

22 **Abstract**

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

41 **Keywords:** dust deposition; photovoltaic modules; efficiency reduction.

42

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

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

- 46 • the type of front cover material,
- 47 • the orientation and angle of inclination,
- 48 • the type of installation (tracking or stationary),
- 49 • localization,
- 50 • solar cell temperature,
- 51 • shadowing,
- 52 • dust deposition and soiling of the front cover.

53 Figure 1. Performance-limiting factors for photovoltaic modules

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

60 Many researchers have devoted their work to studying the origin, composition and gradation
61 of dust grains originating from different regions of the world. Fujiwara et al. [1] stated that the
62 composition of dust varies depending on the location of its formation. In big cities,
63 contamination deposited on surfaces is the result of the interaction of liquids, solids and gases
64 derived from different sources. They may also contain heavy metals and organic compounds,
65 derived mainly from road transport. However, in dry climates, i.e. desert or semi-desert, the

66 main source of the dust is soil. Ta et al. [2] described research conducted over 15 years in the
67 region of Gansu, China. They noted that more particles are deposited on the surface of
68 photovoltaic modules in the areas adjacent to the Gobi desert, rather than in areas of loess.
69 Moreover, they found a strong correlation between the quantities of absorbing impurities and
70 the season; this was associated with changes in weather, including the wind direction. They
71 demonstrated that over 30% of the total annual quantity of dust is deposited in the spring
72 months, and less than 20% in the winter months.

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

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

84 Kazmerski and his group [4] found that the properties of dust vary depending on the location
85 of the photovoltaic system. Dust samples collected from highly urbanized areas in the
86 northern hemisphere contain numerous impurities characteristic of the area. This could be
87 airborne particles from coal-fired power plants, emissions from transport or from urban
88 development. Similarly, in rural areas, pollution is created from fertilizers, land air flow or
89 plant origin.



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

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

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

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

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

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

122 Igathinathane et al. [11] studied the properties of the dust coming from the production of
123 pellets made of wood and bark. The volatile air pollutants emitted from sawmills had
124 relatively large dimensions, and therefore were deposited in the vicinity of the plant. As stated
125 in the article, the average size of the particles from the production of wood pellets was
126 $113.8 \pm 12.3 \mu\text{m}$ in length and $73.6 \pm 7.6 \mu\text{m}$ in width, whereas in the production of cortical
127 pellets, the dimensions were $118.1 \pm 14.9 \mu\text{m}$ in length and $60.7 \pm 7.1 \mu\text{m}$ in width.

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

132 **The impact of dust on PV performance**

133 The influence of the thickness of a dust layer on the performance of photovoltaic modules is
134 significant, as concluded by Jiang, Lu and Sun [13]. The authors conducted experiments with
135 the use of artificially produced impurities with a grain size of 1 to 100 μm , wherein about
136 20% by volume had a particle diameter of 20 μm and 74% were smaller grains. The main



137 components of the dust were SiO_2 and Al_2O_3 . As a result, the study came to several important
138 conclusions:

- 139 • dust caused a significant decrease in the short circuit current I_{sc} , but did not affect the
140 value of the open circuit voltage V_{oc} ,
- 141 • with increasing thickness of the dust layer, i.e. with a dust deposition density from 0 to
142 22 g/m^2 , the efficiency decreased by 0 to 26%; this dependency was linear,
- 143 • the surface material may considerably influence dust deposition and accumulation (the
144 polycrystalline silicon module packaged with epoxy degraded faster than other
145 modules with a glass surface),
- 146 • larger dust grains had a more significant impact on reducing efficiency, which was
147 also confirmed by Biryukov [8].

