energies

Review

The Effect of Dust Deposition on the Performance of Photovoltaic Panels

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Abstract: Given the energy crisis and climate change due to pollution, and given that the largest emissions of greenhouse gases are produced by the energy industry, we must turn our attention to the efficient use of solar energy, which is the cleanest and most abundant of all renewable energies. In this paper, based on an analysis of the specialized literature, we studied the effect of dust accumulation on the surface of photovoltaic modules on some performance characteristics and on the efficiency of these panels and modules compared to the efficiency of clean modules. We analyzed the cause of dust accumulation and the influence of the tilt angles of the photovoltaic panels on the dust deposition rate. We highlighted the influence of atmospheric temperature, solar radiation, wind speed, and relative humidity depending on the density of the dust deposited on the surface of the photovoltaic panel, and we found a decrease in the efficiency of the panel based on the increase in dust density for slightly high values of solar radiation, wind speed, and relative humidity. We highlighted the reduction in CO_2 emissions by replacing electricity from fossil fuels with solar energy. The efficient use of solar energy is a solution for the decarbonization of the energy sector.

Keywords: photovoltaic systems; energy efficiency; performance ratio; dust accumulation; solar cells; reference yield

Citation: Rusănescu, C.O.; Rusănescu, M.; Istrate, I.A.; Constantin, G.A.; Begea, M. The Effect of Dust Deposition on the Performance of Photovoltaic Panels. *Energies* **2023**, *16*, 6794. https://doi.org/10.3390/en16196794

Academic Editors: Maciej Zajkowski, Adam Idzkowski, Zbigniew Sołjan and Stanislav Darula

Received: 8 August 2023
Revised: 11 September 2023
Accepted: 21 September 2023
Published: 24 September 2023

1. Introduction

In the current context of the energy crisis and climate change resulting from increased pollution, and taking into account the fact that approximately 77% of greenhouse gas emissions come from the energy sector [1], we must use solar energy efficiently. By the year 2050, the energy produced by photovoltaic panels is predicted to be 25% of the total energy needed worldwide, and damage to photovoltaic modules must be prevented so that they work efficiently [2]. By transforming sunlight into electricity by photovoltaic cells, environmental pollution is avoided, thus reducing global warming. The reduction in the price of photovoltaic panels and the increase in the price of electricity and petrochemical fuels have determined the increased need to use photovoltaic panels [3]. Since the photovoltaic panels are placed outside, there are variations in wind speed, radiation intensity, air temperature, and relative humidity, and they are exposed to dust pollution [4–8]. Of the sunlight, approximately 8–10% is reflected by the photovoltaic panels [5], and the dust deposited on the surface of the photovoltaic panels can absorb or scatter part of the sunlight. All these factors reduce the output power of photovoltaic panels [4].

In the desert, where there is high solar radiation, dust storms cover the panel surfaces with sand, gravel, and clay, reducing their performance by reducing the solar radiation incident on the panel. The reduction in electricity generation power due to the dust deposited on the surface of the photovoltaic modules depends on the properties of the dust, the size of the dust particles, the type of dust deposited, and the density [6–16].

According to research carried out by Darvwish et al. [2], depositing a quantity of 73 g/m^2 of cement on the surface of the photovoltaic panel determined an 80% decrease in the short circuit voltage of the photovoltaic panel. The smaller the size of the dust particles, the greater the shading effect on the photovoltaic panels [13].

The objective of this paper is to analyze, based on the specialized literature from 1990 to 2023, the performance of photovoltaic panels according to the following factors: dust deposition on their surface, wind speed, solar radiation, relative humidity, precipitation, air temperature, and the angle of inclination of the photovoltaic panels. We present the influence of each factor on dust deposition that has a negative impact on the performance and operation of photovoltaic systems.

2. The Causes of Dust Accumulation on the Surface of Solar Panels

According to McTainsh et al. [17], the size of the dust grains deposited on the surface of the photovoltaic panels depends on the distance from which the wind carries the dust; these solid particles are smaller than 500 μm. The diameter of the deposited dust can be less than 5 μm when it is brought from long distances, between 20 and 40 μm when the dust is deposited from regional sources, between 50 and 70 μm when the dust deposited is from the local area, due to the movement of vehicles and the anthropogenic impact [18–24].

According to Beattie et al. [19], we can know the origin of the dust depending on its particle size. Thus, dust with a particle size between 60 and 2000 μm comes from sand, dust particles with a size of 4–60 μm come from alluvial soil, and dust with a particle size smaller than 4 mm comes from clay.

The largest surface of the photovoltaic panels is covered with dust of particle sizes between 20 and 40 μm [15]. Most of the particles that covered the panel were 5–35 μm [15].

As a result of the deposition of dust on the glass of the solar panels, a reduction of 0.2% in their efficiency was found in the absence of precipitation [24].

The dust that settles on solar panels can have different sources of origin, as follows: soil, ash obtained from burning coal in power plants, soot from the incomplete burning of coal or petroleum products, cement, coal, salt, sand, clay, from cars, from kitchens, smoke from factories, dust from volcanic storms, and detergents [21,22]. Dust can come from pollutants due to road traffic, or from waste incineration. Due to meteorological conditions, the highest concentration of dust is deposited in spring, followed by winter [18]. The increase in the relative humidity of the air and the high wind speed favor the increase in the number of material particles in the air. The composition of the dust deposited on the solar panels is different depending on the locality, and it may contain the following elements: organic compounds from road traffic, cadmium, sulfur, antimony from the abrasion of car brake shoes, zinc, manganese and lead, from mechanical wear and tear, from exhaust gases, organic and inorganic particles containing soluble and insoluble salts [15,18]; it may come from soil, it may contain fungal spores, soot, cement, ash, calcium, clay, sand, or it may come from burning fossil fuels [23].

The causes of dust accumulation on photovoltaic panels are described in Figure 1. They are dependent on environmental factors, the type of dust, and the place where they are placed.

In Figure 2, images of the dust samples that can be deposited on the surface of the photovoltaic cells are shown.

