CHAPTER 2

The Effect of Dust Deposition on Photovoltaic Systems' Electricity Generation and its Economical Analysis

Muhammet Raşit SANCAR[1]

INTRODUCTION

Energy production from renewable energy sources has become very important due to increasing energy demand and global warming. Electricity production from solar energy, which is one of the renewable sources, can be achieved by harnessing both its thermal energy and photovoltaic potential. Turkey has a great potential for electricity generation from solar energy. Global radiation and sunshine durations values for Turkey are presented in Figure 1 and Figure 2 respectively. In order to benefit from this potential, photovoltaic systems have increasingly become widely used. Today, many studies are carried out on electricity generation from photovoltaic panels, and there is a continuous development and improvement. With these developments, the efficiency of photovoltaic panels increases and it is observed that there is a serious opportunity to benefit from solar energy. As important as it is to increase efficiency with the advancement of technological studies, it is also important to minimize the losses in the photovoltaic panels in the field.

1 Isparta University of Applied sciences,Institute of Postgraduate Education, Energy Systems Engineering, Isparta, Turkiye, ORCID Code: (0000-0002-4488-8393) *d1840640001@isparta.edu.tr. YÖK 100/2000 öncelikli alanlar öğrencisidir.

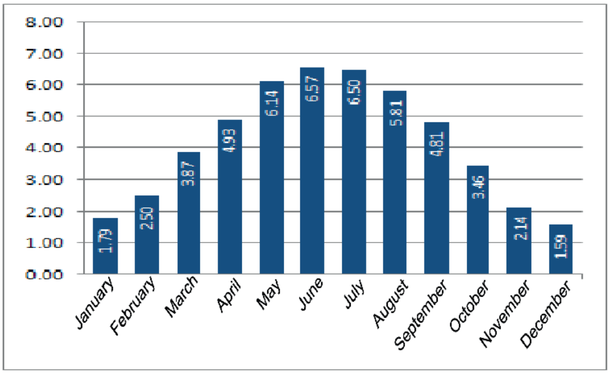

Figure 1. Global radiation values for Turkiye(KWh/m2-day)(GEPA)

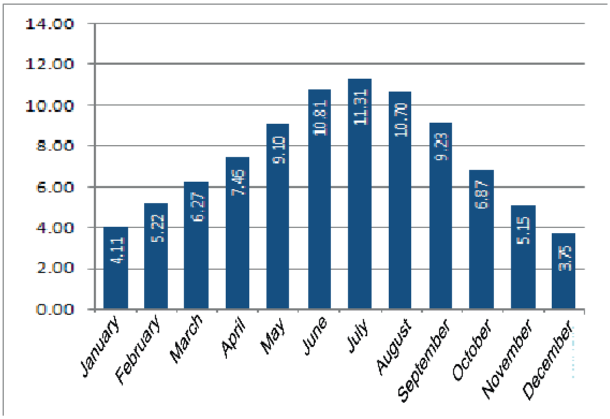

Figure 2. Sunshine duration for Turkiye(hours)(GEPA)

If a conventional silicon crystal photovoltaic panel is lined up from the front surfaces to the inner parts; It consists of an aluminum frame, glass, encapsulant (EVA film), solar cells, encapsulant (EVA film), backsheet and junction box elements. As seen in Figure 3, glass is used on the front surfaces of the panels that meet the sun. Electricity generation in the panels occurs when the sun rays coming to the surface of the panel pass through the transparent protective glass and reach the cells and convert into electrical energy with the photoelectric effect. During this process, the permeability of the protective glass on the top surface is of great importance. Due to environmental conditions, accumulated dust on the surface of the panel causes the glass permeability to decrease and subsequently cause a decrease in the energy obtained.

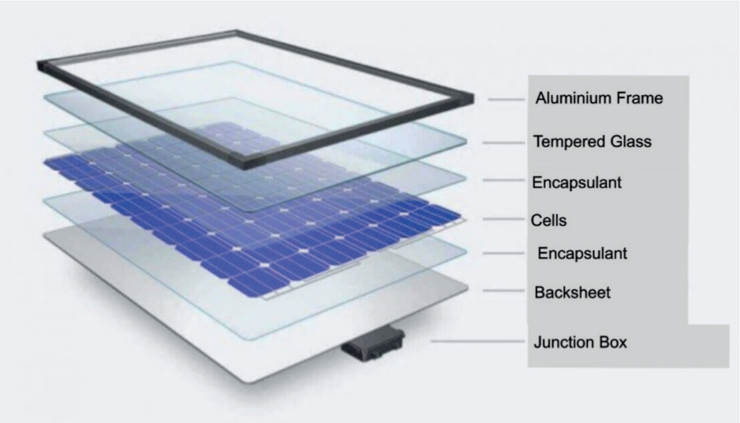

Figure 3. General elements of a photovoltaic panel (Tevı vd.,2018)

There have been many studies done within the scope of the effect of dust deposition on photovoltaic panels. In a study conducted in Iraq, an experiment was done on the surface of the panel with sand, cement, white cement, gypsum and technical gypsum powder samples at a density of 35 g/m2 and a permeability decrease of the glass of 40, 45, 55, 50 and 52 percent was observed for each of the samples used respectively (Alnasser, et al. 2020). As for a study carried out in Algeria, samples of ash, cement, gypsum, salt, soil and sand dust samples with densities of 1.02 g/m2, 1.01 g/m2, 1.01 g/m2, 1.2 g/m2, 1.02 g/m2 and 1 g/m2 showed a decrease in permeability of 73.71 ,74.62, 65.52, 62.79 ,20.02 and 19.11 percent. (Abderrezek ve Fathi 2017)

Table 1 below presents the results of a study conducted in the west of Rajasthan which was aimed to investigate the effect of bird droppings on permeability photovoltaic panels and its relation to different tilt angles in the years 2015, 2016, and 2017. According to the data, the highest permeability reduction was observed at 0° angles by 31% in 2015 and 2017, while the highest power generation reduction was observed at 0° and 10° angles by 23.8%.

Table 1. Loss in permeability and loss power generation with inclination angle β (Sisodia ve Mathur 2019)

angle	year			Power generation loss (%)
β°	2015	2016	2017	
0°	31	30	31	23,8
10°	28	29	29	23,8
20°	27	26	27	21
25°	15	14	14	11,5
30°	14	13	13	10,8
40°	13	13	13	10,5
50°	14	14	15	10,8
60°	15	16	16	10,8
70°	18	19	19	15,8
80°	21	22	21	16
90°	24	23	23	16,5

In Table 2, the calculated permeability reduction and power generation reduction data of a study conducted in Belgium are presented. In this study, measurements were made using two different photovoltaic panel brands, Sanyo and Eurosolare panels and glass samples. In the study carried out with different densities of artificially deposited white sand, clay and cement powder samples, the parameters with the highest loss of permeability was determined to be at 66.66% with the 60 g/m2 density cement powder sample while the highest loss in panel power generation was 65.68% in the Eurosolare brand panel with cement dust.

