ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The effect of particulate matter on solar photovoltaic power generation over the Republic of Korea

To cite this article: Junghoon Son *et al* 2020 *Environ. Res. Lett.* **15** 084004

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
25 January 2020

REVISED
24 April 2020

ACCEPTED FOR PUBLICATION
5 May 2020

PUBLISHED
15 July 2020

LETTER

The effect of particulate matter on solar photovoltaic power generation over the Republic of Korea

Junghoon Son[1], Sujong Jeong[1], Hayoung Park[1] and Chang-Eui Park[2]

[1] Department of Environmental Planning, Graduate School of Environmental Studies, Seoul National University, Seoul 08826, Republic of Korea
[2] Environmental Planning Institute, Seoul National University, Seoul 08826, Republic of Korea

E-mail: sujong@snu.ac.kr **and** nabicherry@gmail.com

Keywords: air quality, solar photovoltaic, particulate matter, solar power generation

Abstract

Degradation in air quality could be a potential factor for decreasing solar photovoltaic (PV) power generation. However, our understandings of the potential of airborne particulate matter (PM) to reduce actual solar PV power generation remain unclear. This study quantifies attenuation impacts of airborne PM on solar PV power generation on cloudless days at Yeongam and Eunpyeong-gu power plants installed in the Republic of Korea. The reduction rate of solar PV power generation according to the substantial amount of PM is calculated by constructing multiple regression models based on actual solar PV power generation record, observed meteorological parameters, and measured PM2.5 and PM10 concentrations for 2015–2017. At both power plants, PM2.5 and PM10 commonly reduce solar PV power generation by more than 10% of the maximum capacity under the conditions of 'normal' air quality, 35 μg m^{-3} and 80 μg m^{-3} for PM2.5 and PM10, respectively. Moreover, the reduction rate of solar PV power generation exceeds 20% of the maximum capacity under 'bad' air quality, 75 μg m^{-3} and 150 μg m^{-3} for PM2.5 and PM10, respectively. Results show that the negative impacts of PM on solar PV power generation should be considered in the process of policymaking on target solar power generation in Korea, as well as in countries with high PM emissions.

1. Introduction

Due to the combustion of fossil fuels since the industrial revolution, the world is currently suffering from environmental problems such as rapid climate change and air pollution (IPCC 2013). To tackle climate change and respective environmental problems, many countries around the world are trying to reduce the use of fossil energy, which is the main cause behind the increase in greenhouse gases and low air quality, and expand the share of renewable energy (IEA 2016). In the Republic of Korea, one of the top ten countries with the highest carbon emissions per capita, the policy titled 'Renewable Energy 3020′ was launched in 2017 to obey the guidelines of global renewable energy policies and expand renewable energy generation to about 60% of the total energy generation capacity by 2040 (IEA 2017, Ministry of Trade, Industry, and Energy(MOTIE) 2017). 'Renewable Energy 3020′ aims to increase the share of renewable energy to account for 20% of the total energy budget by 2030 (MOTIE 2017). The main initiative of this policy is to expand the portion of solar energy. In 2017, the power generation capacity from solar photovoltaic (PV) power generation in Korea was 5.7 GW, accounting for 38% of the total capacity of the country's renewable energy (MOTIE 2017). The energy output based on the solar PV power generation occupied 1.2% of the annual energy production of Korea in 2017 (KEEI 2018). 'Renewable Energy 3020′ will expand the capacity of solar PV power generation to 36.5 GW so that it accounts for 57% of the total renewable energy capacity by 2030 (MOTIE 2017). Therefore, solar PV power generation is in an important position in the energy policy of Korea, and in order for effective policies to be realized, the key is to have sustainable solar PV power generation.

The basic principle of solar PV power is producing energy using solar panels which generate electricity when sunlight passes through the atmosphere and is absorbed in the panels (Rauschenbach 2012). Thus, the energy production of solar PV power plants mainly depends on the amount of solar radiation, and among them, the Global Horizontal Irradiance (GHI) is the most important (Lave *et al* 2015). GHI is solar energy that goes through the earth's atmosphere and reaches a point on the surface horizontally; thus, solar PV power generation is affected by various environmental factors such as geographical and meteorological factors (Benghanem *et al* 2009, Jo *et al* 2012). However, the changes of meteorological factors are fluid and complex, making it difficult to predict solar PV power generation. Among meteorological factors, clouds influence solar PV power generation the most because they reduce solar radiation reaching the surface by reflecting and scattering sunlight entering the Earth at the atmosphere (Norris 1968, Matuszko 2012). In Korea, the effect of clouds describing solar power is well-explained with a margin of error of −1.4–5.7% (Jo *et al* 2012).

Although the impact of GHI and clouds is dominant when predicting solar PV power generation, it is also important to consider the impact of PM on solar PV power generation on clear days without the effect of clouds. High concentrations of airborne PM in the atmosphere reduce solar radiation as well as related solar PV power generation by absorbing or scattering sunlight before it reaches the surface of the Earth (Streets *et al* 2006, Xia *et al* 2007, Zhao *et al* 2013, Li *et al* 2017). The attenuation impacts of PM on solar radiation and respective solar PV power generation have been assessed in East and South Asia where both natural and anthropogenic emissions of PM are relatively higher than other regions. For example, in Delhi, absorbed solar radiation at the land surface decreases as the concentration of PM2.5 increases (Peters *et al* 2018). More than 10% of solar radiation is reduced by ambient PM in the air over the Korean Peninsula based on global climate modelling (Bergin *et al* 2017). A model study based on a PV performance tool shows that aerosols can reduce the amount of solar PV power generation by 20% in eastern China (Li *et al* 2017). However, more assessments on the PM-related reduction of solar PV power generation using actual records of solar PV power generation are necessary to clarify the impacts of PM on solar PV power generation in Asian countries.