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

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



160 Depending on the location, the composition of dust may be significantly different, and these
161 differences affect the degree of reduction in the efficiency of photovoltaic modules [15].
162 Three representative samples of air pollution in Athens, Greece were studied, including red
163 earth, limestone and coal ash as well as dust samples. These pollutants are commonly found
164 in urban areas and in open areas, villages, etc. The absolute decline in the efficiency of the
165 modules for each of the four abovementioned cases of pollution was examined: for the
166 original natural dust layer with a dust deposition density of 0.1 g/m^2 , the efficiency decreased
167 by 0.15%, while for 1 g/m^2 this was equal to 0.4%. The reduction in module efficiency by
168 natural dust was the smallest of all the samples. Contamination by ash led to a decrease in
169 efficiency of only 0.15% for the layer with a dust deposition density of 0.6 g/m^2 , and 0.4% for
170 2.1 g/m^2 , i.e. twice the thickness of the natural dust layer. Red earth caused a much higher
171 efficiency decrease: for 0.1 g/m^2 , this was equal to 0.5% and increased significantly with a
172 small increase in the layer thickness. For limestone, the results were similar, although for
173 thicker layers of dust the efficiency loss was less pronounced than in the case of red earth.

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

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



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

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

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

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

201 Tyliń [21] stated that the efficiency of regularly cleaned photovoltaic increases meaningfully,
202 i.e. from 9% to 26%; for a 150 kW system, it increased by 9.1%, for a 260 kW system it
203 increased by 15% and for a 330 kW efficiency increased by up to 26%. It was calculated how
204 much money would be saved by not washing the systems (the cost of electricity was
205 \$0.15/kWh in Los Angeles in 2013, so savings were on average \$5000 per year for a 100 kW
206 system). The author recommended washing module coatings two to three times a year,
207 depending on the availability and price of water.



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

215 A six-month study was conducted by Nimmo and Said [22] in Saudi Arabia. They reported a
216 40% decrease in the efficiency of PV modules. As a result of the year-long experiment, they
217 estimated a monthly decrease in yield of 7% [23]. Ryan et al. [24] conducted experimental
218 investigations in the state of Oregon in the United States for six years; they found that there
219 was a decrease in efficiency of about 1.4% per year.

220 Pande [25] described an experiment carried out in India, in which, after a year of use, the
221 module that was not cleaned showed a decrease in the short circuit current of 30%.

222 Alamoud [26] reported that in Riyadh, Saudi Arabia, after a year of exposure to climatic
223 factors, the decrease in efficiency was from 5.73% to 19.8%, depending on the type of device.
224 In contrast, in Cairo, Egypt, Elminir et al. [27] recorded a 17.4% monthly decrease in
225 efficiency. In California and in the southwestern part of the United States, daily energy loss
226 due to dust deposition was around 0.2% (in rainless periods), as described by Kimber et al.
227 [28].

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



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

233 Mohamed [30] described an experiment conducted in Libya, based on which they
234 recommended washing the surface of modules with water every week, so that the reduction in
235 output obtained can be maintained in the range of 2-5%.

236 Roth and Pettit [31] presented a 480-day long experiment, on the basis of which they found
237 that the natural cleaning of the surface of photovoltaic modules, associated with rain or snow,
238 may be sufficient. Rain washes away the dust and dirt, restoring the efficiency of the device to
239 almost the maximum level. However, this applies only to certain climatic conditions.

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

252 The general conclusion from this literature review is as follows: the physical properties of
253 dust (composition, morphology, topography, gradation, and mechanical properties) depend on
254 the on geographical area and environmental conditions, and the properties of the front cover

255 material (roughness and chemistry) have a significant impact on the decrease in photovoltaic
256 efficiency. This justifies further study on the impact of dust on photovoltaic efficiency in
257 other areas.

258 **Natural and passive methods of module cleaning**

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

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

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

276 Hegazy [36] conducted an experiment in Egypt and observed that the surface densities of
277 collected particles with small mean diameters ($<1 \mu\text{m}$) were higher on panels with high



278 inclination angles, while coarser dust particles (mean diameter of 3 μm) deposited with higher
279 proportions on panels with a low inclination.

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

282 **Experimental investigations**

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

285 The influence of dust and soiling on outdoor exposure of photovoltaic modules was
286 conducted in Gdansk, Poland (central Europe). The annual sum of global irradiation incident
287 on an optimally-inclined south-oriented surface in Poland is equal to 1100 kWh/m² [37].

