Assessing the Impact of Haze on Solar Energy Potential Using Long Term $PM_{2.5}$ Concentration and Solar Insolation Filed Data in Naples, Italy

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Abstract Atmospheric fine particulate pollutant affects seriously the human health but also the passage of light through the lower atmosphere, reducing the solar radiation reaching the ground as well as the PV panels. In this study, the solar insolation reduction due to air pollution has been investigated in the city of Naples (Italy). Analyzing local long term field data, we have obtained that the solar insolation reduction is exponentially correlated to the PM2.5 concentration. By using the derived empirical relation, for Naples it was estimated that the solar insolation was reduced around 5% or 66.20 kWh/m^{-2} within one-year period (May 2018–May 2019), due to air fine particulate pollution. This study provides the theoretical basis to design successful solar PV systems to be mounted on building rooftops or in other suitable sites, taking into account also the local air pollution condition.

Keywords Solar radiation · Solar photovoltaic potential · Atmosphere particulate pollution

1 Introduction

Air pollution is known to be a serious problem mainly for its effects on human health. Recently, however, the air pollution effects in other fields such as the photovoltaic energy generation have been investigated and, notably, the relation between the reduction of the solar insolation reaching the PV systems and fine particular matter ($PM_{2.5}$) concentration in the air. Air pollution typically includes $PM_{2.5}$ which suspended in the atmosphere can reduce the solar radiation intensity reaching the ground. At this regard, Peters et al. [1], correlating measured particulate concentrations and solar insolation in Delhi over a long period of 19 months, estimated that

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total sunlight reaching the ground during one year was reduced by more than one ninth, due to air pollution.

Wang et al. [3], testing a distributed photovoltaic system on a building roof in Shanghai, showed that the higher the $PM_{2.5}$ concentration, the lower the power generation capacity of the PV module was. Then, the solar radiation received on the surface of the PV module resulted exponentially related to the atmospheric $PM_{2.5}$ concentration.

It is known that the cities in the Eastern Mediterranean and Southeast Asia are often affected by major haze events reaching $PM_{2.5}$ concentrations up to 375 $\mu g\ m^{-3}$ [1, 2]. However, most of cities around the world suffers the air pollution although at several seriousness levels.

In this study, we intend at addressing the impact of $PM_{2.5}$ particles on solar insolation levels in the city of Naples (South Italy), whose air pollution levels exceed often the threshold values.

By 2030, EU countries will have to increase the use of renewables, including the solar PV systems, for realizing the 32% target of renewable energy production, according to the EU's re-cast renewable energy directive [4]. In this regard, EU orientation is to address the use of suitable buildings' surfaces rooftops and facades for distributed solar PV systems deployments.

Recently, Bodis et al. [5] have estimated that the EU cities' building rooftops could potentially produce solar PV electricity, annually covering the 25% of the current electricity. In particular, Italy could potentially cover more than 30% of its electricity consumption by developing rooftop PV systems at its most advantageous rooftops. In view of exploitation of this potential, the estimation of the reduction of solar radiation due to $PM_{2.5}$ particles in the air could be fundamental, making the difference between a solar PV installation meets the expected output and one that fails. In this study, at this scope, an empirical relation between $PM_{2.5}$ concentration and reduction in insolation has been derived by analyzing one-hour $PM_{2.5}$ and insolation measurements from a monitored location in Naples, Italy.

2 Correlating $PM_{2.5}$ Concentration and Reduction in Solar Radiation

The collected data used in our analysis were recorded over 19 months between January 2018 and July 2019. Insolation data were measured by a pyranometer with a frequency of one measurement every hour. This instrument consists in a thermopile sensor coated with an opaque black paint providing a flat spectral response for the full wave length range. It measures the global solar radiation on a plane/level surface as sum of direct solar radiation and diffuse sky one.

Fine particulate data were recorded by an air quality monitor as SWAM 5A DUAL CHANNEL with one-hour frequency.