Among many Asian countries, the Republic of Korea urgently requires the evaluation of PM impacts on solar PV power generation due to the country's unique situation. Events with high PM concentrations are frequently observed in Korea due to local emissions of PM from various anthropogenic sources such as factories and traffic as well as the transport of PM from continents (Kim *et al* 2003, 2017). Dust from arid areas in central Eurasia, commonly known as 'Yellow dust', induces very high PM10 events in spring (Park and In 2003). Further, the concentration of PM varies seasonally with large variations in rainfall and regional circulation following East Asian monsoons (Leibensperger *et al* 2011, Kawamura *et al* 2012, Lou *et al* 2019). As the attenuation impacts of PM on solar radiation and respective solar PV power generation are usually examined in dry regions (Kambezidis *et al* 2012, Begins *et al* 2017, Peters *et al* 2018), verifying PM effects over Korea can be useful in generalizing PM effects.

The aim of the present study is to examine the effects of PM and other meteorological factors affecting the amount of solar PV power generation by applying a multiple regression analysis to actual solar PV power generation data from two solar PV power plants located in Korea. The results can provide a more realistic evaluation of the attenuation impact of PM concentration on solar PV power generation using actual records from solar PV power plants, which can be applied to other modelling assessments and further improve the efficiency of solar PV power generation.

2. Materials and methods

2.1. Hourly data sets of solar PV power generation, meteorology, and PM concentration

We analyzed the hourly amount of solar PV power generation of two power plants installed in Yeongam in the Jeollanam-do province and in Eunpyeong-gu of an area in Seoul (table 1). The solar PV power generation data from the Yeongam Solar PV Power Plant (Y-PV power plant) operated by the Korea Rural Community Corporation is divided into primary and secondary plants located within the same area. The primary and secondary power plants started operating in 2008 and 2009, respectively, and the total capacity of both power plants is 1496.1 kW. Since there was no significant difference in the data between the primary and secondary power generation plants in Yeongam, and as they are both in the same location, the data of the primary solar power generation plant in Yeongam were used. The other solar PV power plant is located in the Eunpyeong Public Garage in Seoul (E-PV power plant) and operated by the Solar and Wind Energy Cooperation. The E-PV power plant has a total capacity of 99.4 kW. Both Y-PV and E-PV power plants are installed at 126°52′59.5"E and 37°25.4"N and 126°28′51.9"E and 34°44′05.5"N. The hourly solar PV power generation data of the Y-PV power plant is found in the Public Data Portal (https://www.data.go.kr/dataset/15005796/fileData.do) and the E-PV power plant data is recorded by the Solar and Wind Energy Cooperation (http://weblink.hex.co.kr/kor/Pages/Monitoring.aspx?p=m).

Data from the weather observation and PM monitoring stations nearest to the plant were used at both sites since weather observation and PM data were not available at the power plant locations. We obtained the hourly observation data such as solar radiation, cloud cover, temperature, and relative humidity (RH) from the 'Weather Data Open Portal', which provides data observed at weather stations operated by the

Table 1. Overall description of solar photovoltaic power stations and automated synoptic observing systems.

Solar photovoltaic power station			Weather station (Station number)	Air quality monitoring station
	Location			
Name (installed capacity)	Latitude	Longitude		
Y-PV power plant (1496.1 kW)	34°44′05.5”	126°28′51.9”	Mokpo(165)	Buheung-dong
E-PV power plant (99.4 kW)	37°35′29.4”	126°52′59.5”	Seoul(108)	Mapo-gu

Korea Meteorological Administration. The closest observatories to the Y-PV and E-PV power plants are the Mokpo Meteorological Station and Seoul Meteorological Observatory located on 126°22′52.4”E and 34°49′00.8”N and 126°57′56.9”E and 37°34′17.1”N, respectively. The Y-PV power plant and the Mokpo Meteorological Station are about 12.9 kilometers away, while the E-PV power plant and the Seoul Meteorological Observatory are about 7.5 kilometers away.

Data of the PM2.5 and PM10 concentrations in μg m^{-3} are obtained from Air Korea's PM monitoring sites. Here, Air Korea is the network of measuring systems operated by the Ministry of Environment of Korea that collects and displays measurements of air pollutants at 398 points in Korea using the National Ambient Air Quality Monitoring Information System (NAMIS). For the Yeongam and Seoul area, we used PM2.5 and PM10 data from the Booheung-dong and Mapo-gu monitoring station, which placed at 126°26′04.6”E and 34°48′15.5”N and 126°54′20.2”E and 37°33′20.2”N, respectively. The distance between the power plant and PM monitoring site is 8.8 kilometers for the Y-PV plant and 4.5 kilometers for the E-PV plant. Since the monitoring of PM2.5 concentrations began in 2015 at both the Booheung-dong and Mapo-gu Air Korea monitoring sites, the analysis was conducted using 3 year data from 01:00 January 1, 2015 to 23:00 December 31, 2017.

