

Case Report

The Cleaning Effect of Photovoltaic Modules According to Precipitation in the Operation Stage of a Large-Scale Solar Power Plant

Wonkyun Jo ¹, Namhyuk Ham ^{2,*} , Juhyung Kim ³  and Jaejun Kim ³ 

¹ Procurement Division, Hyundai Engineering & Construction Co., Ltd., 75 Yulgok-ro Jongno-gu, Seoul 03058, Republic of Korea; wonkyun.jo@hdec.co.kr

² Department of Urban Infra System Engineering, Hanyang Cyber University, 220 Wangsimni-ro, Seongdong-gu, Seoul, 04763, Republic of Korea

³ Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Science and Technology Hall, Seoul 04763, Republic of Korea

* Correspondence: nhham@hycu.ac.kr; Tel.: +82-02-2290-0861

Abstract: A large-scale solar power plant costs a lot of money in the early stage of development and is greatly affected by the natural environment. Therefore, efficient operation is very important. The purpose of this study is to analyze the cleaning effect of photovoltaic modules according to precipitation during the operation stage of a large-scale solar power plant. The first analysis compared ‘average power generation on sunny days under standard cloudiness from after precipitation to the next precipitation’ and ‘average daily power generation per quarter’ and confirmed that precipitation had an effect on increasing power generation by 26%. The second analysis compared ‘average power generation on sunny days under the standard cloudiness from after precipitation to the next precipitation’ and ‘average daily power generation on a clear day just before precipitation’. It was confirmed that the average power generation efficiency of the entire sample increased by 4.8% on average after precipitation than before precipitation. This study quantitatively analyzed the cleaning effect of photovoltaic modules by precipitation through actual power generation data of large-scale solar power plants. This study has sufficient value in establishing an operation manual for decision-making on the appropriate input cost for cleaning photovoltaic modules and improvement of power generation efficiency.

Keywords: precipitation; photovoltaic module; cleaning effect; large-scale solar power plant



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1. Introduction

Efforts to develop sustainable energy sources are ongoing worldwide. Various approaches are being taken, such as expanding the use of renewable energy, signing the Paris Climate Agreement, and regulating the environment through carbon reduction policies. Renewable energy is not depleted and does not cause pollution by converting or recycling energy sources that sufficiently exist in nature. Renewable energy has the advantage of solving the environmental pollution problem caused by fossil fuels, but it has the disadvantage of low economic feasibility in terms of initial investment cost and operation. Since the power generation cost of fossil fuel and nuclear energy is very cheap compared to that of renewable energy, research to improve the power generation efficiency of renewable energy is urgent.

In the global renewable energy market, it is reported that the supply of solar and wind power will continue to increase, starting with Europe in the last 10 years. In 2020, new renewable energy power generation facilities were 258 GW, which increased significantly compared to the previous year, although there were concerns about supply in the COVID-19 situation. In particular, the new supply of solar power in 2020 was 139 GW,

which has continued to increase since exceeding 100 GW for the first time in 2017. The IEA forecasts an average annual growth rate of 7.7% for solar power among renewable energy sources by 2040. It is very important for power generation operators to manage power generation efficiency from an operational point of view in order to respond to the rapid supply of photovoltaic power generation facilities and actively respond to the increasingly conservative policies related to photovoltaic power generation.

Photovoltaic power generation uses the photoelectric effect, that is, the principle that when light energy is input to a solar cell made of semiconductors, electrons move and current flows and electricity is generated. The electrical output generated through this may drop due to environmental factors. Studies have found that various environmental conditions, such as the amount of sunlight, clouds, rainfall, and fine dust, indirectly affect the amount of solar power generation. In particular, dust accumulation in solar panels can significantly reduce the efficiency and electrical output of power generation systems by up to 80% [1–3]. Since dust, dirt, and bird droppings accumulated in photovoltaic modules directly affect power generation efficiency, research on photovoltaic module cleaning is being actively conducted [4,5].

Derakhshandeh et al. (2021) performed a comprehensive review of automatic cleaning systems for solar panels [6]. Active cleaning systems include brush cleaning systems (BCS), electrostatic cleaning systems (ECS), heliotex cleaning systems (HCS), and robotic cleaning systems (RCS). BCS is an inexpensive and reasonable method that requires a human interface for efficient cleaning [7]. ECS is a method of removing fine dust through an electrostatic field and does not damage the solar panel because there is no mechanical friction on the panel surface. However, it is not recommended for very large commercial solar power systems [8,9]. HCS is a method of cleaning the panel by spraying high-pressure water on the surface of the panel, and it is not suitable for large-scale solar power plants because it requires water and other power [10,11]. RCS can clean panels with maximum efficiency, but they have limitations in cost and cleaning time [12–14].

Passive cleaning systems include coating cleaning systems (CCS), manual cleaning, and rainfall cleaning. Coating cleaning systems (CCS) can be applied to the substrates by using gases, solids, or liquids depending on the end-user techniques. This method is considered a self-cleaning method [15]. Manual cleaning depends on laborers to clean the solar cell panels manually [16]. Rainfall cleaning depends on the water droplets that come from rain. Cleaning is available free of charge, but the precipitation schedule is difficult to predict and is not recommended in dusty, dry areas [17]. As such, the cleaning system for increasing the efficiency of photovoltaic power generation may vary according to regional characteristics and maintenance costs.

Efficient operation is very important for solar power plants, which require a lot of money in the early stage of development and are greatly affected by the natural environment. Therefore, this study aims to analyze the cleaning effect of photovoltaic modules according to precipitation in the operation stage of a large-scale solar power plant. The scope of the study used the power generation data for 30 months, from July 2019 to December 2021, of the Seosan Solar Power Plant. The purpose of this study is to confirm the correlation between the change in power generation amount according to the amounts of sunlight, cloudiness, dust, and precipitation that affect the amount of solar power generation, and to analyze the cleaning effect of the photovoltaic module according to precipitation based on the same climatic conditions.

2. Literature Review

2.1. The Impact of Climatic Conditions on Solar Power Generation

Srisuriyajan and Thongchaisuratkrul (2018) studied factors affecting the efficiency of solar power plants in Lampang province, Thailand [18]. Factors investigated included illuminance, humidity, wind speed, ambient temperature, module temperature, and power peaks. All data were correlated with solar power generation. In particular, it was shown that the main factor affecting solar power generation is irradiance, and humidity, wind

speed, ambient temperature, and power peaks have a great effect on solar energy generation. However, it has been determined that increasing module temperature reduces solar energy production. Correlation studies of solar power generation by climatic conditions in Korea have produced research results on the distribution of fine dust, number of clouds, natural cleaning according to rainfall, and correlation analysis of power generation according to photovoltaic module cleaning. Oh et al. (2021) performed a correlation analysis of photovoltaic power generation during a period of high fine dust concentration for the Jeollanam-do region, where a large number of photovoltaic facilities were distributed [19]. As a result of the analysis, it was confirmed that the utilization rate of solar power generation decreased as the concentration of fine dust increased when similar weather conditions were not considered. This means that the higher the fine dust concentration, the lower the power generation. Cha et al. (2019) analyzed the power generation amount correlation according to cloud cover from January to April 2019 (4 months), focusing on photovoltaic modules (90 kW) installed in Uijeongbu, Gyeonggi-do [20]. As a result, it was confirmed that the lower the cloudiness, the higher the power generation. In order to check solar power generation efficiency, it is necessary to define external meteorological factors such as temperature, cloudiness, precipitation, insolation, and fine dust. Park et al. (2012) analyzed the correlation between climatic factors and solar power generation in the climatic conditions of Korea [21]. Climatic conditions include temperature, cloudiness, sunshine hours, etc., and it is necessary to define each climatic condition in a specific area.