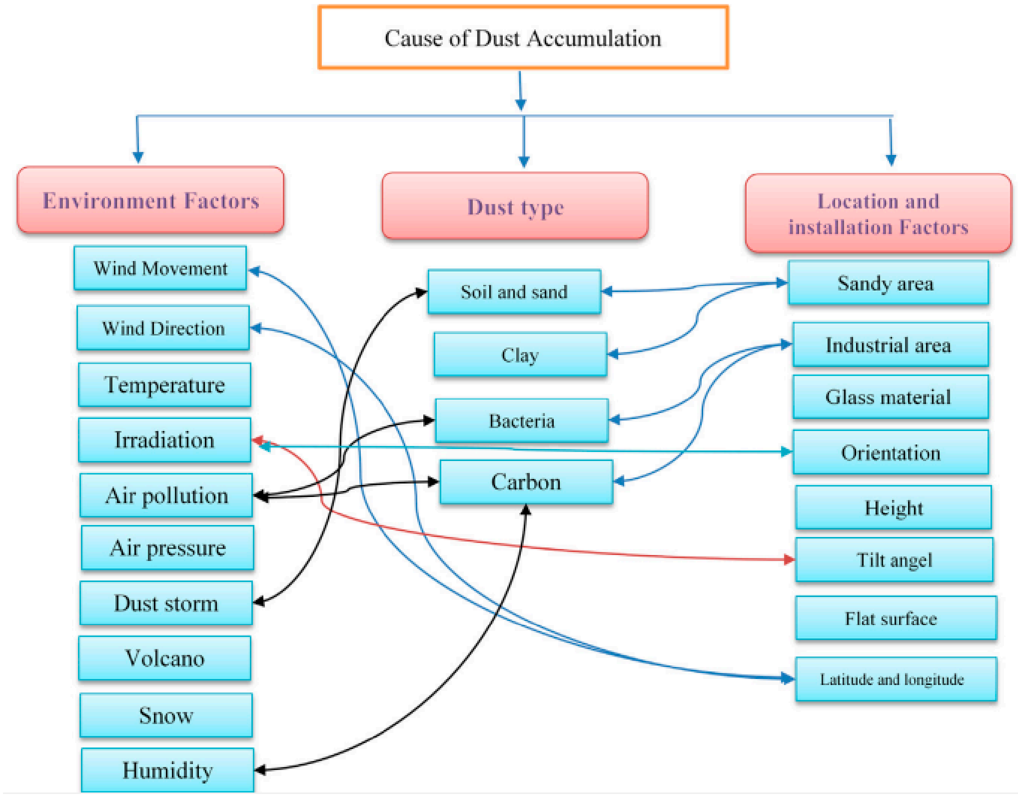


Figure 1. The causes of dust accumulation on the surface of solar panels (adapted from [24]).

Figure 2. Dust samples that can be deposited on the surface of solar cells (adapted from [25]).

The deposition of dust on the surface of photovoltaic panels depends on the properties of the dust [25], namely, components, size, weight [26], and shape, and acidic dust can lead to erosion of the surface of the panels, but the deposition also depends on the local environment, weather conditions, vegetation, and location, and if the surface is horizontal [26], more dust can accumulate on it [25].

According to Maghami et al. [25], if the surface of the photovoltaic panel is not smooth, if it is horizontal, or if it is sticky, it is conducive to the accumulation of dust. The wind can cause the accumulation or scattering of dust: low wind speed is conducive to the deposition of dust, whereas high wind speed removes the dust from the photovoltaic panels [26,27]. Decreases in the output power from the photovoltaic panel between 2 and 50% were found due to the dust accumulated on their surface [28].

Chanchangi et al. [25] found a decrease in power output of 30–40% as a result of dust deposition which correlated with high moisture content and specific gravity [26].

Research on the effects of deposits of red soil, sand, ash, and calcium carbonate highlighted that the deposits of finer particles such as ash caused a greater reduction in the performance of the photovoltaic panel, about 25% of the PV voltage reduction, compared to the coarse ones [26].

An analysis by Kaldellis et al. [29] found that red soil accumulation led to a greater reduction in PV panel performance, followed by limestone and fly ash.

Depositing a quantity of 100 g/m^2 of gypsum, cement, and sand on the surface of the photovoltaic panels determined 9%, 14%, and 12% reductions in the performance of the photovoltaic panels, respectively [25]. The large accumulation of dust on photovoltaic panels occurs in desert areas [30], the dust containing quartz and smectite, carbonates, gypsum, feldspar, illite, kaolinite, and iron oxides [25].

In Figure 3, images of solar panels clean and covered with dust are shown [31]. It is estimated that solar energy will provide 10% of global energy production by 2030, most of which will be produced in desert areas where the Sun shines. However, there is also a lot of dust in these areas, which reduces energy production by up to 30% per month.

Figure 3. Solar panels covered in dust (adapted from [31]).

Dust storms that occurred in Saudi Arabia, Oman, the United Arab Emirates, and eastern areas as far as India and Pakistan covered solar panels within days, reducing the efficiency of each panel by up to 30% [32].

3. The Composition of the Dust Deposited on the Surface of Photovoltaic Panels

Chen et al. [33], by using X-ray fluorescence analysis, highlighted the following component elements in the dust deposited on photovoltaic panels: phosphorus (0.246%), sulfur (0.369%), titanium (0.881%), sodium (1.03%), magnesium (1.65%), potassium (2.7%), iron (8.49%), aluminum (8.69%), calcium (9.22%), silicon (20.63%), and the following oxides: MgO (2.57%), Fe_2O_3 (7.03%), CaO (8.55%), Al_2O_3 (14.84%), SiO_2 (36.26%).

Darwish et al. [3], by using X-ray diffraction analysis, highlighted the following compounds of dust from the city of Sharjah in the United Arab Emirates: NiO (0.09%), SrO (0.13%), Cr_2O_3 (0.23%), MnO_2 (0.21%), SO_3 (0.24%), TiO_2 (0.45%), K_2O (0.87%), MgO (6.33%), Fe_2O_3 (10.46%), Al_2O_3 (10.83%), CaO (24.62%), SiO_2 (45.53%).

It is observed that silicon oxide predominates, resulting from human activities, soil erosion, and sand [33]. The existence of calcium can be determined from the emissions from construction works. The presence of iron oxide is determined by the rusting of the iron frame of the photovoltaic panel. Aluminum and potassium come from rocks.

The appearance of dust particles observed by scanning electron microscopy (SEM) highlights irregular shapes [28], the most common shapes being spherical [15]; the sizes are different and are not completely opaque (Figure 4) [34].

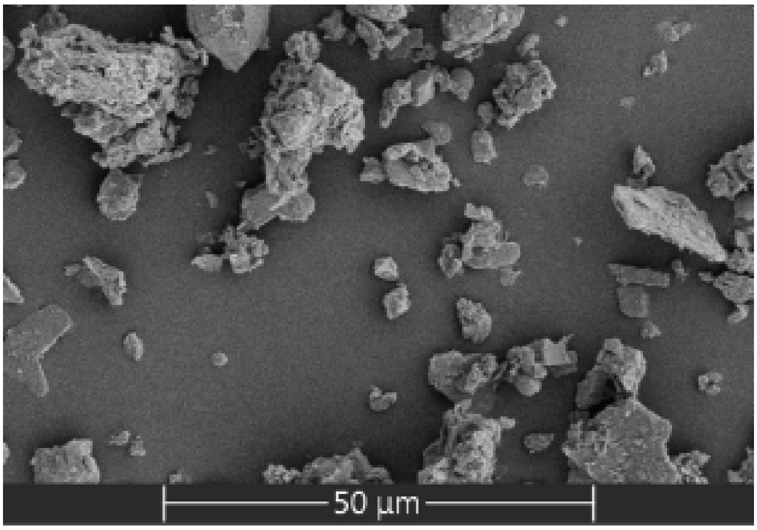


Figure 4. Structural SEM appearance of dust (adapted from [28]).