Table 2. Production losses of Sanyo and Eurosolare brand panels under different dustiness samples (Appels, et al. 2013)

(g/m²)	White sand (250µm)		
	T(%)	P_{max} (%)	
		Sanyo HIP-210 NKHE1	Eurosolare PL160
10	1,05	1,78	0,08
20	4,02	4,84	5,46
40	9,18	9,77	9,1
60	15,03	14,74	13,76
(g/m²)	Clay (68µm)		
	T(%)	P_{max} (%)	
		Sanyo HIP-210 NKHE1	Eurosolare PL160
10	9,97	8,16	9,7
20	20,03	19,38	20,36
40	39,56	38,86	37,12
60	48,42	48,77	47,21
(g/m²)	Cement (10µm)		
	T(%)	P_{max} (%)	
		Sanyo HIP-210 NKHE1	Eurosolare PL160
10	18,41	20,92	19,06
20	40,61	40,65	39,78
40	53,48	51,24	52,44
60	66,66	64,16	65,68

In the experiments conducted on five different powder samples with densities of 100 g/m2, it was determined that the effect of sand, cement, white cement, gypsum and technical gypsum powder samples on panel power generation loss was 12, 14, 15, 9, and 10 percent respectively. (Alnasser, et al. 2020)In a different study, experiments on five different dust types with a density ratio of 10 g/m2, the effect of red soil, ash, sand, calcium carbonate and silica gel samples on panel power generation loss was found to occur at 7, 25, 4, 5 and 5, and 4.5 percent respectively (Kazem ve Chaichan 2016).

In Table 3, the experimental data of the losses in photovoltaic panel power generation of the coal dust sample with different particle sizes and weights made in the Aegean region of Turkey are presented. In this study which to kinds of photovoltaic cells were used, monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si), it was determined that the maximum reduction occurred at the size of 38 μm and the weight of 15 g.

Table 3. Effect of coal dust with different particle sizes on panel power generation loss (Adıgüzel, et al. 2019)

Particle size	Mass (g)	Type of photovoltaic panel	
		m-Si	p-Si
38 μm	5	%39,61	%38,52
	10	%52,15	%47,79
	15	%62.05	%60,07
38-53 μm	5	%36,64	%31,08
	10	%47,86	%43,67
	15	%55,78	%57,03
53-75 μm	5	%32,42	%26,78
	10	%42,91	%40,07
	15	%50,83	%52,15
75-106 μm	5	%26,43	%22,21
	10	%37,96	%30,3
	15	%44,23	%43,67
106-250 μm	5	%20,8	%17,28
	10	%29,25	%20,34
	15	%36,97	%28,93
250-500 μm	5	%15,17	%10,94
	10	%20,1	%11,72
	15	%28,9	%14,96

In Table 4, data of a study carried out in Athens that examined the effect of red soil, limestone and fly ash dust samples at different densities on the panel yield is presented. According to the observed results, it was determined that the highest decrease in panel efficiency occurred in the fly ash dust sample at 1.5% with a density of 3.71 g/m2.

Table 4. Effect of various dust types on panel efficiency

Dust samples	density (g/m^2)	%
red soil	0,12	0,5
	0,35	0,75
limestone	0,28	0,4
	1,51	0,95
fly ash	0,63	0,1
	3,71	1,5

Two identical photovoltaic panels were used in an experiment on the roof of a building in Shanghai. To test the effect of the accumulated dust on the panel efficiency, one of the photovoltaic panels was artificially dusted with a sand dust sample. Spreading the dust samples on the panel surface at densities of 2.199 g/m2, 6.29 g/m2, 17.37 g/m2, 21.067 g/m2 and 30.18 g/m2, the losses in panel efficiency were 5.296, 12.027, 34.332, 38.981 and 43.216 percent respectively. (Wang, Meng ve Chen 2020)

Another experiment investigating the effect of dust on production loss in photovoltaic panels was carried out in Doha, Qatar. Two arrays were used in this experiment, one which was cleaned weekly and the other one which was cleaned every two months. The monthly panel performance loss measured was found to vary between 6% and 23% per month depending on the current environmental conditions and dust characteristics. (Javed, et al. 2021)

In another study conducted in Mauritania, dirty and clean panels were used to determine the effect of dust on electricity generation on photovoltaic panels. The panels defined as clean were cleaned with two different methods, with and without water. According to the results obtained, it was observed that the output power of dusty photovoltaic panels was lost by 21.57% compared to the clean panels. The modules that had a power value of 2.88 kW and 2.95 kW at the beginning showed an increase in power output of up to 3.29 kW and 3.26 kW, respectively after cleaning. (Lasfar, et al. 2021)

A study in Senegal investigated the performance of photovoltaic panels when their surfaces get dry cleaned. Two identical polycrystalline solar panels were used, one of the panels was cleaned daily while the other was not cleaned. After a month, the dirty panel experienced a maximum loss of 17.13% compared to the clean panel. When compared with the data in the initial conditions, a deterioration of 10.16% and 24.09% was detected for the dry-cleaned and the uncleaned panels, respectively. (Aidara, et al. 2018)

A study carried out on a part of a solar power station with an installed power of 1 MW in Zahrani, a coastal region of Lebanon, a water-based robotic on-wheel device was used to remove the dust accumulated on the panels. The detected results showed that the cleaning procedure can effectively minimize the dust effect on the power output of the solar panel. It was calculated that an average increase of 32.27% was achieved in electricity production. (Hammoud, et al. 2019)

The effect of dust accumulation on the performance of photovoltaic panels under outdoor conditions was experimentally investigated in the city of Ouargla, southeast of Algeria. One of the panels, which was taken as a reference, was cleaned regularly using a soft wiper and distilled water at the beginning of each measurement while the other was left uncleaned to examine the effect of dust accumulation on the output power of the solar panels. As a result of the observations, it was determined that 4.36 g/m2 dust accumulated on the surface of the panel which was exposed to external environmental conditions for 8 weeks without cleaning. Due to this deposit, it was concluded that the dirty panel caused a decrease of 8.41%, 6.10% and 0.51%, in the maximum power output, short circuit current and open circuit voltage in energy production respectively, compared to the cleaned panel.

MATERIALS AND METHOD

In this study, a power plant simulation study with an installed power of 1 MW was carried out for the province of Isparta using PVsyst software. In this simulation study, the effects of five different powder samples, namely sand, cement, white cement, gypsum and technical gypsum, on power generation were investigated. An article study conducted by Tamadher and his friends which investigated the effect of the dust samples on power generation of a panel in 5 different cleaning periods was used as a source. Cleaning periods were performed as weekly, bi-weekly, monthly, bi-monthly and quarterly. The first simulation study was carried out without dust loss, while the other simulation studies were carried out according to the yield loss values in the article.

The article used as a source

The study was carried out to determine the effect of different dust samples on photovoltaic panel power generation at different cleaning periods. In the study, white cement, cement, sand, gypsum and technical gypsum powders were used as different powder samples. (Alnasser, et al. 2020). Sand, which is one of these dust samples, is a type of dust that rises as a result of the movement of vehicles and is collected and accumulated from the environment. A sample of gypsum powder, whose chemical compound is $CaSO4 \cdot 2H2O$, is a substance sometimes added to lime to change soil acidity and can be found in different colors. Cement consists of various compounds, primarily lime, silica, alumina and iron oxide. White cement and ordinary cement types were used for this study of this powder sample, which has different types and types. The physical properties of these different powder samples were investigated by different methods.