288 Experimental studies were conducted on the roof of the Faculty of Chemistry, Gdansk
289 University of Technology and in a laboratory situated in the same building. Gdansk
290 University of Technology is located a small distance (5 km) from the coast of the Baltic Sea.
291 There are no actively operating industrial plants near the building; however, the university
292 campus is surrounded on all sides by streets with a significant degree of traffic.

293 During the study, three monocrystalline photovoltaic modules with nominal power of 70 W,
294 75 W and 100 W were used. One of the panels was cleaned regularly, while the others were
295 made dusty using sand dust particles collected from a nearby area.

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

299 To determine the particle size of the dust, a Fritsch ANALYSETTE 22 MicroTec Plus laser
300 particle sizer with a measuring range of 0.08-2000 μm was used. A semiconductor laser with



301 green light carries out the measurement of small particles, while an infrared-semiconductor
302 laser handles the large particle size ranges. Both lasers can be optimally aligned extremely
303 quickly, automatically and independently of each other through lateral motion.

304 The current-voltage characteristics of the modules were measured with the use of variable
305 electrical resistance and universal digital multimeters, i.e. an ammeter and voltmeter, in
306 outdoor conditions under natural sunlight with a constant value of solar irradiance of 1000
307 W/m² (Figure 2).

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

311 Figure 2. An illustration of the laboratory experiment setup

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

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

317
$$\frac{\Delta\eta}{\eta_0} [\%] = \frac{\eta - \eta_0}{\eta_0} \cdot 100\% \quad , \quad (1)$$

318 where $\eta = \frac{P_{max}}{E \cdot S} \cdot 100\%$ - efficiency of the module, η_0 - efficiency of clean module, P_{max} [W] -
319 maximum power of the module, E [W/m²] - solar irradiance, S [m²] - surface area of the
320 module.

321 The dependence of the absolute decrease in the efficiency of the photovoltaic module on the
322 dust layer thickness is shown in Figure 3. This relationship was linear. Points corresponding

323 to natural dust had a slightly higher value, which resulted from the fact that dust particles
324 deposited for a long time on the surface and exposed to changeable weather conditions were
325 more compacted and adhered better to the surface of the module.

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

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

332 Figure 3. Relative efficiency decrease measured for three PV modules tilted at 37° exposed
333 outdoors in Poland with different dust layer thicknesses; points representing measurements
334 with natural dust are encircled

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



347 potassium, calcium, phosphorus and sulfur were also observed; these are commonly found in
348 the environment.

349 Figure 4. Chemical composition of the natural dust sample

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

355 Figure 5. Chemical composition of the reference dust sample

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

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

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

367 In the image on the left side of Figure 7, numerous small grains, which merged to form large
368 clusters, are visible. It can be seen that a larger portion of the dust was at the bottom of the
369 image, with diameters of about 30 μm . In the upper right corner, there are at least two grains

370 with a size of 10 μm , but the remaining dust particles are smaller; the estimated length was
371 about 1 μm . In the image on the right side of Figure 7, one can identify three grains with
372 diameters of 31.1 μm , 33.7 μm and 29.4 μm . The image shows a large number of particles
373 with a size in the range of 5 to 10 μm .

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

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

385 Figure 8. SEM images of the reference dust sample (with acceleration voltages of 10 kV and
386 1 kV, magnification 100 \times and 1000 \times)

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

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

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

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

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

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

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

415 Figure 11. The size distribution of selected samples of dust

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

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

423 **Conclusions**

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

427 The designed and conducted experiment showed a linear relationship between the thickness of
428 the layer of pollution and the loss of productivity for the three tested PV installations in
429 Gdansk, Poland. On the basis of the data analysis, the average reduction in module efficiency,
430 corresponding to each micrometer of residual dust thickness that was calculated, is equal to
431 $25.5 \frac{\%}{1 \mu\text{m}}$ for naturally deposited dust.