2.2. Multiple regression analysis of solar PV power generation

Solar PV power generation is affected by a number of meteorological factors, but it is mostly affected by the Global Horizontal Irradiance (*GHI*) (Lave *et al* 2015). The observed *GHI* data from the Korea Meteorological Administration includes both the Direct Horizontal Irradiance (*DirHI*) and Diffuse Horizontal Irradiance (*DifHI*) as shown in equation (1). Because the *DifHI* is highly correlated with PM concentration (Hu *et al* 2017, Peters *et al* 2018), we used the *DirHI* as a variable representing solar radiation instead of *GHI* to avoid the repetition of PM effects on solar PV power generation (Meinel and Meinel 1976, Forero *et al* 2007, Duffie and Beckman 2013). The *DirHI* is obtained by multiplying the Direct Normal irradiance (*DNI*) and the solar zenith angle (θ_z) by cosine values ($\cos\theta_z$) or the solar elevation angle (α_s) by the sine value ($sin\alpha_s = \cos\theta_z$) as shown in equation (2). The *DNI* is the amount of solar radiation received perpendicular to the sun's ray, expressed as equation (3). As the reciprocal of the solar zenith angle by cosine values, air mass (AM: $1/\cos\theta_z = 1/sin\alpha_s$) indicates the thickness of the atmosphere in which sunlight is affected by the solar altitude (Meinel and Meinel 1976, Forero *et al* 2007).

$$GHI = DirHI + DifHI \tag{1}$$

$$DirHI = DNI \times sin\alpha_s \tag{2}$$

$$DNI = 1.353 \times 0.7^{AM^{0.678}}. \tag{3}$$

We also considered other independent meteorological variables including temperature and RH. Temperature is an important factor to consider because higher temperatures lower the efficiency of solar panel batteries and relevant efficiency of solar PV power generation (Skoplaki and Palyvos 2009, Tan Jian Wei *et al* 2017). Higher humidity sustains more water vapor in the atmosphere, which induces more refraction, reflection, and scattering of solar radiation. Due to this phenomenon, RH has the effect of reducing solar PV power generation (Gwandu and Creasey 1995, Mekhilef *et al* 2012, Kazem and Chaichan 2015). We separated our analysis of PM2.5 and PM10 because of the optical properties of PM, such as single scattering albedo and extinction coefficients, which are different according to the size of the particle (Chylek and Wong 1995, Feng *et al* 2019). In addition, since insolation is exponentially reduced by the PM concentration, the natural logarithm of the PM concentration, ln(PM2.5) and ln(PM10), is used (Peters *et al* 2018).

Generally, clouds have a considerable effect on solar power generation, so we applied the cloudless day solar radiation analysis method using cloud cover observations. On days when the sky is fully covered by clouds, the cloud cover is rated as a 10 and the rating subsequently decreases with less cloud cover. The cloudless day solar radiation analysis can minimize the impacts of clouds on solar radiation by taking into account only the weather of days when the cloud cover ranges within 0 ~ 1. Based on this method, we can remove the effect of clouds and capture the attenuation rate of solar radiation according to the amount of atmospheric concentrations of aerosols, water vapor, and ozone (Mueller *et al* 2012, Smith *et al* 2017). To reduce the impact of clouds and analyze the effects of PM, we only used hourly weather data and solar PV power generation data of days with a cloud cover of 0–1.

In order to analyze the effects of meteorological parameters and PM concentrations on solar PV power generation, we set the hourly solar PV power generation (G) in kW as a dependent variable and *DirHI* in W/m^2 (X_1), ln(PM2.5) and ln(PM10) in μg m^{-3} (X_2), temperature in °C (X_3), and RH in % (X_4) as independent variables. We then carried out a multiple regression analysis using all variables as shown in equation (4).

$$G = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4. \quad (4)$$

We used the Student's t-test to verify the significance of the equation (4). The correlation coefficient between each independent variable is lower than 0.6 for all available combinations of independent variables (tables S1–S2 (available online at stacks.iop.org/ERL/15/084004/mmedia)). In addition, both the variance inflation factor (VIF) and condition index (CI) are used to clarify the multicollinearity of the regression equation. The multicollinearity is rejected when VIF ranges from 1–10 and CI is less than 30 (Belsley *et al* 2005, Belsley 1991). Note that there is no multicollinearity in the constructed regression equations in our analysis based on VIF and CI.

Relative contributions of each independent variable to solar PV power generation are not represented by coefficients as shown in equation (4) because of the difference of units and ranges of individual variables. We applied the Z-transformation to individual variables by subtracting the mean value and dividing by the standard deviation as shown in equation (5), and constructed a multilinear regression model based on normalized variables as shown in equation (6). Coefficients of individual parameters in equation (6) can represent the change in solar PV power generation when each parameter is altered by one-standard deviation. Therefore, coefficients of equation (6) indicate relative contributions of individual parameters to solar PV power generation when the variability of all parameters is the same. The results of the modeled solar PV power generation based on equation (6) is similar to that based on equation (4). The statistical indices of the regression model, VIF and CI, remain the same even when the Z-transformation is applied to independent variables.