In this study, power generation reductions as a result of cleaning the panel were measured at 1-week, 2-week, 1-month, 2-month and 3-month cleaning periods using sand, gypsum, technical plaster, cement and white cement powder types. The power drop graph of the cleaning periods is given in Figure 4.

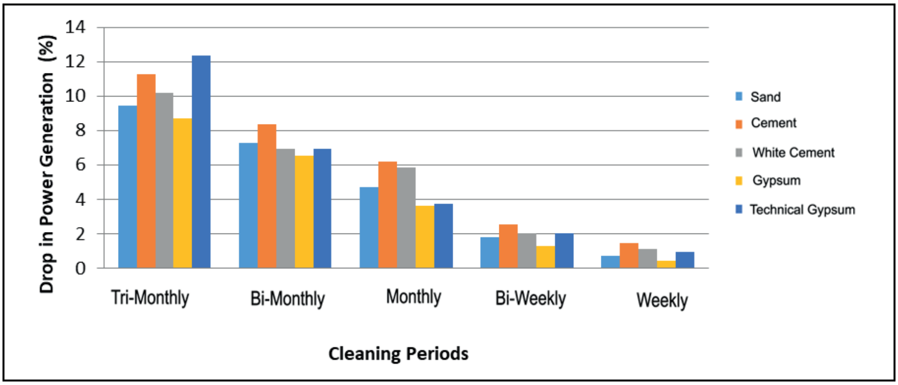

Figure 4. Power drop values according to cleaning periods for used data

2.2 Climate of Isparta province

Isparta province is located in the Mediterranean region. The climate characteristics of the transition zone between the Mediterranean climate and the continental climate are observed. Isparta has a semi-arid climate with less humid winters and hot summers. The hottest months in Isparta are July and August, and the coldest months are January and February. According to meteorological data, the annual average temperature of Isparta province is 12.3 °C, the annual average highest temperature is 18.4 °C and the annual average minimum temperature is 6 °C. Average temperature values of Isparta province are given in Figure 5.

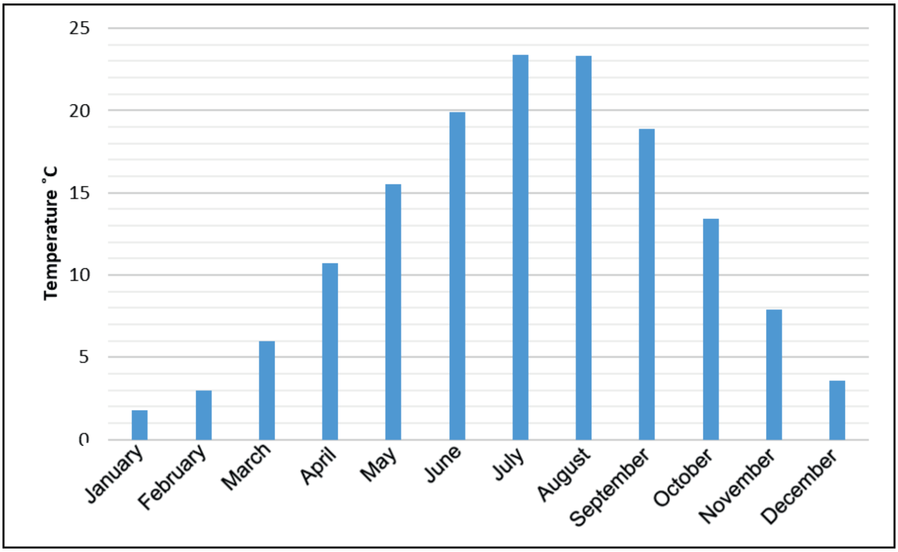

Figure 5. Monthly temperature values of Isparta province

When the monthly average radiation values of Isparta province were examined, it was determined that the highest radiation value observed was 6.80 (kWh/m2day) in June, and the lowest radiation value was 1.82 (kWh/m2day) in December. When the sunshine durations are examined, it is observed that the monthly average maximum sunshine duration is 11.72 hours in July, and the lowest sunshine duration is 4.00 hours in December. The graph of global radiation values of Isparta province is given in Figure 6 and the graph showing the sunshine durations is given in Figure 7.

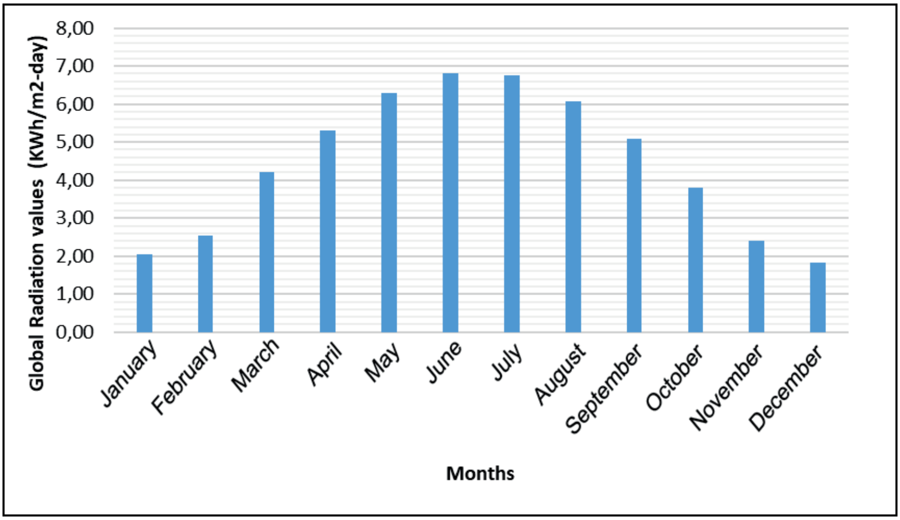

Figure 6. Global radiation values graph of Isparta province

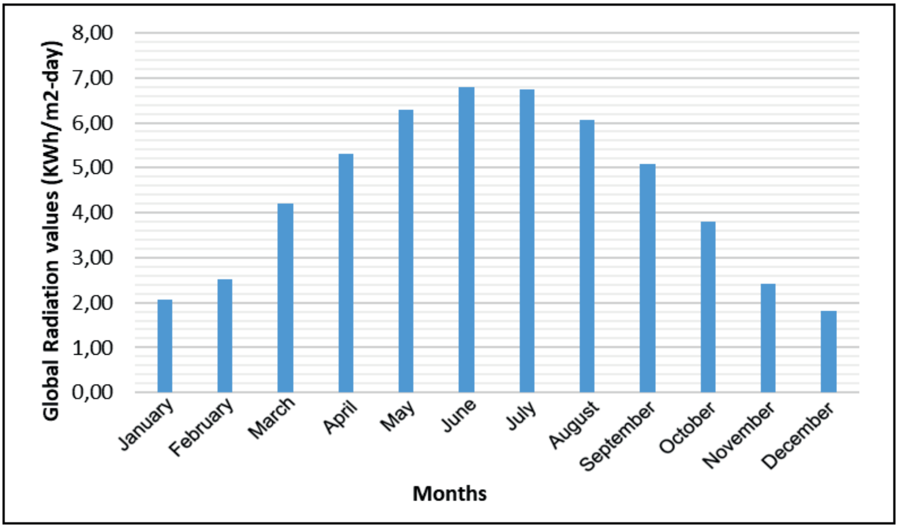

Figure 7. Sunshine duration of Isparta Province

2.3. The power plant

The analyzes were carried out with a simulation study of a photovoltaic power plant with an installed power of 1 MW in Isparta province, which was made on the PVsyst software. The simulation image of the power plant is given in Figure 8.

