Assessing the Effect of NO_2 Pollution on Solar Irradiance

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Abstract. Not only air pollution can affect men's health, but it can have a detrimental impact on solar irradiance reaching the earth, resulting, for instance, in a decrease of photovoltaic plants energy yield. In this paper a theoretical model is proposed to evaluate the effect of air pollutants on solar irradiance using data measured at ground level. The model has been applied to the case of NO_2 pollution in Acerra, a small town near Naples (Italy) where data have been collected for two years. It is found that NO_2 has a negligible effect on solar budget, at least with respect to other pollutants such as $PM_{2.5}$.

Keywords: Air pollution · NO_2 · Global solar irradiance · AOD · $PM_{2.5}$

1 Introduction

In addition to being of vital importance to men, the solar radiation is also one of the most used and promising renewable energy sources. The use of photovoltaic technologies, to convert sunlight into electricity, would generate a quarter (25%) of total electricity needs globally by 2050 [1], reducing CO_2 emissions and limiting the climate change. Therefore, the need for an accurate estimate of the amount of solar energy reaching the earth's surface and of the factors which could be responsible of its reduction, is widely recognized.

PV power plants energy yield mainly depends on the Global Horizontal solar Irradiance (GHI) impinging on them. Although mostly affected by the plant latitude and by meteorological factors, several authors have recently pointed out that air particulate ($PM_{2.5}$, PM_{10}) and chemical pollutants (SO_2, NO_2, CO, O_3) can severely reduce the amount of solar radiation useful for PV power production.

As far as $PM_{2.5}$ is concerned, Peters et al. (2018) [2], correlating in situ measurements of particulate concentrations and solar insolation in Delhi and Singapore over a period of 19 months, estimated that total sun-light reaching the ground during one year was reduced around 12.5% for every 100 μgm^{-3} particulate concentration while, at our latitudes, in a recent paper, Nocerino et al. [3] have conducted a study in Naples showing that, even in the absence of relevant haze events, the solar irradiance reaching the ground is reduced of about 3 $Wm^{-2}/\mu gm^{-3}$. This means that, in Naples, in normal solar average conditions,

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the solar irradiance useful for PV conversion, in a day of clear sky, can be reduced from 5% up to 8% just as a result of $PM_{2.5}$ pollution.

Since, as recalled, several other pollutants can potentially affect the solar irradiance, the above reported observations have resulted in a strong increase of interest to model and measure the effects of other pollutants on solar radiation and, in turn, on PV energy yield in order to understand whether a correlation between pollutants other than $PM_{2.5}$ and solar irradiance exists and its strength. Fan et al. [4], analyzing data related to Beijing (China) from 2014 to 2016, observed for instance that such a correlation exists also with PM_{10}, O_3 and, more in general, with an Air Quality Index, AQI, but actual measurements are still missing, the critical issue being the large unavailability of data correlating the effect of air pollution on solar irradiance.

Over last years, the attenuation effects by the air pollution on solar radiation have been primarily investigated by modeling the relationships between aerosol optical depth (AOD) and the different atmospheric constituents [5]. AOD is, by definition, a measure of how much direct sunlight is prevented from reaching the ground level by the aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location [6]. When AOD is estimated, as it is usual, by means of satellite measurements, its value represents therefore a mean value between ground (earth) and top of atmosphere (TOA) data. As such, its use to model the effect of air pollution due to anthropogenic activities over the solar irradiance is expected to be strongly affected by large uncertainties as it is commonly observed when satellite observation is extrapolated to get insights on effects at the earth surface [7].

On the other hand, model for AOD based on surface related measurements have been also proposed, mainly to cope with satellite non-retrieval times [8]. In this study, we will show how surface measurements can be theoretically correlated to AOD so that the effect of each pollutant can be separately considered to evaluate its effect on solar irradiance. Furthermore, using long-term high resolution field data from monitoring stations located in Acerra (South Italia), we have investigated the attenuation effect by nitrogen dioxide (NO_2) on solar radiation.

2 Theoretical Model

The extraterrestrial solar radiation, G_0, will, in general, depend on the Julian day, n that is $G_0 = G_0(n)$ so that the global solar irradiance on a horizontal terrestrial surface will be depending on the zenith angle θ_z and n following the relation [9, 10]:

$$G(n, \theta_z) = G_0(n) \cdot \cos(\theta_z) \cdot \tau(\lambda, \theta_z) \tag{1}$$

where $\tau(\lambda, \theta_z)$ is the spectral atmospheric transmittance, which is, in general, affected by a number of scattering/absorption processes such as Rayleigh scattering, ozone absorption, particulate matter and air pollutants scattering etc.

Each atmospheric extinction process can be written in the form of:

$$\tau_j(\lambda, \theta_z) = e^{[-m_i(\theta_z) \cdot \delta_i(\lambda, \theta_z)]} \tag{2}$$

where $m(\theta_z)$ is the atmospheric optical air mass and $\delta_i(\lambda, \theta_z)$ is the spectral optical thickness defined by:

$$\delta_j(\lambda, \theta_z) = \int_0^{TOA} best(x, \lambda, \theta_z)dx \tag{3}$$

where b_{ext} is the atmospheric extiction coefficient and x is the solar–sensor distance.

