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DEGRADATION OF ELECTRICAL PERFORMANCE OF A CRYSTALLINE PHOTOVOLTAIC MODULE DUE TO DUST DEPOSITION IN NORTHERN POLAND

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Highlights

- Dust deposition and soiling of photovoltaic modules remain problems in need of a better solution.
- The physical properties of dust (composition, morphology, topography, size and mechanical properties) are dependent on geographical area and environmental conditions, and the properties of the front cover material (roughness, chemistry) have a significant impact on the decrease in photovoltaic efficiency.
- The maximum daily efficiency loss calculated for a silicon crystalline module tilted at 37^{o} in northern Poland was 0.8%
- All modules investigated showed an average decrease in maximum power of 3%/year.

Abstract

The reduction in power output caused by the accumulation of dust on the photovoltaic module surface is an important problem and should receive much more attention in the literature. This study was an evaluation of the performance degradation of crystalline photovoltaic modules due to natural and simulated dust deposition. Dust is created from powdered grains of sand and particles of different bodies. On Earth, dust originates from different sources, e.g. from the soil and volcanic eruptions. Dust in the air is an aerosol, and in high concentrations can cause climate change. Deposition of airborne dust on photovoltaic modules may decrease the transmittance of solar cell glazing and cause a significant degradation in the solar conversion efficiency of photovoltaic (PV) modules. Dust deposition is closely related to the tilt angle of the solar module, the exposure period, site climate conditions, wind movement and dust properties. The cost of washing is not negligible and should not be neglected, especially in regions where the lack of water is felt. In this article, a brief review of the energy yield losses caused by dust deposition on photovoltaic modules and the results of experimental research conducted in Poland are presented. Dust samples were collected after a few years of natural and artificial dust deposition. The reduction in efficiency had a linear relationship with the dust deposition density.

Keywords: dust deposition; photovoltaic modules; efficiency reduction.

Sources and properties of dust, and the impact of weather conditions on the deposition of pollutants

There are several factors that influence the efficiency of photovoltaic modules (Figure 1):

- the type of front cover material,
- the orientation and angle of inclination,
- the type of installation (tracking or stationary),
- localization,
- solar cell temperature,
- shadowing,
- dust deposition and soiling of the front cover.

Figure 1. Performance-limiting factors for photovoltaic modules

Soiling includes not only dust accumulation, but also surface contamination by plant products, soot, salt, bird droppings, and the growth of organic species; these all adversely affect the optical performance. The chemical composition, the dust source, the grain size and the amount of pollutants deposited on the surface of solar modules in various places on the globe differ significantly. The climate, including precipitation, has the greatest influence on the formation of a dust layer.

Many researchers have devoted their work to studying the origin, composition and gradation of dust grains originating from different regions of the world. Fujiwara et al. [1] stated that the composition of dust varies depending on the location of its formation. In big cities, contamination deposited on surfaces is the result of the interaction of liquids, solids and gases derived from different sources. They may also contain heavy metals and organic compounds, derived mainly from road transport. However, in dry climates, i.e. desert or semi-desert, the main source of the dust is soil. Ta at al. [2] described research conducted over 15 years in the region of Gansu, China. They noted that more particles are deposited on the surface of photovoltaic modules in the areas adjacent to the Gobi desert, rather than in areas of loess. Moreover, they found a strong correlation between the quantities of absorbing impurities and the season; this was associated with changes in weather, including the wind direction. They demonstrated that over 30% of the total annual quantity of dust is deposited in the spring months, and less than 20% in the winter months.

Fujiwara et al. [1] found the presence of cadmium, sulfur and antimony in samples of dust, which most likely came from the abrasion of automobile brake shoes. In contrast, the origin of lead, zinc and manganese was attributed to mechanical wear and also, to a lesser degree, exhaust gases.

Bi, Liang and Li [3] stated that the concentration of trace metals in different fractions of dust originating both from the soil and from the roads increases with decreasing particle diameter. This is an interesting phenomenon, because as mentioned in their study, trace metals remain in evenly spread the soil, independent of particle size. The tested dust samples showed that approximately 40% of these elements were connected with a particle size not exceeding 100 μm. The authors found an increased content of lead in dust samples taken from the soil, which was matched to the level of this element in the dust coming from industry.

Kazmerski and his group [4] 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.

Cabanillas and Munguia from Mexico [5] identified clay, sand, soot, fungi, spores and plant fibers as the main components of dust deposited in their area. The material bonding the particles floating in the air and anchoring them to the surface of the module were organic pollutants occurring in rural and urban areas.

Research carried out by McTainsh, Nickling and Lynch [6] showed that the grain size of the dust settling on the surface of PV modules is correlated with the distance from which the dust was brought by the wind. There are three ranges of deposited dust, depending on the size of the grains: small particles with a diameter up to 5 μm come from widely spaced areas, while particles in the range of 20 to 40 μm are dust deposits from regional sources, and larger components of dust, from 50 to 70 μm, indicate a local origin of the dust, which means that these particles were produced by people, vehicles, machines and livestock. The authors found that the pollution coming from the vicinity had a great influence on the deposition of dust on the module cover.

Beattie et al. [7] proposed a classification of grain sizes which allows for the identification of their origin: a particle size from 60 to 2000 μm is mainly sand brought by the wind, while dust with a particle size from 4 to 60 μm originated from alluvial soil, and particles less than 4 μm were from clays.

The particle size of contaminants can vary considerably, as was shown by Biryukov [8], who performed an analysis using a computerized optical microscope and a scanning electron microscope (SEM). The author examined a natural dust sample collected in the Negev, Israel. The largest particle size identified, from 20 to 40 μm, covered about 55% of the surface of the module, and the larger or smaller particle sizes in the test sample constituted a tiny minority. In contrast, the fouling factor, expressed as the number of particles that was deposited per cm^2 per hour, indicated that most of the particles had sizes from 5 to 35 μm.

Bouaouadja and co-authors [9] investigated and described the dust obtained in a desert area. They showed that the particle size distribution can be uniform or bimodal, which means that the particle size of the impurities in the test sample may be similar or completely different. Similarly, the morphology of the particles can be different, from rounded grains with smooth edges, to very rough particles with sharp edges.

Zhang, Cui, Fang, Fan and Zhang [10] described 76 dust samples deriving from Wuhu in the Anhui region of China in order to qualify the size of dust grains. It was found that 34% of the particles were in the range of 120 to 370 μm, and 25% were in the range of 20-55 μm.