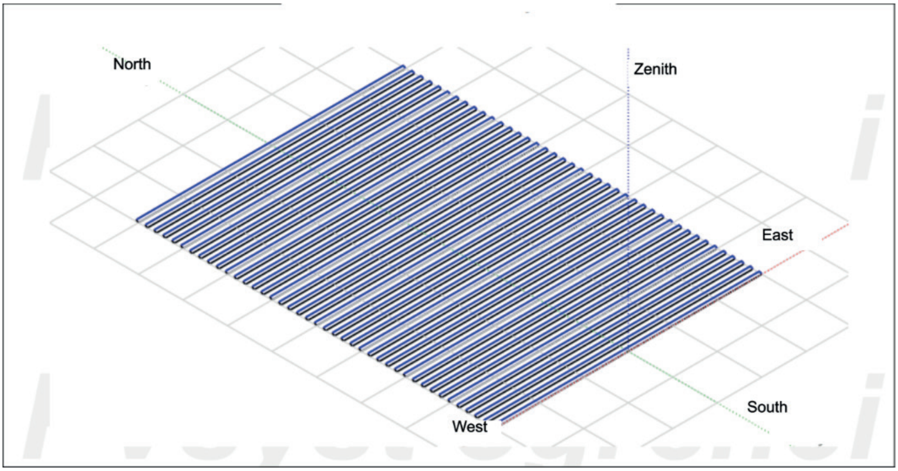

Figure 8. Simulated image of the power plant (PVsyst, 2022)

In the simulation study analyzed, the photovoltaic plant has a single slope and an azimuth angle. This tilt angle is 37.9° and the azimuth angle is 0°. The characteristics of the simulated power plant are given in Table 5. 8 inverters are used in the plant and the technical specifications of these inverters are presented in Table 6.

Table 5. Properties of the panels used in the power plant simulation

Parameters used in simulating the Power Plant	
Numer of series in the system	41 Adet
Numer of panels in each series	203 Adet
Total number of panels	8323 Adet
Tilt angle	37.9°
Per per unit	120Wp
Pmpp (operating conditions 50 ° C)	875kWp
Umpp (operating conditions 50 ° C)	627 V
Immp (operating conditions 50 ° C)	1394 A
Total PV nominal power(STC)	999 kWp

Table 6. Properties of the inverters used in the power plant simulation

Properties of the inverters used	
Model	SUN2000-100KTL-INM0-415Vac
Rated power per unit	100kWac
Number of inverters used	8 adet
Total power	800kWac
Operating voltage	200-1000V
Maximum power(=>35°C)	110kWac
Nominal power ratio (DC:AC)	1.25

THE SIMULATION

Simulation of the power plant

In the simulation study, the 7.2.14 version of the PVsyst software, which enables the simulation and analysis of grid-connected and off-grid systems, was used. Thanks to the software, results related to factors such as electricity generation, system losses and shading of the photovoltaic systems planned to be installed can be obtained. The weather database of this software can be used and the files of the prepared weather data can be added to the interface of the software and then simulated. The interface of the mentioned PVsyst software is presented in Figure 9.

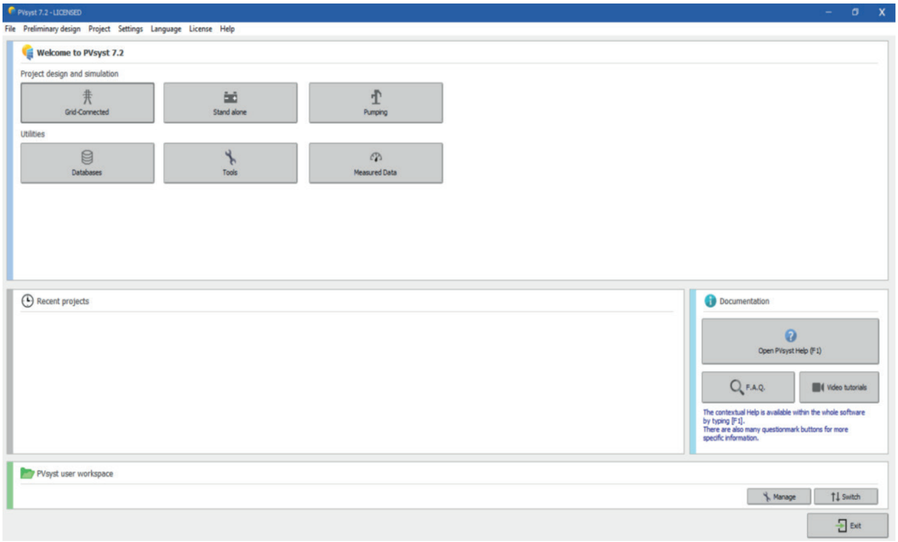

Figure 9. The user interface of the Pvsyst software (PVsyst, 2022)

Since the 1MW installed power system modeled in the simulation studies is planning to produce electricity from a grid-connected solar energy, the "Grid Connected" button in the software interface specified in Figure 9 was selected. The main purpose of the study is to obtain electricity generation data and evaluate it in terms of production. The simple diagram of the grid-connected photovoltaic system belonging to the software is presented in Figure 10.

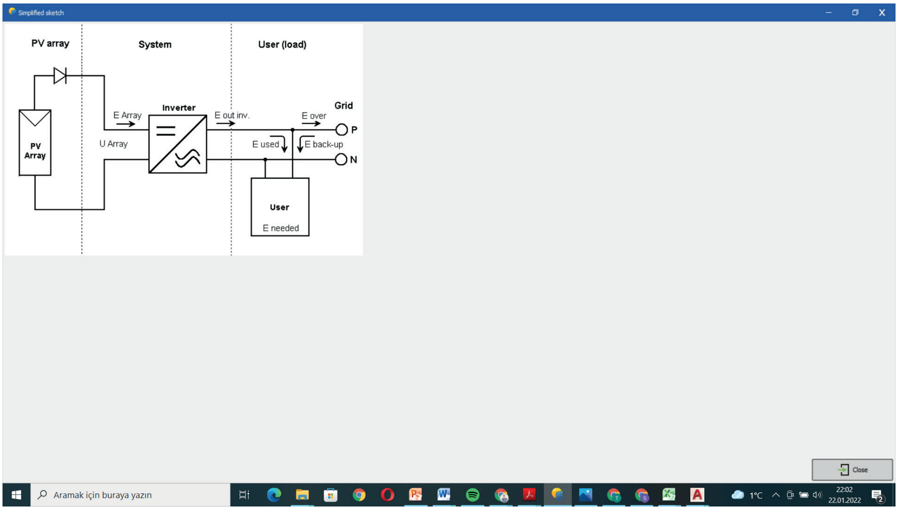

Figure 10. A schematic diagram of a simple Grid-connected photovoltaic system (PVsyst, 2022)

The simulation study was carried out using Meteonorm 8.0 (2003-2013) – Synthetic climate data in the data pool found in the software interface. Some graphics of the data obtained from the software are presented in Figure 11, Figure 12 and Figure 13.

