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Quantifying the decrease of the photovoltaic panels' energy yield due to phenomena of natural air pollution disposal

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ABSTRACT

Photovoltaic (PV) applications, gaining worldwide interest during the last years, comprise a promising renewable energy based solution, able to considerably contribute to the constantly increasing energy demand of our planet. Currently, residential applications possess a considerable share of the global PV market since fiscal and practical incentives have reinforced their promotion. On the other hand, high population concentration, rapid industrialisation and economic development of urban areas all over the world have caused significant degradation of the urban air quality. In this context, the actual performance of five identical pairs of roof-top PV-panels, operating in the aggravated urban environment of Athens (from the atmospheric air pollution point of view), is currently evaluated. For this purpose, a series of systematic experimental measurements is conducted within a certain time period and the influence of different dust deposition densities on the energy yield and the economic performance of the small power station is estimated. According to the results obtained, the presence of dust considerably affects the PV-panels' performance since even a relatively small dust deposition density (≈ 1 g/m^2) may result in remarkable energy losses corresponding almost to 40 €/kW$_p$ on an annual basis.

1. Introduction

During the last years the photovoltaic (PV) market experiences a significant growth all over the world (Fig. 1), not only in rural but also in urban areas. In fact, the worldwide cumulative solar PV capacity reached 20 GW in 2009 [1], out of which approximately 25% concerns residential applications (Fig. 1) [2].

The main limiting factors which decelerate further diffusion of PV applications include the high initial investment cost [3] (e.g. panels, land, electrical infrastructure etc.) and the relatively low conversion efficiency of PV cells. Consequently, in order to establish PVs as a commercially competitive technology [4], high attention should be paid on the factors which affect their energy performance [5–9]. In this context, apart from the variation of the solar radiation intensity, which is the main factor affecting the PV-modules' output, reductions up to 15% on the PVs' energy production may also be the result of several other parameters (see Table 1). The most important amongst them are considered to be the increase of temperature and the accumulation of soil and dirt on the surfaces of PV-panels [10,11]. Although dust effects are a priori site-specific [12,13], i.e. depend on local conditions such as the presence of air pollution, frequency of rain, wind speed, humidity, as well as on the panels' orientation and inclination [14], certain attempts have been made [15–17] to determine the influence of dust on the performance of PV-panels and draw some more generic conclusions. In this context, considering the increasing share of PVs in the building sector [18], investigation of the dust effects on the performance of PV-modules becomes of special interest, especially in the case of a heavily aggravated –from air pollution– urban environment.

Athens is a coastal city located in a very complex terrain within the Athens basin (Fig. 2). It is surrounded by the mountains of Hymettus, Penteli and Parnitha eastwards and northwards, with heights ranging from 400 to 1500 m, and the Saronic Gulf southwards and westwards. The increased industrialization and economic activity as well as the high population density (i.e. nearly to 4 million inhabitants) in the urban area of Athens (≈ 412 km^2) constitute the prime causes for the increased levels of air pollution. Two types of air pollution are most commonly observed. The first one is composed by high concentrations of particulate matter (PM) mainly deriving from the combustion of fossil fuels and industrial processes. The second one originates from a series of chemical reactions of sunlight with nitrogen oxides (NO_x), hydrocarbons (C_xH_x), carbon monoxide (CO), ozone (O_3) and organic nitrates. In addition, a notable part of air pollution is attributed to long-range transfer of fine particles deriving from some severe dust outbreaks traced back to the Sahara

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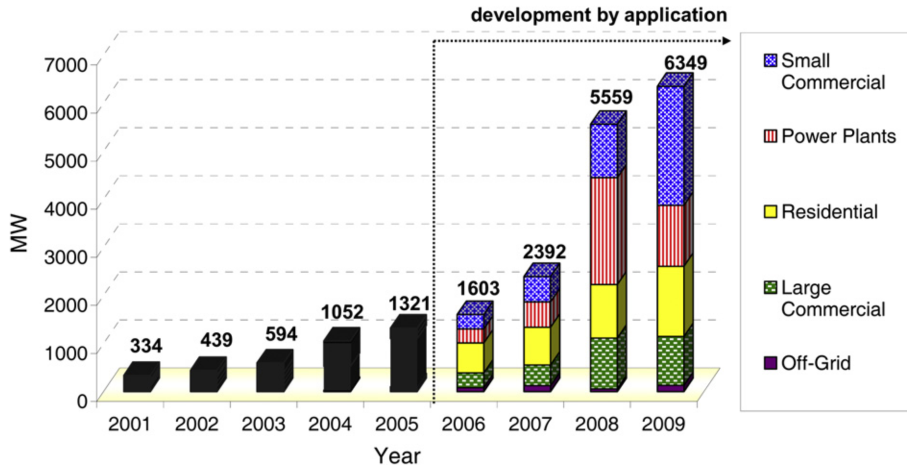

