# Simplified method for evaluating the effects of dust and aging on photovoltaic panels

Loredana Cristaldi [a,1], Marco Faifer [a,1], Marco Rossi [a,1], Sergio Toscani [a,1], Marcantonio Catelani [b], Lorenzo Ciani [b], Massimo Lazzaroni [c,d,*]

[a] DEIB – Politecnico di Milano Piazza L. Da Vinci, 32, 20133 Milano, Italy
[b] Dipartimento di Elettronica e Telecomunicazioni – Università degli Studi di Firenze, Firenze, Italy
[c] Dipartimento di Fisica – Università degli Studi di Milano, Via Celoria, 16, 20133 Milano, MI, Italy
[d] INFN – Milano, Via Celoria, 16, 20133 Milano, MI, Italy

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## 1. Introduction

It is well known that the presence of dust on the surface of a PV modules have significant impact on their efficiency [1–4]. Then, the consequent reduction in energy production has a non-negligible effect on the incomes [5].

Different environmental and weather conditions can influence dust deposition as, for instance, volcanic eruptions, sand, pollution, rain, wind, etc. [3,6–10]. The presence of dust and sand produces a negative impact on PV performance due to the fact that dust is able to block incident photons which are not able to reaching the PV cells. In [6] the effect of dust particles accumulation has been modeled as a reduction of the useful area of the PV module. In [1,2,10–12] dust accumulation is taken into account and the relative effects in terms of loss in effective availability irradiance have been discussed.

In any case the most important effect of the presence of dust is a reduction of the PV performances in term of energy production. The reduction can be evaluated by considering, in the same conditions, the difference between the actual power production of the panel and that it would be produced at the beginning of its operative life. This can be performed by considering a model of the panel, which has to be identified as soon as it has been installed [13,14]. In addition to the presence of dust, also the aging of the PV cells have an impact in a reduction of the energy production. So, in order to plan an effective maintenance activity, it is fundamental to distinguish the aforementioned two phenomena [5]. In [2] the authors propose a

* Corresponding author at: Dipartimento di Fisica – Università degli Studi di Milano, Via Celoria, 16, 20133 Milano, MI, Italy. Tel.: +39 02 50317772.

*E-mail addresses:* loredana.cristaldi@polimi.it (L. Cristaldi), lorenzo.ciani@unifi.it (L. Ciani), massimo.lazzaroni@unimi.it (M. Lazzaroni).

[1] Tel.: +39 02 23993715.

solution based on a statistical approach in which a reference panel is cleaned periodically, so that its energy production is just affected by aging. In this proposal the most part of PV panels work at the maximum power point (MPP). Therefore, the model of the PV panel can be replaced by a simple expression which predicts the maximum power in each environmental condition, namely for a given solar irradiance level and cell temperature. This condition allows simplifying both the identification of the model and the prediction of the energy production. In [15], authors propose a possible implementation starting from the data acquired during the normal operation of the reference panel. It is clear that this approach requires the knowledge of the solar radiation [16]. However, it is important to underline that pyranometers, used for solar radiation measurement, are expensive and periodic cleaning and maintenance of these instruments are mandatory, thus resulting in high cost. However, in [13,15] authors investigate the possibility to avoid the employment of a dedicated radiometer. In fact, during sunny days the solar irradiance level on a PV module can be inferred using the measurements provided by a third-part weather station.

In Section 2 the proposed method will be presented. The method is based on an MPP model, which will be presented in the following Section 3. In Section 4 the issue related to the use of data provided by public weather station will be discussed. In Section 5 the experimental setup used for the validation of the model will be presented. In Section 6 the experimental validation is presented considering data provided both by local sensors and public weather station. Conclusions are finally given in Section 7.

## 2. Proposed method

Regarding requirements presented in the previous section, in this paper the authors propose the new method verifying the panel degradation caused by dust and aging. It reduces costs related to the periodic measurement operations (i.e., the periodic human actions on the monitoring apparatus).

To decrease the maintenance costs due to the irradiance measurement and periodic model updates, the authors introduce a new approach based on the model evaluating the maximum power point (MPP).

This model allows estimating the energy production using either a public weather station or a local radiometer data. The use of data provided by public weather station allows furthering reducing the costs of the maintenance.

The method is based on the idea that energy produced by a PV reference panel can be inferred to the energy produced by a PV plant. This assumption is true if two conditions are satisfied:

- The reference PV panel belongs to the same production batch of the panels installed in the PV plant; in this way, it can be considered statistically representative of the batch itself [2].
- An electric model of the PV panel able to predict in each conditions of solar radiation and PV panel temperature must be available.

