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# Decrease in Photovoltaic Module Efficiency Due to Deposition of Pollutants



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# Decrease in Photovoltaic Module Efficiency Due to Deposition of Pollutants

Ewa Klugmann-Radziemska, Małgorzata Rudnicka

*Abstract*--**The deposition of pollutants on the surface of photovoltaic (PV) modules reduce the efficiency that can be achieved in given climatic conditions. This results in the loss of energy yield obtained from the solar installation. A number of factors determine the scale of this problem. The first of these is the amount of impurities deposited, the associated amount of precipitation, and the speed and direction of the wind. A second aspect is the type of pollution and the composition and structure of the sludge, which depends on the location of the installation. The type of installation, either stationary or sun tracking, is essential because the angle of inclination of modules, depending on the latitude, will determine the amount of dust deposited, especially for stationary installations. The observed decrease in efficiency of PV modules covered with dust equals 6–10% of the efficiency of a module free of impurities. This means that the user should maintain the module surface and schedule routine cleaning.**

***Index Terms*--Soil pollution, solar energy, solar power generation, solar panels, photovoltaic cells.**

## I. Introduction

SEVERAL factors influence the efficiency of PV modules: the type of front cover material, the orientation and angle of inclination, the type of installation (tracking or stationary), location, solar cell temperature, shadowing, dust deposition and soiling of the front cover.

The reduction in power output caused by the accumulation of dust on a PV module surface is an important problem. Deposition of airborne dust on PV modules reduces power output and decreases the transmittance of solar cell glazing, causing a significant degradation in the solar conversion efficiency of the modules. The effect of the dust layer on the efficiency of solar modules is significant because the sediment reduces the short-circuit current and hence, the power generated by the PV module and its efficiency.

Losses due to soiling refer to loss in power resulting from snow, dirt, dust and other particles that cover the surface of the PV module. Shading due to soiling is divided into two categories: soft shading such as air pollution and hard shading which occurs when a solid such as accumulated dust blocks the sunlight [1]. The characteristics of dust settlement on PV systems are dictated by a few primary factors that influence each other (Fig. 1).

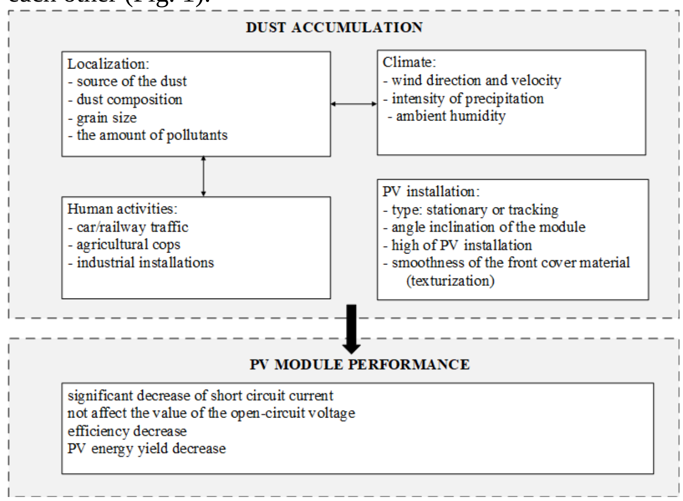


Fig. 1. Primary factors influencing dust accumulation

The properties of the dust are determined by the particle size, composition, shape and mass. The origin, composition and gradation of dust grains coming from various sources are key elements in the analysis of the impact of pollution on the amount of energy generated by PV modules. On the other hand, in a dry desert climate, the main source of dust is soil.

The article [2] presents a comparison of results of investigations on the influence of sediment of a given thickness on the decrease in the efficiency of modules exposed to atmospheric conditions for over two years and in the short term. The conclusions point to the fact that long-term accumulation of pollutants cause a greater reduction in energy than short-lived sediments of the same amount.

Some researchers point to the fact that a substantial amount of pollution accumulates on the surface of the module during the first 30 days [3, 4]. These conclusions are based on measurements of the change in the glass transmittance as well as measurements of the mass of deposited impurities.

Gupta [5] presented results of natural soiling studies from different parts of the world. The author collected research results with different implementation periods: from several days to several years, carried out in different locations around the world, both in outdoor conditions and in the laboratory, therefore these studies are widely distributed. The average values of efficiency drop differ in different locations. For example, measurements conducted in the US showed a drop in efficiency of about 1% per month, in the dry climate 9.33% per month, and in Europe 6.5%. These results indicate large

E. K.-R. Author is with the Gdansk University of Technology, Faculty of Chemistry, Department of Energy Conversion and Storage, 11/12 Gabriela Narutowicza Street, 80-233 Gdansk, Poland (e-mail: ewa.klugmann-radziemska@pg.edu.pl).