Fig. 1. Historical development of the Global annual PV market by sector.

desert and the Western Mediterranean [19,20]. Parameters such as topography (basin surrounded by mountains), temperature inversions, low wind speed and extensive periods of drought surcharge the concentration of air pollutants over the city [21,22]. Moreover, the situation is even more aggravated during the summer months, when intense sunshine and high temperatures facilitate the formation of photochemical smog [22,23].

Taking into consideration the lack of systematic analyses that determine the effect of air pollution (i.e. dust deposition) on the energy performance of PV-panels quantitatively, an experimental based investigation was undertaken in order to draw some reliable conclusions, with emphasis given on the area of Athens (Attica region).

2. Position of the problem

Financial and practical incentives implemented in Greece during the last years aimed to stimulate the incorporation of PV applications (up to 10 kW_p) into the building sector (domestic or small enterprises) of the mainland (i.e. the interconnected electricity network). According to the last of incentives, the entire energy production of a PV installation may be directly fed to the electrical grid for 0.55 €/kWh, while the investor keeps buying energy from the Greek Public Power Corporation (PPC) at the current price of 0.1–0.12 €/kWh. Moreover, it is expected that people who are interested in installing roof-top PVs will no longer be involved in costly and complicated bureaucracy procedures since the installation processes are now considerably simplified [24].

Considering that the Attica region is determined by considerable air pollution and that the interest to install PV applications into the building sector is constantly growing worldwide, the basic aim of this study is to investigate the degree at which the presence of dust in the atmosphere may affect the PV-panels' energy performance in the urban environment of Athens. Actually the proposed analysis estimates the expected maximum energy yield decrease due to the air pollution disposal concentrated on the surface of PV-panels during the dry (but also sunny) months of the year.

In this context, the energy yield "E" of a PV-power station for a time period "Δt" is given as:

$$E(t_o \rightarrow t_o + \Delta t) = \int_{t_o}^{t_o+\Delta t} P(t)\cdot dt \tag{1}$$

where "P" is the power output of the PV-generator, expressed as:

$$P(t) = U(t)\cdot I(t) \tag{2}$$

with "U" being the voltage and "I" being the current of the PV-generator, both normally comprising a function of time "t".

Accordingly, the income "$R(\Delta t)$" of the PV-power station for the time period "Δt" is given on the basis of the electricity generation selling price "$p(\Delta t)$" and the corresponding energy yield, i.e.:

$$R(\Delta t) = p(\Delta t)\cdot E(\Delta t) \tag{3}$$

Based on the above, any reduction "δE" in energy production (or power output) of the PV-generator corresponds to a proportional decrease "δR" of the investment's income, i.e.:

$$\delta R = p\cdot \delta E \tag{4}$$

Table 1
Additional major effects on the energy production of PVs, based on [11].

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

3. Experimental methodology

The experimental analysis was conducted in the Laboratory of Soft Energy Applications & Environmental Protection (SEALAB), located at the campus of the Technological Educational Institute of Piraeus (TEIP) (see Fig. 2). The laboratory's installation used in the current study [25] (Fig. 3) is composed by a PV-generator of 12 panels (maximum power of every panel 51 W_p, corresponding dimensions 988 mm × 448 mm) of poly-Si, properly connected, a solar collector, a water tank, certain electrical loads, a lead-acid battery storage system, a DC/DC charge controller (1 kW rated power), a monitoring station and a control panel. The PV-panels are south oriented and their tilt-angle is adjustable for a range of 0° to 90°. During the experimental procedure the energy production of