432 The maximum daily efficiency loss calculated for the silicon crystalline module tilted at 37°
433 in northern Poland was equal to 0.8%

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

435 In conclusion, it can be stated that in the case of crystalline silicon PV modules tilted at an
436 optimum angle, the natural cleaning of the module surface by rainfall, melting snow, wind



437 and gravitational forces is not sufficient. To maximize the output of solar PV modules and
438 reduce the degradation caused by dust accumulation, frequent cleaning is strongly
439 recommended.

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442

443 **References**

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- 542

Figure 1

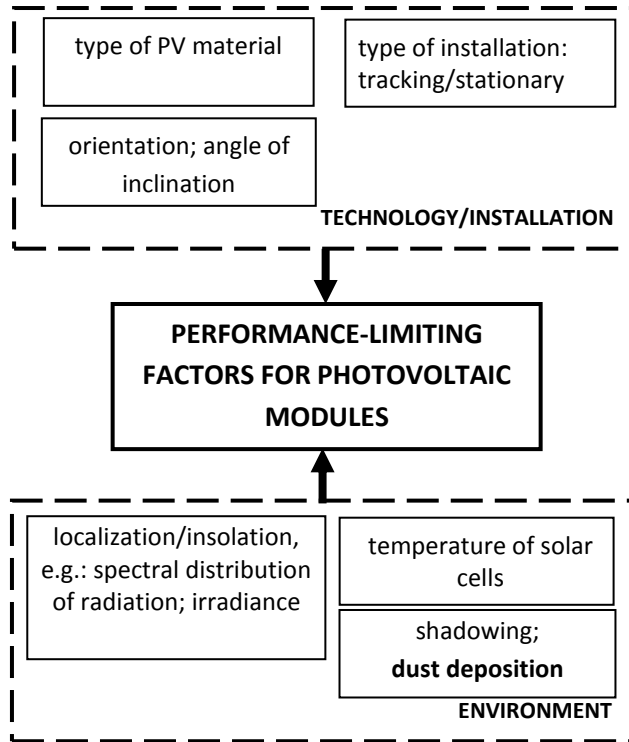


Figure 2