According to [11], $m_i(\theta_z) \cdot \delta_i(C, \theta_z)$ can be expressed as:

$$m_i(\theta_z) \cdot \delta_j(\lambda, \theta_z) = f(\theta_z) \cdot AOD_i(\lambda) \tag{4}$$

where AOD is the Aerosol Optical Depth that is in general depending on λ and on the concentration of the various sources of scattering/absorption:

$$AOD_i(\lambda) = [C_i] \tag{5}$$

$f(\theta_z)$ is a function modulating the scattering intensity as a function of the zenith angle. Two processes compete to control the scattering intensity: the sun-sensor distance, which has a minimum at $\theta_z = 0$ (and therefore results in a maximum of intensity) and the number of scatterers per unit of volume that increases as the sun-sensor distance increases and therefore results in an increase of scattering for θ_z approaching 90°. In Fig. 1 a fit of $f(\theta_z)$ is shown after data from Ref. [11] and [12].

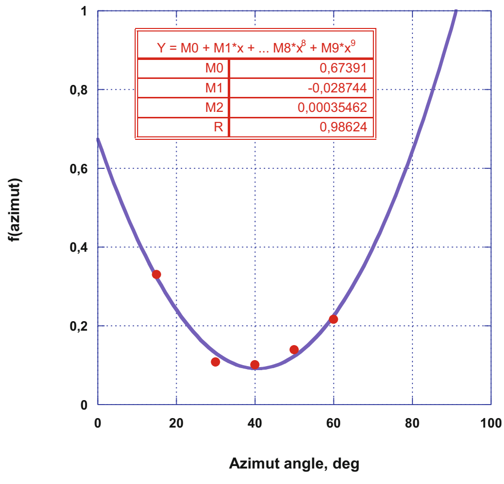

Fig. 1. Fit of $f(\theta_z)$ after data from Ref. [11] and [12].

If measurements are performed averaging over the zenith angle and using the above empirical relation expression for $f(\theta_z)$:

$$G(n) = G_0(n) \cdot \cos(\theta_z) \cdot \tau(\lambda, \theta_z) = G_0(n) \cdot \prod_{i=1}^{n} \left(\frac{2}{\pi}\right) \int_0^{\frac{\pi}{2}} cos(\theta_z) \cdot e^{[-f(\theta_z) \cdot AOD_i(\lambda)]} d\theta_z = G_0(n) \cdot \left(\frac{2}{3}\right) \cdot \prod_{i=1}^{n} e^{[-f(0) \cdot AOD_i(\lambda)]} \tag{6}$$

In conclusion the global horizontal irradiance at day n will in general exponentially decrease with the scatterer/absorbing concentration source i, following the equation:

$$G(n) = A_0(n, \lambda) \cdot e^{-\left(\frac{C_i}{b_i}\right)} \quad (7)$$

where $A_0(n, \lambda)$ is given by $G_0(n) \cdot \prod e^{-\left(\frac{C_i}{b_i}\right)}$ for all the terms except $j = i$.

Therefore, in clear sky conditions the measured global horizontal irradiance integrated over λ can be related to each single specific scattering process by means of the equation:

$$ln(G) = \ln[A(n)] - \left(\frac{C_i}{b_i}\right) \quad (8)$$

and thus a plot of ln(G) vs C_i should result in a straight line with a slope given by b_i. Clearly, the higher is b_i, the less relevant is the effect of pollutants C_i over solar irradiance.

3 The Effect of $PM_{2.5}$ Concentration on Solar Radiation

In a previous work, Nocerino et al. [3] have investigated the effect of fine particulate matter on insolation, using long term field data from a monitored location at a longitude of 14.34°E and latitude of 40.86°N in the city of Naples. More specifically, it was analysed the correlation between $PM_{2.5}$ concentration and the loss in insolation, since fine particulate matter is considered the primary reason of urban air pollution and reduced visibility events in the cities.

Hourly solar radiation and $PM_{2.5}$ data were collected for 19 months (January 2018–July 2019) from a traffic air quality monitoring station adjacent a school. The approach used for relating $PM_{2.5}$ concentration and insolation data consisted in three main steps: (1) normalizing insolation data, (2) clustering $PM_{2.5}$ concentration data, (3) deriving the correlation curve.

Following the above methodology, Eq. 8 was specialized for the case of $PM_{2.5}$, the result being:

$$ln(G) = \ln[A(n)] - \left(\frac{PM_{2.5}}{250}\right) \quad (9)$$

At first, the derived functional relation was used to calculate the annual amount of solar radiation which Naples would have received without air particulate pollution. Then, by comparing the ideal exposure at 0 μgm^{-3} $PM_{2.5}$ with the annual amount of irradiance measured, it was estimated that due to airborne particulate matter, the insolation in Naples was reduced around 5%, considering an yearly average $PM_{2.5}$ concentration of 16 μgm^{-3}.