Table 1 shows the composition of dust from different countries. It can be seen that the predominant components are quartz SiO_2, Al_2O_3, and calcite ($CaCO_3$).

Table 1. The composition of dust samples in different places (data from [33,34]).

	Location	Major Oxides	Major Elements (Except O)	Origin
[33]	Hangzhou, China	SiO_2, Al_2O_3, CaO, Fe_2O_3, etc.	Si, Ca, Al, Fe, K, Mg, Na	Sand, potash feldspar, mechanical wear, straw burning
[33]	Doha, Qatar	Calcite ($CaCO_3$), Dolomite ($CaMg(CO_3)_2$), Quartz (SiO_2), etc.	Ca, Si, Fe, Mg, Al	Dolomite, Calcite, local soil, and buildings
[33]	Northern Poland	SiO_2, Al_2O_3, MgO, etc.	Si, Al, Mg, Fe, K. Ca, P, S	Sand, the wear of frictional elements of mechanical components
[34]	Cairo, Egypt	Quartz (SiO_2), Calcite ($CaCO_3$), etc.	Si, Ca, Al, Fe, Mg, K, Na	Deserts, cement industry emissions, fossil fuel combustion
[34]	Perth, Australia	Quartz (SiO_2), Calcium oxide (CaO), Orthoclase ($KAlSi_3O_8$), etc.	Si, Ca, Al, Fe, K	Dominated by acid and sandy soils that might be caused by deserts

4. The Effect of Temperature on the Output Power of the Photovoltaic Mode

The electrical performance of the output panel of the photovoltaic module decreases with the increase in the temperature of the photovoltaic cell. To produce electricity, photovoltaic systems use a small part of the solar radiation; the rest of the energy received at the surface is transformed into heat, which leads to an increase in the temperature of the component cells and a decrease in their efficiency [35]. Each degree of heating of the cell causes a loss of efficiency of the order of 0.5% [8]. Testing the effect of the cell temperature on the module performance is carried out for standard conditions under irradiation of

1000 W/m^2, module temperature of 25 °C, and air mass of 1.5 according to Equation (1), where $P_{\max}$ is the maximum power of the module (%) and T_c is the operating temperature of the cell (°C) [36]. At solar radiation less than 100 W/m^2, the power of photovoltaic panels is close to zero. The yield of photovoltaic panels falls below the values provided in the technical data sheets, for insolation values lower than 400 W/m^2. Performance can drop up to 80% when the surface of the panels is heated [4]. The maximum power of a 10 cm^2 silicon cell is 1.25 W. Since the photoelectric cell is an electric generator of very low power, the photoelectric generators are made by connecting in series and/or in parallel a large number of elementary cells, called modules that form the panels. The photoelectric cell allows the direct conversion of light energy into electrical energy [37].

$$\%ChangeP_{\max} = \left[(T_c - T_{stc}) \cdot \left(\frac{TempCoeffP_{\max}\%}{{}^0C} \right) \right] \quad (1)$$

Irradiance G_0 can be calculated according to Equation (2), where I_{sc} represents the short-circuit current of the reference photovoltaic module (mA), I_{rc} its calibration value at standard test conditions (mA), T_m, module temperature (°C), α_{rc} current-temperature coefficient (%/°C):

$$G_0 = \left(\frac{1000 \cdot I_{sc}}{I_{rc}} \right) \cdot (1 - \alpha_{rc}(T_m - 25)) \quad (2)$$

According to the values presented in Table 2, a reduction in the efficiency of the panel located in the desert is observed with the increase in dust density for slightly high values of solar radiation, wind speed, atmospheric temperature, and air humidity [3].

Table 2. The impact of dust density and meteorological parameters on the efficiency of the photovoltaic panel (data from [3]).

Density (Mass/Area) g/m^2	Solar Radiation (W/m^2)	Temperature (°C)	Wind Velocity (m/s)	Humidity (%)	Efficiency (%)
0	697	31.8	2.5	79.9	11.1
11.11	698	32.0	5.0	80.6	10.1
22.22	702	31.9	2.5	79.8	9.9
33.33	704	31.9	5.0	79.9	9.8
44.44	709	31.9	5.0	79.4	9.6
55.55	710	31.9	2.5	79.8	9.6
66.66	710	32.0	2.5	80.3	9.6
77.77	710	32.0	5.0	80.8	9.5
88.88	710	32.0	2.5	81.5	9.4
100	713	31.8	5.0	81.7	9.3
111.11	713	31.7	5.0	82.4	9.1

5. The Impact of Humidity on the Performance of Photovoltaic Cells

According to research carried out by Mekhilef et al. [38], at high values of relative humidity, the level of irradiation decreases. It was found that the performance of photovoltaic panels exposed to humidity in the long term decreased. Moisture in the air and hot weather can accelerate the deterioration of the panels [39].

The sunlight that falls on the raindrops on the surface of the photovoltaic panel can be diffracted, reflected, or refracted. The moisture on the panels can change the solar radiation, causing changes in the voltage in the open circuit. The moisture on the surface of the photovoltaic panels can penetrate into their cells, damaging them [40–42].

Figure 5a shows the solar panel without moisture, Figure 5b shows it after 24 h of exposure to moisture, Figure 5c shows the solar panel after 120 h of exposure to moisture.

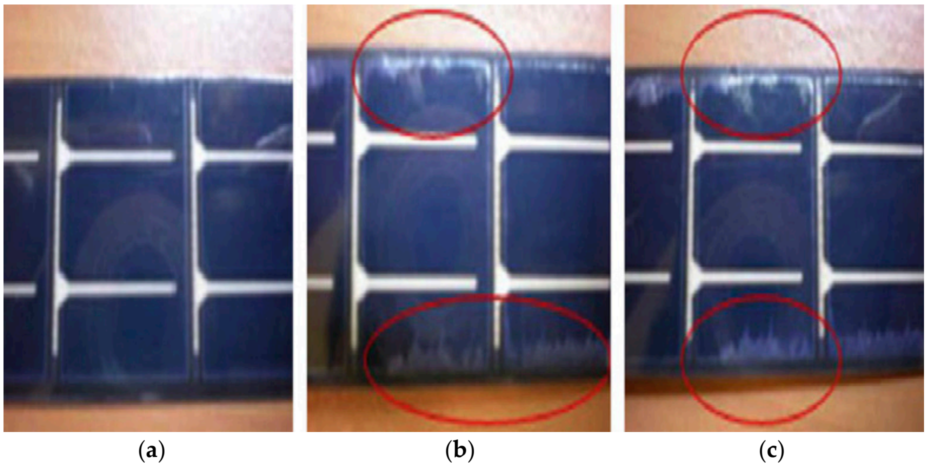


Figure 5. (**a**–**c**) Solar cells that received water (adapted from [38]).