2.2. Cleaning Effect of Photovoltaic Module

Cha et al. (2019) analyzed the correlation of power generation according to rainfall and confirmed that the power generation increased after the rainfall compared to before the rainfall [20]. As a result of the analysis, it was confirmed that the greater the rainfall, the greater the difference in power generation. Lee et al. (2019) analyzed the power generation effect of an unmanned washing robot for artificial washing in April 2019 (five times), focusing on a photovoltaic module (158 kW) installed on the roof of a building [22]. As a result, it was confirmed that the amount of power generated in the washing section was improved. Studies on the cleaning effect of photovoltaic modules have been conducted in very diverse areas. Ko and Gu (2015) built a demonstration complex with a total solar power capacity of 9.8 kW at KFU (King Faisal University) in Saudi Arabia [23]. Of these, a photovoltaic module cleaning system for the desert was installed at 2.45 kW, and the data were analyzed. This system was analyzed to increase the daily average power generation by 2% (0.7 kWh) by washing the surface of the photovoltaic module with a rotating brush. Zhou and Xin (2020) investigated that the power generation efficiency of 1.9% to 2.6% of solar power is improved by washing the photovoltaic module with a brush [24]. Srisuriyajan and Thongchaisuratkrul (2018) studied factors affecting the efficiency of solar power plants in Lampang province, Thailand. It was determined that the energy generated after cleaning the solar panel improved by 5.6–12.7% [18].

Dida et al. (2020) analyzed the effect of dust accumulation on solar power generation efficiency reduction under outdoor conditions in the Sahara environment of southeastern Algeria [25]. It was determined that dust accumulation had a significant effect on the reduction in power generation compared to washed photovoltaic modules, and that the power generation productivity of photovoltaic modules was reduced by 32% due to sandstorms. Abdallah et al. (2016) also determined that the power generation productivity of photovoltaic modules was reduced by 15% due to dust accumulation in Qatar's environment [26]. Sakarapunthip et al. (2017) also revealed that power generation efficiency may decrease if photovoltaic modules are not cleaned in a Thai environment [27]. When the photovoltaic module is not cleaned for 1 month, that is, when dust accumulation lasts 1 month, the efficiency of solar power generation decreases by 1.6–3%, and when it lasts 2 months, it can be reduced to 6–8%. It was also found that cleaning the dust increased the output of solar power by 10%. Klugmann-Radziemska and Rudnicka (2020) determined that dust accumulation reduces the efficiency of photovoltaic modules by 6–10% [28].

Because the subject of analysis, the amount of sample, and the analysis method are different for each study, it is not possible to numerically define the power generation effect according to photovoltaic module cleaning. However, the commonality found in all studies is that the power generation efficiency of the photovoltaic module increased when foreign substances (dust or sand) were removed from the module. Therefore, analysis of power generation efficiency according to photovoltaic module cleaning requires continuous research. In previous studies, various analyses of the correlation between various climatic conditions and the amount of photovoltaic power generation were performed, but all of them were for small-scale photovoltaic modules or the analysis was not performed under similar climatic conditions. In addition, there is a limitation that the analysis was performed using data collected over a short period of time. This study intends to conduct empirical analysis on a large number of samples by securing operation data for about 3 years from large-scale solar power plant. First of all, we analyzed the relationship between the amount of power generation of the photovoltaic module for each climatic condition targeting the demonstration target project. Based on this, this study aims to quantitatively present the cleaning effect of photovoltaic modules according to precipitation.

3. Methods

3.1. Correlation Analysis

Correlation analysis is a method of analyzing the relationship between variables and confirming how one variable is related to another variable. It was used to confirm the correlation between various climate factors and power generation. The measure of correlation between variables is expressed through the Pearson correlation coefficient (r) and represented by the symbol ' r '. The expression range is divided into values ranging from -1 to 1 . When the correlation coefficient is positive ($+$), it indicates a positive correlation, and when it is negative ($-$), it indicates a negative correlation. The closer the absolute value of r is to 0 , the weaker the correlation. In this study, to interpret the degree of analysis results, the formula used in the analysis and degree of correlation of Pearson's correlation coefficient were classified as shown in Table 1.

Table 1. Correlation degree of Pearson's correlation coefficient.

Pearson's Correlation Coefficient r Range	Degree of Correlation	Formula
± 0.9 or more	very high correlation	$r = \frac{\sum[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum(x_i - \bar{x})^2 * \sum(y_i - \bar{y})^2}}$
$\pm 0.9 \sim \pm 0.7$	high correlation	
$\pm 0.7 \sim \pm 0.4$	rather high correlation	
$\pm 0.4 \sim \pm 0.2$	low correlation	
± 0.2 below	no correlation	

In the correlation analysis, whether or not the correlation coefficient is significant can be confirmed through the p -value. Generally, a level of 0.05 or less is good; 0.05 means there is a 5% risk of concluding that a correlation exists when, in fact, it does not exist. In other words, if the p -value is less than 0.05 , it can be concluded that the correlation is statistically significant.

Linear regression is a representative method of linearly analyzing the influence of other variables on one variable. The influencing variable is called the independent variable or explanatory variable, and the affected variable is called the dependent variable or response variable. In this study, linear regression was used to confirm the relationship between the amounts of power generation (dependent variable) according to the degree of change of each climatic factor (explanatory variable). The formulas are used as shown in Table 2.

Table 2. Linear regression.

Description	Formula
Simple Linear Regression	$y = wx + b$
Multiple Linear Regression	$y = w_1x_1 + w_2x_2 + \dots + w_nx_n + b$

3.2. Definition of Climate Factors and Data Collection Methods

For stable operation and efficient maintenance of photovoltaic power plants, it is necessary to know the principles of photovoltaic power generation and to understand correlations through factors affecting power generation. Park et al. (2012) analyzed the correlation between solar power generation according to climate factors such as cloud cover, temperature, and sunshine hours [21]. This study defined the climatic factors that can affect the amount of solar power generation as shown in Table 3 with reference to this study.

Table 3. Definition of climate factor.

Climate Factor	Definition	Data Source
Temperatures	Actual local temperature at 14:00	Korea Meteorological Administration data
Cloudiness	Average daily cloud cover from 06:00 to 18:00	
Precipitation	Precipitation per day	
Daylight hours	Total daylight hours per day	
Fine dust	Time-averaged PM10 concentration ($\mu\text{g}/\text{m}^3$)	
Insolation	Insolation on the slope of the module at 14:00	Power plant system operation records
Module temperature	Temperature of module surface at 14:00 (the sensor installed PV module backside)	
Power generation	Power plant daily power generation (MW)	

For the temperature, the temperature data of the empirical area at 14:00 were collected through the data of the Korea Meteorological Administration. For cloudiness, daily average (6:00~18:00) cloudiness data were obtained from the Korea Meteorological Administration. Considering the solar power generation time, the average cloudiness data for the cloudiness from 6:00 to 18:00, when power generation is possible, were used for analysis. The amount of cloudiness when there are no clouds in the sky is set to 0, and the amount of cloudiness when clouds completely cover the sky is set to 10. Depending on the degree of cloudiness, it is displayed in 11 stages from 0 to 10. In general, a cloudiness of 1 or less is sunny, 2 to 5 is slightly cloudy, 6 to 8 is cloudy, and 9 or more is cloudy.

Precipitation is the amount of precipitation that falls on the ground and refers to the depth of water that has accumulated without evaporation or runoff as it falls to the horizontal surface within a certain period of time. Winter snowfall was converted considering that the density of snow is about 1/10 of the density of water (e.g., snowfall 10 cm = precipitation 10 mm). Daylight hours is the time when the sun's rays hit the ground, and it means the duration of the sun's rays reaching the ground without being obscured by clouds or fog. For the daylight hours, the daily total time data from the Korea Meteorological Administration were used. Fine dust refers to dust with a diameter of less than 10 micrometers (μm) floating in the air, and time-averaged PM10 concentration ($\mu\text{g}/\text{m}^3$) data were collected from the Korea Meteorological Administration and used for analysis.

Insolation, photovoltaic module temperature, and power generation data were collected from 30 months of plant system records. Insolation refers to solar radiation, and insolation refers to the amount of solar energy received by a unit area per unit time. It has characteristics that are reduced by air molecules, dust, water vapor, pollutants, clouds, and humidity. The insolation data of the slope of the photovoltaic module were collected at 14:00. The photovoltaic module temperature was checked from the power plant system through the sensor installed on the surface of the module. The amount of power generation

is the total amount of power generated per day, and the daily power generation MW data of the power plant were collected.