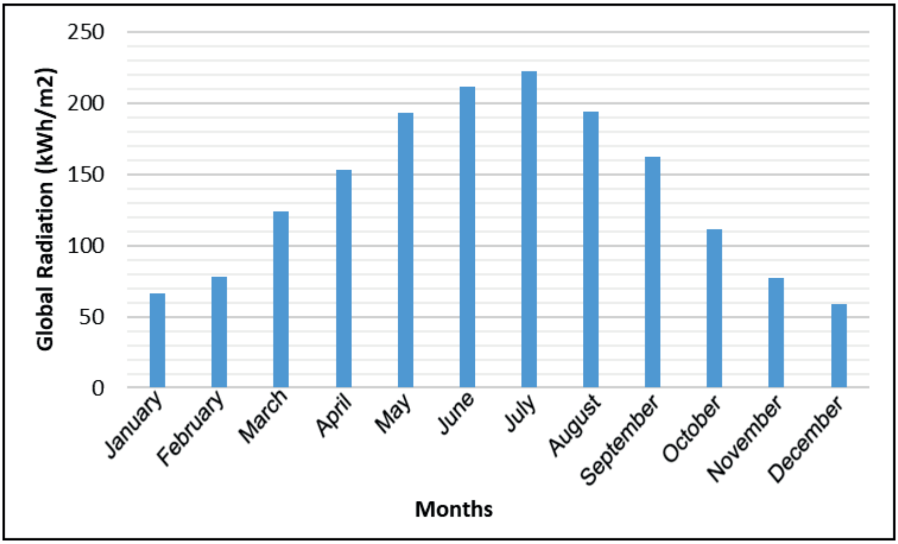

Figure 11. Monthly global radiation values (PVsyst, 2022)

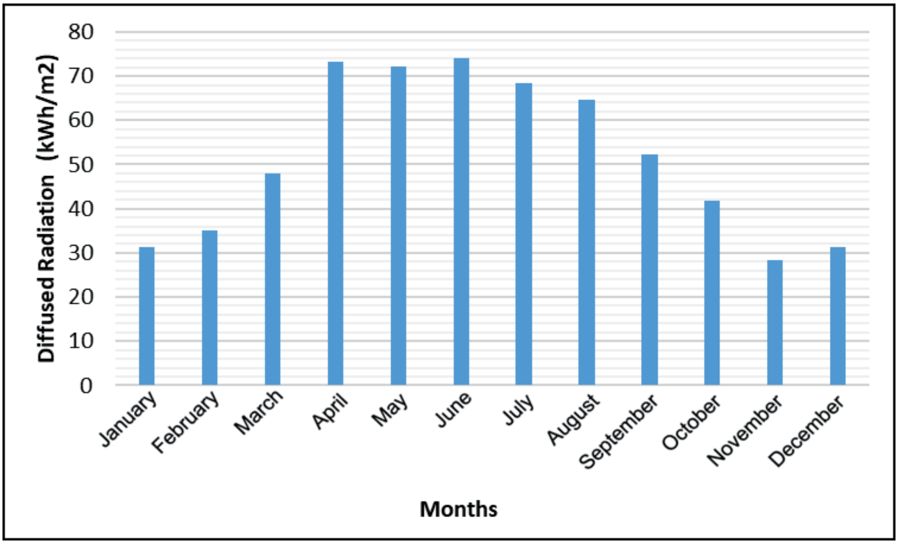

Figure 12. Monthly diffused radiation values (PVsyst, 2022)

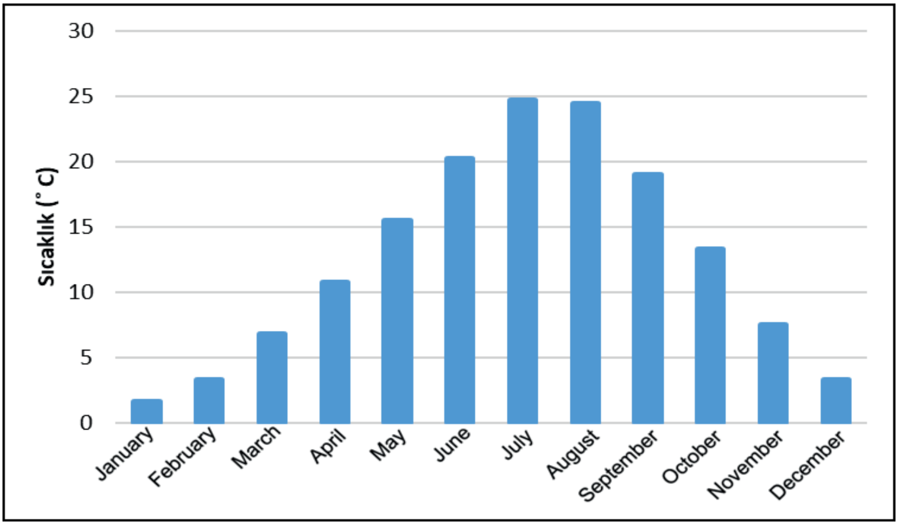

Figure 13. Monthly average temperature values (PVsyst, 2022)

By using the "Orientation" button in Figure 14, the values of the simulated power plant were determined and these values were defined by the software as 0° for the azimuth angle and 37.9° for tilt angle.

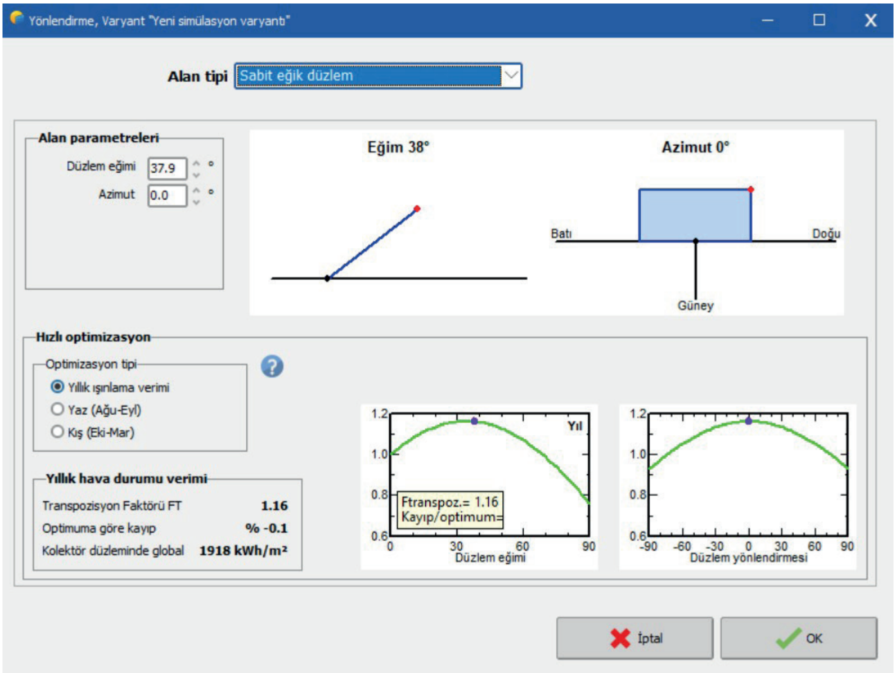

Figure 14. "Orientation" button interface (PVsyst, 2022)

The panel and inverter properties used while performing the plant simulation are defined by the software from the "System" button interface. The "System" interface is presented in Figure 15.