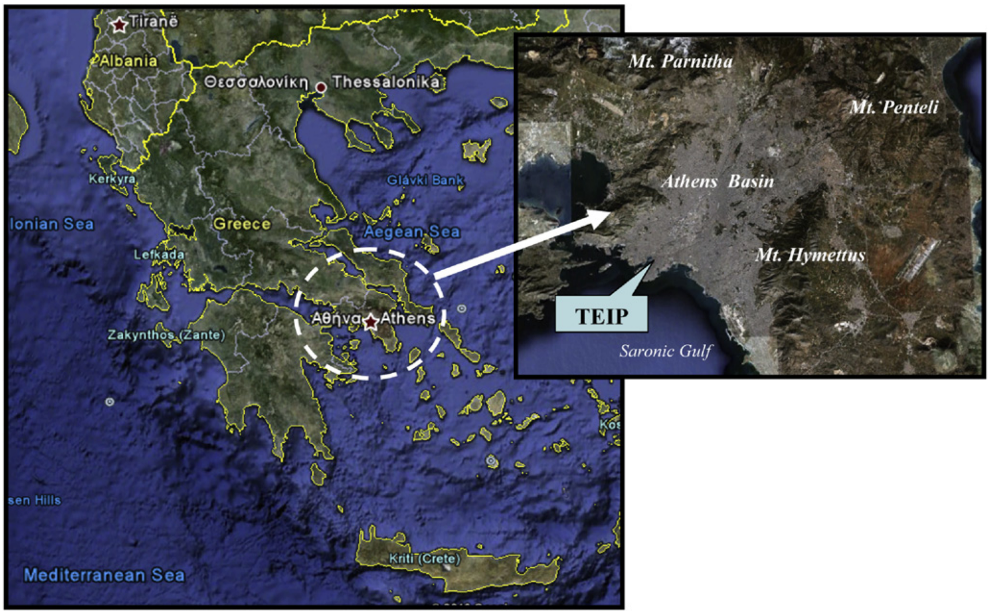

Fig. 2. A map of Greece and a land overview of the Athens basin.

a number of PV-panels' pairs, operating under the same environmental conditions but with different levels of dust deposition on their surfaces, was compared. More specifically, the performance of five pairs of PV-panels was examined, each one composed by two panels connected in series (Fig. 4). In Fig. 5, the *I*–*U* curve for one of the pairs is depicted for various solar irradiance densities "G_T" a cell temperature of 25 °C and with a spectral distribution corresponding to air mass 1.5. At this point, it is worth mentioning that based on the results of a systematic statistical analysis [26], the selected pairs of PVs present the same energy behaviour.

According to the experimental procedure adopted, the pairs of PV-panels were firstly well cleaned and were accordingly kept exposed to natural air pollution over a certain time period (i.e. from 2 to 8 weeks), adjusted at 30° inclination. After the first 2 weeks, pair panel 1 was carefully cleaned and its performance was compared with the polluted pair panel 2. The procedure was repeated every two weeks so that the performance of the rest of polluted pair panels (3, 4 and 5) would be evaluated (always compared with the clean pair panel 1) after a specific time interval of their outdoor exposure, i.e. 4, 6 and 8 weeks respectively. Note that special attention was paid on the weather forecast so that cases of rainfall could be avoided. For that reason, the exact time period under investigation was considered to start during the summer and to end during the beginning of autumn. Periods of up to three months of drought are very common in the Athens region and the proposed analysis is also appropriate for regions with similar or bigger periods of drought. Keep in mind that almost two thirds (2/3) of the available solar energy is available during the dry months of the year. More