4. Case Study

4.1. Project Description

This study analyzed the generation record of Seosan Solar Power Plant in actual operation in Buseok-myeon, Seosan-si, Chungcheongnam-do, Korea, in order to conduct basic research to improve the operational efficiency of solar power plants. This power plant was constructed by Hyundai E&C from 2018 to 2019, and it is currently being operated by Hyundai Eco Energy Corporation, a consortium of Hyundai E&C and Korea South-East Power, since 2019 (Figure 1).



Figure 1. (left) Satellite image and (right) panoramic view of Seosan Solar Power Plant.

The object of analysis in this study is about 180,000 fixed (30°) type photovoltaic modules installed in the Seosan Solar Power Plant; the power generation capacity is 65 MW (Figure 2). The solar power plant installed in Seosan is 65 MW (energy storage system, ESS: 130 MW). It is the second largest solar power plant in Korea based on the amount of power generated in 2021.



Figure 2. Stationary photovoltaic modules.

4.2. Data Collection

Among the data required for data analysis, hourly data were obtained for temperature, cloudiness, precipitation, sunshine hours, insolation, and fine dust through data disclosed to the Korea Meteorological Administration. As shown in Figure 3, the data of the Korea Meteorological Administration were used from the Seosan ASOS (Synoptic Weather System) data of the Seosan Meteorological Observatory located 30 km away from the Seosan Solar Power Plant.

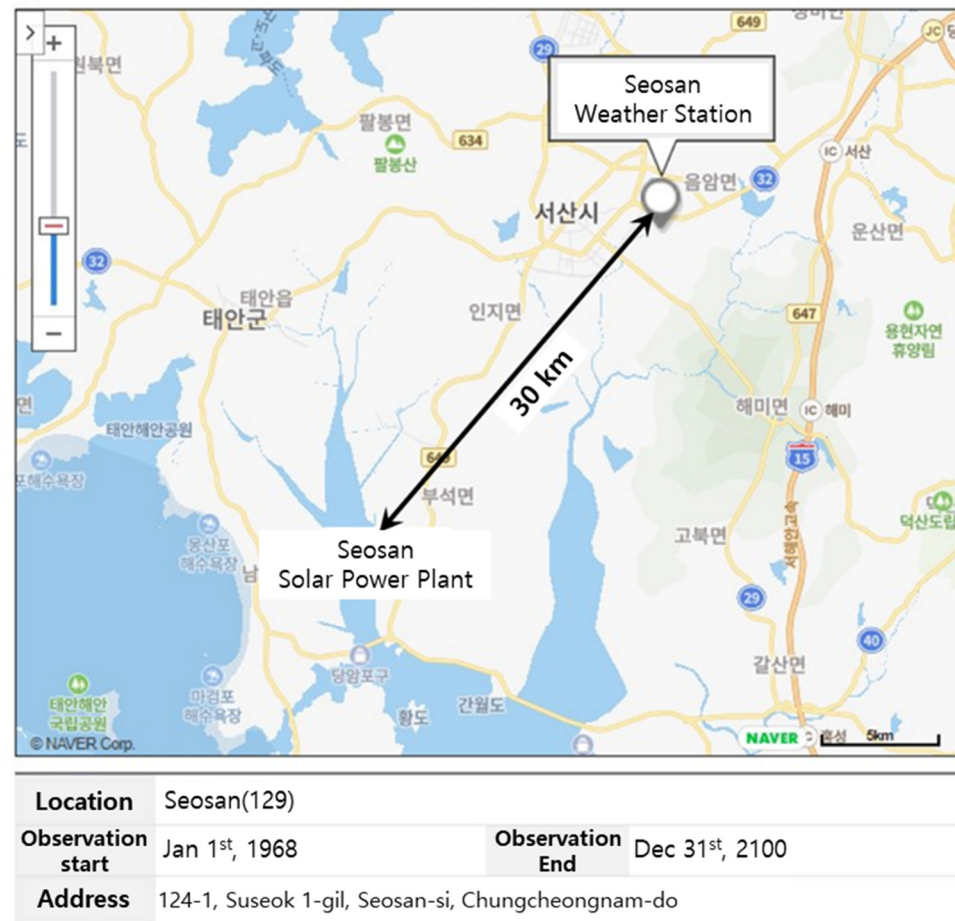


Figure 3. Location of Seosan Solar Power Plant and Seosan Weather Station.

Among them, the temperature was used as the standard for 14:00, when the most power is generated on average. The cloudiness was used as the average cloudiness for a total of 12 h, from 06:00 when power generation starts to 18:00 when power generation ends. As for the daylight hours, the value of the total daylight hours per day was used as it is. Precipitation and solar radiation were used for analysis based on the total daily amount. For fine dust, hourly values were converted into daily average values and used for analysis. Insolation on the slope of the photovoltaic module, module temperature, and power generation, which show a direct relationship with the power plant, were used for analysis by securing the power plant operating system records. In the case of the solar radiation on the slope of the photovoltaic module and the module temperature, 14:00 was used as the standard in consideration of the relationship with air temperature. The amount of power generation used was the total amount of power generated per day.

4.3. Solar Power Generation Correlation Analysis According to Climate Factors

Figure 4 shows the total generation amount by quarter during the 30-month operating period of the Seosan Solar Power Plant. Quarterly total power generation increased in the

quarter with high temperature and generally decreased in the quarter with low temperature. The correlation r between the quarterly average temperature and the quarterly average power generation at 14:00 per day from July 2019 to December 2021 was 0.467551.

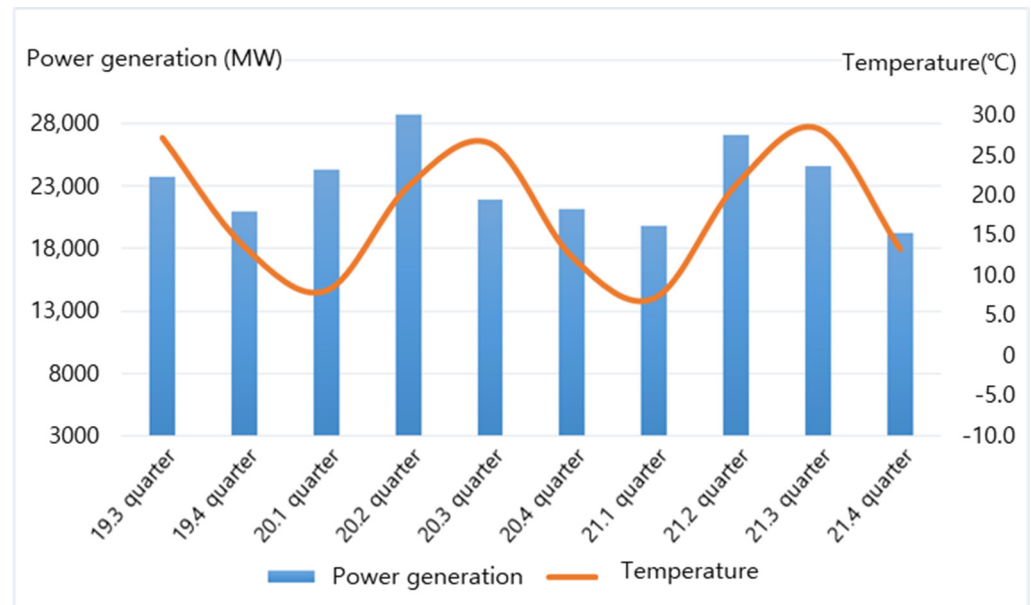


Figure 4. Quarterly temperature and solar power generation.