M. R. Author is with the Gdansk University of Technology, Faculty of Chemistry, Department of Energy Conversion and Storage, 11/12 Gabriela Narutowicza Street, 80-233 Gdansk, Poland (e-mail: malgorzata.rudnicka@pg.edu.pl).

discrepancies resulting both from different sources of dust and significant climatic differences.

The maximum daily efficiency loss calculated for the silicon crystalline module tilted at 37° in northern Poland was equal to 0.8%. and all modules investigated showed an average decrease in maximum power of 3% per year [2]. Natural dust was characterized by the vast predominance of very small particle sizes with a tendency to agglomerate. Most of the dust examined contained particles with diameters up to 30 µm. A few larger particles accounted for about 15% of the sample.

The particle size of contaminants can vary considerably, as was shown by Biryukov [6]. Beattie et al. [7] proposed a classification based on grain size which allows for the identification of origin, that is, a particle size of 60–2000 µm is mainly sand brought by the wind, while dust with a particle size of 4–60 µm originated from alluvial soil, and particles less than 4 µm were from clays.

Mani and Pillai [8] conducted an experiment that used artificial dusts such as limestone, cement and carbon particulates under halogen lamps. They reported that small particulates had the most deteriorating effect on PV efficiency as compared to coarse particles.

Taking into account the effect of gravity, horizontal surfaces usually tend to accumulate more dust than inclined ones. This however is dependent on the prevalent wind movements. Generally a low-speed wind pattern promotes dust settlement while a high-speed wind regime would, on the contrary, dispel dust settlement and have a cleaning effect [8]. Elminir et al. [9] presented results of the experiment, which indicate that the reduction in glass normal transmittance depends strongly on the dust deposition density in conjunction with plate tilt angle, as well as on the orientation of the surface with respect to the dominant wind direction.

Sayigh [10] has measured the reduction in the transmittance of the glass plates with different tilt angles. The linear decrease in glass transparency as a function of the surface inclination angle proves that the amount of dust accumulated is closely related to the angle of inclination. This means that locations for which the angle of optimal slope is small will be less favorable due to the significant tendency for deposition. At the same time, it should be taken into account that dust particles have distinct transmittance indices: some are completely opaque, while others have a specific degree of transparency [11].

Ta et al. [12] found a strong correlation between the quantities of absorbing impurities and the season; this was associated with changes in weather. They stated that dust deposition is highest during spring months and lowest during autumn months, in both the desert and Gobi areas and the Loess Plateau. There is a significant inverse correlation between dust deposition and precipitation. This correlation with seasons may have a different character for other locations all over the world, but it should always be taken into account.

Sayigh et al. [13] presented the results of dust effect on the photovoltaic power reduction in the function of number of days without cleaning for the 30° angle of inclination (Fig. 2.). The presented dependence indicates that the impact of pollution is proportional to the time in which the module is exposed to the impact of depositing dust. In the case of measurements carried out in natural conditions for a long period, the influence of atmospheric precipitation and wind can be significant.

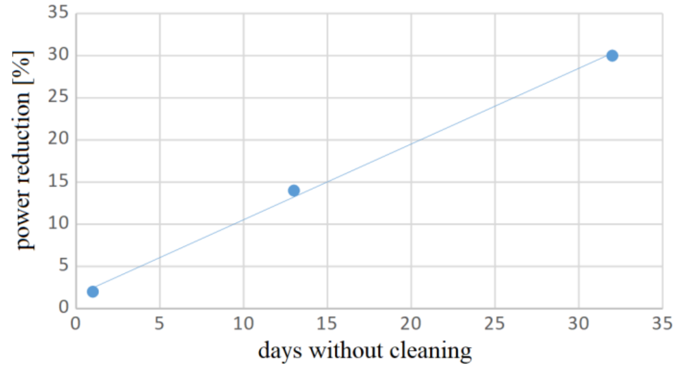


Fig. 2. Reduction of photovoltaic generated power due to the dust effect in the number of days without cleaning (on the base of [10])

Roth and Pettit [14] presented a 480-day long experiment, on the basis of which they found that the natural cleaning of the surface of photovoltaic modules, associated with rain or snow, may be sufficient. Most of the works, however, point to the fact that in order to obtain a high efficiency of the installation, it is necessary to regularly remove impurities.

The composition of contaminants existing in the air and atmospheric precipitation depends on the location. Of particular importance is the existence of nearby agricultural crops, industrial zones and express roads. Pollutant emissions from industrial plants contain a large amount of various chemical substances, including ash, soot, smoke, sulphates, nitrates, metal oxides and other solid components. As a result of technological processes and combustion of various types of fuels, dust is generated.