Igathinathane et al. [11] studied the properties of the dust coming from the production of pellets made of wood and bark. The volatile air pollutants emitted from sawmills had relatively large dimensions, and therefore were deposited in the vicinity of the plant. As stated in the article, the average size of the particles from the production of wood pellets was 113.8±12.3 μm in length and 73.6 ± 7.6 μm in width, whereas in the production of cortical pellets, the dimensions were 118.1 ± 14.9 μm in length and 60 7 ± 7.1 μm in width.

In semi-arid desert areas, the amount of naturally deposited dust is very high. As has been shown by Ta and co-authors [12], in the area of the Gobi desert, a layer formed with a dust deposition density of about 365.48 g/m^2, while in areas of loess, the layer was thinner, i.e. approximately 251.75 g/m^2.

The impact of dust on PV performance

The influence of the thickness of a dust layer on the performance of photovoltaic modules is significant, as concluded by Jiang, Lu and Sun [13]. The authors conducted experiments with the use of artificially produced impurities with a grain size of 1 to 100 μm, wherein about 20% by volume had a particle diameter of 20 μm and 74% were smaller grains. The main components of the dust were SiO_2 and Al_2O_3. As a result, the study came to several important conclusions:

- dust caused a significant decrease in the short circuit current I_{sc}, but did not affect the value of the open circuit voltage V_{oc},
- with increasing thickness of the dust layer, i.e. with a dust deposition density from 0 to 22 g/m^2, the efficiency decreased by 0 to 26%; this dependency was linear,
- the surface material may considerably influence dust deposition and accumulation (the polycrystalline silicon module packaged with epoxy degraded faster than other modules with a glass surface),
- larger dust grains had a more significant impact on reducing efficiency, which was also confirmed by Biryukov [8].

Based on these results, the authors stated that in order to maintain the high efficiency of solar energy conversion, it is necessary to clean the surface of photovoltaic modules regularly and quite often, particularly if they are located in regions with high urbanization and its associated air pollution or in dry areas.

Module performance is also affected by humidity and wind speed, as a result of creating additional shading and coagulation of dust on the front cover of the module; combinations of these factors are also important, as shown by Mekhilef et al. [14]. They concluded that an increase in the level of moisture in the atmosphere deteriorates the working conditions of photovoltaic installations, whereas higher wind speeds cool the surface and relatively reduce the ambient humidity; additionally, this increases the number of particles floating in the air, which may lead to their deposition on the modules, This also entrains contaminants on the surface of the installation. However, the clear identification of this impact is difficult.

Depending on the location, the composition of dust may be significantly different, and these differences affect the degree of reduction in the efficiency of photovoltaic modules [15]. Three representative samples of air pollution in Athens, Greece were studied, including red earth, limestone and coal ash as well as dust samples. These pollutants are commonly found in urban areas and in open areas, villages, etc. The absolute decline in the efficiency of the modules for each of the four abovementioned cases of pollution was examined: for the original natural dust layer with a dust deposition density of 0.1 g/m^2, the efficiency decreased by 0.15%, while for 1 g/m^2 this was equal to 0.4%. The reduction in module efficiency by natural dust was the smallest of all the samples. Contamination by ash led to a decrease in efficiency of only 0.15% for the layer with a dust deposition density of 0.6 g/m^2, and 0.4% for 2.1 g/m^2, i.e. twice the thickness of the natural dust layer. Red earth caused a much higher efficiency decrease: for 0.1 g/m^2, this was equal to 0.5% and increased significantly with a small increase in the layer thickness. For limestone, the results were similar, although for thicker layers of dust the efficiency loss was less pronounced than in the case of red earth.

Kazem et al. [16] conducted an experiment using samples of ash, sand, red earth, calcium carbonate and silica with masses of 5 and 10 g, simulating the shading of the PV module by natural dust. The decrease in voltage was measured, resulting from pollution and its change over time; the results were related to a change in temperature. The smallest registered open-circuit voltage drop occurred in the case of sand (about 4%), followed by silica, calcium carbonate, and red earth, and the greatest decline was observed for ash (about 24%). As was expected, the device works best when is chilled and clean, and the worst when it is uncooled and dirty.

Al Busairi and Moller [17] described an experiment examining the monthly decrease in the efficiency of photovoltaic thin layer CdTe modules in Kuwait during the five months of summer, from April to August. They observed the largest decrease in system efficiency in

May, by about 25%, which had a direct relationship with a significant accumulation of pollution caused by rain with a high content of sediments.

Zorrilla-Casanova et al. [18] provided information that the average daily loss of energy produced by a photovoltaic module caused by the accumulation of dust is 4.4%, while in the long rainless periods may rise as high as 20%. The study was conducted at the University of Malaga, Spain. It was concluded that even a small amount of rain cleanses the coating of the module, which significantly improves the conditions of its operation.

Research conducted in Senegal and described by Ndiaye et al. [19] showed that the greatest decrease in the maximum power ranged from 18% to 78% for polycrystalline and monocrystalline modules, respectively. In this experiment, the modules were exposed to natural climatic factors for one year; embedded dust was typical for the region.

Knowing that the deposition of dust on the surface of the PV module reduces its efficiency, Mani and Pillai [20] created a recommendation for a cleaning cycle of the front cover of PV modules. Many factors were taken into account, including climate, latitude, temperature and the amount of annual precipitation. Poland was classified in Group II, in which it is recommended to clean the surface of photovoltaic modules every week.

Tylim [21] stated that the efficiency of regularly cleaned photovoltaic increases meaningfully, i.e. from 9% to 26%; for a 150 kW system, it increased by 9.1%, for a 260 kW system it increased by 15% and for a 330 kW efficiency increased by up to 26%. It was calculated how much money would be saved by not washing the systems (the cost of electricity was \$0.15/kWh in Los Angeles in 2013, so savings were on average \$5000 per year for a 100 kW system). The author recommended washing module coatings two to three times a year, depending on the availability and price of water.

Sarver, Al-Qaraghuli and Kazmerski [4] performed a comprehensive assessment of the impact of dust on the work of photovoltaic modules. The authors reviewed articles from all around the world, taking into account the location, device type, duration of measurements and key findings. The analysis relates to systems located in different countries and on all continents except Europe (the analysis refers to a system tested in Spain). The authors stated that several noteworthy studies showed large performance variations from location to location as a function of exposure time.