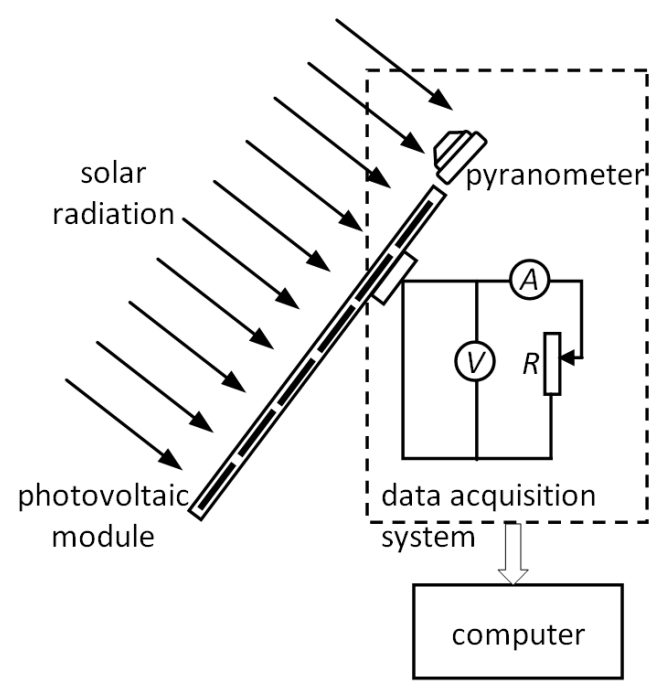


Figure 3

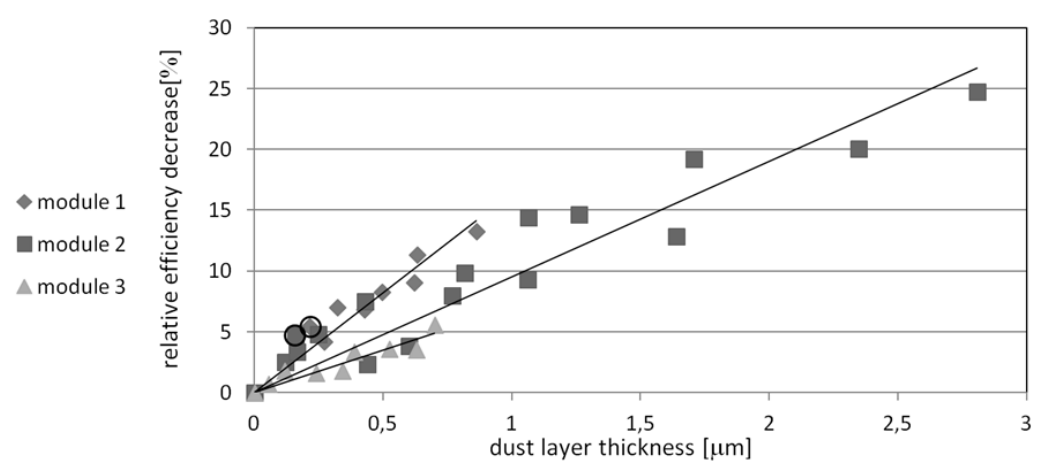


Figure 4

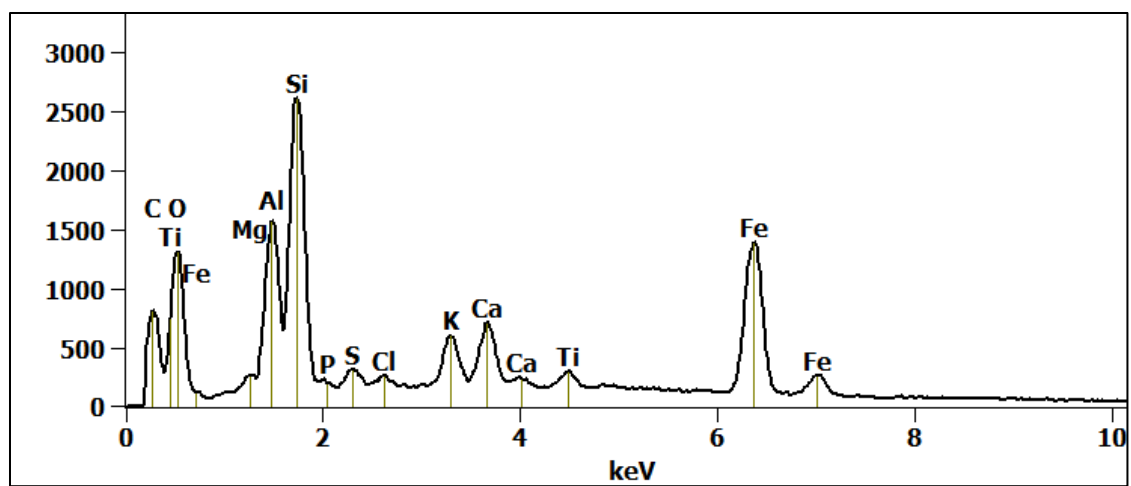


Figure 5

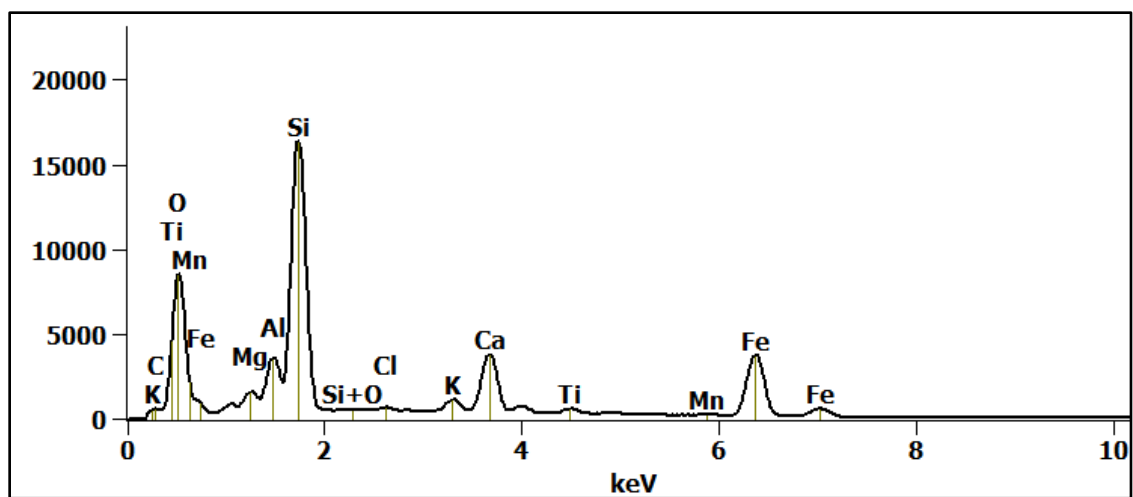


Figure 6

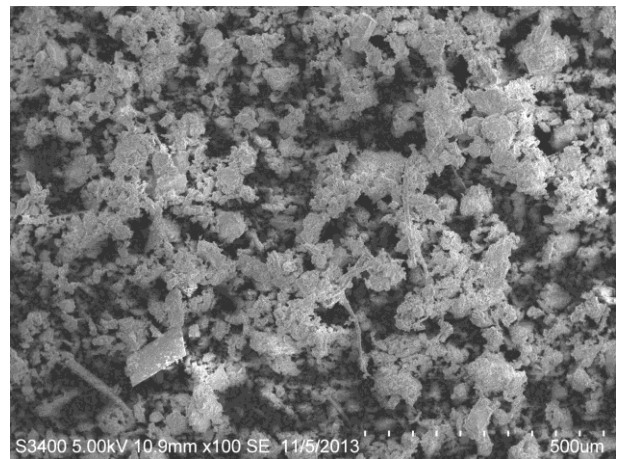
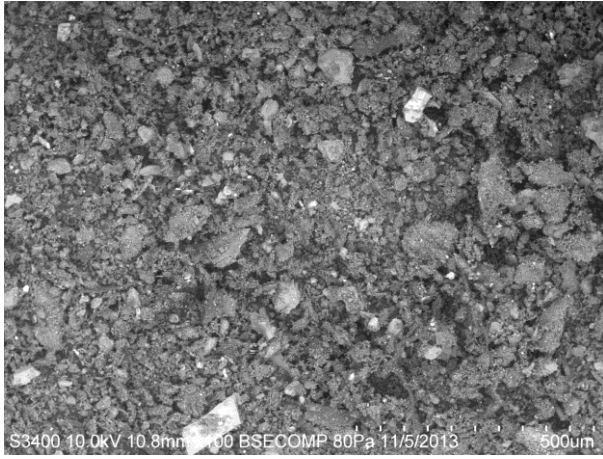


Figure 7

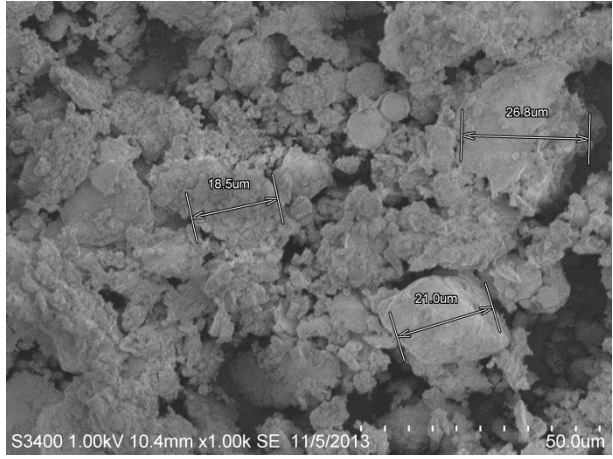
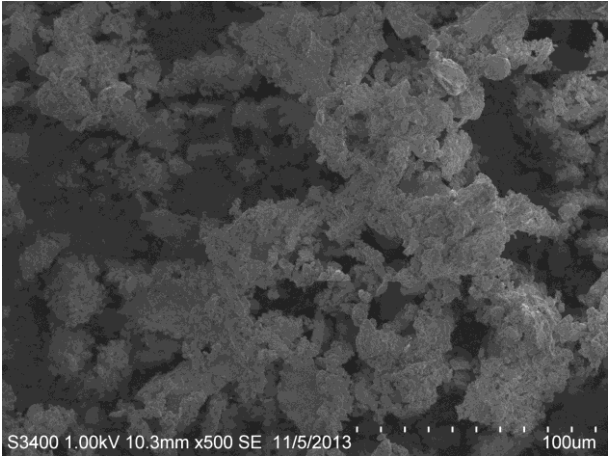