Since the margin of error is too large to judge by the quarterly average, daily data were analyzed by various climatic factors such as temperature, cloudiness, and insolation for a more detailed analysis. The correlation between the surface temperature of the photovoltaic module and air temperature was 0.8505028, which was confirmed as a high correlation. Significant F and p -values were also confirmed to be statistically significant analysis with 0.05 or less. Through this, it can be seen that the degree to which the surface temperature of the photovoltaic module is affected by the atmospheric temperature change is large (Figure 5). (In the correlation analysis, samples corresponding to clear days were analyzed except for rainy or snowy days, and variables other than temperature and power generation were assumed to be the same or similar).

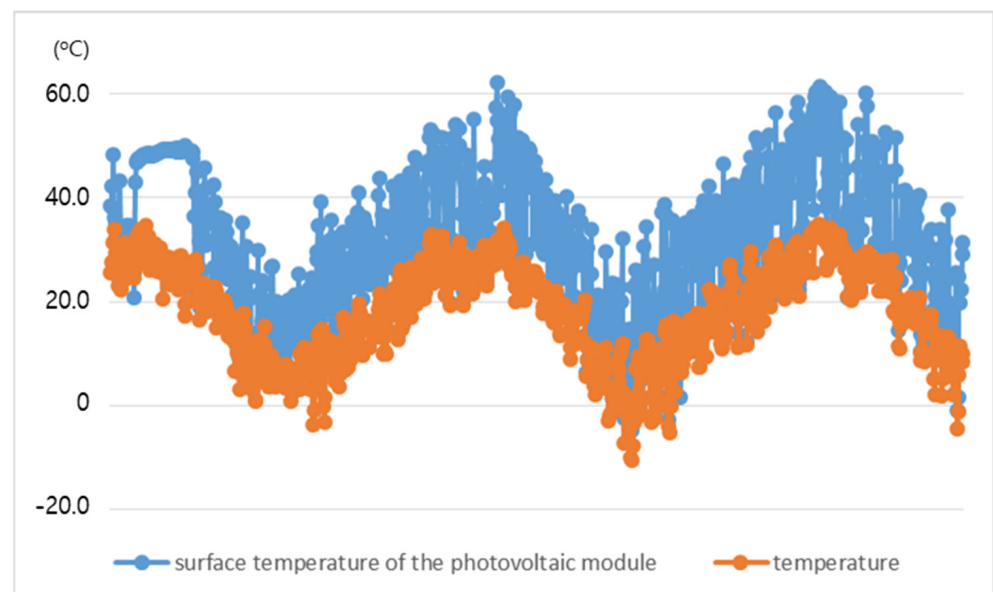


Figure 5. Correlation between temperature and surface temperature of photovoltaic module.

The correlation between average cloud cover per hour per day and power generation was -0.73524 , confirming a high correlation. In order to confirm that the two factors have an inverse relationship, the results of checking the correlation distribution of power generation by cloud volume for the operating period are shown in Figure 6.

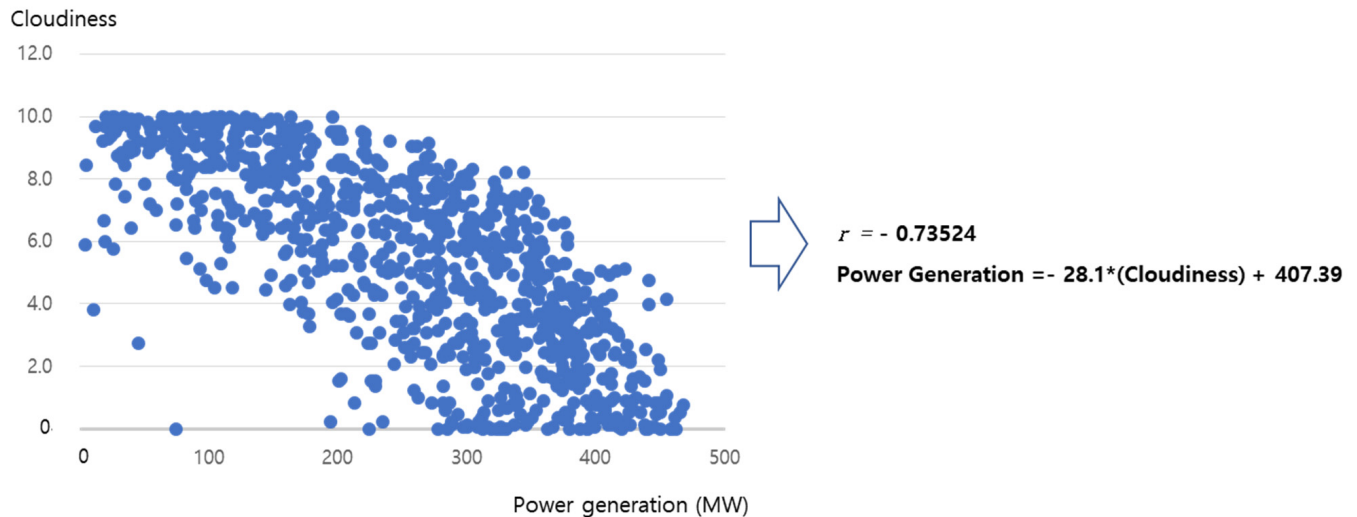


Figure 6. Correlation between cloudiness and power generation.

In order to express the amount of felt cloudiness, the average amount of power generation according to the degree of cloudiness was analyzed as shown in Table 4.

Table 4. Average power generation according to the degree of cloudiness.

Weather Classification	Based on Cloudiness	Average Power Generation (MW)	Days	Total Power Generation (MW)
Sunny	0~2.9	354	217	76,915
Few clouds	3.0~5.9	301	264	79,316
Cloudy	6.0~7.9	229	199	45,557
Blur	8.0~10	130	227	29,610

Figure 7 shows the results of checking the trend of power generation according to the cloudiness criteria. Through this, it was confirmed that the significant F and p -values were 0.05 or less, which was a statistically significant analysis, and it could be seen that the cloudiness was greatly related to the factor that had a negative effect on the amount of solar power generation.

The correlation between daily insolation and power generation was confirmed using two types of data. First, the correlation between solar radiation (MJ/m^2) measured by the Korea Meteorological Administration and power generation was 0.890599. As shown in Figure 8, it can be confirmed that the greater the insolation, the greater the power generation. As a result of linear regression analysis, significant F and p -values were 0.05 or less, confirming statistical significance.

Second, the correlation between solar radiation (Wh/m^2) on the slope of the photovoltaic module measured in the power plant system and the amount of power generation was as high as 0.820126. As shown in Figure 9, it can be seen that the higher the insolation measured from the photovoltaic module, the higher the power generation.

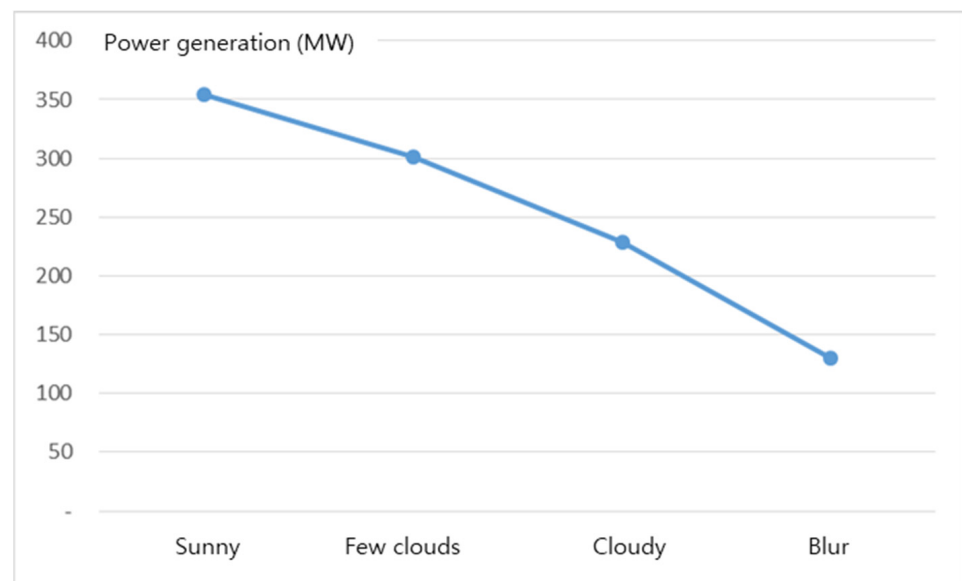


Figure 7. Average power generation based on cloudiness.