A six-month study was conducted by Nimmo and Said [22] in Saudi Arabia. They reported a 40% decrease in the efficiency of PV modules. As a result of the year-long experiment, they estimated a monthly decrease in yield of 7% [23]. Ryan et al. [24] conducted experimental investigations in the state of Oregon in the United States for six years; they found that there was a decrease in efficiency of about 1.4% per year.

Pande [25] described an experiment carried out in India, in which, after a year of use, the module that was note cleaned showed a decrease in the short circuit current of 30%.

Alamoud [26] reported that in Riyadh, Saudi Arabia, after a year of exposure to climatic factors, the decrease in efficiency was from 5.73% to 19.8%, depending on the type of device. In contrast, in Cairo, Egypt, Elminir et al. [27] recorded a 17.4% monthly decrease in efficiency. In California and in the southwestern part of the United States, daily energy loss due to dust deposition was around 0.2% (in rainless periods), as described by Kimber et al. [28].

In a 90-day research study conducted by Cabanillas and Munguía [5] in Hermosillo and Sonoro, Mexico, there was a reduction in power obtained from silicon crystalline modules equal to 4-7%, and for amorphous silicon modules from 8-13%.

As a result of laboratory tests, Sulaiman [29] found that there was an 18% decrease in maximum power.

Mohamed [30] described an experiment conducted in Libya, based no which they recommended washing the surface of modules with water every week, so that the reduction in output obtained can be maintained in the range of 2-5%.

Roth and Pettit [31] 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. Rain washes away the dust and dirt, restoring the efficiency of the device to almost the maximum level. However, this applies only to certain climatic conditions.

Extensive research on the deposition of dust and the mechanics of contamination was carried by Cuddihy [32, 33, 34]. The most important identified processes was cementing of the dirt, which takes place in many areas around the world where high levels of pollutants occur together with high humidity, which manifests itself as abundant morning dew. Atmospheric dust is composed of organic and inorganic particles, which in turn contain soluble and insoluble salts. In periods of high atmospheric humidity, the water soluble form of dust particles forms films of microscopic droplets of salt solutions, which can retain insoluble compounds. Intermolecular forces increase with a particle diameter less than 10 μm, which means that the grains of this size are deposited in the largest quantities. When dry, the deposited salt behaves like cement and forms a shadow on the module surface. It was further stated that at low wind speeds, dust with particle sizes below 10 μm are not effectively removed.

The general conclusion from this literature review is as follows: the physical properties of dust (composition, morphology, topography, gradation, and mechanical properties) depend on the on geographical area and environmental conditions, and the properties of the front cover material (roughness and chemistry) have a significant impact on the decrease in photovoltaic efficiency. This justifies further study on the impact of dust on photovoltaic efficiency in other areas.

Natural and passive methods of module cleaning

Natural cleaning processes of surfaces exposed to natural climatic outdoor conditions include rainfall, melting snow, wind and gravitational forces. Rainfall is considered to be the most efficient natural cleaning process. However, when the rain is light, it scavenges the airborne dust particles and forms sticky mud patches on the surface of the module.

The tilt angle of the PV module has a strong influence on dust deposition, since because of gravitational forces, some of the larger particles can roll off the panel's surface or move to the lower parts as the tilt angle increases. Both the mass concentration density (g/m^2) and the particle size distribution of the deposited particles will depend upon the angle of inclination. Cleaning of panels by rain and wind is also dependent upon the tilt angle and orientation of surfaces with respect to the wind direction.

Wind causes the removal of deposited dust. The dust removal rate at a relatively high wind speed will be more effective at a high tilt angle. Removal of the deposited dust also depends upon the particle diameter *d* and the microstructure of the dust layer. A thin layer of dust deposited on a horizontal surface cannot easily be removed by wind, even at a relatively high velocity (50 m/s). The removal force, which is limited by the boundary-layer air velocity, has been found to be ineffective for particles with $d < 50$ μm when the free stream velocity is less than 50 m/s [35].

Hegazy [36] conducted an experiment in Egypt and observed that the surface densities of collected particles with small mean diameters (<1 μm) were higher on panels with high inclination angles, while coarser dust particles (mean diameter of 3 μm) deposited with higher proportions on panels with a low inclination.

Passive methods of cleaning include modifications to the module front cover and the use of anti-soiling coatings to minimize the surface adhesion of dust.

Experimental investigations

To investigate the influence of dust deposition on photovoltaic module efficiency, field and laboratory experiment under controlled conditions were designed and conducted.

The influence of dust and soiling on outdoor exposure of photovoltaic modules was conducted in Gdansk, Poland (central Europe). The annual sum of global irradiation incident on an optimally-inclined south-oriented surface in Poland is equal to 1100 kWh/m^2 [37]. Experimental studies were conducted on the roof of the Faculty of Chemistry, Gdansk University of Technology and in a laboratory situated in the same building. Gdansk University of Technology is located a small distance (5 km) from the coast of the Baltic Sea. There are no actively operating industrial plants near the building; however, the university campus is surrounded on all sides by streets with a significant degree of traffic.

During the study, three monocrystalline photovoltaic modules with nominal power of 70 W, 75 W and 100 W were used. One of the panels was cleaned regularly, while the others were made dusty using sand dust particles collected from a nearby area.

For the dust analysis, a Hitachi S-3400N variable pressure scanning electron microscope was used. The layer of dust was coated with a gold layer with a thickness of 19.4 nm with a Cressington auto sputter coater 108.

To determine the particle size of the dust, a Fritsch ANALYSETTE 22 MicroTec Plus laser particle sizer with a measuring range of 0.08-2000 μm was used. A semiconductor laser with green light carries out the measurement of small particles, while an infrared-semiconductor laser handles the large particle size ranges. Both lasers can be optimally aligned extremely quickly, automatically and independently of each other through lateral motion.

The current-voltage characteristics of the modules were measured with the use of variable electrical resistance and universal digital multimeters, i.e. an ammeter and voltmeter, in outdoor conditions under natural sunlight with a constant value of solar irradiance of 1000 W/m^2 (Figure 2).

In the laboratory soiling studies, a controlled environment test chamber was equipped with a xenon lamp solar simulator to provide simulated sunlight. An SP Lite2 Kipp & Zonen pyranometer was used to measure and control irradiance to simulate field conditions.