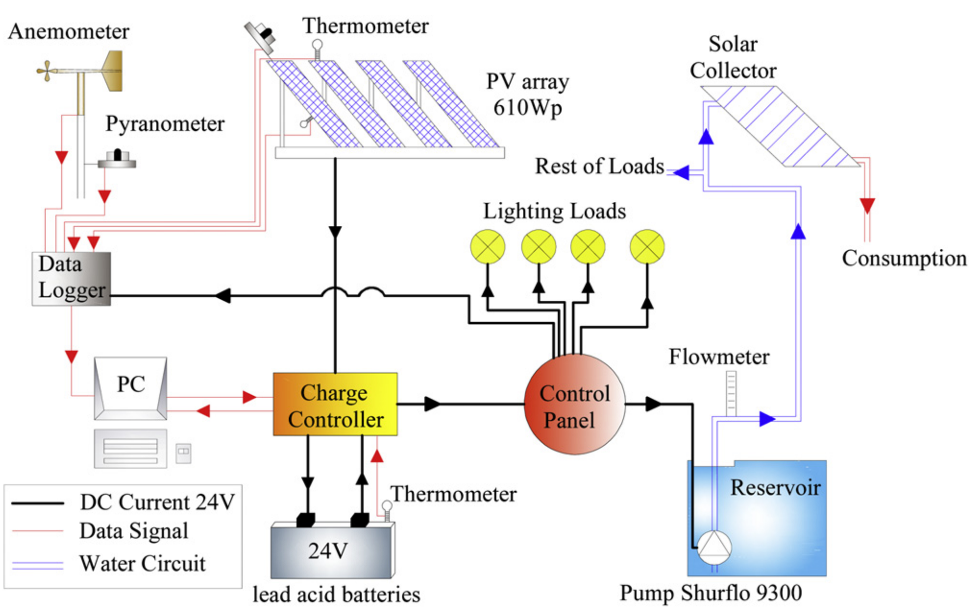

Fig. 3. The experimental installation of the SEALAB.

Fig. 4. The experimental PV-generator.

specifically, the experimental procedure comprised the following steps:

i. The previous day of the experiment the PV-panels were switched off in order for the batteries to be drained up to a point via the consumption loads.
ii. The day after, during the hours of increased solar radiation (usually around noon), under cloudless sky, a number of measurements was conducted. The high solar radiation (700–900 W/m^2) hours were selected in order to ensure the calculation of the maximum energy difference (loss) between the clean and the polluted PV-panels. Firstly, pair panel 1 was well cleaned so that the total mass of the accumulated dust on its surface would be removed. During the recording procedure (approximately 1 h) the values of the current and the voltage of the two pairs of PV-panels under investigation were recorded along with the intensity of solar radiation on the PVs' surfaces. Besides that, the ambient temperature was also specified and compared with that of the panels.
iii. When the recording procedure was completed, the surface of the polluted panel was carefully cleaned with the use of known weight wetted (with filtered water) cotton pieces which had been previously put in a dehumidifier (for 24 h) so that any trace of humidity could be removed. Later on, after repeating the dehumidification of the polluted cotton pieces, weighing with the use of a precision weighing balance of 0.1 mg accuracy was performed, in order for the total mass of the pollutant ($M_j^{\text{after}} - M_j^{\text{before}}$) accumulated on the panel's surface "A_c" (area of each panel equal to 0.442624 m^2) during the time period of study to be estimated. In this context, the specific mass deposition is expressed as:

$$\delta M_j = \frac{M_j^{\text{after}} - M_j^{\text{before}}}{A_c}, \quad j = 2,3,4,5 \tag{5}$$

iv. By using Eq. (1) and the resulting power output of the polluted "P_j" and the clean pair panel 1 "P_1" the respective electricity generation values "E_j" and "E_1" were estimated so as to quantify the effect (if any) of the natural air pollution on the performance of the PVs and thus on the corresponding income of the small power station.

In order to evaluate the accuracy of the results, the total error "ε_{tot}" was determined as a function of the systematic "S" and random "ε_r" errors, induced by the series of measurements [27,28]. Thus,

$$\varepsilon_{\text{tot}} = \sqrt{\varepsilon_r + S^2} \tag{6}$$

Accordingly, on the basis of the error theory [27,28] and Eq. (2), the relative error of the power output is expressed as:

$$C_P^2 = C_I^2 + C_U^2 \tag{7}$$

Note that by definition the relative error is expressed as the ratio between the standard deviation "s" and the statistical average value "$\overline{x}$" of the sample for the i parameter (P, I, U), i.e.:

$$C_i = \frac{s_i}{\overline{x}_i} \tag{8}$$

4. Experimental results analysis and discussion

Applying the above presented experimental procedure, a systematic series of measurements was conducted for several time periods corresponding to different dust deposition densities. In fact, the experimental analysis was carried out, as already discussed, during the time period of two months (i.e. August–September 2009). Particularly, the performance of the clean pair panel 1 was compared with the corresponding of the polluted pair panels 2, 3, 4 and 5 under different natural air pollution quantities accumulated on the PVs' surfaces within 2, 4, 6 and 8 weeks respectively. The experiment was always conducted under clear sky, usually around noon (solar irradiance between 700 W/m^2 and 900 W/m^2), under different atmospheric conditions (e.g. ambient temperature, humidity, wind velocity etc.) each time, while the procedure lasted approximately for 1 h with about 40 measurements recorded (approximately 1 measurement per 90 s). During the recording procedure the values of the current and the voltage of the PV-panels were recorded along with the values of the ambient temperature and solar radiation (W/m^2). The intensity of solar radiation was recorded by the monitoring system data logger, which measures the solar irradiance at the horizontal plane and at the PV-panels' surface (coplanar with the PV-panels' surface) with the use of two Kipp & Zonnen pyranometers "Li-Cor" type.

Throughout the time period of these two months, four different values of specific dust deposition were recorded on the basis of the experimental procedure. More specifically, the values varied from 0.1 to 1 g/m^2 (or from 0.01 to 0.1 mg/cm^2), amounts which correspond to the shortest (2 weeks) and the longest period (8 weeks) of the polluted PV-pairs' exposure to the atmospheric air pollution. According to the experimental results, one may state that the

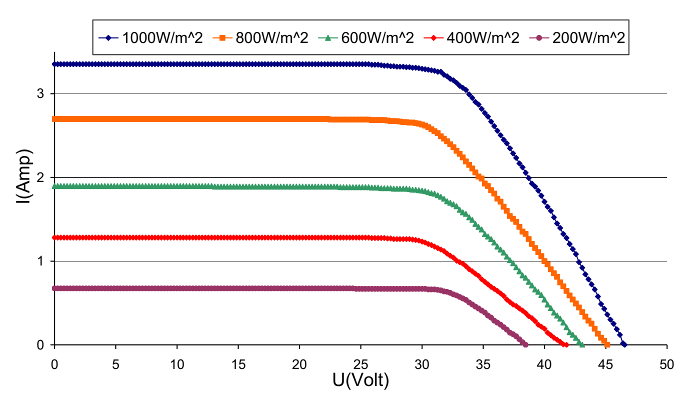

Fig. 5. I–U curves for one pair of PV-panels for various solar irradiance densities.

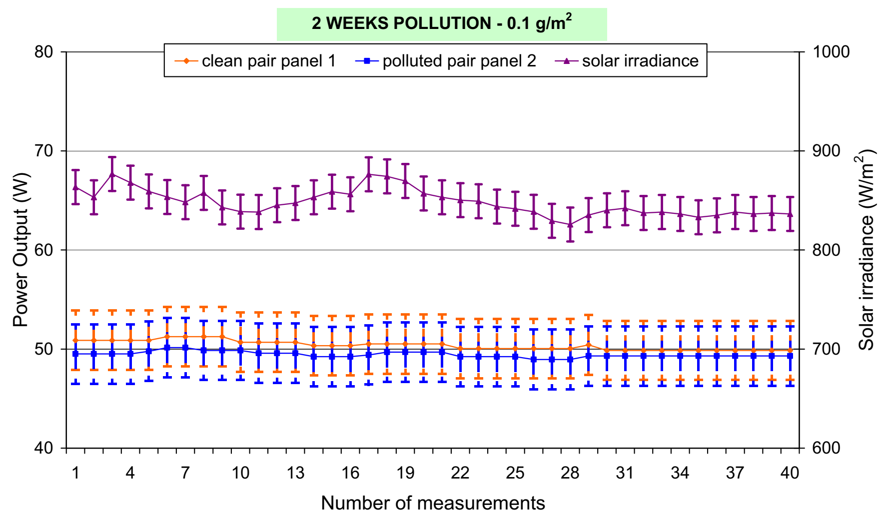

Fig. 6. Power output under clean and polluted panel conditions along with the solar radiation and the total errors of the measurements in case of $\delta M_2 = 0.1$ g/m^2.

presence of dust considerably affects the PVs' performance since the reduction of the generated power reached almost 6.5% of the respective mean pair panel output in the examined case of the highest dust deposition density (i.e. 1 g/m^2 − 8 weeks pollution). Although this value may not seem considerable, it is comparable with the one imposed by the temperature increase of the PV-panels' surface (see Table 1) and it is higher than the one related with the ageing effect of the PV-generator. Note that the ageing effect appears mainly during the last years of the installation's service period while the energy yield decrease (due to the air pollution disposal) is evident from the first operational year of the installation and may be even more significant in cases of longer periods of drought.