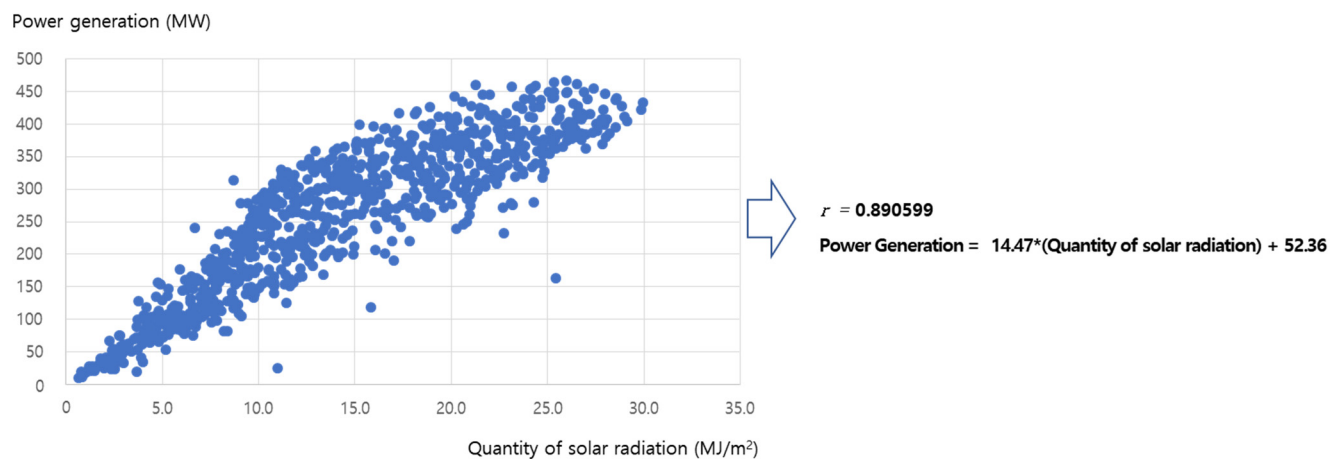


Figure 8. Correlation between solar radiation and power generation.

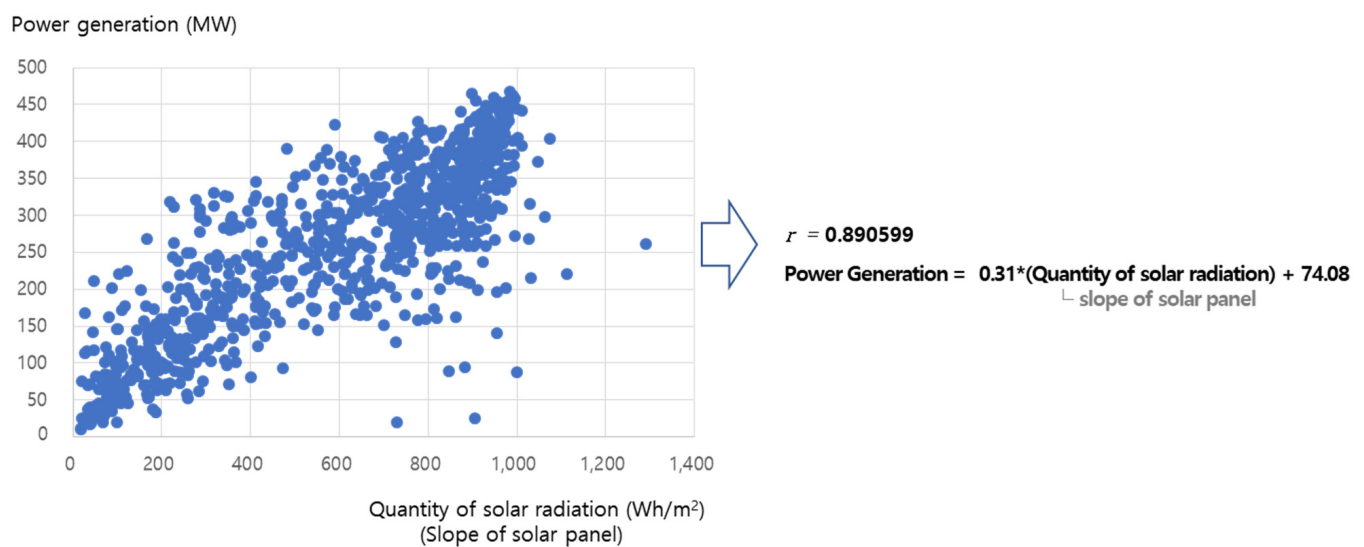


Figure 9. Correlation between insolation on the slope of the photovoltaic module and power generation.

Since cloudiness and solar radiation have a high relationship with the amount of power generation, the result of linear regression analysis by defining the two factors as the cause variable and the amount of power generation as the response variable was analyzed to be a very high correlation with a multiple correlation coefficient of 0.9323145. Based on the Table 2 formula, the relationship between these two variables and the amount of power generation can be expressed as the following equation.

$$\text{Power Generation} = 182.02 + 10.82 \times (\text{Quantity of solar radiation}) - 14.59 \times (\text{Cloudiness})$$

Significant F and *p*-values below 0.05 were analyzed as statistically significant interpretations. The result of correlation analysis between fine dust (PM10) and power generation was 0.1135, showing a level of no correlation (Figures 8–11); correlation analysis is based on clear days as shown in Figure 5, and it is assumed that variables other than solar radiation, fine dust, and power generation of samples are similar or the same.

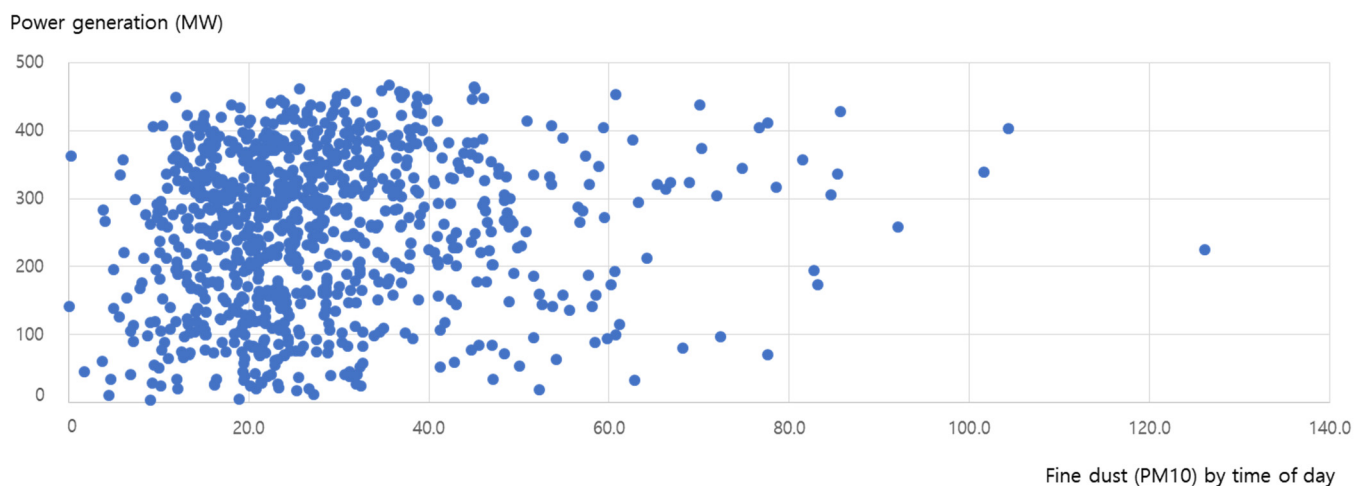


Figure 10. Correlation between fine dust (PM10) and power generation by time of day.