As can be seen from Figure 6, the irradiation decreases with the increase in relative humidity.

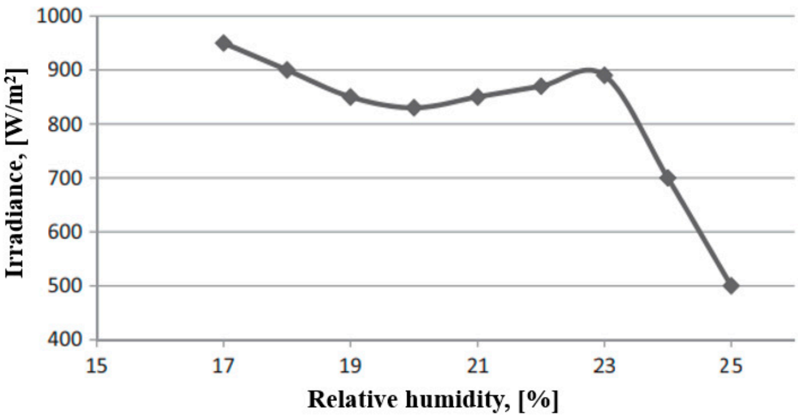


Figure 6. The influence of relative humidity on irradiation (adapted from [38]).

6. The Influence of the Tilt Angles of the Photovoltaic Panels on the Dust Deposition Rate

The orientation of the photovoltaic panels towards the Sun influences the conversion efficiency of a photovoltaic system (Figure 7). To be able to use the solar radiation to the maximum, during the entire period of the day, the optimal orientation of the solar panels must be towards the south. The angle of the Sun's radiation on the solar panels changes continuously, along with the rotation of the Earth. Since most of the Sun's rays hit the solar panel at an angle, the positioning of the solar panels is important when designing the solar power system. Following the path of the Sun, the orientation of the panels can be continuous and the orientation can be discrete, the total angle of 360° being divided into a certain number of discrete steps. The discretion of the angle must be chosen based on the considerations of minimizing the reduction in the conversion efficiency of the system and minimizing the relative costs of the orientation systems [43].

According to Lu and Zhao [41], the dust deposition rate increased with the dust diameter, then decreased; the highest depositions were for the tilt angle 25° (the dust deposition rate was 14.28%), followed by the angles of 40° (13.53%), 140° (6.79%), and 155° (9.78%). For a photovoltaic panel placed horizontally, the deposition of dust on its surface was higher [44]. The maximum dust deposition was for the diameter of 150 μm. Increasing the dust particle diameter to 300 μm and tilt angles of 25° (0.17%) and 40° (0.19%), the dust diameter of 1 μm and panel tilt angles of 140° (0%) and 155° (0%) minimum deposition values were obtained.

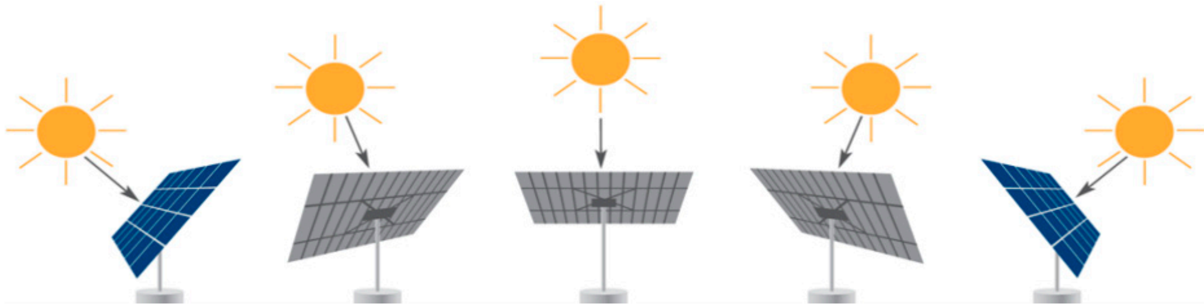


Figure 7. Orientation of photovoltaic panels towards the Sun (adapted from [42]).

According to a study carried out by Cano [45], the following insolation losses before rain were found: 3.82% for an inclination angle of 0°, 2.12% for 23°, 1.84% for 33°. After rain, the energy losses were lower due to the cleaning of the panels (Table 3) [46,47]. The higher the angle of inclination, the lower the insolation loss. The energy loss due to the dust deposited on the photovoltaic panels is higher at angles of inclination below 23°.

Table 3. Average daily insolation losses before and after rain (data from [45]).

	Daily Average Insolation (kWh/m^2)					
	0°	**23°**	**33°**	**0°**	**23°**	**33°**
	Before Rain			**After Rain**		
Clean	4.97	7.09	7.59	3.74	4.75	4.95
Unclean	4.78	6.94	7.45	3.69	4.71	4.90
Insolation Loss	3.82%	2.12%	1.84%	1.34%	0.84%	1.01%

According to research carried out by Lu and Zhao [41], for the dust diameter of 50 μm and tilt angles of 25°, 40°, 140°, and 155°, the wind facilitated the deposition of dust particles on the surface of the photovoltaic panels. For dust particle sizes of 150 μm, the effect of the wind was less; the particles being larger, the dust particles fell almost vertically on the PV panels. For tilt angles of 140° and 155°, dust deposition was caused by gravity, and greater deposition was for angles of 25° and 40° due to gravitational effects. For 250 μm size, very few dust particles reached the solar PV panel; most of them settled on the ground due to high gravity. Small dust particles were deposited on the surface of the photovoltaic panels due to turbulence, whereas large particles were deposited due to the effect of gravity. Dust deposition was reduced at larger dust sizes [35]. The wind removes the dust from the surface of the panel and cools the photovoltaic panel, thus increasing the absorbed radiation.

Dust particles with a diameter larger than 100 μm are deposited on the surface of the photovoltaic panels due to gravity; those smaller than 1 μm are deposited due to Brownian motion. For dust sizes between 1 and 100 μm, the gravitational and viscous forces are similar [5].

Figure 8 shows the insolation values depending on the angle of inclination at 0°, 23°, and 33° of the photovoltaic panels covered with dust and clean. Small variations are observed: the insolation losses are slightly higher in the case of panels covered with dust and at higher tilt angles. According to research carried out by Kumar and Sarkar [27], the energy loss due to the deposition of dust on the surface of photovoltaic modules on sunny days depends on the angle of incidence.