Fujiwara et al. [15] found that the composition of the sludge varies depending on the location of its formation: in large cities, the pollution deposited on surfaces is the result of the interaction of liquids, solids and gases from various sources. The pollutants also include heavy metals and organic compounds, mainly from road transport.

Sarver et al. [16] found that the properties of dust vary depending on the location of the photovoltaic system. Dust samples collected from highly urbanized areas in the northern hemisphere contain numerous impurities characteristic of the area. This could be airborne particles from coal-fired power plants, emissions from transport or from urban development. Similarly, in rural areas, pollution is created from fertilizers, land air flow or plant origin.

Zagorodnov et al. [17] examined particle size distribution and component composition of industrial dust emissions. They stated that median particle sizes of different industries range from 4 to 800 microns. In some cases, nano-scale particles (with a diameter less than 0.01 micrometers) were identified in emissions. The greater part of the emissions component composition (over 50%) consists of metal oxides: iron, aluminum, lead, titanium, copper, manganese, zinc and chromium.

This study has experimentally investigated the effect that soil accumulated on the PV module surface has on the efficiency. Various amounts of surface dust density, as well as different dust types, have been taken into consideration.

## II. Experimental

### A. *Naturally deposited dust study*

Four different PV modules were mounted on a rooftop on a metal stand, facing south with a tilt angle of roughly 35° as shown in Fig. 3. Beforehand, their surface was thoroughly cleaned, first by scraping off any remaining pollution, then by rinsing with isopropyl alcohol. Placing the rack with the modules outside allowed for a small scale imitation of soil adhesion on the actual PV installation. The same mounting position provided identical dust accumulation on each module surface. This exact arrangement was maintained for the entire year 2019.

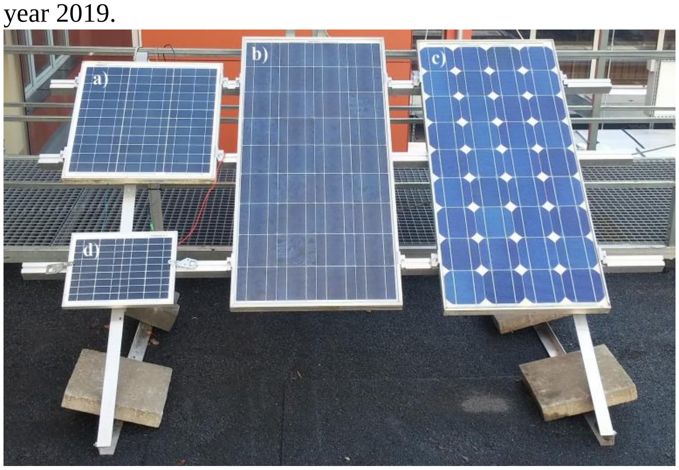


Fig. 3. PV modules used for field studies: a) MWG-30, b) AP-7105, c) STP-085, d) CLC010-12P

Once every month, MWG-30, AP-7105 and STP-085 modules were dismantled and taken inside to measure their current-voltage characteristics in the laboratory. The test stand presented in Fig. 4 allowed for preserving the same irradiation conditions, namely a steady light source perpendicular to the module surface. The surface temperature of each PV module was kept at 30°C. After obtaining the data necessary for the efficiency calculation, the modules were once again set on the metal frame on the rooftop. Module CLC010-12P was kept on the stand for the sole purpose of collecting dust, which was scraped off of its surface at the end of the year.

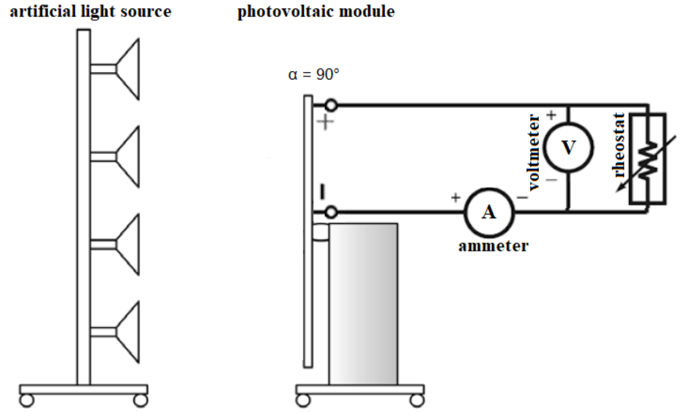


Fig. 4. Scheme of the measuring unit in the laboratory

Technical data of measuring devices are listed in Table I.