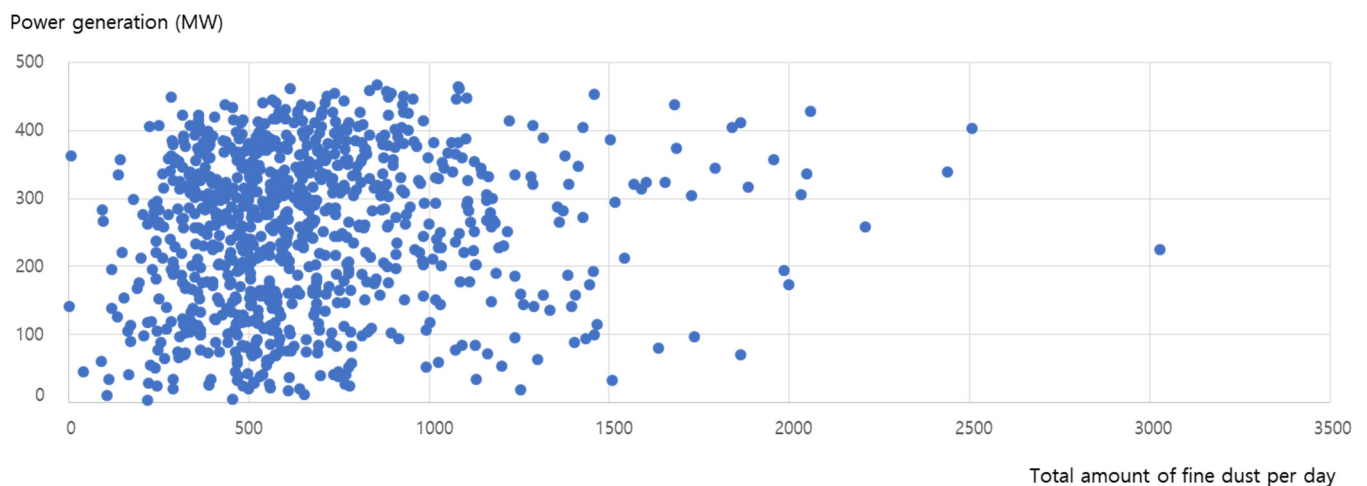


Figure 11. Correlation between total daily fine dust (PM10) and power generation.

This can be seen as suggesting that the fine dust alone does not have a significant effect on the amount of power generation compared to other climatic factors. As a result of linear regression analysis, significant F and *p*-values were less than 0.05, confirming that this was a statistically significant interpretation.

In Section 4.3, the correlation between climate factors and solar power generation was confirmed based on temperature, module temperature, cloudiness, solar radiation, and fine dust (PM10). It was confirmed that these factors had a high relationship with the

amount of power generation, except for fine dust. Through this result, it will be possible to predict changes in power generation according to climate based on highly related factors. However, it is impossible to artificially adjust the climate to increase power generation. Therefore, in the next section, we will analyze the cleaning effect of photovoltaic modules that can be artificially managed other than climate factors.

4.4. Analysis of the Cleaning Effect of Photovoltaic Modules

4.4.1. Sample Target Definition

Prior to analyzing the cleaning effect of the photovoltaic modules, sample subjects with similar climatic conditions were defined as shown in Table 5.

Table 5. Sample target definition.

Classification	Definition
Before precipitation	– No precipitation for at least 5 days (consider the dust accumulation period on the module as at least 5 days) – The average cloudiness of the period without precipitation is 6 or less (based on sunny days, excluding cloudy days) – The effect of fine dust PM10 is not considered (due to poor correlation; see above analysis) – Excluding the period of power generation suspension due to device repair (reflecting operation records)
After precipitation	– Average power generation for days with cloudiness of 6 or less until the next precipitation

There are a total of 27 samples that satisfy all conditions in Table 5, and the details (total number of days, quarterly classification, average cloudiness, and average temperature) for each sample are shown in Table 6. In this study, in order to analyze the cleaning effect of photovoltaic modules according to precipitation, the average cloudiness and average temperature before and after precipitation were similar, and the analysis was conducted considering that it was appropriate for comparison.

Table 6. Analytical sample details.

Classification	Sample (EA)	Target Number of Days		Average Cloudiness		Average Temperature	
		Before Precipitation	After Precipitation	Before Precipitation	After Precipitation	Before Precipitation	After Precipitation
1st Quarter	6	61	43	2.9	2.5	8.1	11.4
2nd Quarter	6	66	28	3.5	4.0	21.6	23.6
3rd Quarter	8	75	80	4.0	4.6	29.3	27.2
4th Quarter	7	85	43	3.6	3.8	12.2	8.3
Total	27	287	194	3.5	3.7	17.8	17.6

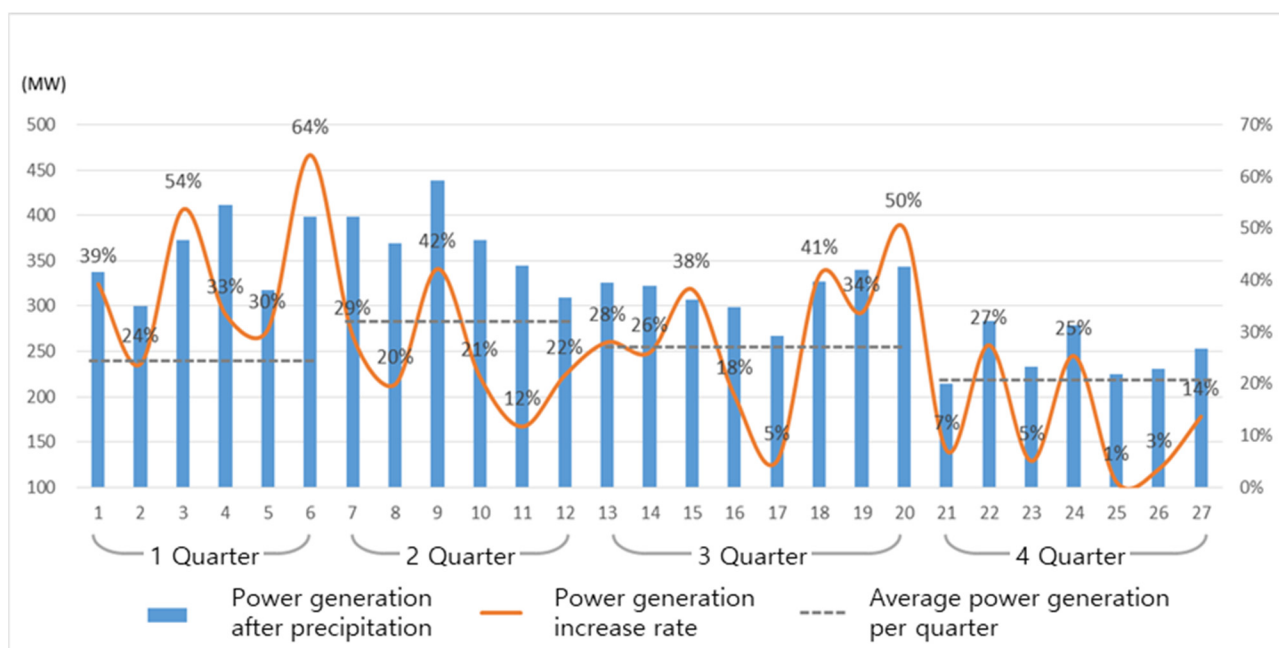
4.4.2. Analysis of Cleaning Effect According to Precipitation

The analysis of the cleaning effect by precipitation was analyzed in two ways, considering temperature, solar radiation, and quarterly average power generation. The first analysis compared ‘average power generation on clear days with cloudiness of 6 or less from after precipitation to the next precipitation’ and ‘average daily power generation by quarter’ to confirm whether precipitation has an effect of increasing power generation. Due to the nature of the four seasons in Korea, the ranges of temperature and solar radiation by season are different, so this comparison was made to reduce the margin of error. Since the temperature and cloudiness before and after precipitation of the samples were defined as similar, it was judged suitable for confirming the module cleaning effect due to precipitation. Table 7 shows the daily average power generation per quarter of the Seosan Solar Power Plant.