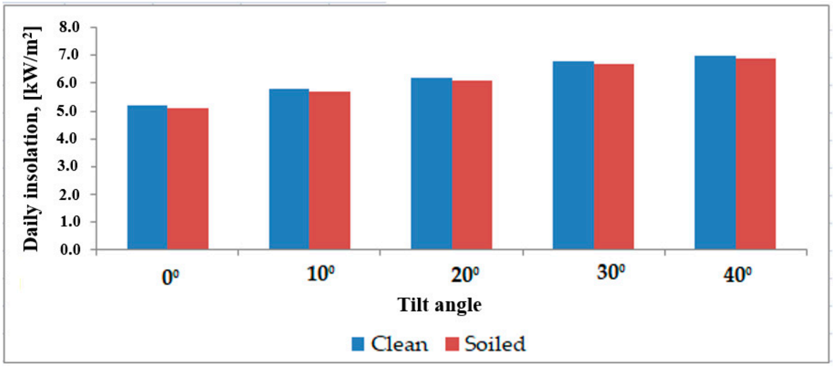


Figure 8. Average daily insolation values for dust-covered and clean PV panels as a function of tilt angles (adapted from [45]).

For panels arranged horizontally, the energy loss due to covering the surface of the panel with dust increases by between 8 and 22% [13]; for inclined panels (45°), the loss is 1–8%. Rainfall of 4–5 mm per day cleans the panels [46].

7. The Effect of Dust Accumulation on the Performance of Photovoltaic Panels

Photovoltaic (PV) cells on panels are semiconductors [41] that produce electricity from the Sun, converting sunlight into electricity [47,48]. The performance of the photovoltaic panel is measured in Wp (watt peak, or power). A 200 Wp solar panel produces between 24 and 40 kWh per month (or 800 to 1300 Wh per day) and around 100 W (or 0.1 kW) to 165 W (or 0.16 kW) per hour with a consumption of 8 h per day [49]. The standard warranty for the efficiency (performance) of a solar panel is 25 years, at 80% of the initial performance [50].

The efficiency of photovoltaic modules is influenced by the following factors: their location, longitude, latitude, angle of inclination, the material from which they are made, orientation, temperature of the solar cell, pollution, humidity, solar radiation, dust coverage [14].

According to Kazem et al. [47], dust affects photovoltaic panel performance, yield, and profitability. The maximum power of the photovoltaic panel covered with dust was reduced by 8.41% compared to that of the clean solar panel [46]. According to Chen et al. [33], covering the panel with dust reduces the power and efficiency of the panel [33,49]. According to Chaichan et al. [51], the dust deposited on the panel acts as a barrier between the solar radiation and the panel [15,18,23].

The thickness of the dust layer influences the performance of photovoltaic modules [38]. At concentrations of dust with a size of 1–100 μm, containing SiO_2 and Al_2O_3, it was found that the short-circuit current I_{sc} decreased, without influencing the voltage in the open-circuit V_{oc}, increasing the thickness of the deposited dust from 0 to 22 g/m^2, and the efficiency decreased by 0–26%; larger dust particles have a greater impact on reducing the efficiency of photovoltaic modules [21]. In order for the photovoltaic modules to have high efficiency in the conversion of solar energy, they must be cleaned regularly, taking into account atmospheric pollution.

We found a decrease in the efficiency of the photovoltaic panel of 0.4% for 1 g/m^2 of dust deposited on the surface of the panel and 0.15% for a dust deposition of 0.1 g/m^2. The efficiency of the panel decreased more in the case of ash covering, as follows: by 0.4% for 2.1 g/m^2 of ash and by 0.15% for 0.6 g/m^2 of ash. The device works better when it is cool and clean compared to when it is cold and dirty. It was found that the efficiency of the solar panel decreased in the warm months, from April to August. The largest decrease in solar panel efficiency was in May, by 25%, when there was a large accumulation of pollution due to low rainfall, when dust particles are removed from the air and form mud on the surface of the photovoltaic module [40]. Heavy precipitation cleans the module shell, which improves operating conditions. The relatively high wind speed determines the removal of dust deposited on inclined solar panels compared to a horizontal surface. The deposition of dust on the surface of the photovoltaic panel is also influenced by the angle of inclination of the panel; when the tilt angle is high, large particles may roll off the panel surface or move to the lower parts [15].

The amount of dust accumulated on the surface of the photovoltaic cell negatively influences the efficiency of the cell [19,52–54]; the increase in the amount of dust, determines the decrease in the energy generated by the photovoltaic cell [16,52–59], having a negative impact on the performance of photovoltaic cells.

According to their research on the effect of dust deposition on the surface of photovoltaic panels, Ghazi et al. [49] observed a reduction in the power of the panels by 30%, 14%, and 2% after thirty-two, thirteen, and one day without the surface of the panel being cleaned, respectively. It was found that the efficiency was reduced by 65.8% as a result of dust deposition for a period of six months and by 33.5% after one month of dust deposition [20]. Another study highlighted the reduction in the output power from the photovoltaic panel between 2 and 50% [16].

According to research by Zorrilla-Casanova et al. [60] the deposition of dust on the surface of the photovoltaic panels determined an average daily loss of energy produced by them of 4.4% during rainy periods; in periods without rain, the energy loss reached 20%. The rain cleans the panel coating, improving its performance. According to research carried out by Kumar and Sarkar [27], light rain reduces the efficiency and output power of photovoltaic panels, and high-intensity rain improves efficiency by cleaning the panels of dust. Efficiency is reduced in the absence of precipitation by 0.16% daily. Annual energy lost is between 2.5 and 6.0% [27]. It was found that by cleaning the surfaces of the photovoltaic panels, the output power increased by 23% [27].

According to research carried out by Ndiaye et al. [61] over a period of one year, with panels exposed to dust in natural conditions, there was a decrease in maximum power between 18% and 78% for polycrystalline and monocrystalline modules [60].

Tylim [62] recommends cleaning the surface of the photovoltaic panels every week to ensure the high efficiency of photovoltaic panels.

The efficiency of cleaned photovoltaic panels increased from 9% to 26% for a 150 kW system, it increased by 15% for a 260 kW system, and it increased by 26% for a 330 kW system. According to research carried out by Klugmann-Radziemska [15], the washing of the module layers is re-ordered two or three times a year. Another study showed a 40% decrease in the efficiency of photovoltaic panels in Saudi Arabia [15]. A study carried out in the state of Oregon in the United States showed a decrease in efficiency of 1.4% annually [2,15,63,64].

In Cairo, Egypt, a 17.4% decrease in monthly panel efficiency was recorded [64]. In California and the southwestern part of the United States, the daily energy loss due to dust deposition was 0.2% (during periods without rain) [34].