TABLE I
Technical data for artificial light source as well as gauging devices used for temperature, irradiance, current and voltage measurement

| Instrument | Producer | Serial number | Description |
|---|---|---|---|
| Light source | G.U.N.T. Hamburg | HL-313.01 | 8 halogen lamps<br>power of 1 lamp: 1000 W |
| | G.U.N.T. Hamburg | ET-250 | Voltage measuring range: 0 – 200 V<br>Current measuring range: 0 – 20 A<br>Irradiance measuring range: 0 – 3000 W/m$^2$<br>Tilt angle measuring range: 0 – 90°<br>Temperature range: 0 – +100°C |
| Pyranometer | Kipp & Zonen | METEON 07080865 | Measuring accuracy: 0,1%<br>Operating temperature: -10 – +40°C |
| Pyrometer | Fluke | 62 mini IR Thermometer | Measuring accuracy: ± 1,5°C<br>Operating temperature: -30 – +500°C<br>Sensor: laser<br>Standard measurement distance: 2 m |

Table II contains electrical parameters provided by manufacturers of each PV module. Bigger modules–AP-7105 and STP-085— were constructed using both monocrystalline and polycrystalline silicon, respectively.

TABLE II
Data sheet of PV modules MWG-30, AP-7105 and STP-0852

| | MWG-30 | AP-7105 | STP-0852 |
|---|---|---|---|
| $P_{MAX}$ [$W_{peak}$] | 30.0 | 75.0 | 85.0 |
| $V_{MAX}$ [V] | 17.5 | 17.0 | 17.1 |
| $I_{MAX}$ [A] | 1.71 | 4.4 | 4.97 |
| $V_{OC}$ [V] | 21.7 | 21.0 | 21.4 |
| $I_{SC}$ [A] | 1.83 | 4.8 | 5.32 |
| Dimensions [mm] | 680 x 353 x 25 | 1210 x 526 x 35 | 1195 x 541 x 30 |
| Weight [kg] | 3.9 | 8.2 | 8.0 |
| Cell type | Polycrystalline | Monocrystalline | Polycrystalline |

### B. Artificially deposited dust study

Simultaneously, a study based on the varying mass density unit has been conducted because it seemed to be the most uniform data used by the majority of researchers in the presented field of study. Around 0.5 kg of soil was gathered from three locations and sieved 15–20 times with a 1-mm netted strainer to remove any elements that did not belong to loose debris. In the first place, with coordinates of 54°37″ N and 18°62″ E, dust was gathered from the roads near the Chemistry building. Second and third sampling points were situated in the sandy beach area at coordinates of 54°41'N, 18°64'E and 54°41'N, 18°62'E, respectively. In order to obtain the desired layer of dust on the surface of the PV module, the dust was once again sieved and then sprayed with isopropyl alcohol to ensure adhesion and uniform distribution (Fig. 5).

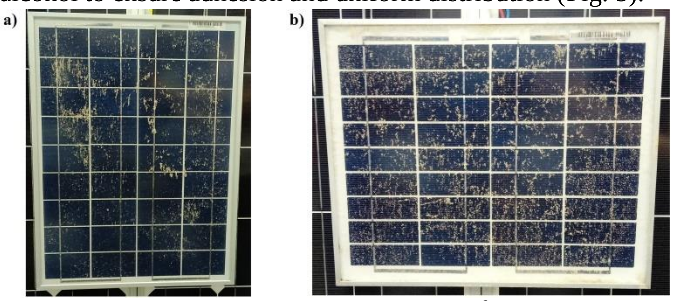

Fig. 5. PV modules contaminated with around 13.2 g/m$^2$ dust density on their surface: a) MWG-20, b) CLC010-12P

Throughout the whole experiment, the same two polycrystalline modules were used—MWG-20 and CLC010-12P. Their electrical parameters, as specified by the producer in the module data sheet, are presented in Table III. Maximum power generated by MWG-20, the 20 $W_{peak}$, is twice as high as CLC010-12P.

TABLE III
Data sheet of PV module MWG-20 and CLC010-12P

| | MWG-20 | CLC010-12P |
|---|---|---|
| $P_{MAX}$ [$W_{peak}$] | 20.0 | 10.0 |
| $V_{MAX}$ [V] | 17.2 | 17.5 |
| $I_{MAX}$ [A] | 1.17 | 0.57 |
| $V_{OC}$ [V] | 21.8 | 22.0 |
| $I_{SC}$ [A] | 1.23 | 0.63 |
| Dimensions [mm] | 505 × 353 × 28 | 340 × 280 × 17 |
| Weight [kg] | 2.3 | 1.1 |
| Cell type | Polycrystalline | Polycrystalline |

Each soil type applied in both natural and artificial dust experiments is listed in Table IV. All pollution scraped off of MWG-30, AP-7105 and STP-085 module surfaces is named soil 1. Dust accumulated throughout the year 2019 was collected from the additional small CLC010-12P module and is referred to as soil 2. Soil 3 was taken directly from roads in the vicinity of the Chemistry building, on Gdansk University of Technology campus, and soil 4 came solely from the inside of the laboratory hall. The last two pollutants, namely soils 5 and 6, were gathered from a sand beach area in close proximity to the walking pier and the tram loop, respectively, both located in the Gdansk Brzeźno district.