Table 7. Quarterly daily average power generation.

Classification	The Year	Average Daily Power Generation (MW)
1st Quarter	2020/2021	243
2nd Quarter	2020/2021	308
3rd Quarter	2019/2020/2021	254
4th Quarter	8.0~10	222

For example, in the case of 280 MW of average power generation after precipitation in sample A (Q1), it was judged as a 15% increase effect after precipitation compared to 243 MW of average power generation in the first quarter of Table 7. As such, the results of analyzing all 27 samples are shown in Figure 12. It can be seen that the average power generation efficiency of the entire sample increased by 26%, on average, after precipitation. As a result of the analysis, each sample showed a power increase effect after precipitation ranging from a minimum of 1% to a maximum of 64%, and there was no sample with reduced power generation efficiency. The efficiency increase rate seems to have a wide range, but the correlation before/after precipitation was 0.7757 based on the amount of power generation of the samples, confirming that the correlation was high.

**Figure 12.** Effect of increasing power generation after precipitation by sample (first analysis).

In order to show the correlations comprehensively, we grouped them by quarter as shown in Figure 13. In the quarterly trend, the effect of increasing power generation after precipitation in the first quarter was the highest, and it was confirmed that it gradually decreased as the fourth quarter progressed. The quarterly average power generation efficiency improvement seems to be the highest in the first quarter, but when calculating the quarterly variance, the mutual deviation was confirmed to be 1.1% to 2.3%. On the distribution map, the third quarter seems to have a relatively high concentration on the average value, which can be inferred from the stable daily average power generation of Seosan Solar Power Plant from July to September every year. Figure 14 shows the power generation by sample and the efficiency of the increase in power generation after precipitation as a distribution chart.

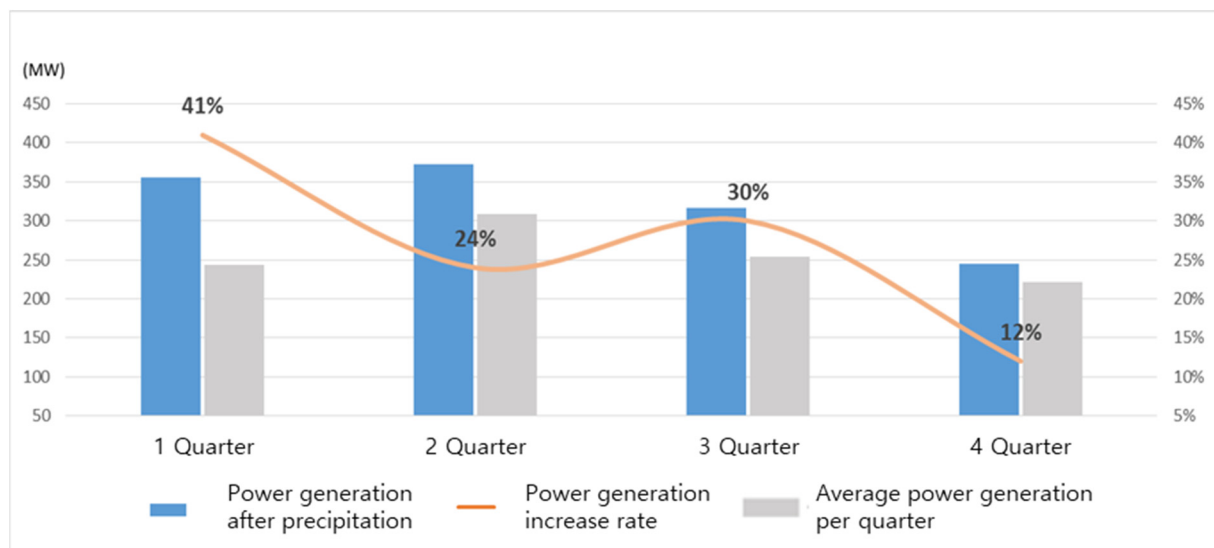


Figure 13. Effect of increasing quarterly average power generation after precipitation.

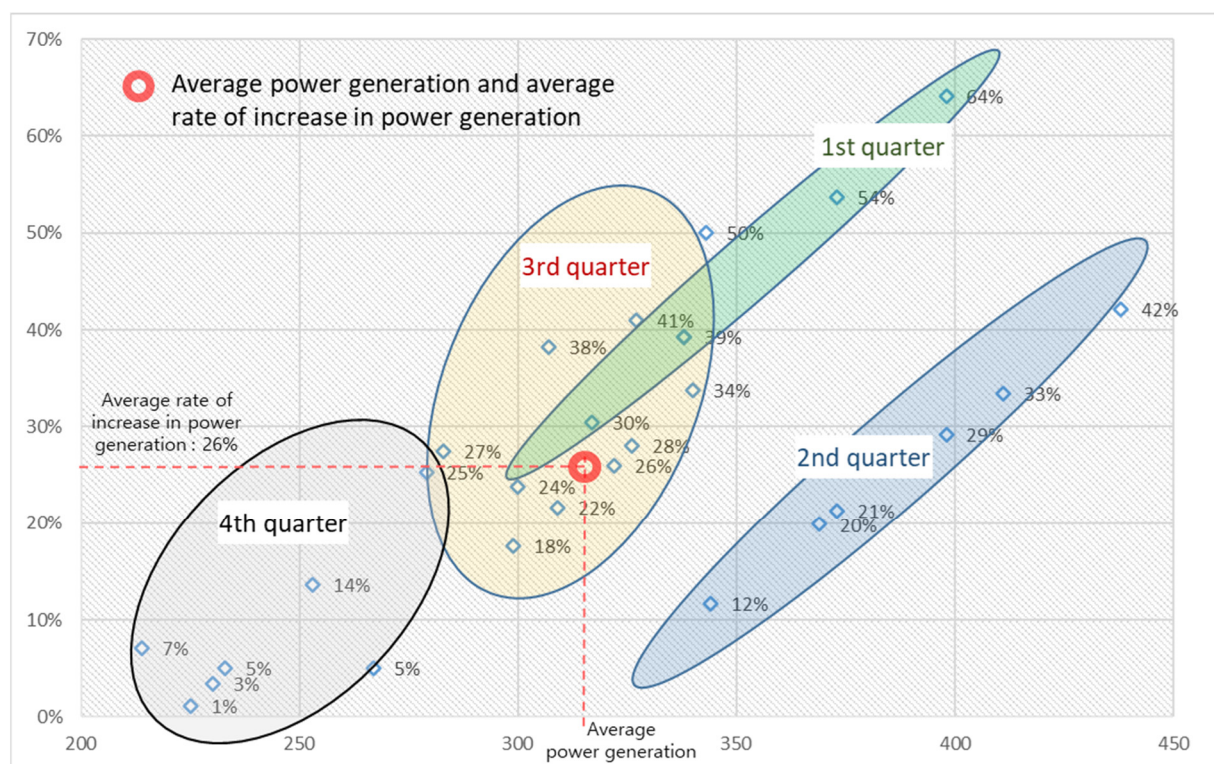


Figure 14. Quarterly distribution of power generation increase rate after precipitation (first analysis).

The second analysis compared 'average power generation on a clear day with cloudiness of 6 or less from after precipitation to the next precipitation' and 'daily average power generation on a clear day immediately before precipitation'. The purpose was to reduce the error range of the effect of increasing power generation due to precipitation through climate comparison at a more similar time point rather than comparison with the quarterly average analyzed previously. It can be confirmed that the average power generation efficiency of the entire sample increased by 4.8%, on average, after the precipitation compared to before the precipitation. As a result of the analysis, as shown in Figure 15, the generation fluctuation rate for each sample ranged from a minimum of -8% to a maximum of 25% , and unlike the first analysis, seven samples (25% of the total sample) with reduced generation efficiency

were identified. Based on the amount of power generation of the samples, the correlation before/after precipitation was 0.7757, which was confirmed to be high. In order to show the correlations comprehensively, we grouped them by quarter, as shown in Figure 16.