Figure 2. An illustration of the laboratory experiment setup

The current-voltage characteristics were determined for clean modules and modules covered with a layer of dust, which allowed us to calculate the value of maximum power and efficiency. Knowing the mass of the dust accumulated on the module, the average layer thickness was calculated. The results are presented in Figure 3.

The relative efficiency decrease was calculated on the basis of Equation (1):

$$\frac{\Delta\eta}{\eta_0}[\%] = \frac{\eta-\eta_0}{\eta_0}\cdot 100\% \quad , \qquad (1),$$

where $\eta = \frac{P_{max}}{E \cdot S} \cdot 100\%$ - efficiency of the module, η_0- efficiency of clean module, P_{max}[W] - maximum power of the module, E[W/m^2] - solar irradiance, S[m^2] - surface area of the module.

The dependence of the absolute decrease in the efficiency of the photovoltaic module on the dust layer thickness is shown in Figure 3. This relationship was linear. Points corresponding to natural dust had a slightly higher value, which resulted from the fact that dust particles deposited for a long time on the surface and exposed to changeable weather conditions were more compacted and adhered better to the surface of the module.

The dust was deposited on the module surface for two years; therefore, it can be concluded that during the operation of the module in the climate conditions of northern Poland, the efficiency loss will be equal to about 3% of the initial value of efficiency per year.

On the basis of the results, the value of the PV module efficiency relative loss with a dust layer thickness of 1 μm was calculated; it was equal to $25.5\,\frac{\%}{1\ \mu\mathrm{m}}$ for the naturally deposited dust and two times less for the reference sample of dust.

Figure 3. Relative efficiency decrease measured for three PV modules tilted at 37^{o} exposed outdoors in Poland with different dust layer thicknesses; points representing measurements with natural dust are encircled

The next step was to conduct a qualitative analysis, which allowed for the identification of the chemical elements included in the dust. A comparison was made between the chemical structure of the dust deposited on the surface of the photovoltaic module in a natural way and the reference sample, prepared for the purposes of this experiment. The element which was identified in the greatest amount in natural dust sample was silicon, followed by aluminum and magnesium (Figure 4). The greatest volume of the sample was taken up by silica (SiO_2), a compound commonly found in the earth's crust and the main component of sand. Dialuminum trioxide and magnesium oxide (Al_2O_3 and MgO) also occur in nature, so their contents were relatively high. Iron present in the sample was likely of anthropogenic origin and may occur both in the form of oxides and chemically homogeneous ore particles. The source of this element may be from the wear of frictional elements of mechanical components of machines, for example automotive brakes. Extremely low contents of elements such as potassium, calcium, phosphorus and sulfur were also observed; these are commonly found in the environment.

Figure 4. Chemical composition of the natural dust sample

The chemical composition of the reference sample is shown in Figure 5. It was similar to the spectrum of natural dust samples. The largest share of the elements was composed of silicon and oxygen. The amounts of aluminum, magnesium and iron were less than in the natural dust sample. Other elements such as calcium, potassium, manganese and chlorine were present in very small amounts, even smaller than was the case in natural dust samples.

Figure 5. Chemical composition of the reference dust sample

The analysis conducted with the use of scanning electron microscopy allowed us to determine the diameter of dust grains, their shape and structure. Significant differences between natural pollution deposition on the surface of the module and the reference sample can be seen in the images below (Figures 6-9).

Figure 6. SEM images of the natural dust sample (with acceleration voltages of 10 kV and 5 kV, magnification 100×)

In the image on the left side of Figure 6, very different cross-sectional sizes of the dust are visible, with a few bigger particles with a diameter of about 50 μm. They are covered with and surrounded by smaller particles. In the image on the right side of Figure 6, the particles of dust appeared to stick together, forming agglomerates. In addition, we could distinguish oblong and thin objects on which the smaller particles of pollution were deposited.

In the image on the left side of Figure 7, numerous small grains, which merged to form large clusters, are visible. It can be seen that a larger portion of the dust was at the bottom of the image, with diameters of about 30 μm. In the upper right corner, there are at least two grains with a size of 10 μm, but the remaining dust particles are smaller; the estimated length was about 1 μm. In the image on the right side of Figure 7, one can identify three grains with diameters of 31.1 μm, 33.7 μm and 29.4 μm. The image shows a large number of particles with a size in the range of 5 to 10 μm.

Figure 7. SEM images of the natural dust sample (with an acceleration voltage of 1 kV, magnification 500× and 1000×)

The SEM images of the reference sample are shown in Figure 7. In the image on he left, one can see that the sample is not a cake, but uniformly distributed on the carbon tape, covering it with a layer of similar thickness throughout the whole area. The distribution of particles is random, with apparent mixing of particles of different sizes. This dust had a much more granular texture, with far more regular shapes, which made it easier to identify than in the case of the dust deposited naturally on the surface of the photovoltaic module over two years. On the right, selected grains are shown with diameters of 48.4 μm, 38.7 μm and 29.6 μm. In addition to numerous smaller particles with sizes around 5 μm, larger particles could be identified, whose sizes could be estimated to be approximately 20 μm.

Figure 8. SEM images of the reference dust sample (with acceleration voltages of 10 kV and 1 kV, magnification 100× and 1000×)

The grains had clear edges, and did not tend to connect with each other. However, the surface was not smooth, which may indicate that they did not originate from a strictly coastal or desert area, as the degree of roundness was relatively low. This is understandable, given the fact that the localization of dust was more than 4 km from the coast and was from an area originally covered with forest.

Figure 9. SEM images of the reference dust sample (with an acceleration voltage of 1 kV, magnification 1000×)

In Figure 9, dust grains with sizes of 39.7 μm, 27.2 μm and 32.7 μm are shown. Smaller grains are also visible, with sizes not exceeding 5 μm, but they were more difficult to distinguish from the rest of the particles. One can see only one particle with a size up to 20 μm, which is in contrast to the previously analyzed images, presented in Figure 8. On the right, particles of dust with sizes of 23.8 μm, 20.7 μm, 23, 1 μm and 17.7 μm were selected, in addition to several smaller particles with a size of about 5 μm.

On the basis of the SEM images, the size distribution of dust particles in the sample of natural dust and the reference dust was determined (Figure 10).

Natural dust was characterized by the vast predominance of very small particle sizes with a tendency to agglomerate. Few, larger particles accounted for only about 15% of the whole sample. This was due to the natural processes occurring on the surface coated with dust over a long period of time: grains form agglomerations and the grains with larger diameters and thus a higher molecular weight were removed as a result of the natural cleaning of the surface by rain, wind and snow.