Figure 8

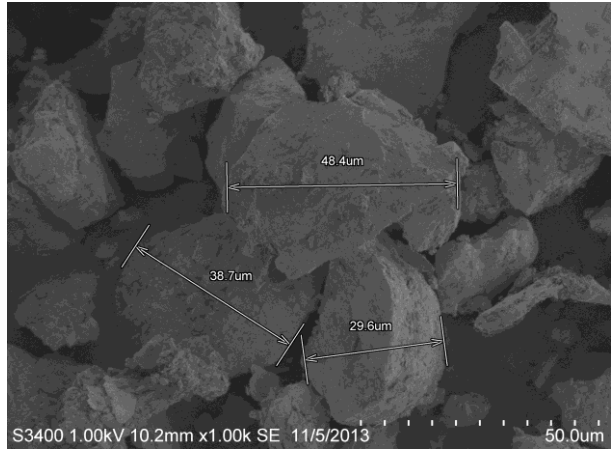
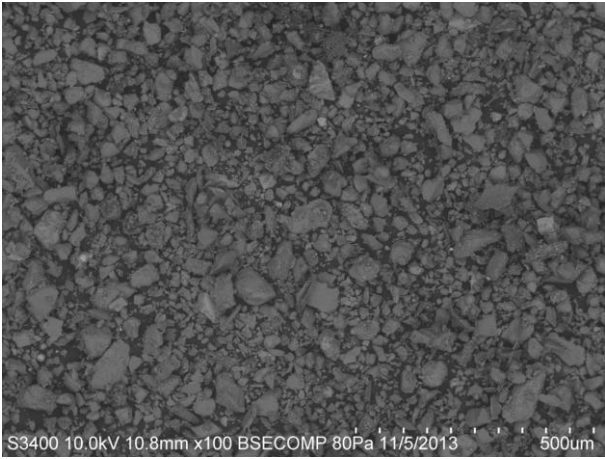


Figure 9

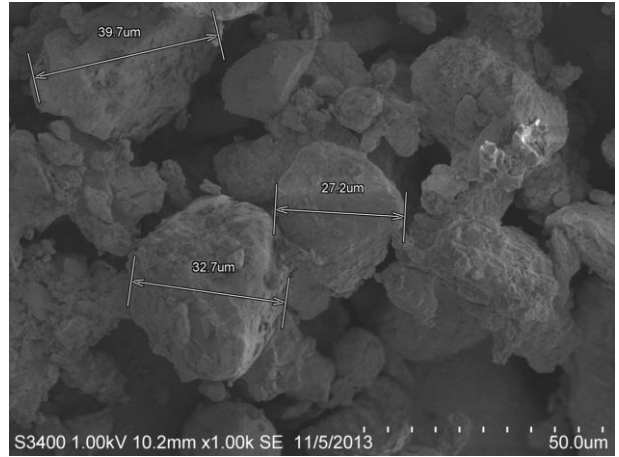
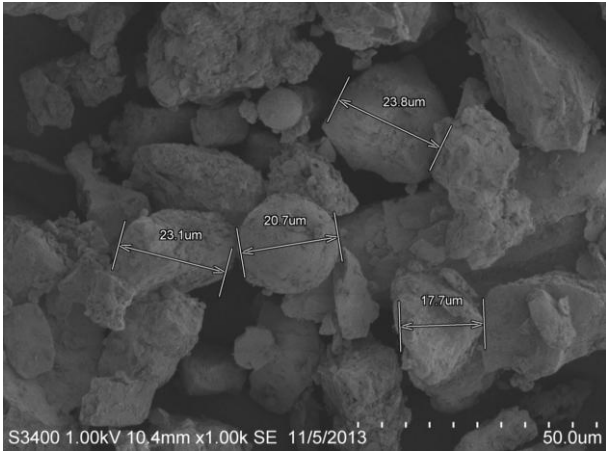