The total error ($\approx$3%) of the experimental procedure was calculated by carrying out a number of independent measurements and by analysing the accuracy of the equipment used for recording the current intensity, voltage and solar radiation throughout the experimental procedure [25,27]. At this point, what is worth pointing out is the reliability of the results obtained, since an appropriate statistical *t*-test was executed for the mean power output values of the clear "$\overline{P}_1$" and the polluted "$\overline{P}_j$" pair of PV-panels, in order to ascertain if the resulting power output differences "δP_j" ($\delta P_j = P_1 - P_j$) constitute real values or have been configured by the systematic and random errors of the measurements. Actually, on the basis of rejecting the alternative hypothesis (see Eq. (10)), Eq. (9) was validated, thus confirming the null hypothesis with a probability of error $\alpha = 5\%$ [28].

$$H_o : \overline{P}_1 - \overline{P}_j = \delta P_j \quad (9)$$

$$H_1 : \overline{P}_1 - \overline{P}_j \neq \delta P_j \quad (10)$$

According to the results obtained, as far as the smallest recorded quantity is concerned (i.e. 0.1 g/m^2 − 2 weeks pollution), the corresponding effect is almost negligible, i.e. 1 W reduction in the generated power (or 2% reduction of the mean clean pair panel output). This case is depicted in Fig. 6 where one may also obtain the statistically-checked, as mentioned above, almost identical behaviour of the two panel pairs since the very small quantity of dust does not cause a worth noticing difference to their performance.

Fig. 7, illustrates the energy yield (Wh/h), resulting from the corresponding power output values for the clean and the polluted pair of PV-panels, against different dust deposition densities and recorded mean solar radiation. The dust effect becomes more obvious at highest dust deposition densities which occurred after 6 and 8 weeks of panels' exposure to the natural air pollution (summer

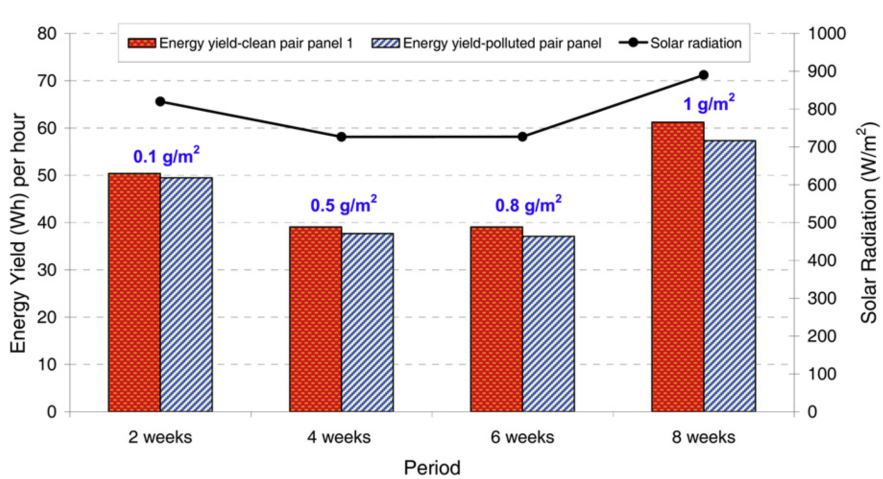

Fig. 7. Energy yield of the clean and the polluted pairs of PV-panels according to specific values of dust deposition and mean solar radiation.