Figure 10. Size distribution of dust particles in the sample of natural dust and the reference dust

Dust samples were analyzed with the use of a laser particle analyzer. In Figure 11, the size distribution of selected samples is presented. A large number of grains of medium size was found, in accordance with the results of the microscopic analysis. Studies carried out with a laser particle analyzer allowed us to confirm the earlier particle size classification of the examined dust samples.

Figure 11. The size distribution of selected samples of dust

The maximum daily efficiency loss was calculated and compared with the literature reports (Figure 12). The obtained value of 0.8% was relatively high, compared to the results obtained from Spain, for example.

Figure 12. Maximum daily efficiency loss for various latitudes. The locations in the order of increasing latitude are: Hong Kong, China; Abu Dhabi, UAE; Riyadh, Saudi Arabia; Dhahran, Saudi Arabia; Gran Canaria, Spain; Arava Valley, Israel [38] (grey bars) and Gdansk, Poland - the current experiment (black bar)

Conclusions

The deposition and accumulation of dust significantly reduce the output performance of PV modules. Here, the performance of solar photovoltaic modules subjected to environmental dust was experimentally studied.

The designed and conducted experiment showed a linear relationship between the thickness of the layer of pollution and the loss of productivity for the three tested PV installations in Gdansk, Poland. On the basis of the data analysis, the average reduction in module efficiency, corresponding to each micrometer of residual dust thickness that was calculated, is equal to $25.5\,\frac{\%}{1\ \mu\mathrm{m}}$ for naturally deposited dust.

The maximum daily efficiency loss calculated for the silicon crystalline module tilted at 37^{o} in northern Poland was equal to 0.8%

All modules investigated showed an average decrease in maximum power of 3%/year.

In conclusion, it can be stated that in the case of crystalline silicon PV modules tilted at an optimum angle, the natural cleaning of the module surface by rainfall, melting snow, wind and gravitational forces is not sufficient. To maximize the output of solar PV modules and reduce the degradation caused by dust accumulation, frequent cleaning is strongly recommended.

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Figure 1

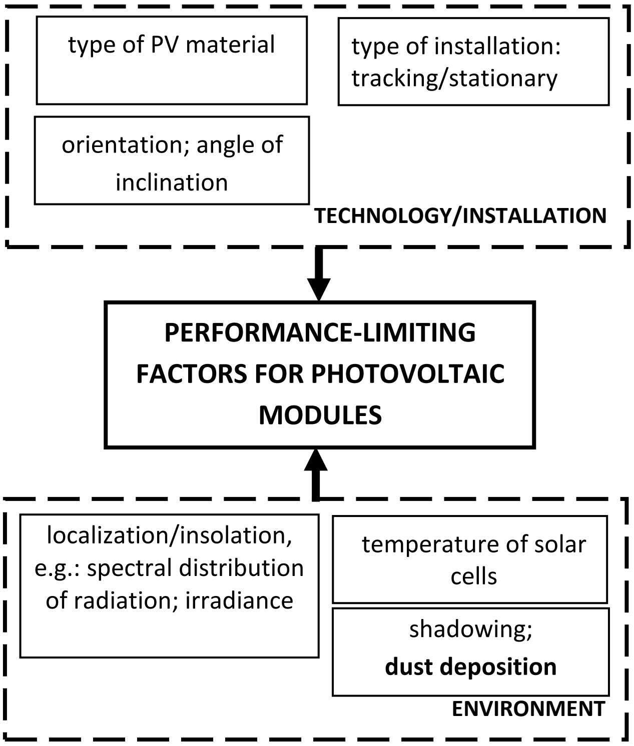

type of PV material
type of installation: tracking/stationary
orientation; angle of inclination
TECHNOLOGY/INSTALLATION
PERFORMANCE-LIMITING FACTORS FOR PHOTOVOLTAIC MODULES
localization/insolation, e.g.: spectral distribution of radiation; irradiance
temperature of solar cells
shadowing;
dust deposition
ENVIRONMENT

Figure 2

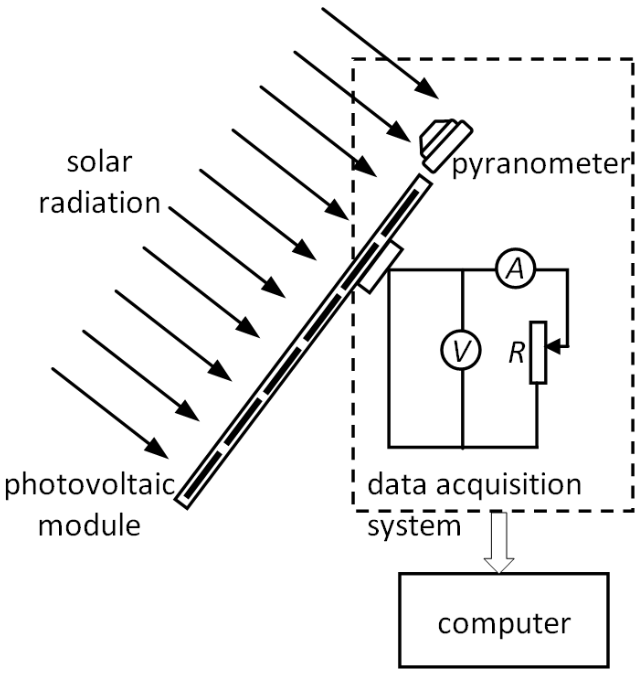
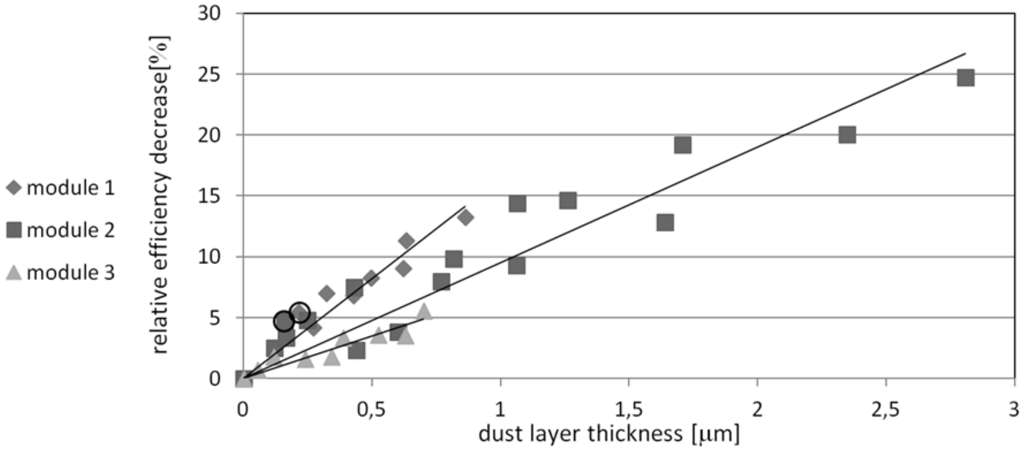

solar
radiation
pyranometer
A
V
R
photovoltaic
module
data acquisition
system
computer