TABLE IV
Numbering of soil samples collected from photovoltaic modules, laboratory hall and three various locations in Gdansk

| Soil number | Description | Coordinates |
|---|---|---|
| 1 | Taken after 2 years of deposition on MWG-30, AP-7105 and STP-085 modules in outdoor conditions | 54°37″ N 18°62″ E |
| 2 | Taken after 1 year of deposition on CLC010-12P module in outdoor conditions | 54°37″ N 18°62″ E |
| 3 | Taken from roads nearby Chemistry C GUT building | 54°37″ N 18°62″ E |
| 4 | Taken from laboratory hall in Chemistry C GUT building | 54°37″ N 18°62″ E |
| 5 | Taken from sand beach area near the walking pier in Gdansk | 54°41″ N 18°64″ E |
| 6 | Taken from sand beach area near the tram loop in Gdansk | 54°41″ N 18°62″ E |

## III. Results and Discussion

### A. Naturally deposited dust study

Current-voltage characteristics of MGW-30, AP-7105 and STP-085 modules were measured once a month in the laboratory hall, starting in January 2019 and ending in November 2019. This allowed us to establish the efficiency of each module because, aside from monthly measurements, the modules were kept outdoors and as such were subjected to atmospheric dust build-up. The average efficiency calculated for four meteorological seasons helped to reveal the relation between efficiency decrease over the course of time for each PV module. Table V contains exact values, whereas Fig. 6 presents their course for each PV module after normalization.

TABLE V
Efficiency values calculated as an average for each meteorological season

| | Efficiency [%] | | | |
|---|---|---|---|---|
| PV module | Winter | Spring | Summer | Autumn |
| MWG-30 | 12.0 | 10.3 | 10.0 | 10.8 |
| AP-7105 | 8.5 | 8.1 | 7.1 | 7.7 |
| STP-085 | 10.4 | 9.7 | 9.0 | 9.5 |

A noticeable decrease in efficiency was observed for all of the modules over the course of months. Exposure to outside conditions in spring resulted in the biggest efficiency loss for MWG-30, over 15%, whereas the two other modules exhibited much lower reduction, around several percentages. However, in the summer period further efficiency decline, in comparison to spring, was greater for AP7105 and STP-085 modules, namely 12 and 7%, respectively. MWG-30 lost only around 3%. An interesting pattern emerged during autumn months, as all three PV modules seem to have recovered part of their power. This may be caused by heavy precipitation that is characteristic of that time and location in the north of Poland.

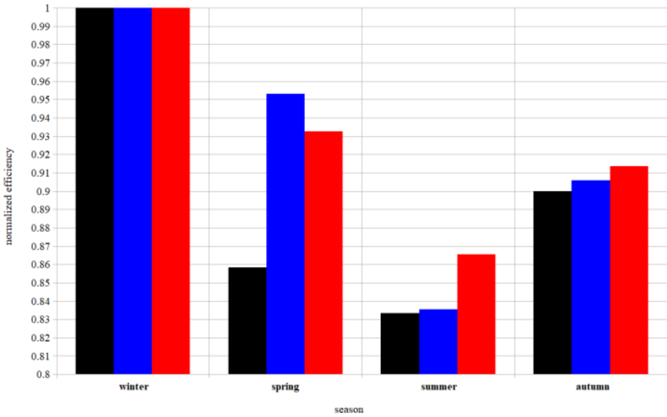


Fig. 6. Average seasonal normalized efficiency for the year 2019 for PV module: (♦) MWG-30, (♦) AP-7105, (♦) STP-085

SEM examination of both pollutants scraped off of module surface helped to visualize uneven structure (Fig. 7). Molecule grains vary in size and are have uneven edges, some sharply defined and other resembling more spongy structure. There are few places of an increased molecule concentration, thus indicating that the process of agglomeration new pollutant particles on top of the old ones might have taken place over the course of time.

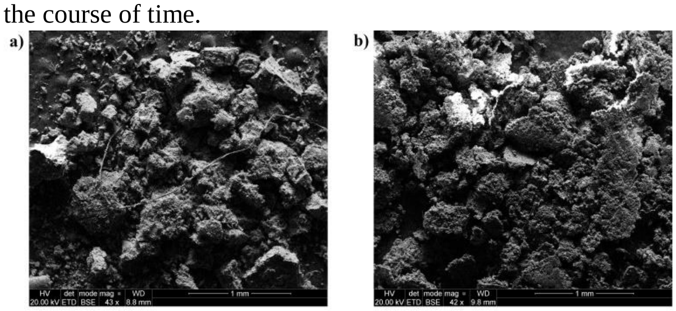


Fig. 7. SEM analysis of: a) soil 1 (magnitude 43), b) soil 2 (magnitude 42)

EDS spectra in Fig. 8 were collected from two small areas for soil 1 and from one large area for soil 2. It was found that both materials contain considerable content of oxygen, silicon, aluminum and trace quantities of sulfur, iron and magnesium. Additional carbon peak observed in both Fig. 7a and 7b comes from carbon tape used during EDS measurement and should not be counted as part of soil 1 or 2.