$$Z_i = \frac{X_i - \overline{X_i}}{S_i}\left(\overline{X_i} = \text{average}, S_i = \text{standard deviation}, 1 \le i \le 4\right) \quad (5)$$

$$G = B_0{}' + B_1{}'Z_1 + B_2{}'Z_2 + B_3{}'Z_3 + B_4{}'Z_4. \quad (6)$$

3. Results

Results of the multiple regression analysis at the Y-PV power plant based on *DirHI*, temperature, ln(PM2.5), and RH are presented in table 2. In the formulation, only the coefficient of *DirHI* is positive, indicating that *DirHI* contributes to the solar PV power generation as the main energy source. Negative coefficients of temperature, ln(PM2.5), and RH indicate impeding effects on solar PV power generation. Table 3 provides the results of the multiple regression model of the Y-PV power plant when the PM10 concentration is used. In general, coefficients of individual independent parameters are similar to those of the previous model based on PM2.5 (tables 2–3). Tables 4–5 show results of the regression models of the solar PV power generation at the E-PV power plant using PM2.5 and PM10 concentrations, respectively. Effects of individual variables on solar PV power generation at the E-PV power plant are similar to those at the Y-PV power plant. Positive coefficient of *DirHI* means energy generation, and the coefficients of the other factors are negative values (tables 4–5). All regression models are statistically significant at 99% confidence level (significance probability <0.01), indicating that the constructed regression model is suitable for estimating solar PV power generation.

Regression coefficients or beta coefficients (β) of individual parameters are unsuitable for comparing the attenuation impacts of temperature, PM, and RH because individual parameters have different units as well as different ranges of fluctuation. Here, contributions of temperature, PM, and RH are compared by using the variation in the solar PV power generation in accordance with individual parameters, which is computed by the product of relevant coefficients and measured values. For example, the variation in solar PV power generation due to temperature is computed by the coefficient of temperature in the regression model and observed temperature records. At the Y-PV power plant, the 5%–95% ranges in solar PV power generation according to variation in temperature, ln(PM2.5), and RH are 3.0–29.7%, 8.4–20.5%, and 2.1–4.9% of total capacity, respectively. When the PM10 concentration is used, the decrease in solar PV power generation due to temperature, PM10, and RH varies from 3.2%, 12.7%, and 3.3% to 31.5%, 20.3%, and 7.9% in the 5%–95% range, respectively. Hence, the negative impact of PM2.5 and PM10 on solar PV power generation at the Y-PV power plant is comparable to that of temperature, and is larger than that of RH. At the E-PV power plant, the 5%–95% range of decrease in the solar PV power generation due to PM2.5 is 8.3–14.6% of total capacity, which is smaller than that due to PM10, 13.4–21.5%. The contribution of PM2.5 is smaller than that of temperature, but is larger than that of RH. However, the attenuation impact of PM10 is comparable to that of temperature and larger than that of RH.

Table 2. Results of the multiple linear regression analysis between the recorded solar PV power generation in Y-PV power plant, and *DirHI*, temperature, concentration of PM2.5, and RH following equations (4) and (6). B and B′ are coefficients of individual variables and y-intercept when the model is constructed using original and normalized variables, respectively. The β indicates the beta coefficient, which is the percent of variance in the solar PV power generation due to the unit change of relevant predictor variables. The t and p-value are the test statistics and probability value of the student's t test.

Variable	B	B′	β	t	p-value
Constant	309.049	811.486		10.464	0.001<
DirHI	1699.481	328.088	0.956	61.493	0.001<
Temperature	–16.117	–131.549	–0.383	–27.071	0.001<
ln(PM2.5)	–78.260	–52.084	–0.152	–12.762	0.001<
RH	–0.857	–12.884	–0.038	–2.770	0.006

Generation = 309.049 + 1699.481 *DirHI* – 16.117 Temperature – 78.26 ln(PM2.5) – 0.857 RH (adj $R^2 = 0.728$, VIF = 1.359, CI = 19.298)

Table 3. Same as table 2, but using the concentrations of PM10.

Variable	B	B′	β	t	p-value
Constant	384.1	811.486		9.917	0.001<
DirHI	1691.617	326.570	0.952	59.242	0.001<
Temperature	–17.089	–139.484	–0.406	–26.832	0.001<
ln(PM10)	–65.923	–35.849	–0.104	–8.346	0.001<
RH	–1.370	–20.605	–0.060	–4.395	0.001<

Generation = 384.1 + 1691.617 *DirHI* – 17.089 Temperature – 65.923 ln(PM10) – 1.37 RH (adj $R^2 = 0.716$, VIF = 1.322, CI = 24.613)

Table 4. Results of the multiple linear regression analysis between the recorded solar PV power generation in E-PV power plant, and *DirHI*, temperature, concentration of PM2.5, and RH following equations (4) and (6). B and B′ are coefficients of individual variables and y-intercept when the model is constructed using original and normalized variables, respectively. The β indicates the beta coefficient, which is the percent of variance in the solar PV power generation due to the unit change of relevant predictor variables. The t and p-value are the test statistics and probability value of the student's t test.

Variable	B	B′	β	t	p-value
Constant	19.820	49.137		15.160	0.001<
DirHI	109.109	22.336	0.975	102.237	0.001<
Temperature	–0.859	–9.646	–0.421	–44.339	0.001<
ln(PM2.5)	–3.593	–1.924	–0.084	–9.944	0.001<
RH	–0.246	–3.217	–0.140	–16.447	0.001<

Generation = 19.820 + 109.109 *DirHI* – 0.859 Temperature – 0.246 RH – 3.593 ln(PM2.5) (adj $R^2 = 0.811$, VIF = 1.033, CI = 18.464)

Table 5. Same as table 4, but using the concentrations of PM10.