Figure 3



module 1
module 2
module 3
relative efficiency decrease[%]
30
25
20
15
10
5
0
0
0,5
1
1,5
2
2,5
3
dust layer thickness [μm]

Figure 4

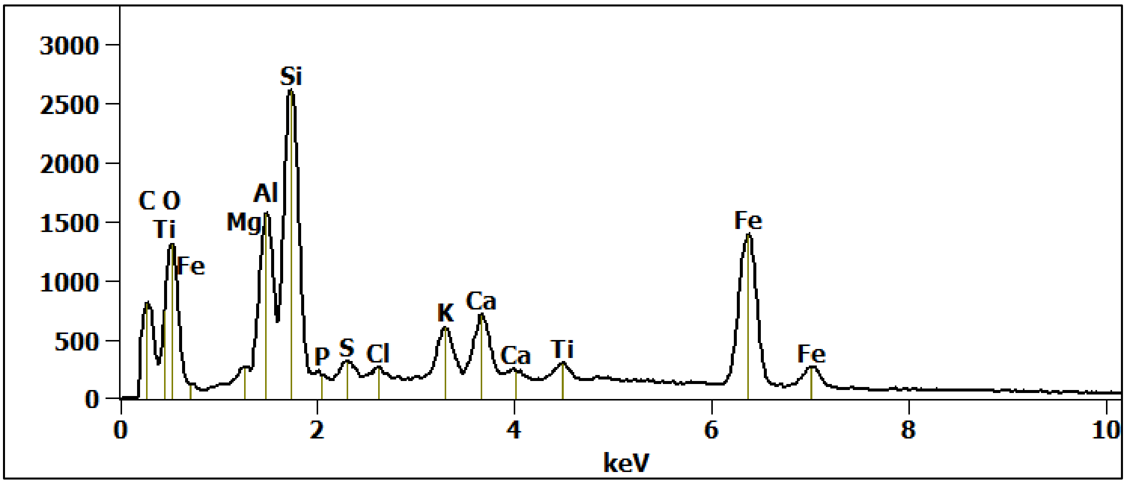

3000
2500
2000
1500
1000
500
0
Si
C O
Ti
Fe
Al
Mg
Fe
P
S
Cl
K
Ca
Ca
Ti
Fe
0
2
4
6
8
10
keV

Figure 5

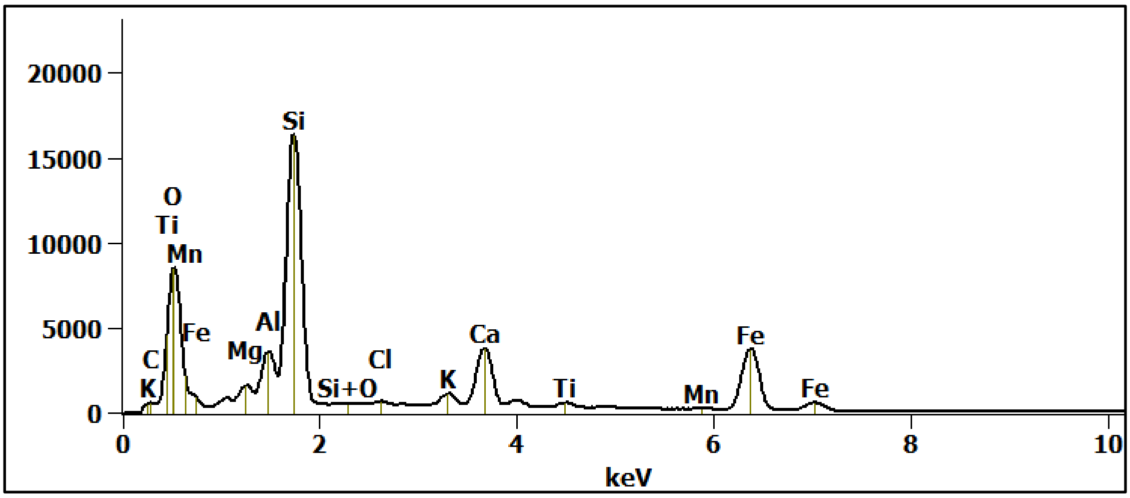

20000
15000
10000
5000
0
Si
O
Ti
Mn
Fe
C
K
Mg
Al
Si+O
Cl
K
Ca
Ti
Mn
Fe
Fe
0
2
4
6
8
10
keV

Figure 6

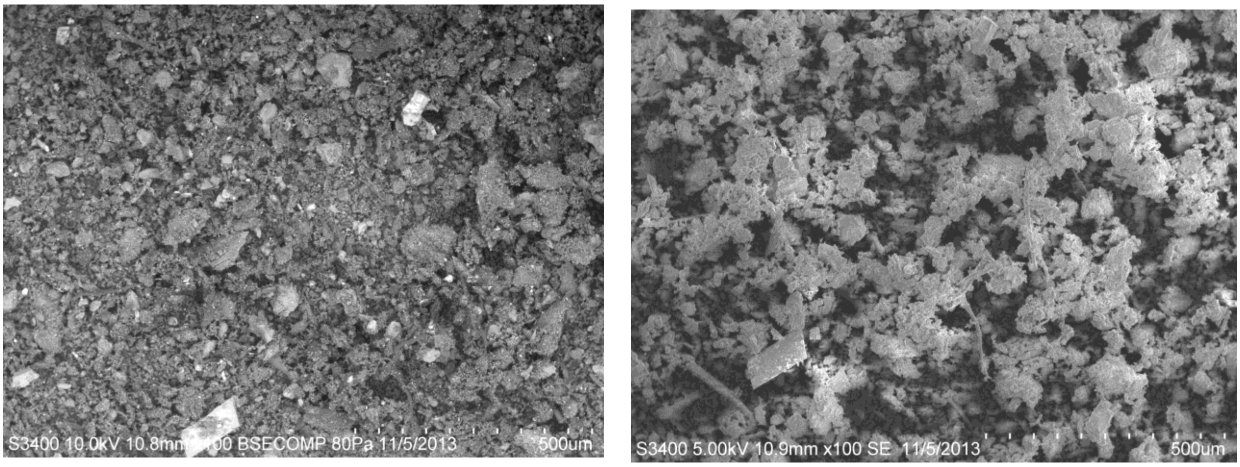

S3400 10.0kV 10.8mm
00 BSECOMP 80Pa 11/5/2013
500um
S3400 5.00kV 10.9mm x100 SE 11/5/2013
500um