Table 1 PM2.5 concentration ranges and corresponding AQI color code

Concentration range (μg m⁻³)	Color code	Levels of health concern
0-20	Green 1	Extremely Good
21-30	Green 2	Very Good
31-40	Green 3	Moderate Good
41-50	Green 4	Good
51-100	Yellow	Moderate
101-150	Orange	Moderate unhealthy
151-200	Red	Unhealthy
201-300	Purple	Very unhealthy
Above 300	Maroon	Hazardous

Both instruments are located at the air quality gauge station, located in Naples, managed by ARPAC (Italian Agency of Environmental Protection). This station is identified by the EU code IT1493A.

The approach, used for relating $PM_{2.5}$ concentration and insolation data, consists in three main steps: (1) normalizing insolation data, (2) clustering $PM_{2.5}$ concentration data, (3) deriving the correlation curve.

At first, $PM_{2.5}$ concentration levels were classified according the color coding of Air Quality Index (AQI). We observed that most of recorded concentration levels fell in the first AQI class ranging among 0–50 $\mu g\ m^{-3}$. For making the analysis consistent, we split the first class in sub-classes as showed in Table 1, transferring more properly the recorded data in AQI levels.

Hence, insolation data were sorted in bins corresponding to the defined different $PM_{2.5}$ concentration levels. Then, humidity and clear sky filters were used for identified data representative of clear sky conditions.

It is to be noted that, over the course of a year, the insolation varies via the zenith angle and the eccentricity of the Earth's orbit around the sun as well as due to seasonal variations in atmospheric conditions. Since insolation data covered a longer period than one year, these variations were to be considered in the correlation analysis. At this scope, insolation data were analyzed for each month separately and normalized by taking the 90 percentile value of all insolation measurements at noon for all months.

Figure 1 shows the results of the normalization for the most representative months of June and November.

For identifying the conditions representative of a clear sky, the 80 percentile filter of the datasets for each hour and pollution level was calculated.

This data was used for deriving the correlation curve between $PM_{2.5}$ concentration levels and reduction of insolation, considering the relative reduction for each hour. For generating this functional relation, only datasets containing more than seven data points were considered.

The data analyzed were fitted by an exponential decay curve with a value R^2 of 55%.

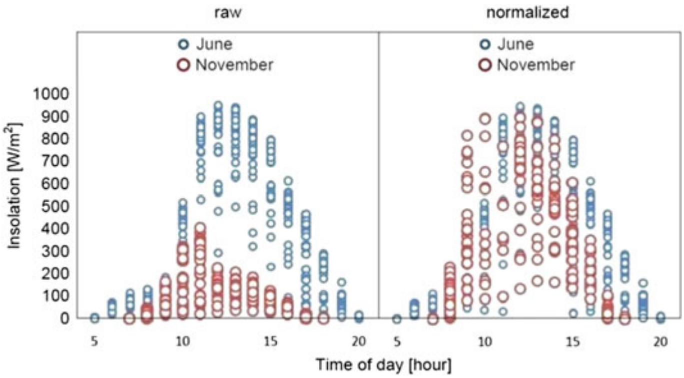

Fig. 1 Graphs of insolation data. On the left, the raw data and on the right the data normalized, corresponding at June and November months

Exponential decay was expected according to Lambert–Beer's law. The fitted exponential decay is shown as a black line in Fig. 2.

The fitted curve is described by the following equation:

$$\frac{I(PM_{2.5})}{I_o} = \exp\left(\frac{-PM_{2.5}}{250}\right) \tag{1}$$

where I_0 is the isolation at 0 μg m^{-3} and I is the insolation affected by PM2.5 concentration.