Variable	B	B'	β	t	p-value
Constant	25.784	49.137		17.189	0.001<
DirHI	110.14	22.547	0.984	103.735	0.001<
Temperature	–0.863	–9.697	–0.423	–45.127	0.001<
ln(PM10)	–4.710	–2.433	–0.106	–12.752	0.001<
RH	–0.254	–3.331	–0.145	–17.354	0.001<

Generation = 25.784 + 110.14 *DirHI* – 0.863 Temperature – 0.254 RH – 4.71 ln(PM10) (adj $R^2 = 0.815$, VIF = 1.028, CI = 22.139)

Regression models of the E-PV power plant show smaller coefficients for all independent variables than those of the Y-PV power plant because of the smaller capacity of the E-PV power plant. Thus, we compared the β of ln(PM2.5) and ln(PM10), designating the percent of solar PV power generation change by unit change in ln(PM2.5) and ln(PM10), between two power plants. Based on the regression model using PM2.5 concentrations, the β is −0.152 and − 0.084 for the Y-PV and E-PV power plants, respectively (tables 2 and 4). This indicates that attenuation effect of PM2.5 on solar PV power generation is larger at the Y-PV power plant than that at the E-PV power plant by twofold for the same amount of PM2.5 concentration. For the case of PM10, the β is −0.104 and −0.106 for the Y-PV and E-PV power plants, respectively, demonstrating similar attenuation effects of PM10 at both power plants (tables 3 and 5).

Coefficients of regression models using normalized variables indicate the amount of solar PV power generation according to variations in individual parameters by one-standard deviation at both the Y-PV and E-PV power plants (tables 2–5). For the solar PV power generation at both plants, the positive coefficient of *DirHI* is larger than even the sum of the negative impacts of temperature, PM, and RH (tables 2–5). Excluding *DirHI*, the order of coefficients of regression models formulated for the Y-PV power plant from highest to lowest is temperature, PM, and RH (tables 2–3). On the other hand, the regression models of the E-PV power plant show that the coefficient of ln(PM2.5) and ln(PM10) is the lowest among all variables (tables 4–5). Thus, the relative importance of PM for solar PV power generation is different by location of power plant.

Through these regression models constructed for the Y-PV and E-PV power plants, we evaluated how much of the solar PV power generation is reduced by the substantial amount of PM concentration. We adopted the 4 levels of PM concentrations from the Comprehensive Air-quality Index (CAI) in Korea: 'good', 'normal', 'bad', and 'very bad' air quality for low, moderate, high, and very high concentrations of PM, which are 0 ~ 15 μg m^{-3}, 16 ~ 35 μg m^{-3}, 36 ~ 75 μg m^{-3}, and >75 μg m^{-3} for PM2.5 and 0 ~ 30 μg m^{-3}, 31 ~ 80 μg m^{-3}, 81 ~ 150 μg m^{-3}, and >150 μg m^{-3}, for PM10. Note that these levels of PM2.5 and PM10 concentrations are originated from how harmful the impacts of PM are to health because higher concentrations of PM2.5 and PM10 lead to higher adverse effects on the human body (WHO 2005).

Figure 1 depicts the reduction rate of solar PV power generation of PM2.5 and PM10 concentrations according to the above four levels of the air quality index, multiplied by the PM coefficient of the multiple regression model. The results show that solar power generation decreases as air quality worsens. The reduction rate of solar PV power generation due to PM2.5 is higher in the Y-PV power plant than that in the E-PV power plant (figure 1(a)). The amount of power generation is reduced by 14.2%, 18.6%, and 22.6% from the maximum capacity of the Y-PV power plant when the PM2.5 concentration is 15 μg m^{-3}, 35 μg m^{-3}, and 75 μg m^{-3}, denoting 'good', 'normal', and 'bad' air quality, respectively. These amounts are larger than those in the E-PV power plant by about 1.5 times (figure 1(a)). In the Y-PV power plant, the reduction rate of solar PV power generation from the maximum capacity according to PM10 is 14.9%, 19.3%, and 22.0% under 30 μg m^{-3}, 80 μg m^{-3}, and 150 μg m^{-3} of PM10 concentration, indicating 'good', 'normal', and 'bad' air quality, respectively. This indicates that PM2.5 and PM10 shows similar reduction of solar PV power generation at Y-PV power plant (figure 1). Also, the reduction rate of solar PV power generation in the E-PV power plant due to PM10 concentrations is similar to that in the Y-PV power plant. Consequently, the negative impacts of PM2.5 is larger in the Y-PV power plant than in the E-PV power plant, whereas both power plants show similar reduction rates of solar PV power generation according to PM10 concentrations.