Figure 7

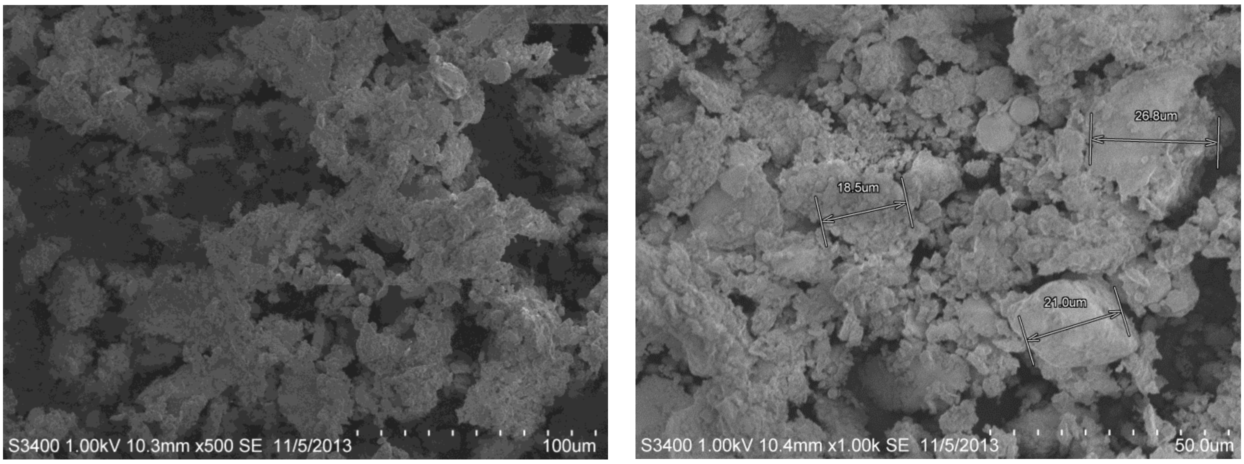

S3400 1.00kV 10.3mm x500 SE 11/5/2013
100um
18.5um
26.8um
21.0um
S3400 1.00kV 10.4mm x1.00k SE 11/5/2013
50.0um

Figure 8

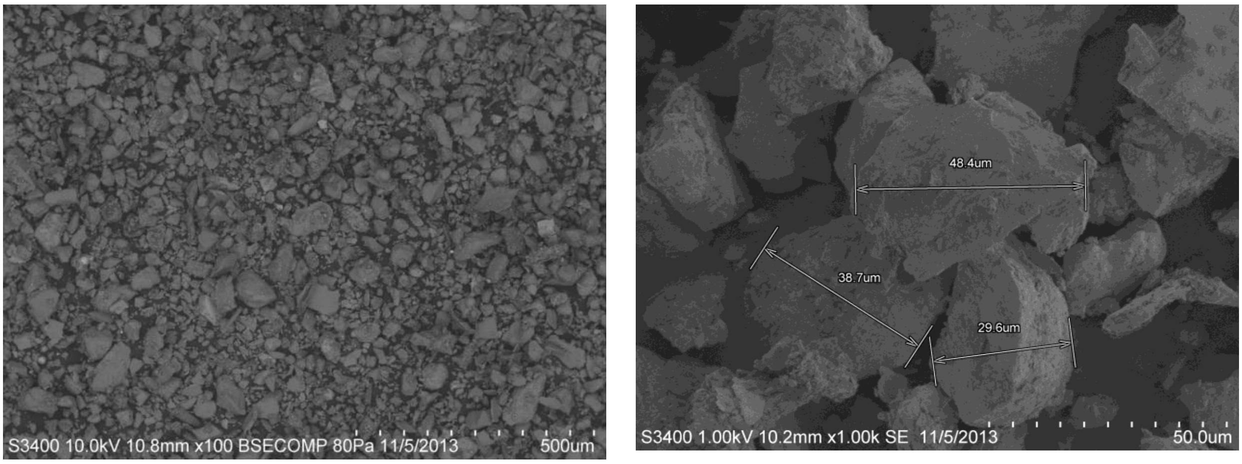

S3400 10.0kV 10.8mm x100 BSECOMP 80Pa 11/5/2013
500um
48.4um
38.7um
29.6um
S3400 1.00kV 10.2mm x1.00k SE 11/5/2013
50.0um

Figure 9

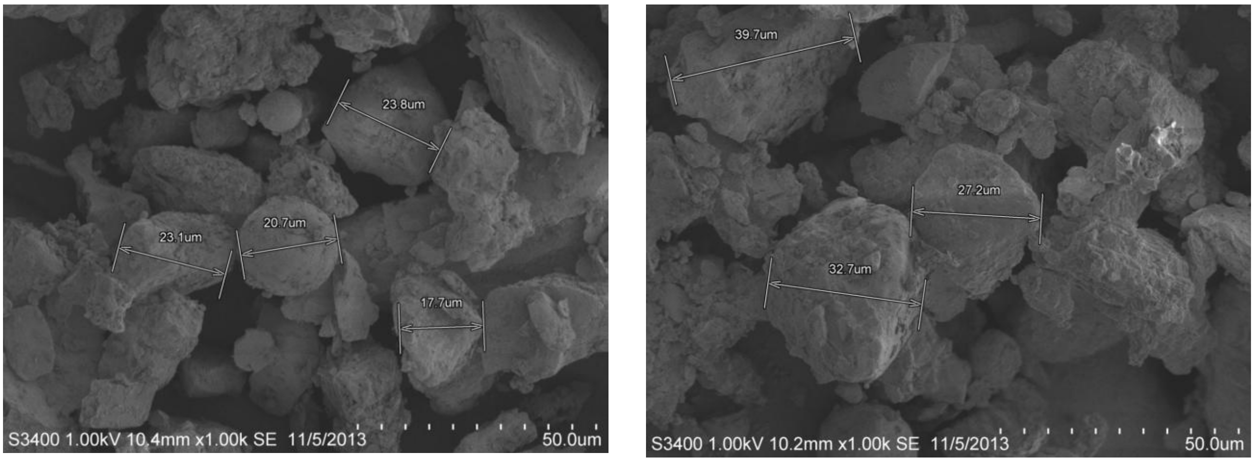

23.8um
23.1um
20.7um
17.7um
S3400 1.00kV 10.4mm x1.00k SE 11/5/2013
50.0um
39.7um
27.2um
32.7um
S3400 1.00kV 10.2mm x1.00k SE 11/5/2013
50.0um