4 Correlating NO_2 Concentration and Insolation Data

Hourly ground measurements used to investigate the effect by NO_2 on solar radiation, were collected from the monitoring station of Acerra located at longitude of 14.37°E and latitude of 40.94°N. This station, along with the station of Naples, belongs at the regional air quality monitoring network, operated by ARPAC (Italian Agency of Environmental Protection), which counts 24 ground monitoring sites on the regional territory. Irradiation data were recorded by a thermopile sensor of a pyranometer which measures global solar radiation on a plane/level surface (Watt/m^2) as the sum of direct solar radiation and diffuse sky radiation. The sensing surface of the thermopile is coated with an opaque black paint providing a flat spectral response for the full wavelength range. Regarding NO_2, the Thermo Scientific™ Model 42i NO_2 Analyzer measured levels of the pollutant in the emissions using chemiluminescent technology to provide concentration data (μgm^{-3}).

To correlate NO_2 concentration and insolation data, the same methodology of ref. [3] was implemented in MATLAB Software R2018b. Briefly, insolation data over 24 months (September 2018–September 2020) were firstly normalized to consider seasonal variations, and then clustered in bins corresponding different levels of NO_2. Finally, a function describing the exponential decay of irradiance by NO_2, was derived.

In Fig. 2 and 3 it is reported the variation of GHI vs NO_2 concentration in 2019 and in 2020, respectively. The two observation periods are particularly interesting since 2020 was characterized by COVID-19 pandemia that, as it is well known, strongly affected our lives.

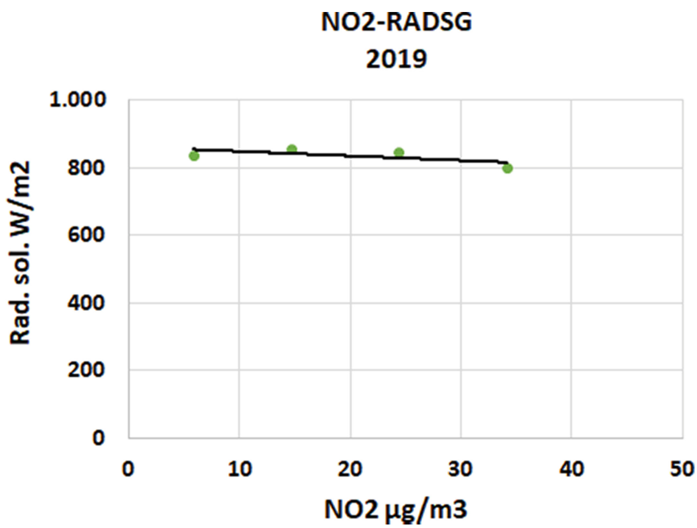

Fig. 2. Effect of NO_2 pollution over GHI in 2019 as measured in the regulatory monitoring station of Acerra (Naples, Italy).

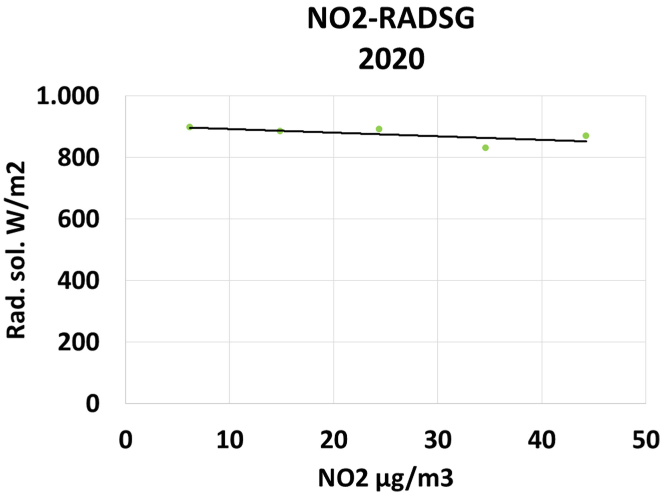

Fig. 3. Effect of NO_2 pollution over GHI in 2020 as measured in the regulatory monitoring station of Acerra (Naples, Italy).

In 2019 the NO_2 slope b has a value around 500, while in 2020 its value was about 1000, for NO_2 increasing in the range from 10 μgm^{-3} up to 60 μgm^{-3} strongly suggesting that NO_2 pollution has a 2^{nd} order effect on the solar radiation, at least with respect to $PM_{2.5}$. It is worth to note that, quite surprisingly, in 2020 a small, but still clearly observable increase in NO_2 concentration has been observed in spite of the running pandemia.

5 Conclusions

Air pollution can seriously affect solar irradiance reaching the earth surface and in turn modify the energy yield of PV plants. In this paper a theoretical background has been proposed to measure this effect relying on earth surface air pollution measurements and the model has been applied to evaluate NO_2 effect. It has been found that NO_2 pollution negligibly affects the solar irradiance at least when compared to $PM_{2.5}$ effect.

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