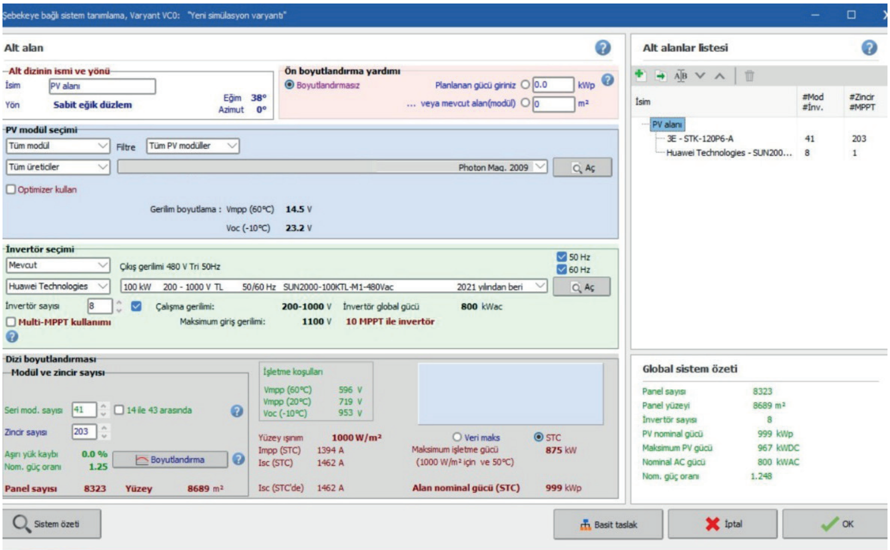

Figure 15. "System" button interface (PVsyst, 2022)

Using the tables of "Activity-based tariffs approved by EMRA(Energy Market Regulatory Authority) are to be applied as of June 1, 2022", the kWh unit price values of "Industry", "public and private services sector and other" and the sub-fields "agricultural activities" using binary and single term subheadings under the main title of medium voltage are given in Table 7.

Table 7. Table of The EMRA tariff on June 1st (EPDK, 2022)

	Activity-based tariffs approved by EMRA(Energy Market Regulatory Authority) are to be applied as of June 1, 2022					
	1/6/2022	**Activity-based consumer tariffs (kr/kWh)**				
Users of the Transmission system	**Users of the Transmission system**	**Retail Monomial Energy Price**	**Retail Day-time Energy Price**	**Retail Peak Demand Energy Price**	**Retail Night-time Energy Price**	**Distribution Price**
	Medium voltage					
	Binary					
	Industry	248.3714	251.3801	395.2221	135.2853	14.7972
	Public and private services sector and other	230.2455	232.5236	363.0085	128.7021	23.0611
	Agricultural activities	157.6777	159.2914	251.4048	85.6839	18.9925
	Monomial					
	Industry	256.6870	259.8001	408.5735	139.7250	16.3448
	Public and private services sector and other	235.0787	237.3568	367.8417	133.5347	28.7660
	Agricultural activities	159.7360	161.3497	253.4633	87.7413	23.6477

Research Findings

Presented Figure 16 is annual total electricity generation data of 25 different simulation studies in total created in the PVsyst program based on the power reduction values predetermined for 5 different dust samples according to 5 different cleaning periods. According to the data obtained, the highest value of electricity production was attained with 1-week cleaning periods. In addition to this, simulations in which the cleaning process was applied every 3 months achieve the lowest values in terms of electricity generation. As seen in Figure 16, it was observed that the highest electricity production in all cleaning applications was in the gypsum powder sample. In total, the highest electricity generation was 1470.9 MWh in the gypsum powder sample and the lowest electricity generation was 1392.9 MWh in the technical gypsum powder sample.

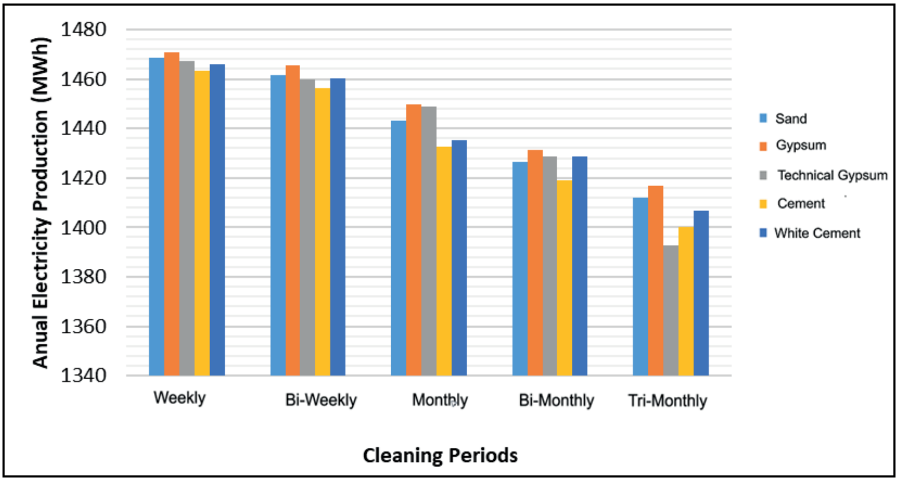

Figure 16. Annual electricity production values as a result of cleaning different dust samples at varying intervals

The annual electricity generation data of the simulation studies carried out for different dust samples and variable cleaning intervals were analyzed in the light of the data in Figure 16. These calculations were made for the data belonging to the industrial sub-field, and are given in Table 8 and Table 9 for the binomial and monomial titles respectively.

In Table 8, it is seen that the highest loss, ₺189 428.68, occurred with the technical gypsum powder sample which had a three-month cleaning interval while the lowest loss was ₺7 240.80 in the gypsum powder sample, which had a weekly cleaning interval.

Table 8. Economic analysis in which dust loss data is applied to the medium voltage and binary tariff of the "Industry" sub-field, in the light of EMRA values (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺12 613.01	₺29 430.35	₺72 174.43	₺ 111 414.89	₺145 049.58
Gypsum	₺7 240.80	₺20 320.96	₺56 291.38	₺99 502.61	₺133 370.87
Technical Gypsum	₺15 649.47	₺32 933.96	₺56 291.38	₺105 575.54	₺189 428.68
Cement	₺24 992.44	₺40 875.49	₺96 466.14	₺128 465.81	₺ 172 377.76
White Cement	₺18 685.94	₺31 999.67	₺90 393.22	₺105 575.54	₺ 157 429.01

In Table 9, it was seen that the highest economic loss value was ₺194 918.17 in the technical gypsum powder sample during the three-month cleaning period while the lowest economic loss value, ₺7 450.63, occurred in the gypsum powder sample during a one-week cleaning period.