Figure 10

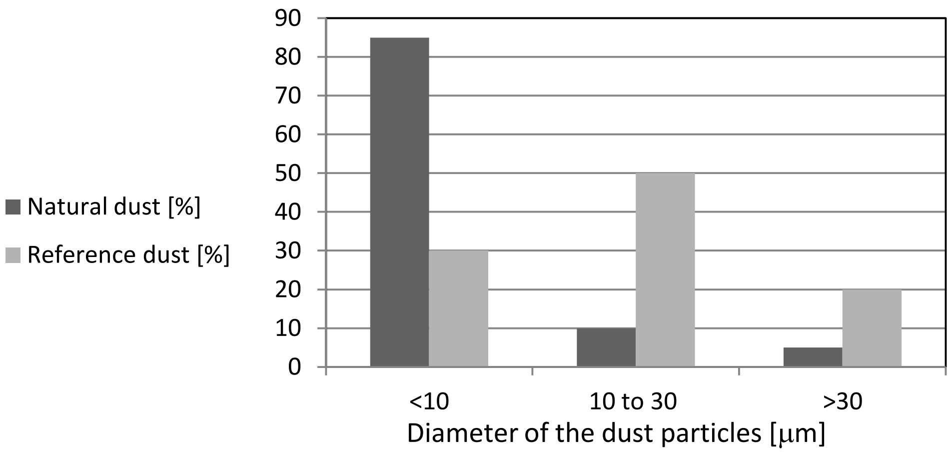

Natural dust [%]
Reference dust [%]
90
80
70
60
50
40
30
20
10
0
<10
10 to 30
>30
Diameter of the dust particles [μm]

Figure 11

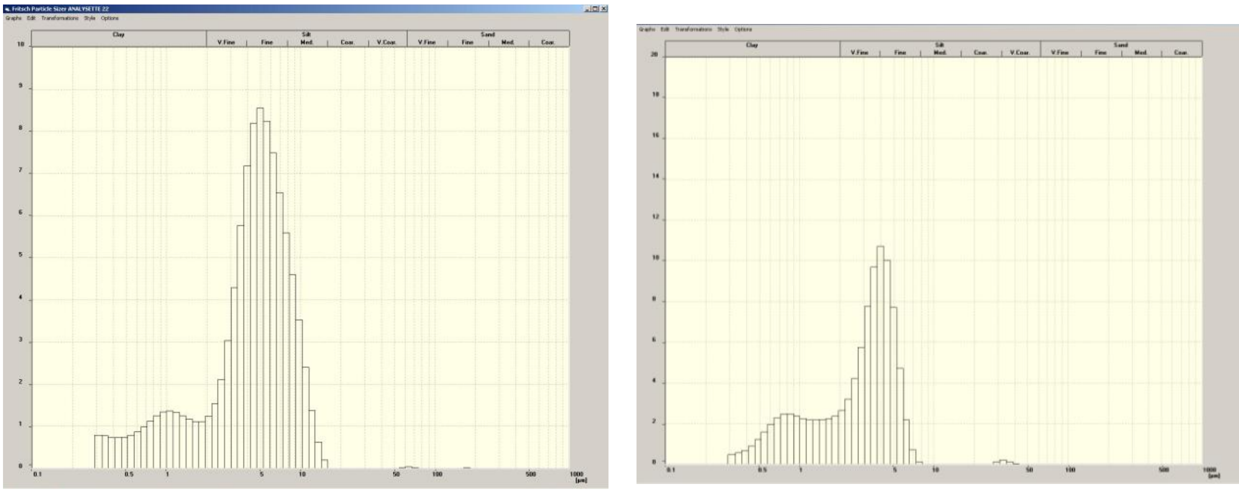
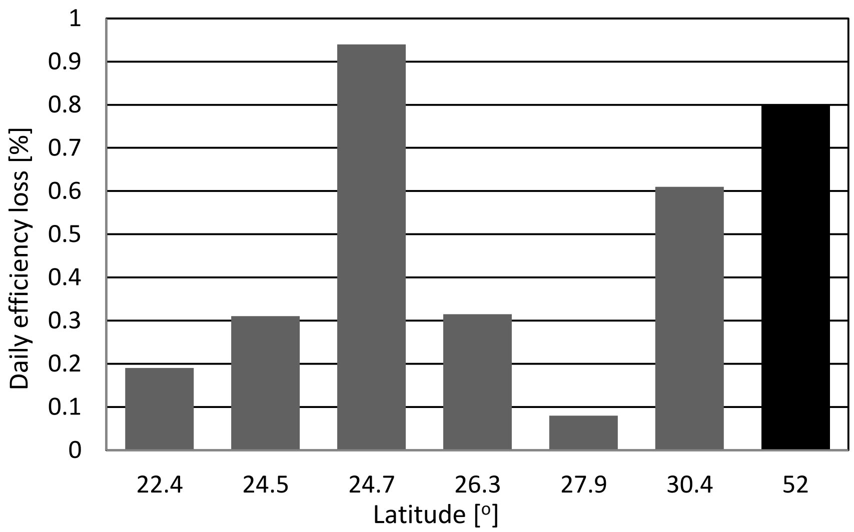

Fritsch Particle Sizer ANALYSETTE 22
Graphs Edit Transformations Style Options
Clay
Silt
Sand
V.Fine Fine Med. Coar. V.Coar.
V.Fine Fine Med. Coar.
[µm]

Figure 12



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Daily efficiency loss [%]
22.4
24.5
24.7
26.3
27.9
30.4
52
Latitude [o]