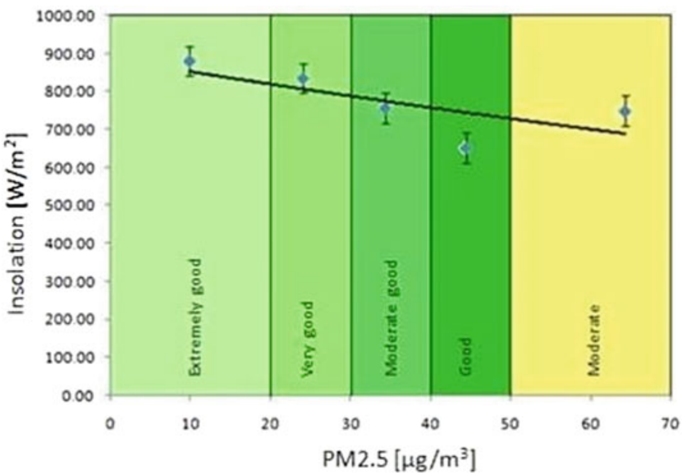

Fig. 2 Exponential variation of solar radiation with $PM_{2.5}$ concentration

As simplification, this result is obtained assuming consistent, over the entire period considered, the composition and size distribution of air pollution as well as the optical behavior of the aerosol.

3 Estimating $PM_{2.5}$ Related Reduction in Solar Insolation

Equation (1) was used to estimate over one year how much light is lost due to $PM_{2.5}$ related air pollution in Naples.

Figure 3 shows the measured insolation and the insolation estimated by means of Eq. (1), considering $PM_{2.5}$ concentration of 0 μg m^{-3} (I_0), over one year from May 2018 to May 2019. Integrating this insolation data, we calculated the annual insolation and the projected insolation at 0 μg m^{-3} $PM_{2.5}$, as shown in Table 2.

So, we found that the amount of insolation for Naples was reduced by 5% or 66.20 kWh/m^{-2} of the annual solar energy reaching the ground.

From this result, we can derive that the air fine particulate pollution at concentration levels of 0–100 μg m^{-3} can affect the solar energy potential of viable rooftops for PV installations. Moreover, using this empirical relation, the insolation loss due to air quality can be directly evaluated, making more reliable the solar PV potential estimations [6].

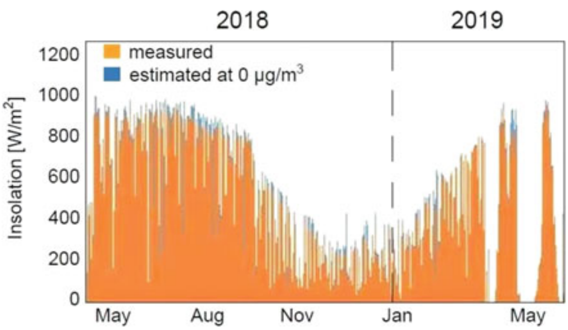

Fig. 3 Measured insolation and estimated insolation without air pollution due to $PM_{2.5}$ over one year

Table 2 PM2.5 effects on solar insolation in Naples

Annual radiant exposure	
Projection 0 μg m^{-3}	1368.41 (kWh m^{-2})
Measured data	1302.21 (kWh m^{-2})
Difference	66.20 (kWh m^{-2})
Loss in percentage	4.84%

4 Conclusions

Atmospheric particulate pollutant can affect the transition of light through the lower atmosphere, reducing the solar radiation reaching a PV panel. So, the variation of solar radiation intensity with $PM_{2.5}$ concentration, mainly in the cities, is investigated in order to make more reliable PV power estimations.

In this work, we have analyzed the correlation between $PM_{2.5}$ concentration and the loss in isolation, using long term field data from a monitored location in Naples. As result, we obtained that the amount of solar radiation is exponentially correlated to the $PM_{2.5}$ concentration.

Using the formulated functional relation, we calculated the amount of insolation Naples would have received without the air particulate pollution within one-year period. In particular, we estimated that the insolation due to $PM_{2.5}$ pollution was reduced around 5%, from 1368 to 1302 kW m^{-2}.

The derived empirical relation represents itself a result. It enables a way to predict the influence of air fine particulate pollution on the solar energy potential in different PV suitable sites.

In conclusion, this study provides the theoretical basis to design solar PV systems to be mounted on a building rooftop as well as in other suitable sites, taking also into account the local air pollution condition.

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