Table 9. Economic analysis in which dust loss data is applied to the "Industry" sub-field of the medium voltage and monomial tariff in the light of EMRA values (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺12 978.52	₺30 283.22	₺74 265.99	₺ 114 643.61	₺149 253.00
Gypsum	₺7 450.63	₺20 909.84	₺57 922.66	₺ 102 386.12	₺137 235.85
Technical Gypsum	₺16 102.98	₺33 888.36	₺57 922.66	₺108 635.04	₺194 918.17
Cement	₺25 716.70	₺42 060.03	₺99 261.66	₺132 188.65	₺177 373.13
White Cement	₺19 227.44	₺32 926.99	₺93 012.74	₺108 635.04	₺161 991.18

According to the data obtained Table 8 and Table 9 presented, it was observed that the highest the lowest economic losses were experienced in the samples with a 3-month cleaning interval and a 1-week cleaning interval in both tables respectively.

In Figure 16, Calculations made for the data belonging to the "Public and Private Services Sector and Other" sub-field of EMRA is presented in Table 10 and Table 11 for the binomial and monomial titles, respectively.

In Table 10, we can see that the highest economic loss was experienced at ₺168 027.44 in the technical gypsum powder sample with a three-month cleaning period and the lowest economic loss was ₺6 422.75 in the gypsum powder type with a weekly cleaning interval. Considering the sand dust sample separately, it was seen that while a loss of ₺11 188.02 was experienced in the one-week cleaning period, this loss was ₺ 128 662.20 in the tri-monthly cleaning period.

Table 10. Economic analysis in which dust loss data are applied to the "Public and Private Services Sector and Other" sub-field of the medium voltage and binary tariff in the light of EMRA values (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺11 188.02	₺26 105.37	₺64 020.32	₺ 98 827.48	₺128 662.20
Gypsum	₺6 422.75	₺18 025.14	₺49 931.71	₺88 261.02	₺118 302.92
Technical Gypsum	₺13 881.43	₺29 213.16	₺49 931.71	₺93 647.85	₺ 168 027.44
Cement	₺22 168.85	₺36 257.46	₺85 567.61	₺113 952.03	₺152 902.90
White Cement	₺16 574.84	₺28 384.41	₺80 180.79	₺93 647.85	₺139 643.03

In Table 11, it can be seen that the highest economic loss was experienced at ₺167 319.60 in the technical gypsum powder sample with a three-month(tri-monthly) cleaning period and the lowest economic loss was ₺6 395.69 in the gypsum powder type with a one-week(weekly) cleaning period.

Table 11. Economic analysis in the light of EMRA values, where dust loss data are applied to the "Public and Private Services Sector and Other" sub-field of the medium voltage and monomial tariff (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺11 140.89	₺25 995.40	₺63 750.62	₺98 411.16	₺ 128 120.19
Gypsum	₺6 395.69	₺17 949.20	₺ 49 721.36	₺87 889.21	₺ 117 804.55
Technical Gypsum	₺13 822.95	₺29 090.09	₺49 721.36	₺93 253.34	₺ 167 319.60
Cement	₺22 075.46	₺36 104.72	₺85 207.15	₺113 471.99	₺ 152 258.77
White Cement	₺16 505.02	₺28 264.84	₺79 843.01	₺93 253.34	₺ 139 054.76

Finally, calculations made for the data in Figure 16 belonging to the "Agricultural Activities" sub-field of EMRA are presented in Table 12 and Table 13 for the binomial and monomial headings, respectively.

In Table 12, it was observed that the highest economic loss value was at ₺112 475.72 in the technical gypsum powder sample during the three-month cleaning interval and the lowest economic loss value at ₺4 299.32, occurred in the gypsum powder sample during a one-week cleaning interval.

Table 12. Economic analysis in which dust loss data is applied to the "Agricultural Activities" sub-field of the medium voltage and binary tariff in the light of EMRA values (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺ 7 489.14	₺17 474.65	₺42 854.50	₺66 154.03	₺86 125.06
Gypsum	₺ 4 299.32	₺12 065.83	₺33 423.74	₺59 080.96	₺79 190.68
Technical Gypsum	₺ 9 292.08	₺19 554.97	₺33 423.74	₺62 686.84	₺112 475.72
Cement	₺14 839.58	₺24 270.35	₺57 278.02	₺76 278.24	₺102 351.52
White Cement	₺11 095.02	₺19 000.21	₺53 672.14	₺62 686.84	₺ 93 475.51

In Table 13, it was observed that the highest economic loss value was ₺110 368.18 in the technical gypsum powder sample during the three-month cleaning period while the lowest economic loss value, ₺4 218.76, occurred in the gypsum powder sample during a one-week cleaning period.

Table 13. Economic analysis in which dust loss data is applied to the "Agricultural Activities" sub-field of the medium voltage and monomial tariff in the light of EMRA values (Annual)

Cleaning intervals	Weekly	Weekly	Monthly	Bi-monthly	Tri-monthly
Sand	₺7 348.81	₺17 147.21	₺42 051.50	₺64 914.45	₺84 511.27
Gypsum	₺4 218.76	₺11 839.74	₺32 797.45	₺57 973.91	₺ 77 706.82
Technical Gypsum	₺ 9 117.96	₺19 188.55	₺32 797.45	₺61 512.23	₺ 110 368.18
Cement	₺14 561.52	₺23 815.58	₺56 204.76	₺74 848.95	₺100 433.68
White Cement	₺10 887.12	₺18 644.19	₺52 666.44	₺61 512.23	₺91 723.99

In Figure 17, a graph was created to show the annual total loss of electricity production under the exposure of different dust samples of the power plant simulation with variable cleaning periods. In order to create this graph, firstly, the dust deposition factor of the power plant was removed and annual electricity production values were accepted as reference.

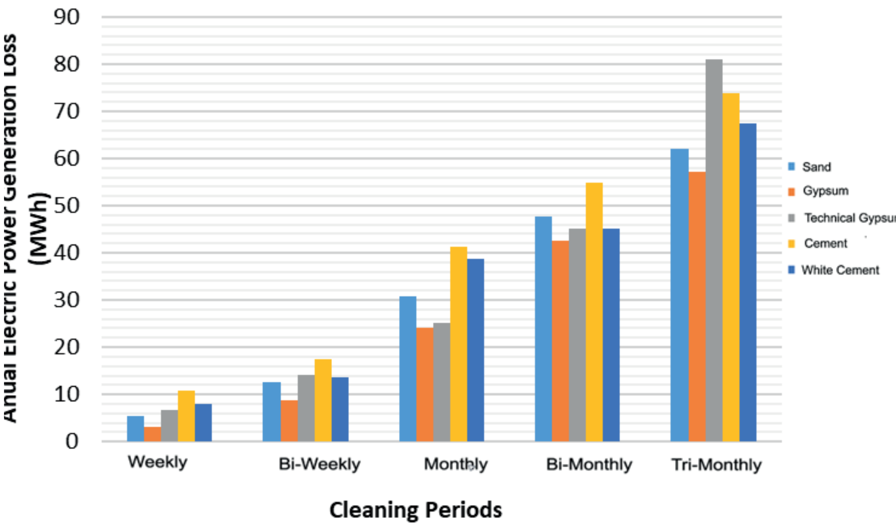

Figure 17. The effect of different dust samples on annual electricity production with variable cleaning periods

When the values calculated by eliminating the dusting factor are taken as reference; It was determined that the highest electricity production loss was 81.1MWh with the technical gypsum dust sample in the 3-month cleaning period, and the lowest electricity production loss was 3.1MWh with the gypsum dust sample in the 1-week cleaning period.