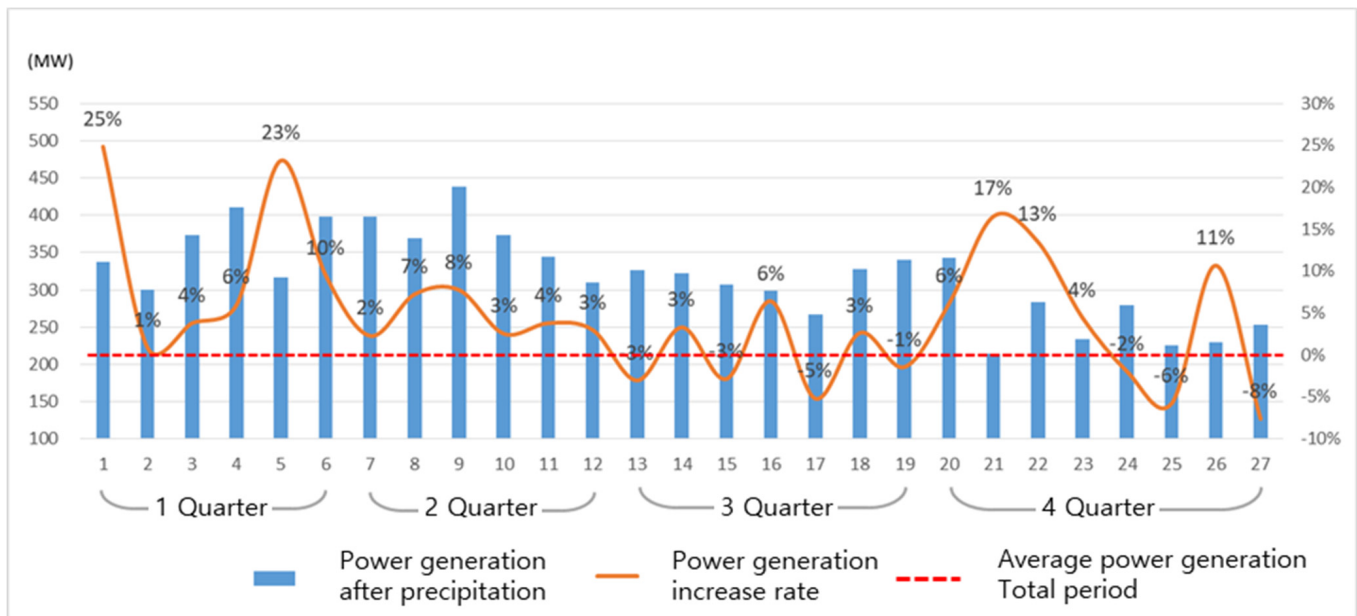


Figure 15. Effect of increasing power generation after precipitation by sample (second analysis).

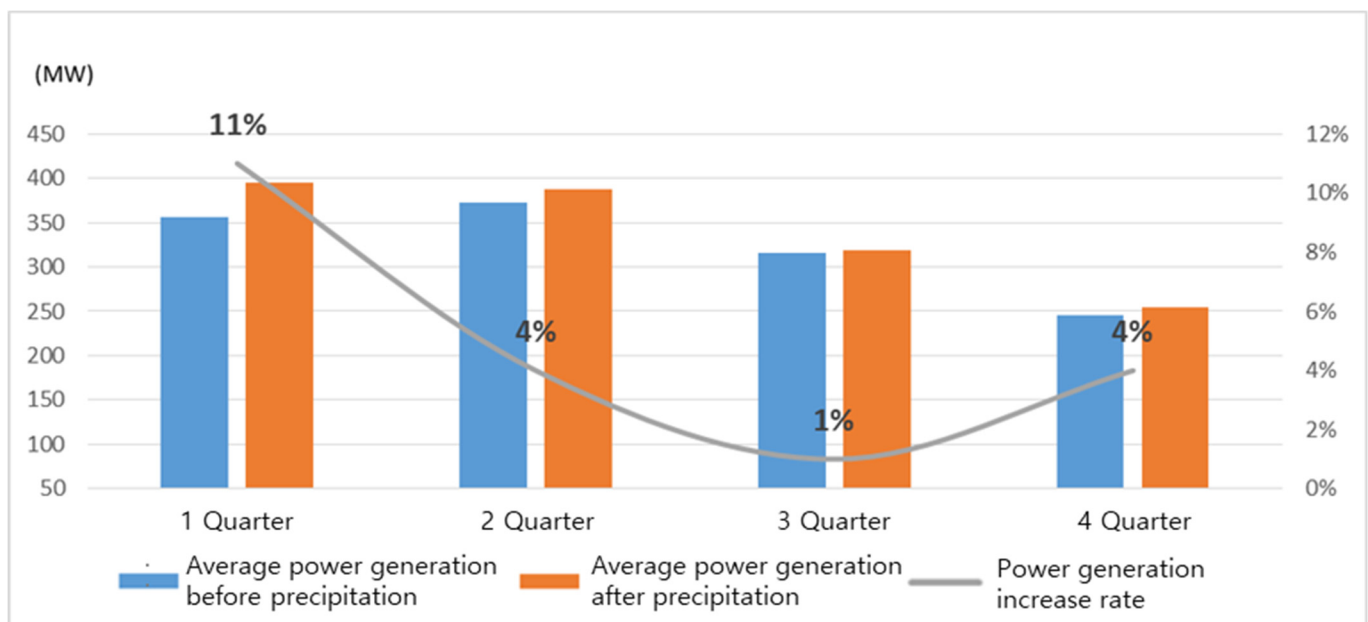


Figure 16. Average power generation before/after quarterly precipitation and rate of increase in power generation.

The average amount of power generation immediately before precipitation was based on a sunny day, and the number of days immediately before precipitation was limited to a maximum of 15 days in consideration of temperature and insolation variables according to seasonal changes. As a result, the amount of power generation based on the entire sample increased by an average of 4.8% after precipitation, and in some periods the value was confirmed as if the power generation efficiency decreased. This was shown in a total of seven samples, and the correlation between them was additionally examined to confirm

5. Conclusions

Since the amount of power generation generated in the operation stage of a solar power plant directly affects sales and profits, it is important to operate the solar power plant to receive minimal influence from the environment that hinders the amount of power generation. In this respect, many studies have analyzed the effects of dust accumulation as well as various climate factors on power generation, but it is difficult to find many studies that have secured the reliability of the analysis results through a large number of samples.

Photovoltaic module cleaning is a part that can be controlled artificially, and many studies have been conducted on the effect of dust removal by various cleaning methods on power generation. In particular, this study analyzed the cleaning effect of photovoltaic modules according to precipitation in the operation stage of a large-scale photovoltaic power plant. Before analyzing the cleaning effect of photovoltaic modules related to precipitation, we analyzed how climate factors in Korea affect power generation. Temperature and photovoltaic module temperature, cloudiness, solar radiation, etc. were analyzed as factors influencing the amount of power generation. The cleaning effect of photovoltaic modules due to precipitation was analyzed in two ways. First, when compared to the quarterly average power generation, an average power generation increase effect of 26% was confirmed after precipitation. Second, when compared with the amount of power generation immediately before precipitation, the effect of increasing power generation by 4.8%, on average, after precipitation was confirmed. In the analysis results of the two methods under domestic climatic conditions, it was confirmed that the increased rate of power generation in the third-quarter sample was the most stable with little deviation.

This study has the research value of confirming that cleaning of photovoltaic modules according to precipitation can have a positive effect on the increase in power generation efficiency through actual power generation data of large-scale solar power plants. The results of this study can be used to quantify the effect of increasing power generation due to cleaning into revenue, and to derive appropriate input costs for cleaning photovoltaic modules during operation of solar power plants based on these data. In addition, it can be used as a reference for establishing a photovoltaic module cleaning manual suitable for the environment by predefining an appropriate dust adsorption period according to the surrounding climate conditions.

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