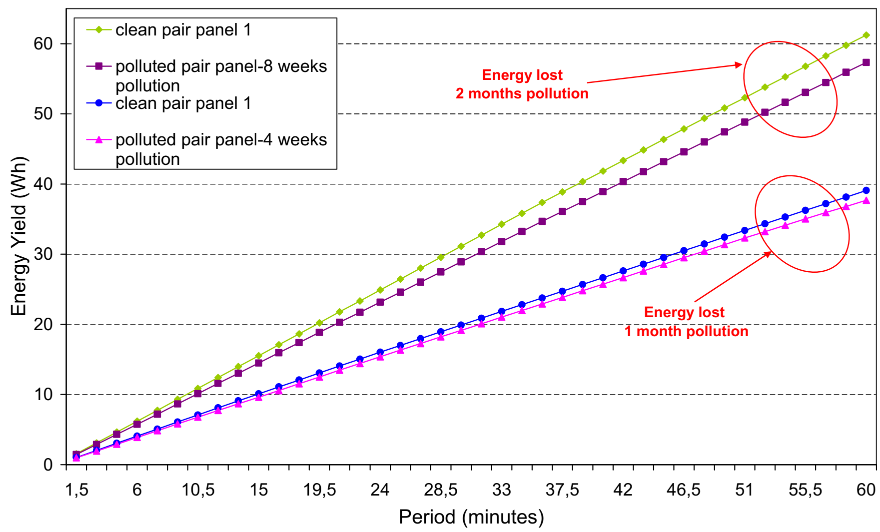

Fig. 8. Energy yield of the clean pair of PV-panels compared with the polluted one after one and two months of the polluted pair's exposure to natural air pollution.

2009). Particularly, as the dust deposition increases on the panels' surface the cells receive less solar irradiance, thus leading to remarkable degradation of the PVs' performance. In this context, the hourly energy yield of a clean pair panel is compared with the respective of the polluted one, which has remained exposed to air pollution for a time period of 1 and 2 months (see Fig. 8).

Finally, an attempt is made to evaluate the fiscal impact of dust deposition on the energy performance of PV-panels on an annual basis. For that reason, the corresponding energy yield decrease is estimated [27] on the basis of long-term solar energy potential measurements for the Attica region (see Fig. 9) [29]. In this context, according to the current legislation for roof-top solar PV-modules ($\leq$10 kW_p) [24], the produced energy selling price is considered to be 0.55 €/kWh. Considering the above, Fig. 10 presents the expected annual energy yield decrease (kWh/kW_p) and hence the corresponding income loss per year in €/kW_p as a function of the mean dust deposition densities measured on the PV-modules' surface. As a result, if considering a small power station of 10 kW_p the annual income loss may reach up to 400 € if the panels have accumulated on their surfaces dust density of the order of 1 g/m^2.

The annual income loss value estimated, although may not seem considerable, represents almost 0.8–1.0% of the current turnkey cost (4000 €/kW_p–5000 €/kW_p) of domestic PV installations, while the corresponding annual M & O cost is in the order of 0.5%. Note also that the air pollution disposal effect is normally encountered throughout the entire lifetime period of the PV installation while one may also argue that the annual income loss estimated on the basis of the analysis presented comprises a measure for the evaluation of the cost of regular cleaning techniques. Furthermore, confrontation of the specific problem may become even more imperative for small domestic PV applications installed in urban areas of considerable air pollution and longer periods of drought (i.e. longer than two months), where frequent cleaning of PV surfaces may be requisite on the basis of better economic and operating conditions. Finally, at this point one should also consider the additional factor of erosion –due to the presence of dust– which by leading to the degradation of PV