The efficiency of the panels is calculated according to Equation (3), where η is the efficiency of the photovoltaic panel, A is the surface of the photovoltaic module, $P_{\max}$ is the maximum nominal power of the photovoltaic module (W), G is the inclined irradiation on the photovoltaic module, E is the solar radiation (W/m^2), and S is the surface of the panel (m^2). The efficiency reduction $\eta_{reduction}$ of photovoltaic panels is calculated with Equation (4), where η_{clean} is the efficiency of the clean panel and η_{dusty} is the efficiency of the panel covered with dust [61].

$$\eta = \frac{P_{\max}}{AxG} \cdot 100\% \quad (3)$$

$$\eta_{reduction} = \frac{\eta_{clean} - \eta_{dusty}}{\eta_{clean}} \cdot 100\% \quad (4)$$

The performance value of photovoltaic panels can be calculated with the following Formula (5) [4]:

$$PR = \frac{E}{GE \cdot A\ plant \cdot \eta_{module} \cdot (1 - Ptpv)} \quad (5)$$

$$Ptpv = (Tc - NOCT) \cdot \frac{\gamma}{100} \quad (6)$$

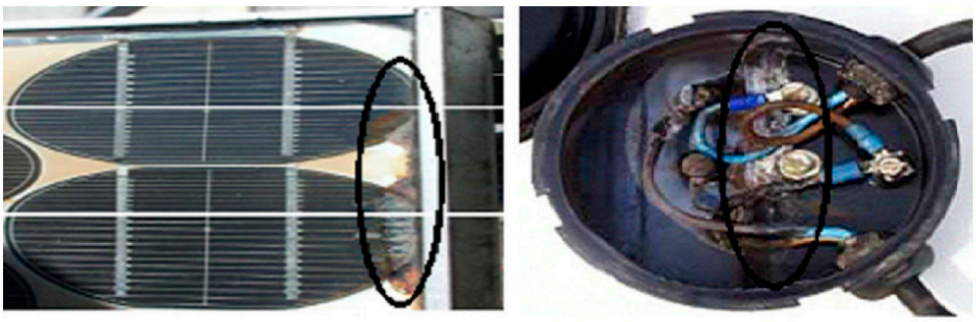
where *PR*—photovoltaic panel performance; *E*—produced energy (kWh); *GE*—irradiation energy on module plane (kWh/m^2); *Ptpv*—thermal losses factor for the photovoltaic generator; *A plant*—area of the modules installed (m^2); γ—power temperature coefficient of module; η_{module}—module efficiency; *Tc*—cell temperature (°C); *NOCT*—nominal operating cell temperature. The deposition of dust on the optical surfaces of photovoltaic modules decreases their power by 30%. According to other studies, the power loss of photovoltaic modules due to deposited dust [64,65] varies between 10% and 70% [35].

The influence of dust on the efficiency of photovoltaic modules depends on the size, weight, shape, and components of the dust [30,66–70]. It was found in Malaysia that acidic dust can cause erosion of the panel surface. Another study highlighted the deterioration of the glass surface and the transmission of light through the surface of the panel due to sand erosion leading to a decrease in the efficiency of the panel [28].

If the panel surface is horizontal, rough, and sticky, slow wind [27] favors the accumulation of dust, whereas strong wind cleans the panel surface [16,66,70].

Corrosion of panel parts exposed to Arizona road dust caused a low corrosion rate, soot deposited on the panel did not cause panel corrosion, and sea-salt deposition caused glass corrosion and decreased panel performance. Corrosion of the panel parts is due to moisture entering the cells through the edges of the chips; this moisture in the cells increases the electrical conductivity of the material, causing the corrosion of the metal joints of the panel cells and a decrease in performance. As a result of the corrosion of the photovoltaic panels, the series resistance increases and their power decreases [71].

Figure 9 shows the corrosion of the edges of the photovoltaic cell and the coupling case exposed to relative humidity of 85% for 1000 h [28].



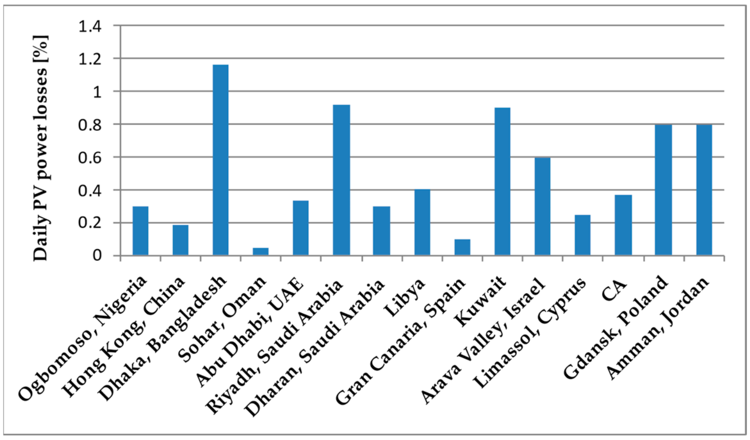
(a) (b)

Figure 9. Corrosion effects on PV module at (**a**) edge and (**b**) junction box (adapted from [28]).

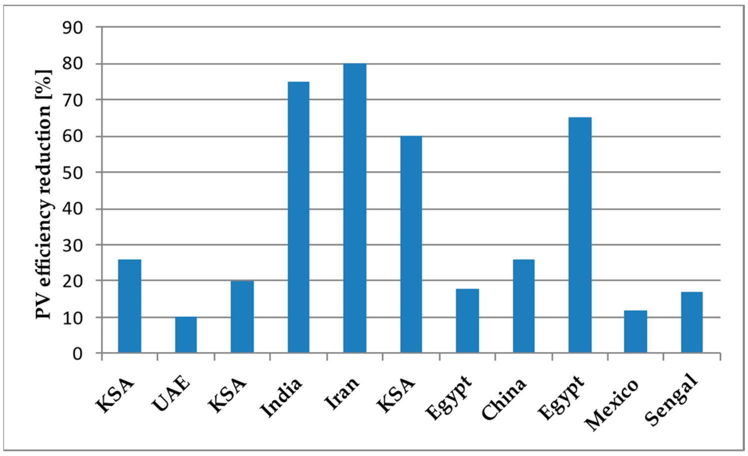
The broken glass of photovoltaic modules (Figure 10) as a result of faulty installation and maintenance can produce less energy, moisture can penetrate through the cracks. The power of the photovoltaic module can decrease between 10 and 13% due to the discoloration of the photovoltaic module [71].

In Figure 11a,b, based on the analysis of research carried out in the period 2015–2022 [15,30,34,62–104], we graphically represented the reduction in the efficiency of the panels as a result of the deposition of dust on the photovoltaic systems. The daily loss of panel power is between 0.05% in Oman and 1.15% in Bangladesh (Figure 11a) and the monthly decrease in panel efficiency (Figure 11b) is high, reaching 80%. Periodic cleaning of the panels is recommended for good efficiency [27].

Figure 10. PV module with broken glass (adapted from [70]).



(**a**)



(**b**)

Figure 11. (**a**) Daily energy losses of photovoltaic panels (adapted from [28]); (**b**) The monthly decrease in the efficiency of photovoltaic panels due to dust coverage (adapted from [28]).

Next, we analyze the effect of dust accumulation on the surface of photovoltaic modules on some performance characteristics of the modules.

According to Ndiaye et al. [61], the accumulation of dust on polycrystalline and monocrystalline photovoltaic modules over a period of one year without being cleaned highlighted losses of the maximum output power (P_{max}) between 18 and 78%, the fill factor (FF) of recorded decreases between 2% for the polycrystalline module and 17% for the monocrystalline module, losses of the maximum output current (I_{max}) between 23 and 80%, and losses were also recorded for the short-circuit current (I_{sc}), whereas the voltage in the circuit open (V_{oc}) and the maximum output voltage (V_{max}) had no changes as a result of the deposition of dust on the photovoltaic modules (Table 4).