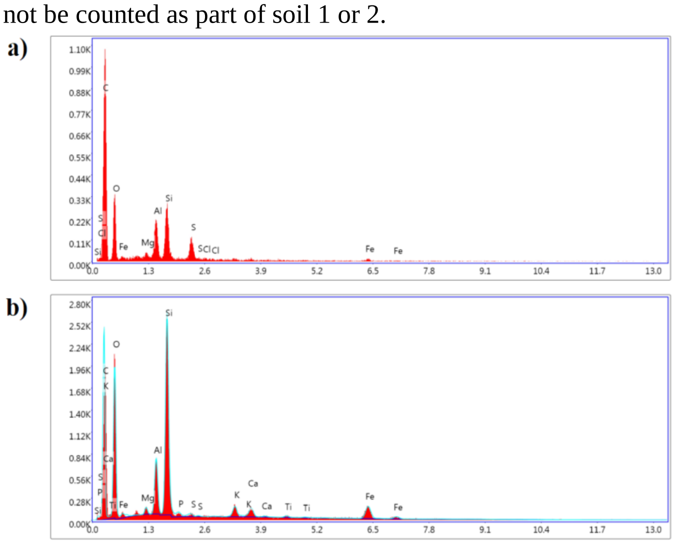


Fig. 8. EDS analysis of: a) soil 1, b) soil 2

## *B. Artificially deposited dust study*

Measurements of voltage and current were carried out for polycrystalline PV modules, MWG-20 and CLC010-12P, contaminated with 3 different types of dust, namely soil 3, 5 and 6. Irradiance of 1000 $W/m^2$ was obtained by artificial light source and the temperature for each measurement did not exceed 30°C. Based on the obtained characteristics maximum power and efficiency were calculated for each module and soil type. Normalized efficiency values are presented as a graph in Fig. 9, as the efficiency obtained for maximum power generated by the polluted module divided by the efficiency for maximum power generated by the clean module.

Both MGW-20 and CLC010-12P modules were assembled using polycrystalline solar cells, however their response to pollutants is slightly different. For the surface density falling within the range 0 – 14 $g/m^2$ CLC010-12P experiences more efficiency loss, notwithstanding the type of dust applied. 3 $g/m^2$ of soil is enough for this module to lose nearly 5% of efficiency, and for the dust density of the order of 10 $g/m^2$ this number is even higher and reaches around 10%. However, MWG-20 module better withstands soil contamination, as its efficiency is never reduced by more than 6% for each of three pollutants.