The method based on the previous assumptions allows reaching two important aims:

- The first one is monitoring the energy losses due to the dust thus allowing to evaluate the time to maintenance (in this case we refer to cleaning activity) of the PV plant.
- The second one is represented by the analysis of the aging.

These aims can be reached by comparing the actual energy production of the reference panel with that estimated on the base of its MPP model.

The reference PV panel is modeled by means of four parameters. Their evaluation does not require additional human resources and can be done in any environmental conditions. Moreover the reference panel has not to be put in out of service.

The model parameter estimation is performed at the PV plant installation time, thus defining the reference condition (aging zero and clean surface). Now comparing the actual energy production with the estimated one, it is possible to evaluate the production reduction. On the base of this evaluation it is possible to plan maintenance activity as shown in [5].

After having cleaned the panels the effect of aging can be evaluated always by means of a comparison between the actual and estimated production. At this point the model parameters can be easily recomputed (in any environmental conditions) thus to define the new reference point for the evaluation of the dust effects.

The trend of the model parameters along time is a clear indicator of the panel degradation due to the aging.

## 3. Prediction of the maximum power

As aforementioned, the presence of dust, the aging process and degradation of the cells leads to a reduction of the power generated by a PV panel for given electrical load and environmental conditions [1,2,15–17]. Therefore, the difference between the actual energy production and the energy that the panel would have produced at the beginning of its operating life for the same solar radiation and panel temperature represents a robust indicator of a malfunction. In [13] authors propose a possible implementation based on a model of the photovoltaic panel. Its parameters have to be estimated just after it has been installed, so that the model can be used to predict the power which the PV module should have produced if it were not affected by dust and aging. The model requires the knowledge of temperature of the cells, which can be estimated by measuring the temperature of a point of the module which has to be as close as possible to the cells [18,19]. Furthermore, the model requires the solar radiation $G$, which in sunny days can be easily estimated with good accuracy from the data provided by weather stations following the procedure descripted in [13] and reported in the next section. Finally, in order to predict the power output, and therefore to estimate the energy production, the model also needs the $V$–$I$ curve of the load connected to the panel. In general, the panel is supposed to operate at its maximum power point, since in most cases it is connected to a switch mode power converter controlled by a maximum power point tracker. In this case, the difference between the predicted maximum power and the actual power of the module represents an indicator of its performance.

Assuming that the PV module always operates at its MPP, another approach can be followed.

An expression of the maximum power point voltage, $V_{mp}$, which the authors have employed to implement a maximum power point tracker [18,20,21] is here reported:

$$V_{mp} = A_0 + A_1 T_c + A_2 \ln(G) + A_3 \ln^2(G) \tag{1}$$

where $T_c$ is the cell temperature, $G$ the solar radiation and $A_0 \ldots A_3$ are constant parameters.

Furthermore, [20] also reports an expression of the maximum point current, $I_{mp}$, which in turn is given by:

$$I_{mp} = B_0 G + B_1 T_c G \tag{2}$$

The product of expressions (1) and (2) gives the maximum power, $P_{mp}$, as a function of the cell temperature $T_c$ and solar radiation $G$:

$$P_{mp} = C_0 G + C_1 G T_c + C_2 G \ln(G) + C_3 G \ln^2(G) + C_4 G T_c^2 + C_4 \ln(G) G T_c + C_6 G \ln^2(G) T_c \tag{3}$$

It can be shown that some terms of the previous equation are very small, so the formula can be simplified without significant loss in accuracy:

$$P_{mp} = C_0 G + C_1 G T_c + C_2 G \ln(G) + C_3 G \ln^2(G) \tag{4}$$

After the elaboration of the unknown parameters, this equation can be used to predict the energy production of the panel if it were not affecting by dust and degradation instead of using a more detailed model. It should be noticed that the estimation of these parameters is extremely simple, and requires a database which contains the values of maximum power together with the corresponding panel temperature and solar radiation. $C_0 \ldots C_3$ can be obtained through an ordinary least squares estimation, since the problem is linear in the parameters.

The data can be gathered during the regular operation of the PV plant, without the need of putting the panel offline. However, an adequate range of temperature and solar radiation should be covered, and of course the behavior of the panel is supposed not to change during the collection of the data. Therefore, the database construction should be quick if compared with the accumulation of dust and the degradation of the cells. Since both these processes are quite slow, the data collection may take a whole month.

Both the building of the database and the prediction of the power output require the measuring of the temperature of the cells, which is quite difficult. In most cases they are mounted on a frame which also acts as a heath sink. Therefore the frame temperature $T_p$ is quite close to $T_c$ thus allowing to use $T_p$ instead of $T_c$.