Table 4. The effect of dust accumulation on photovoltaic modules on performance characteristics (data from [61]).

Modules	Parameter	Initial Value	Clean Module after One Exposition Year	Dusty Module after One Exposition Year
Monocrystalline PV module	P_{max} (W)	145	144.59	32.17
	V_{max} (V)	17.9	17.83	20.79
	I_{max} (A)	8.1	8.06	1.57
	V_{oc} (V)	22.7	22.7	22.7
	I_{sc} (A)	8.5	8.47	2.09
	FF (%)	75.14	73.64	60.4
Polycrystalline PV module	P_{max} (W)	230	217.37	178.19
	V_{max} (V)	29.2	28.04	30.09
	I_{max} (A)	7.88	7.75	5.93
	V_{oc} (V)	36.6	36.16	36.16
	I_{sc} (A)	8.44	8.33	6.61
	FF (%)	74.48	72.09	70.64

Table 5 shows the efficiency of the photovoltaic panels according to their performance. The performance is influenced by the energy losses that may occur. The performance of the analyzed systems did not fall below 70%. The analyzed monocrystalline and polycrystalline systems are from 23.92 MW to 2.04 kW.

Table 5. Performance of photovoltaic panels (data from [91,93,94,99,103,104]).

PV Type	Rated Capacity	Energy Generation (kWh/year)	Final Yield (kW h/kW$_p$-day)	*PR* (%)	CF (%)	η_{syst}	Tilt Angle (°)	R
MC	20 MW	26,304,000	4.19	76.8	15.22	11.54	15	[99]
PC	23.92 MW	43,261,400	4.95	82.0	20.64	-	15	[99]
MC	28 kW	45,119	4.4	71.89	18.58	10.99	27	[99]
PC	10 MW	15,798,192	4.07	85	17.68	10.12	33.7	[91]
PC	2.5 MW	3,547,800	4.49	70.6	16.2	11.56	12.5	[103]
MC	56.7 kW	68,625	3.32	82.4	-	14.45	18	[104]
PC	9.6 kW	8839	3.07	77.22	-	9.8	30	[93]
MC	2.04 kW	3370.89	4.96	76.7	18.86	11.7	30	[94]

PC—poly-crystalline silicon, MC—mono-crystalline, *PR*—performance ratio partial, CF—capacity factor, η_{syst}—system efficiency, R—references.

The capacity factor (CF) is the actual power of the photovoltaic system divided by the theoretical production of the photovoltaic plant for a period of time.

The transmissivity decreases with the increase in the density of the dust deposited on the surface of the panels (Figure 12).

It is observed that the performance of clean photovoltaic panels is higher compared to the performance of photovoltaic panels covered with dust (Figure 13).

Large and small-sized dust particles have a smaller deposit than medium-sized dust particles. The efficiency of the photovoltaic panels depending on the dust coverage of different particle sizes over time is shown in Figure 14.

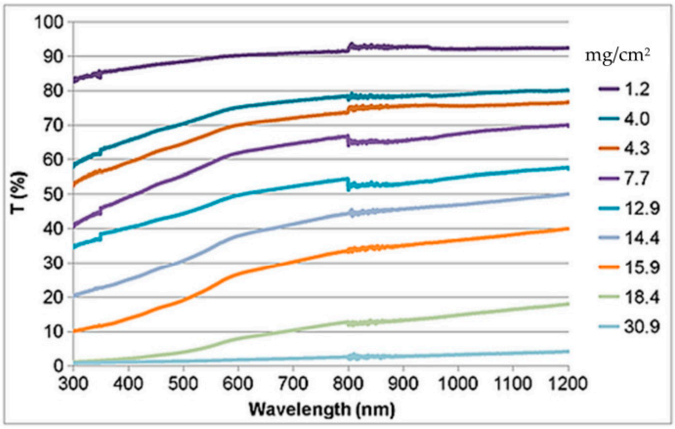


Figure 12. The variation of transmittance depending on the density of deposited dust (adapted from [5]).

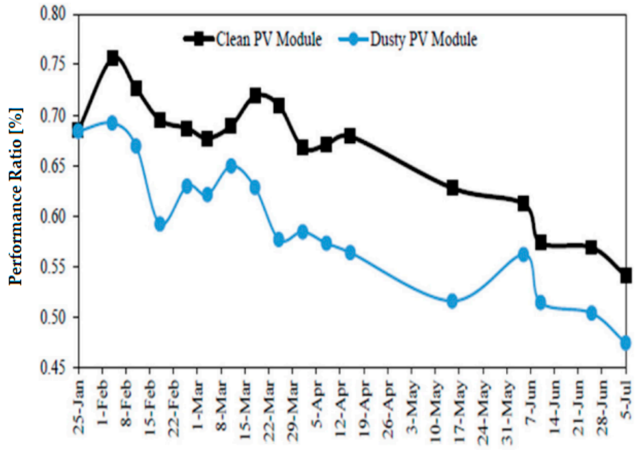


Figure 13. The ratio performance of clean and dust-covered photovoltaic panels (adapted from [95]).

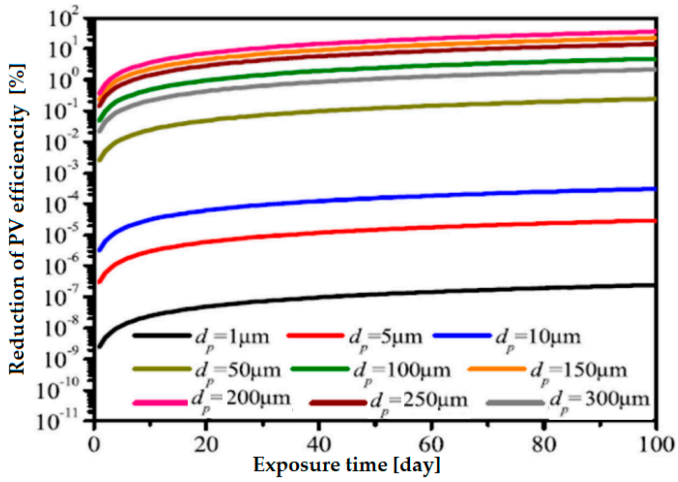


Figure 14. Effect of dust size on the efficiency of PV modules (adapted from [95]).

Figure 15 shows the performance rate for several photovoltaic systems: monocrystalline, p-Si polycrystalline silicon, m-Si multi crystalline silicon, a-Si amorphous silicon, c-Si crystalline silicon, thin film, triple-junction, multi-junction. It can be seen that the photovoltaic cells with multijunction (generally with triple or quadruple junction) have the highest efficiency.