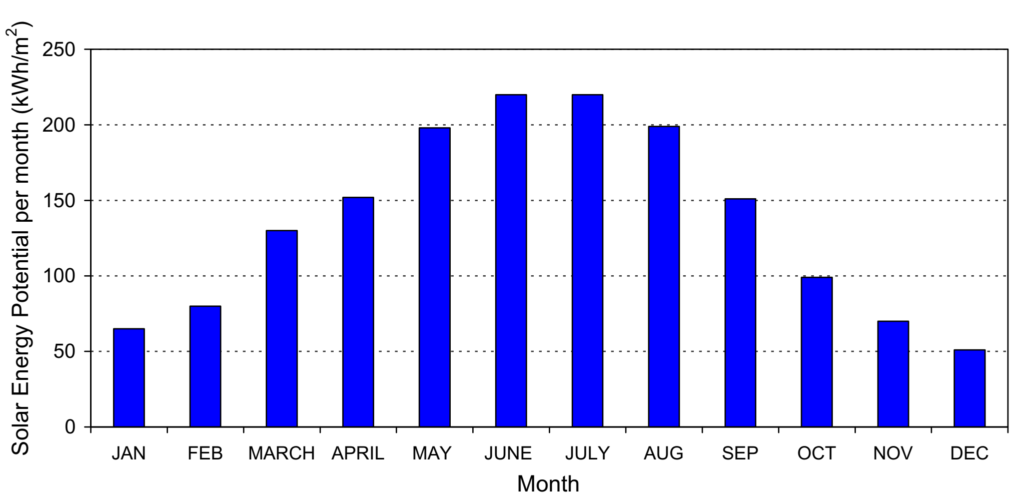

Fig. 9. Solar energy potential measurements on the horizontal plane for Athens (TEI of Piraeus) region (1990–2000).

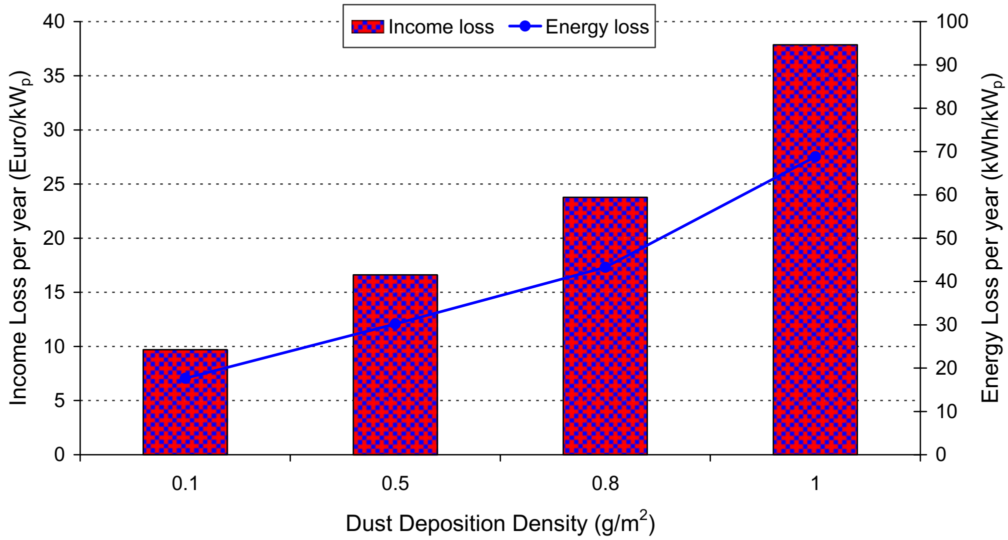

Fig. 10. Income and energy loss per year as a function of mean dust deposition densities on PV-panels' surfaces.

surfaces may further deteriorate the panels' performance in the long run.

5. Conclusions

An experimental study was carried out during a time period of two months (i.e. August–September 2009) in order to appraise the effect of urban air pollution on the energy performance of PV-panels. The experiment was conducted in the densely populated and well-known —for its heavy air pollution— Greek capital, Athens. More specifically, the performance of five pairs of PV-panels, all being south oriented and adjusted at 30° inclination, was investigated in detail under both clean and polluted panel surface conditions.

According to the results obtained, the presence of urban air pollution may significantly deteriorate the energy yield of PV-panels, even after a short period of the panels' outdoor exposure (e.g. two months) without cleaning. In fact, if considering mean dust deposition density of the order of 1 g/m^2 (i.e. the highest quantity recorded within the time period under investigation), the PV-panels' energy production may be reduced up to approximately 6.5% (in comparison with a clean panel) thus resulting to an annual income loss of almost 40 €/kW$_p$ which represents 1% of the current turnkey specific price of domestic PV-generators. In this context, additional research is required in order to evaluate the impact of natural air pollution on the energy performance of PVs for a longer period of outdoor exposure, e.g. one year, so that the influence of certain weather parameters (such as rainfalls, relative humidity and wind velocity) on the dust accumulation can also be evaluated. Finally, of special interest is also the extension of the problem in order to investigate the impact of the panels' tilt-angle variation on the corresponding dust deposition.

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