## 4. Using the data provided by a public weather station

As discussed in the previous section, the proposed approach requires the measurement of the solar radiation. Using the data provided by a public weather station instead of installation of a dedicated radiometer, advantages in terms of reliability, accuracy and cost can be obtained. However it is important to highlight that this solution shows some potential limitations:

(a) The time resolution of the provided data.
(b) The transformation of the solar radiation from the horizontal plane to the PV panel one.
(c) The distance between the PV panel and the weather station.

In the following a brief discussion about these problems is reported.

### 4.1. Time resolution of the data

Weather stations usually provide the data with a relatively slow sampling time, which typically goes from some minutes to 1 h. It is clear that the impact of the time resolution on the predicted energy production strictly depends on the variability of the solar radiation. In fact, during cloudy days, when the solar radiation may quickly change, the large time step may introduce a significant error. On the contrary, during sunny days, the solar irradiance changes slowly, therefore low sampling rates can be employed as discussed in [13].

### 4.2. Inclination of the PV panel

In general, meteorological measurement stations are installed to provide information useful in agricultural applications. For this reason the measurement of the solar radiation is performed on the horizontal plane. Since its value on an inclined plane may be significantly different, an algorithm for estimating the irradiance level on the PV panel under test has to be employed [13]. Of course, obstacles which partially hide the Sun path have to be taken into account.

According to Fig. 1 where shadows due to the presence of obstacles on the Sun is represented, the estimation of the solar irradiance level $G_{PV}$ on the module can be performed as follows:

$$G_{PV} = \begin{cases} G_{bh} \max\left\{\frac{\cos(\psi_{PV})}{\cos(\psi_0)}, 0\right\} + G_{dh}\frac{1+\cos(\rho_{PV})}{2} & \text{when the rays directly hit the panel} \\ G_{dh}\frac{1+\cos(\rho_{PV})}{2} & \text{when the Sun is behind an obstacle} \end{cases} \tag{5}$$

Considering the coordinate system adopted to compute the solar radiation on the panel surface represented in Fig. 2, the angles in Eq. (5) can be summarized as:

- $\psi_0$, angle between the normal to the horizontal surface and the direction of the beam radiation (solar altitude angle).
- $\psi_{PV}$, angle between the normal to the surface of the PV module and the direction of the beam radiation (solar altitude angle with respect to the panel surface).

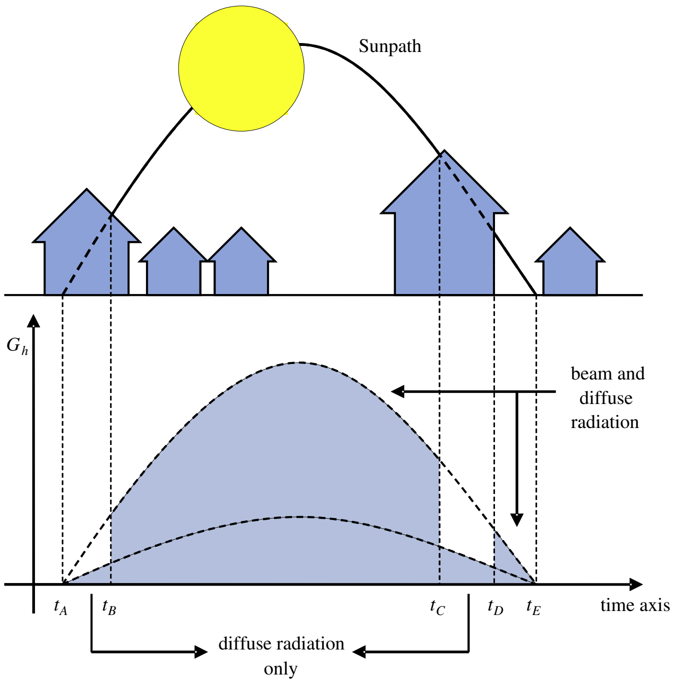


**Fig. 1.** Shadows due to the presence of obstacles on the Sun path.

- $\rho_{PV}$, inclination angle of the module.
- $\zeta$, angle between the south direction and the direction of the beam radiation on the horizontal plane.
- $\zeta_{PV}$, angle between the south direction and the direction normal to the panel surface on the horizontal plane.

Both $\psi_0$ and $\psi_{PV}$ depend on the direction of the beam radiation; therefore the pattern of the apparent position of the Sun has to be considered in order to compute the corresponding values for a given time [13].