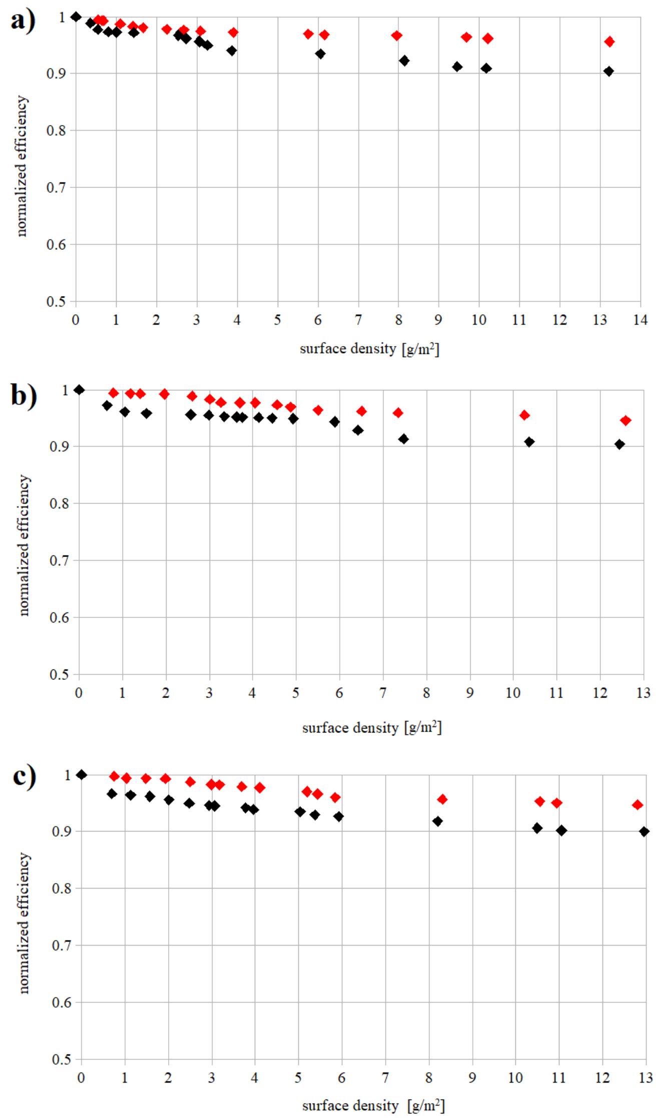


Fig. 9. Normalized efficiency $\eta/\eta_{MAX}$ for module MWG-20 (♦) and CLC010-12P (♦) with their surface covered with three different contaminants: a) soil 3, b) soil 5, c) soil 6

Additional comparison graph of efficiency decrease for both modules was presented in Fig. 10. It was calculated as a ratio of efficiency $\eta$ after soil contamination to the efficiency $\eta_0$ of a clean module. Such mismatch in response could not be explained by the module or dust type, as both CLC010-12P and MWG-20 were manufactured in polycrystalline technology and polluted only with soil 3. Most probable cause can be found in the glass layer, as it likely is different for both modules. Such conclusion is supported by an analysis of results obtained by two independent research groups – under Cabanillas' [18] and Gandhi's [19] supervision. Efficiency decrease acquired in those experiments does not appear to exhibit any correlation to the solar cell type (monocrystalline or polycrystalline).

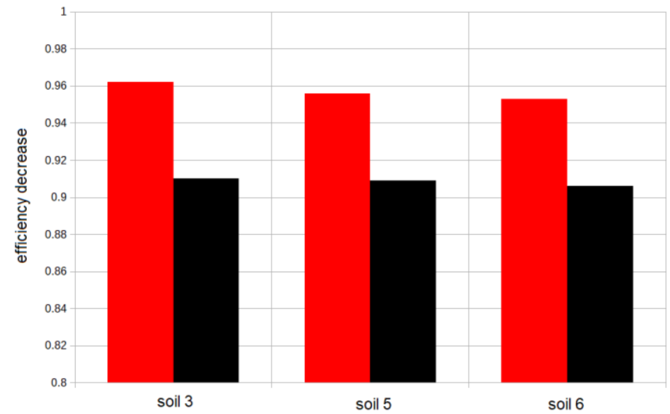


Fig. 10. Efficiency decrease $\eta/\eta_0$ for the amount of dust density around 10.4 $g/m^2$: MWG-20 (♦) and CLC010-12P (♦)

Additionally, one conclusion can be formulated with regards to the soil applied in this experiment. The carried out analysis was supposed to imitate outdoor conditions that allow for dust accumulation on PV module surface. For this purpose soil 3 seems to be resembling the effect of natural dust the most, as obtained graphs of efficiency as a function of dust surface density follow the actual relation of pollutant adhesion to glass surface. Such dependence exhibits initial linear decline followed by an exponential fall. It is a result of molecule deposition on top of an already existing layer of dust and has been observed by many researchers, including Al-Hasan [20], El-Shobokshy and Hussein [21] and Rao [22].

Fig. 11 presents SEM pictures of soil types, gathered from 3 different outside locations and from the laboratory hall. Unlike in Fig. 7 all of them have well defined edges. Dust collected from roads nearby university campus (Fig. 11a) as well as from the laboratory hall (Fig. 11b) consists of grains of varying size, that are marked with cracks in some places. Soil 3 is made of dust elements of two distinct sizes – smaller grains with average diameter of around 0.2 mm, and bigger ones with average diameter of roughly 0.45 mm. The average grain size for soil 4 is in the range of 0.2 – 0.35 mm, with some noticeably bigger parts exceeding 0.5 mm. Soil 5 (Fig. 11c) and soil 6 (Fig. 11d), both taken from locations placed at short distance to the beach, contain grains with a similar diameter, which have more even edges and are less fractured. Average grain diameter for soil 5 falls in the range of 0.23 – 0.36 mm, and for soil 6 in the range of 0.22 – 0.33 mm.