3.CONCLUSION

Electricity generation using photovoltaic panels from solar energy is a known, continuous, renewable and common method. Considering the effects of dusting factor, which is one of the biggest losses that can be encountered in the electricity generation process with photovoltaic panels, the decrease in efficiency and energy production results have been by use of simulations and analyzes. Electricity production loss due to loss of permeability of solar panels caused by settlement of various types of dust on the surface of the panel was investigated.

In this study, energy production losses due to the cleaning of sand, gypsum, technical plaster, cement and white cement powder samples accumulated on the surface of photovoltaic panels at different intervals were investigated. According to the data obtained as a result of cleaning the 5 dust samples mentioned above off the panel surfaces in 1 week, 2 weeks, 1 month, 2 months and 3 months' intervals, it was calculated that the highest amount of production loss occurred in the 3-month cleaning interval, with the technical gypsum powder sample at a total of 81.1 MWh per year.

The calculated losses were examined economically in the light of EMRA data; In binomial tariffs the losses were 189 428.68 TL, 168 027.44 TL and 112 475.72 TL for "Industry", "Public-Private Services Sector and Other" and "Agricultural Activities" respectively, and in the same order 194 918.17 TL, 167 319.60 TL and 110 368.18 TL for Monomial tariffs.

Table 14. Annual financial loss caused by dust deposition with a 3-month cleaning interval.

EMRA sub sectors	Binomial	Monomial
Industry	189 428.68TL	194 918.17TL
Public-Private Services Sector and Others	168 027.44TL	167 319.60TL
Agricultural activities	112 475.72TL	110 368.18 TL

In the calculations made with all cleaning periods, gypsum caused the lowest loss, while the highest loss was observed with cement in all cleaning intervals except for the three-month cleaning interval. In the three-month cleaning interval, it was determined that the highest loss occurred with the technical gypsum. For this reason, it has been determined that cement powder causes higher losses in cleaning intervals of two months or less, while higher losses occur with technical gypsum powder in long-term cleaning intervals such as three months.

In this study, guiding information is given in terms of the decrease in electricity production and material damage that may be experienced in case of establishing a power plant near the enterprises that produce the dust samples. Considering the calculated values, the importance of solar panel surface cleaning has been demonstrated by using numerical data in order to minimize the losses in electricity production. The use of cleaning machines and surface coating methods that prevent dust collection, which are some of the methods that can provide panel surface cleaning, are effective methods that can be used in order to minimize the losses that may occur.

In addition, many studies have been carried out on the effect of different dust types on photovoltaic panel electricity production, except for the dust samples used in this study. By using the data obtained from these studies, the effect of different dust types on the electricity production of the photovoltaic system can be investigated and an economic analysis can be carried out with the help of the method applied in the article. If the dust types can be spatially determined in our country, the dust-related losses could also be spatially calculated using the existing data, and as a result, a comprehensive study can be carried out on which region the dust-related losses will occur and at what level. As a result of these studies, data can be provided to guide commercial investments and academic studies.

REFERENCES

Abderrezek, M., & Fathi, M. (2017). Experimental study of the dust effect on photovoltaic panels' energy yield. Solar Energy, 142, 308-320.

Adıgüzel, E., Özer, E., Akgündoğdu, A., & Yılmaz, A. E. (2019). Prediction of dust particle size effect on efficiency of photovoltaic modules with ANFIS: An experimental study in Aegean region, Turkey. Solar Energy, 177, 690-702.

Aıdara, M. C., Ndıaye, M. L., Mbaye, A., Sylla, M., Ndıaye, P. A., & Ndıaye, A. (2018). Study of the performance of a system for dry cleaning dust deposited on the surface of solar photovoltaic panels. International Journal of Physical Sciences, 13(2), 16-23.

Alnasser, T. M., Mahdy, A. M., Abass, K. I., Chaichan, M. T., & Kazem, H. A. (2020). Impact of dust ingredient on photovoltaic performance: An experimental study. Solar Energy, 195, 651-659.

Appels, R., Lefevre, B., Herteleer, B., Goverde, H., Beerten, A., Paesen, R., ... & Poortmans, J. (2013). Effect of soiling on photovoltaic modules. Solar energy, 96, 283-291.

Dida, M., Boughali, S., Bechki, D., & Bouguettaia, H. (2020). Output power loss of crystalline silicon photovoltaic modules due to dust accumulation in Saharan environment. Renewable and Sustainable Energy Reviews, 124, 109787.

Enerji, T. C., & Bakanlığı, T. K. Yenilenebilir Enerji Genel Müdürlüğü,"Güneş enerjisi potansiyeli atlası (GEPA)".

EPDK, E. P. D. K. (2022). Elektrik piyasasında lisanssız elektrik üretimi.

Hammoud, M., Shokr, B., Assi, A., Hallal, J., & Khoury, P. (2019). Effect of dust cleaning on the enhancement of the power generation of a coastal PV-power plant at Zahrani Lebanon. Solar Energy, 184, 195-201.

Javed, W., Guo, B., Figgis, B., & Aïssa, B. (2021). Dust potency in the context of solar photovoltaic (PV) soiling loss. Solar Energy, 220, 1040-1052.

Kaldellis, J. K., Fragos, P., & Kapsali, M. (2011). Systematic experimental study of the pollution deposition impact on the energy yield of photovoltaic installations. Renewable energy, 36(10), 2717-2724.

Kazem, H. A., & Chaichan, M. T. (2016). Experimental analysis of the effect of dust's physical properties on photovoltaic modules in Northern Oman. Solar Energy, 139, 68-80.

Lasfar, S., Haidara, F., Mayouf, C., Abdellahi, F. M., Elghorba, M., Wahid, A., & Kane, C. S. E. (2021). Study of the influence of dust deposits on photovoltaic solar panels: case of Nouakchott. Energy for Sustainable Development, 63, 7-15.

MGM, M. G. M. (2018). İklim verileri bülteni.

PVsyst, 2022. Software for Photovoltaic Systems, www.pvsyst.com/7.2/Index

Sisodia, A. K. (2019). Impact of bird dropping deposition on solar photovoltaic module performance: a systematic study in Western Rajasthan. Environmental Science and Pollution Research, 26(30), 31119-31132.

Tevı, G. J. P., Faye, M. E., Moustapha, S. E. N. E., Issa, F. A. Y. E., Blieske, U., & Maiga, A. S. (2018, May). Solar photovoltaic panels failures causing power losses: a review. In 2018 7th International Energy and Sustainability Conference (IESC) (pp. 1-9). IEEE.

Wang, H., Meng, X., & Chen, J. (2020). Effect of air quality and dust deposition on power generation performance of photovoltaic module on building roof. Building Services Engineering Research and Technology, 41(1), 73-85.