4. Discussion and conclusions

This study examined the effects of PM2.5 and PM10 on solar PV power generation by applying multiple regression methods to actual solar PV power generation records of two power plants located in Korea, Y-PV and E-PV, and observed temperature, RH, and concentration of PM2.5 and PM10 at relevant stations from 2015–2017. Our approach, using actual solar PV power generation record and observed environmental parameters, is distinct to previous assessments, which generally deal with PM impacts on solar irradiance and simulated solar PV power generation (Benghanem *et al* 2009, Jo *et al* 2012, Calinoiu *et al* 2013, Peters *et al* 2018). The attenuation effect of PM on solar PV power generation becomes larger as the concentration of PM increases. The 'good' air quality according to 15 μg m^{-3} of PM2.5 and 30 μg m^{-3} of PM10 concentration reduced the solar PV power generation by 14.2% and 14.9% at Y-PV power plant and 9.8% and 16.1% at E-PV power plant. The PM-induced decrease in the solar PV power generation reaches 22.6% and 22.0% at Y-PV power plant and 15.6% and 23.7% at E-PV power plant under 'bad' air quality condition based on the concentration of PM2.5, 75 μg m^{-3}, and PM10 concentration, 150 μg m^{-3}. Results indicate that the impact of PM concentration on the solar PV power generation is considerable in Korea.

The range of the estimated reduction rate of solar PV power generation according to PM in the present study is generally consistent with the decrease in solar irradiance and solar PV power generation provided in previous assessments performed in various regions. In Mexico, air pollution decreased the observed solar irradiance by 21.6% (Jáuregui and Luyando 1999). Another modelling study showed that due to aerosols, solar irradiance decreased by 8% and 17.75% for California and near the Sahara, where the aerosol concentrations were relatively low and high, respectively (Ben-tayeb *et al* 2020). Many studies targeting several sites over South Asia observed that aerosols attenuate solar irradiance by 10%–25% (Kambezidis *et al* 2012, Millstein and Fischer 2014, Bergin *et al* 2017, Peters *et al* 2018). A study on a solar radiation model demonstrated that more than 20% of solar radiation was lost due to the effects of aerosol contamination in the Romanian state of Timishora (Calinoiu *et al* 2013). Also, satellite-retrieved observations showed

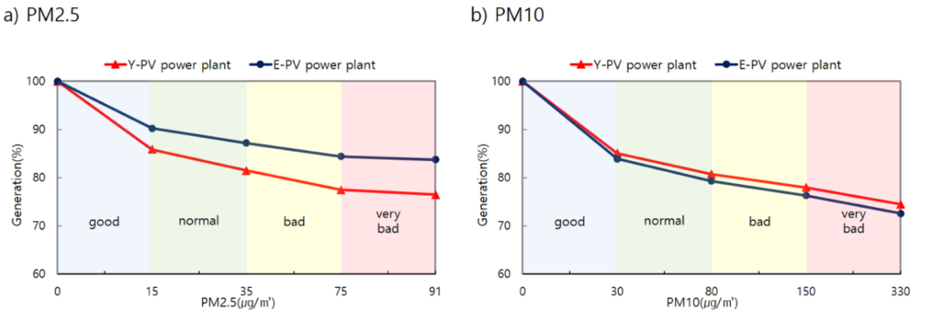

Figure 1. Comparison of reduction rates of solar PV power generation according to four levels of air quality based on the concentration of (a) PM2.5 and (b) PM10 between E-PV and Y-PV power plants.

that solar radiation was reduced by 20%–35% in China when aerosol optical depth (AOD) exceeded 0.8 (Li *et al* 2017). Global climate modelling showed that particulate matter reduces 10%–20% of solar energy over Korea (Bergin *et al* 2017). Using actual records of solar PV power generation, our results verified the suggested impact of insolation loss according to PM on solar PV power generation which were suggested by previous assessments. In addition, this is a very rare case study using both observed solar PV power generation and relevant PM concentrations in East Asia, one of the hotspots of air pollution. Therefore, despite the use of limited data of power plants located in Korea, our results can be an initiation of real evaluation of PM attenuation impacts on solar PV power generation.

In addition to the PM concentration in ambient air, which the present study focused on, the deposition of PM on the solar panel also has potential to reduce absorbed solar radiation and relevant solar PV power generation (Liqun *et al* 2012, John *et al* 2016, Bergin *et al* 2017, Jaszczur *et al* 2019). The loss of solar PV module power reaches 5%–40% according to observation sites and exposure periods (Jaszczur *et al* 2019). However, previous assessments on the PM deposition impact on solar PV power generation are usually performed in dry regions such as Taiyuan in China and Ahmedabad in India (Liqun *et al* 2012, Bergin *et al* 2017). The climate of Korea is dominated by the East Asian Monsoon, characterized by large rainfall in the summer and strong northwesterly winds in the winter (Yihui and Chan 2005). The extratropical cyclones, usually accompanied by rainfall and strong wind, frequently passes Korea in spring, autumn, and winter (Lee *et al* 2019). As a result, rainfall can repeatedly wash off the deposited PM on the solar panels installed in Korea. Thus, the loss of solar PV power generation associated with PM deposition at the Y-PV and E-PV power plants might be less than that measured at other sites located in dry regions.

The data of Seoul and Yeongam weather observation sites show that cloudless days amounted up to 29% for Seoul and 22% for Yeongam for 30 years (1985–2014). As there are 365 days in a year, Seoul and Yeongam had over 100 and around 80 cloudless days per year, respectively. Cloudless days showed the highest efficiency of solar PV power generation, but if PM2.5 and PM10 play a similar role as clouds, this will effectively hinder solar PV power generation (Peters *et al* 2018). Therefore, based on the results of this study, PM can significantly reduce solar PV power generation on such cloudless days in Korea.

