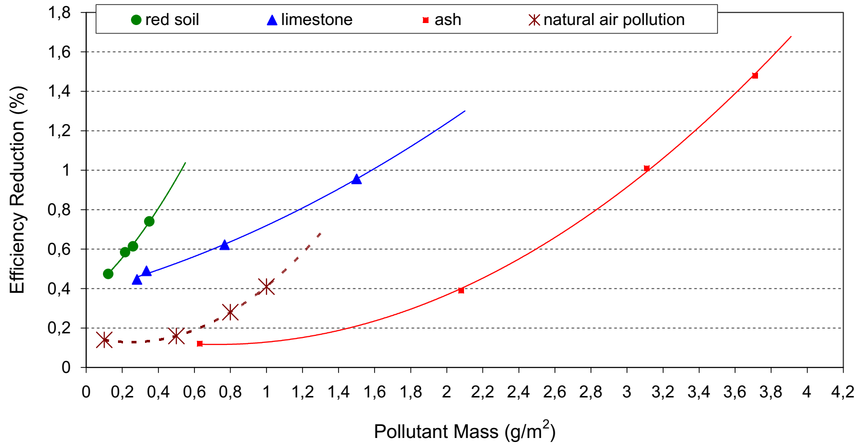

Fig. 12. Efficiency differences between the clean and the polluted pair panels for various mass depositions in cases of naturally and artificially polluted PV-panels.

expected, the experimental values under discussion are located between the corresponding points for the artificially polluted PV-panels with ash and limestone.

5. Conclusions

The results of a detailed experimental study, carried out in view of identifying and displaying the dust effect on the energy performance of PV-panels, have been used. Considering that the dust effect is site-specific/dependent, three representative air pollutants (i.e. red soil, limestone and carbonaceous fly-ash), which are commonly met in urban and other environments, were examined. The main target of the present study was to develop a simple and easy to apply theoretical model, able to provide reliable results concerning the effect of regional air pollution on PV-panels' energy performance.

According to the results obtained, a considerable deterioration of PVs' energy yield and efficiency is observed when dust particles are deposited on the panels' front sides (naturally or artificially), firstly depending on the type of the pollutant (i.e. composition, diameter, etc.) and secondly on the mass accumulated on the panel's surface. More specifically, the dust effect on the capacity factor (or energy yield) ratio between a clean and a polluted PV-panel presents (negative) exponential behavior and may be estimated by setting the appropriate values for the parameters of the proposed model, based on the dust composition existing in the region where the PV-panels are installed.

In this context, the theoretical model developed takes into account the type of the pollutant as well as the mass deposition density examined and describes quite satisfactorily the corresponding experimental data. Accordingly, the proposed theoretical model is applied to accurately describe the energy yield decrease of a PV generator operating under the influence of urban natural pollution. In this context, all the energy related parameters, i.e. capacity factor, conversion efficiency, etc. are also well described, thus allowing for an explicit estimation of the reduction induced in both the PV-panels' energy generation and the respective revenues.

Recapitulating, a reliable and easy to apply model that is able to simulate the dust deposition impact on the energy behavior of PV installations (found mainly in dry regions) has been developed, based on extensive experimental measurements. The accuracy of the model is thought to be rather satisfying, especially for practical calculations, however additional tests are also thought to be required (already under schedule) in order to include other application cases and air pollutants (e.g. salt, water vapors) as well. Meanwhile, further investigation of the parameters involved is necessary in order for the proposed methodology to be widely accepted as a standard energy yield calculation tool for numerous solar projects (e.g. solar water heating applications, street lighting, domestic or industrial PV devices used for electricity generation, etc.) implemented in aggravated – from air pollution – environments. Overall, for the developed model to be fully established, evaluation of its predictive ability on a long-term basis and sufficient comparison with actual real-life results are both required so as to further examine its levels of reliability.

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