Figure 10

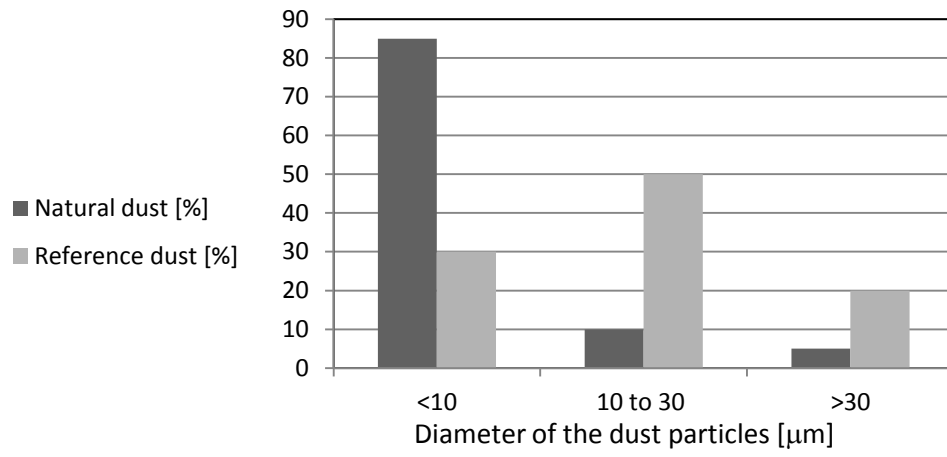


Figure 11

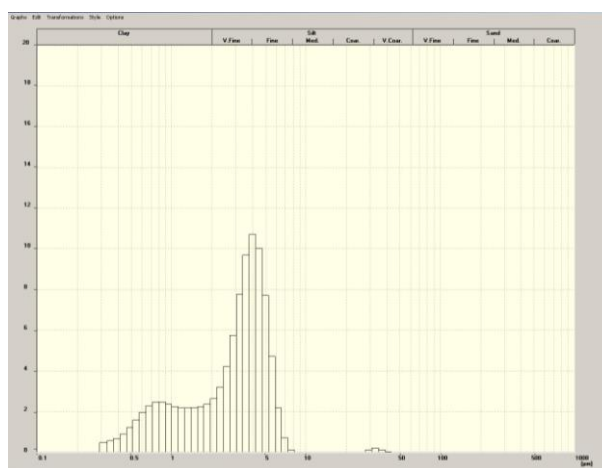
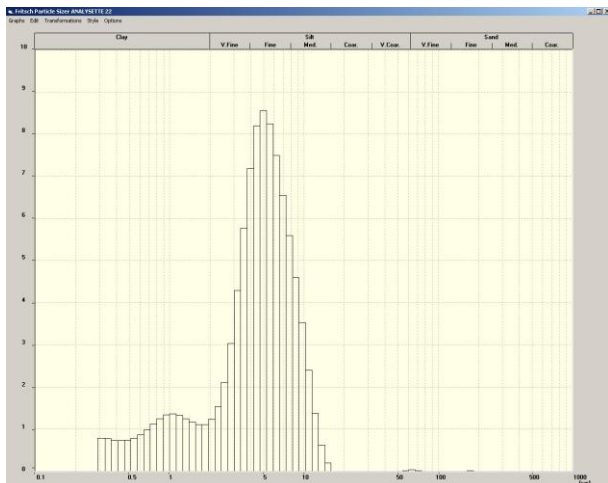


Figure 12