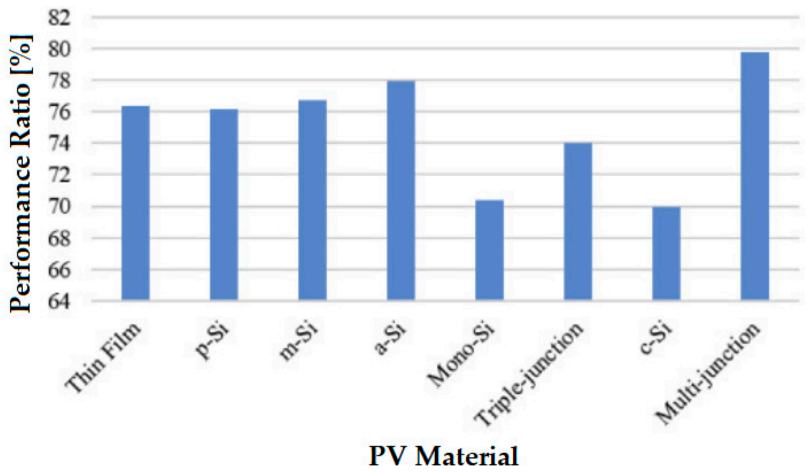


Figure 15. Performance ratio of photovoltaic panels (adapted from [99]).

8. Reduction in CO_2 Emissions

Next, we carry out an analysis of the reduction in CO_2 emissions through the use of photovoltaic panels. Taking into account global warming, researchers' attention is directed towards the use of renewable energy, i.e., solar energy, to reduce greenhouse gas emissions in the atmosphere.

The electrical energy produced in homes in Mexico by photovoltaic systems is 39.750 GWh, equivalent to a reduction in CO_2 emissions of 20.27 Tg [102].

CO_2 emissions resulting from the consumption of electricity generated by fossil fuels, which favor global warming, are reduced by using the energy generated by photovoltaic panels [101,102].

According to research carried out by Haibaoui et al. [94], by using photovoltaic panels for one year, a total amount of 4.022 tons of CO_2 emissions is reduced (Figure 16).

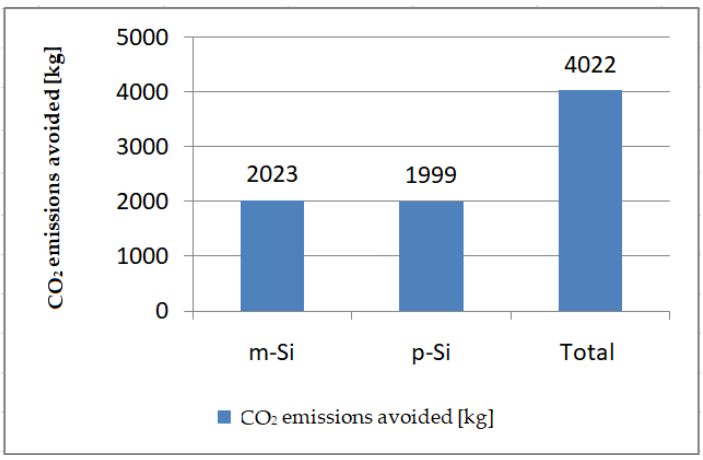


Figure 16. The performance of clean and dust-covered photovoltaic panels (adapted from [94]).

According to Anang et al. [98], for a house using energy from a 7.8 kWp PV system for 21 years, the total avoided CO_2 emissions calculated with Equation (7) are 136.5–156.5 tons.

$$EM_{av} = \frac{E_C \cdot F_C}{1000} \tag{7}$$

9. Conclusions

In this paper, based on the specialized literature, we analyzed the influence of dust deposits on the surface of photovoltaic panels, taking into account the effect of environmental factors of wind, precipitation, temperature, humidity, and solar radiation on the performance of the panels.

The influence of dust on the efficiency of photovoltaic modules depends on the amount of dust deposited on their surface, the size, weight, shape, and components of the dust.

The shading of photovoltaic panels as a result of the deposition of dust influenced by environmental factors reduces the efficiency of the panels.

The smaller the size of the dust particles, the greater the shading effect on the photovoltaic panels.

The efficiency of the panel decreases depending on the increase in the density of dust deposited on the surface of the photovoltaic panel, for slightly high values of solar radiation, wind speed, and atmospheric humidity.

Acidic dust can cause panel surface erosion. The thickness of the dust layer negatively influences the performance of the photovoltaic modules, and the increase in the amount of dust determines the decrease in the energy generated by the photovoltaic cell.

Wind scatters dust and dirt onto the surface of the solar panel, affecting the efficiency of the panel, reducing its transparency and preventing the Sun's rays from reaching the surface of the panel.

Shading the surface of the photovoltaic panel by the deposition of dust attenuates the solar radiation, reducing its transmission to the surface of the panel.

We analyzed the insolation losses before and after rain and found that rain cleans the panel coating, leading to its better efficiency.

The deposition of dust on the surface of the photovoltaic panel is also influenced by the angle of inclination of the panel; when the angle of inclination is high, large particles can roll off the surface of the panel or move to the lower parts.

The largest dust deposits are found on panels with smaller tilt angles; when the photovoltaic panel is placed horizontally, it leads to energy loss due to covering the panel surface with dust.

Due to the dust deposited on the surface of the polycrystalline and monocrystalline photovoltaic modules over a period of one year, without being cleaned, there were losses of maximum output power ($P_{\max}$) between 18 and 78% of the maximum output current ($I_{\max}$) and between 23 and 80% of the short-circuit current (I_{sc}). The efficiency of the panel decreases depending on the increase in the density of dust deposited on the surface of the photovoltaic panel, for high values of solar radiation, wind speed, and atmospheric humidity. If the surface of the panel is rough or sticky, a slow wind speed favors the accumulation of dust. Moisture in the air can accelerate the deterioration of photovoltaic panel cells, reducing their efficiency.

By using photovoltaic panels, a total amount of 4.022 tons of CO_2 emissions is reduced in one year.

When we install photovoltaic panels, we must take into account their angle of inclination, environmental factors in their location, and pollutant emissions, and we must keep the photovoltaic panels clean to achieve a high yield.

Author Contributions: Conceptualization: C.O.R.; methodology: C.O.R. and M.R.; investigation: C.O.R. and M.R.; formal analysis: G.A.C., I.A.I. and M.B.; visualization: G.A.C., I.A.I. and M.B.; resources: C.O.R.; writing-review and editing: C.O.R. and M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the project, Establishment and operationalization of a Competence Center for Soil Health and Food Safety-CeSoH, Contract no.: 760005/2022, specific project no. 1, with the title, Soil health and food safety by introducing a soil remediation protocol and developing mobile remediation equipment to reduce the concentration of organic/inorganic pollutants, Code 2, financed through PNRR-III-C9-2022–I5 (PNRR-National Recovery and Resilience Plan, C9 Support for the private sector, research, development, and innovation, I5 Establishment and operationalization of Competence Centers).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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