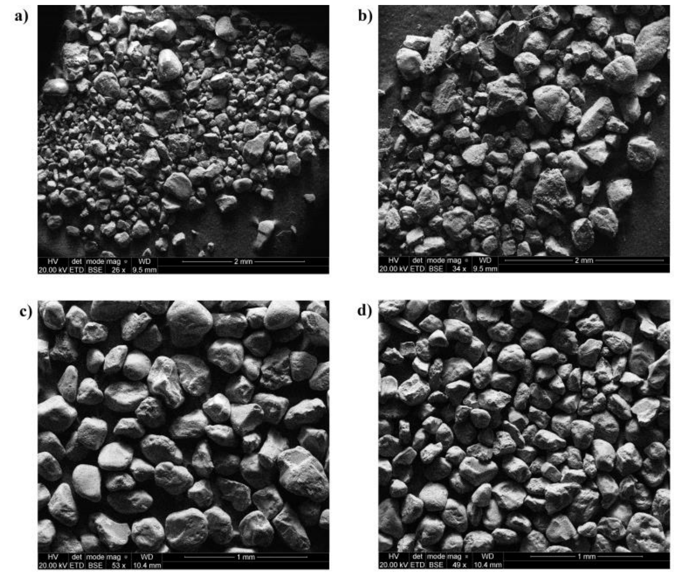

Fig. 11. SEM analysis of: a) soil 3 (magnitude 26), b) soil 4 (magnitude 34), c) soil 5 (magnitude 53), d) soil 6 (magnitude 49)

EDS spectra in Fig. 12 correspond to soil 3, soil 4, soil 5 and soil 6 respectively, and were gathered from different spots and areas of each sample. The main elements of soil 3 (Fig. 12a) comprise oxygen, silicon and aluminum. Trace quantities of calcium, potassium, magnesium and iron were detected. The last element most likely is a result of a sampling point being located in the vicinity of road much frequented by vehicles. Additional peak from carbon is caused by the carbon tape used as a substrate during EDS measurement and should not be taken as a part of soil 3. The composition of soil 4 (Fig. 12b) is similar to a large extent to soil 3. However, instead of magnesium, trace elements of sodium, chlorine and sulfur appear. Soil 5 (Fig. 12c) and 6 (Fig. 12d) are less differentiated element-wise than other types of dust. Those two pollutants were obtained in the close proximity of the beach. The location heavily influences their composition, as it consists of two explicitly visible peaks, correlating to silicon and oxygen. It was therefore concluded that soil 3 is best suited to be used for experimental studies concerning artificial dust influence, because of a strong convergence in composition with regards to natural pollutant as soil 1 and 2.

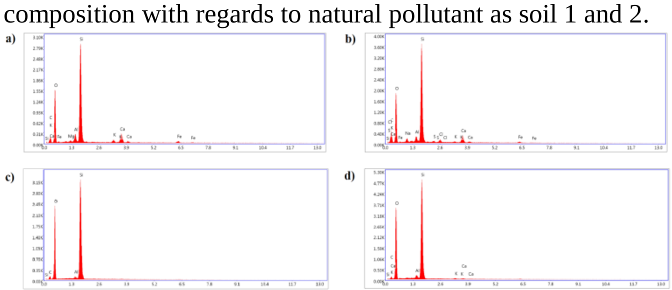

Fig. 12. EDS analysis of: a) soil 3, b) soil 4, c) soil 5, d) soil 6

## IV. Conclusions

Decreasing the efficiency of photovoltaic modules caused by the deposition of pollutants on their surface is a significant problem, causing the reduction of generated energy, and thus the reduction of economic viability. A number of factors determine the amount of depositing contaminants, which results in a large discrepancy in the assessment of the degree of this impact.

It should be noted that there is a lack of proportionality in the amount of accumulated contaminants by the time. This is related to the significant impact of precipitation and wind. Therefore, comparing the average effects, without analyzing the location in relation to the environment (agricultural crops, deserts, traffic or industrial activity in the near vicinity), the composition of pollutants cannot lead to correct conclusions. The accumulation process runs at different speed for regions that vary in average precipitation and atmospheric humidity. Less build-up is expected for areas with regular rainfalls that ensure rinsing some of the soil off of module or solar collector surface.

Additional analysis was carried out on photovoltaic modules, for both natural and artificial dust. It provided more insight into hard shading effect and its consequences for possible power generation. Average efficiency decrease is observed over the course of months, however in autumn it recovered a few percentile point. Such effect is most likely caused by heavy precipitation occurring in this meteorological season, since the modules are located in the temperate, coastal climate in the northern hemisphere. Artificial dust experiments conducted on two different solar modules helped to further depict soiling effect as a linear relation of efficiency decrease for a varying surface density, thus confirming data cited in literature by other research groups. Out of three various artificial dust types one was selected (soil 3) to imitate natural soil, on the grounds of composition resemblance to the air pollution found on the surface of all modules kept outdoors.

A significant decrease in the efficiency of photovoltaic modules was observed, caused by the deposition of impurities, depending on the thickness of the dust layer and its morphology, but it is different for the various modules tested. This means that the structure of the glass surface constituting the top layer of the module plays an important role here.

## V. Acknowledgment

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