As PM2.5 particles cause more Rayleigh scattering than PM10 particles (Hinds 1999), it was expected that PM2.5 concentrations would reduce solar PV power more than PM10 concentrations. However, the results of the present study show that PM2.5 and PM10 concentrations have almost similar effects of reducing solar PV power generation. Since it is difficult to analyze the exact difference by separating the effects of PM2.5 and PM10 on reducing solar PV power generation, a more accurate analysis is necessary to distinguish clearly the effects of PM2.5 and PM10 on solar PV power generation. In addition, the coefficients of PM2.5 in the Y-PV power plant and the E-PV power plant are different, which might be in accordance with the location characteristics of the E-PV power plant. Since the E-PV power plant is installed in a parking lot of a garage area, emissions of PM2.5 from vehicles might be high compared to other areas (Ntziachristos *et al* 2007). In addition, data of PM are obtained from a measurement site that is located 4.5 kilometers away from the E-PV power plant. For this reason, the coefficient of PM2.5 of the E-PV power plant is likely to be underestimated. If the same conditions were provided where the power plants, weather observation sites, and PM measurement sites were located in the same area, this would aid in making a more explicit analysis on solar PV power generation. Such research will be effective in making accurate predictions of the amount of solar PV power generation and finding optimal sites where solar PV power generation can be made most efficiently.

Acknowledgments

This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Public Technology Program based on Environmental Policy Program, funded by Korea Ministry of Environment (MOE)(2019000160007). Chang-Eui Park was supported by Korea Research Fellowship Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2019H1D3A1A01071022).

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Sujong Jeong https://orcid.org/0000-0003-4586-4534
Chang-Eui Park https://orcid.org/0000-0001-8792-6778

References

Belsley D A 1991 A guide to using the collinearity diagnostics *Comput. Sci. Econ. Manag.* **4** 33–50

Belsley D A, Kuh E and Welsch R E 2013 *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity* (New York: Wiley)

Benghanem M, Mellit A and Alamri S N 2009 ANN-based modelling and estimation of daily global solar radiation data: A case study *Energy Convers. Manag.* **50** 1644–55

Ben-tayeb A, Diouri M, Meziane R and Steli H 2020 Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico city *Air Qual. Atmos. Health* **13** 259–69

Bergin M H, Ghoroi C, Dixit D, Schauer J J and Shindell D T 2017 Large reductions in solar energy production due to dust and particulate air pollution *Environ. Sci. Technol. Lett.* **4** 339–44

Calinoiu D, Paulescu M, Ionel I, Stefu N, Pop N, Boata R, Pacurar A, Gravila P, Paulescu E and Trif-Tordai G 2013 Influence of aerosols pollution on the amount of collectable solar energy *Energy Convers. Manag.* **70** 76–82

Chylek P and Wong J 1995 Effect of absorbing aerosols on global radiation budget *Geophys. Res. Lett.* **22** 929–31

Duffie J A and Beckman W A 2013 *Solar Engineering of Thermal Processes* 4th Ed pp 9–15 (New York: John Wiley & Sons)

Feng Y, Chen D and Zhao X 2019 Estimated long-term variabillity of direct and diffuse solar radiation in North China during 1959–2016 *Theor. Appl. Climatol.* **137** 153–63

Forero N L, Caicedo L M and Gordillo G 2007 Correlation of global solar radiation values estimated and measured on an inclined surface for clear days in Bogotá *Renew. Energy* **32** 2590–602

Fu P, Kawamura K, Kobayashi M and Simoneit B R T 2012 Seasonal variations of sugars in atmospheric particulate matter from Gosan, Jeju Island: significant contributions of airborne pollen and Asian dust in spring *Atmos. Environ.* **55** 234–9

Gwandu B A L and Creasey D J 1995 Humidity: a factor in the appropriate positioning of a photovoltaic power station *Renew. Energy* **6** 313–6

Hinds W C 1999 *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles* (New York: Wiley-Interscience)

Hu B *et al* 2017 Quantification of the impact of aerosol on broadband solar radiation in North China *Sci. Rep.* **7** 1–8

IPCC 2013 Climate change 2013: the physical science basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)

IEA 2016 WEO 2016 Special Report: Energy and Air Pollution (available at: https://iea.org/publications/freepublications/publication/WorldEnergyOutlookSpecialReport2016EnergyandAirPollution.pdf)

IEA 2017 WEO 2016 Special Focus on Renewable Energy (available at: https://www.iea.org/media/publications/weo/WEO2016SpecialFocusonRenewableEnergy.pdf) (accessed on 1 June 2017)

Jaszczur M, Teneta J, Styszko K, Hassan Q, Burzyńska P, Marcinek E and Łopian N 2019 The field experiments and model of the natural dust deposition effects on photovoltaic module efficiency *Environ. Sci. Pollut. Res.* **26** 8402–17

Jáuregui E and Luyando E 1999 Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico City *Int. J. Climatol.* **19** 683–94

Jo D-K, Yun C-Y, Kim K-D and Kang Y-H 2012 A study on the estimating solar radiation in Korea using cloud cover and hours of bright sunshine *J. Korean Sol. Energy Soc.* **32** 28–34

John J J, Warade S, Tamizhmani G and Kottantharayil A 2016 Study of soiling loss on photovoltaic modules with artificially deposited dust of different gravimetric densities and compositions collected from different locations in India *IEEE J. Photovoltaics* **6** 236–43

Kambezidis H D, Kaskaoutis D G, Kharol S K, Moorthy K, Satheesh S K, Kalapureddy M C R, Badarinath K V S, Sharma A R and Wild M 2012 Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico City *Atmos. Environ.* **50** 360–72

Kazem H A and Chaichan M T 2015 Effect of humidity on photovoltaic performance based on experimental study *Int. J. Appl. Eng. Res.* **10** 43572–7

KEEI 2018 *Yearbook of Energy Statistics* (Korea Energy Economics Institute)

Kim H C *et al* 2017 Recent increase of surface particulate matter concentrations in the Seoul Metropolitan area, Korea *Sci. Rep.* **7** 1–7

Kim K H, Choi G H, Kang C H, Lee J H, Kim J Y, Youn Y H and Lee S R 2003 The chemical composition of fine and coarse particles in relation with the Asian Dust events *Atmos. Environ.* **37** 753–65

Lave M, Hayes W, Pohl A and Hansen C W 2015 Evaluation of global horizontal irradiance to plane-of-array irradiance models at locations across the United States *IEEE J. Photovoltaics* **5** 597–606

Lee J, Son S-W, Cho H-O, Kim J, Cha D-H, Gyakum J R and Chen D 2019 Extratropical cyclones over East Asia: climatology, seasonal cycle, and long-term trend *Clim. Dyn.* **54** 1131–44

Leibensperger E M, Mickley L J, Jacob D J and Barrett S R H 2011 Intercontinental influence of NOx and CO emissions on particulate matter air quality *Atmos. Environ.* **45** 3318–24

Li X, Wagner F, Peng W, Yang J and Mauzerall D L 2017 Reduction of solar photovoltaic resources due to air pollution in China *Proc. Natl. Acad. Sci.* **114** 11867–72

Liqun L, Zhiqi L and Chunxia S Z L 2012 Degraded output characteristics at atmospheric air pollution and economy analysis of PV poer system: a case study *Prz. Elektrotech.* **88** 281–4

Lou S, Yang Y, Wang H, Smith S J, Qian Y and Rasch P J 2019 Black carbon amplifies haze over the North China plain by weakening the East Asian winter monsoon *Geophys. Res. Lett.* **46** 452–60

Matuszko D 2012 Influence of the extent and genera of cloud cover on solar radiation intensity *Int. J. Climatol.* **32** 2403–14

Meinel A B and Meinel M P 1976 *Applied Solar Energy: An Introduction* (Boston, MA: Addison-Wesley)

Mekhilef S, Saidur R and Kamalisarvestani M 2012 Effect of dust, humidity and air velocity on efficiency of photovoltaic cells *Renew. Sustain. Energy Rev.* **16** 2920–5

Millstein D E and Fischer M L 2014 Reflective 'cool' roofs under aerosol-burdened skies: radiative benefits across selected Indian cities *Environ. Res. Lett.* **9** 104014

Ministry of Trade, Industry, and Energy(MOTIE) 2017 Jaesaengeneoji 3020 Ihaeng gyehwek (Renewable Energy 3020 Action Plan, in Korean)

Mueller R, Behrendt T, Hammer A and Kemper A 2012 A new algorithm for the satellite-based retrieval of solar surface irradiance in spectral bands *Remote Sens.* **4** 622–47

Norris D J 1968 Correlation of solar radiation with clouds *Sol. Energy* **12** 107–12

Ntziachristos L, Ning Z, Geller M D and Sioutas C 2007 Particle concentration and characteristics near a major freeway with heavy-duty diesel traffic *Environ. Sci. Technol.* **41** 2223–30

Park S U and In H J 2003 Parameterization of dust emission for the simulation of the yellow sand (Asian dust) event observed in march. 2002. in Korea *J. Geophys. Res. D: Atmos.* **108** 1–21

Peters I M, Karthik S, Liu H, Buonassisi T and Nobre A 2018 Urban haze and photovoltaics *Energy Environ. Sci.* **11** 3043–54

Rauschenbach H S 1980 *Solar Cell Array Design Handbook: The Principles and Technology of Photovoltaic Energy Conversion* (Dordrecht: Springer)

Skoplaki E and Palyvos J A 2009 On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations *Sol. Energy* **83** 614–24

Smith C J, Bright J M and Crook R 2017 Cloud cover effect of clear-sky index distributions and differences between human and automatic cloud observations *Sol. Energy* **144** 10–21

Streets D G, Wu Y and Chin M 2006 Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition *Geophys. Res. Lett.* **33** 2–5

Tan Jian Wei N, Nan W J and Guiping C 2017 Experimental study of efficiency of solar panel by phase change material cooling *IOP Conf. Ser. Mater. Sci. Eng* **217** 012011

WHO Regional Office for Europe 2006 Air quality guidelines global update 2005: particulate matter, ozone, nitrogen dioxide and sulfur dioxide (Copenhagen: WHO Regional Office for Europe) (available at: https://apps.who.int/iris/bitstream/handle/10665/107823/E90038.pdf?sequence=1&isAllowed=y)

Xia X, Chen H, Li Z, Wang P and Wang J 2007 Significant reduction of surface solar irradiance induced by aerosols in a suburban region in northeastern China *J. Geophys. Res.* **112** D22S02

Yihui D and Chan J C L 2005 The East Asian summer monsoon: an overview *Meteorol. Atmos. Phys.* **89** 117–42

Zhao L, Lee X and Liu S 2013 Correcting surface solar radiation of two data assimilation systems against FLUXNET observations in North America *J. Geophys. Res. Atmos.* **118** 9552–64