Unfortunately some weather stations just provide the global radiation on the horizontal plane, while the transformation technique requires separating the beam from the diffuse radiation. It is not easy to directly estimate the direct radiation, since it is highly dependent on the weather conditions. On the contrary, the diffuse component is just weakly affected by the weather, and can be estimated by means of a clear sky model [13]. So, the beam radiation can be computed as the difference between the global radiation and the diffuse component.

Moreover, since diffuse radiation is lower than the direct one (in sunny and partly cloudy days) the errors have a relatively weak effect in computing the solar irradiance on the surface of the PV panel.

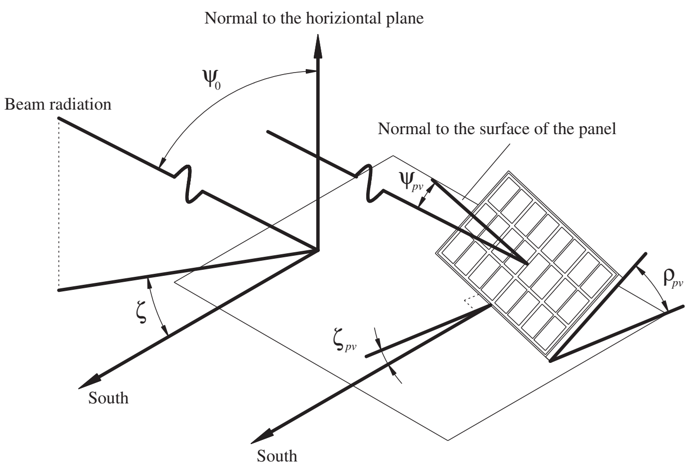


**Fig. 2.** Coordinate system for computing the solar radiation on the panel surface.

### 4.3. Distance between the PV panel and the weather station

Another factor which could significantly affect the estimation of the production is represented by the distance between the weather station and the PV panel under test. However, assuming that the weather station is close to the tested panel (about few kilometers) the apparent position of the Sun with respect these two points can be reasonably considered the same. The study assumes that the solar radiation measured on the weather station is the same of the place where the PV panel is installed. This hypothesis is true with good accuracy during sunny days, but it is not in case of non-uniform clouds. In this case the irradiation of the ground can vary significantly in the range of few hundreds of meters, thus employing the radiation data provided by the weather station may lead to unacceptable errors.

## 5. Experimental setup

The accuracy of the estimated energy production has been evaluated through an experimental activity. The test setup is depicted in Fig. 3, and comprises a ICO5W PV module made of 36 $50 \times 20$ mm poly-crystalline silicon cells [22]. The panel is connected to an electronic load which allows setting the operating point on the *V–I* plot. The voltage and current have been acquired by means of a PC equipped by a National Instruments NI 9215 board, with four simultaneous sampling, isolated 16-bit analog input channels, with a ±10 V range and 100 kHz maximum sampling rate. A resistive divider has been used as voltage transducer, while the current measurement is provided by a shunt resistor. The frame temperature of the module $T_p$ has been measured by using a PT100, while a class 1 CMP 21 global radiometer has been employed as solar radiation transducer; its position has been carefully adjusted in order to match the orientation of the PV module. The PC with a dedicated 16 bit serial interface provides the acquisition of the two environmental quantities. The computer clock has been synchronized with a primary network time protocol server of the Italian Istituto Nazionale di Ricerca Metrologica (INRIM). The management of the data acquisition and the control of the electronic load have been provided by a Virtual Instrument (VI) developed by the authors in National Instrument LabView.

## 6. Validation of the proposed approach

The experimental setup described in the previous section has been employed to test the accuracy of the predicted power production using the proposed technique. The solar radiation $G$ and the panel temperature $T_p$ have been acquired from May 2013 to June 2013 with a sampling time of 60 s. For each sample of temperature and solar irradiance, the *V–I* curve of the panel have also been acquired thanks to a proper control of the electronic load. The process is extremely fast – less than 100 ms – so that both the solar radiation and panel temperature can be assumed constants in this interval. This allows to obtain in an easy way the maximum power for each value of solar radiation and module temperature, as required by proposed the method. In the same period, the solar radiation acquired by a weather station is available. It is about 1.5 km far from where the modules have been installed, the sampling time is 60 s and synchronized with the GPS PPS signal. The synchronization accuracy between two data acquisition systems is better than one second, which is more than adequate since the variation of the solar irradiance is slow during sunny days.

The solar irradiance on the panel has been estimated by using the data from the weather station together with the technique reported in a previous section, thus obtaining $G_{est}$. As expected, $G$ and $G_{est}$ are quite close during sunny days, as shown in Fig. 4. In this case, the maximum

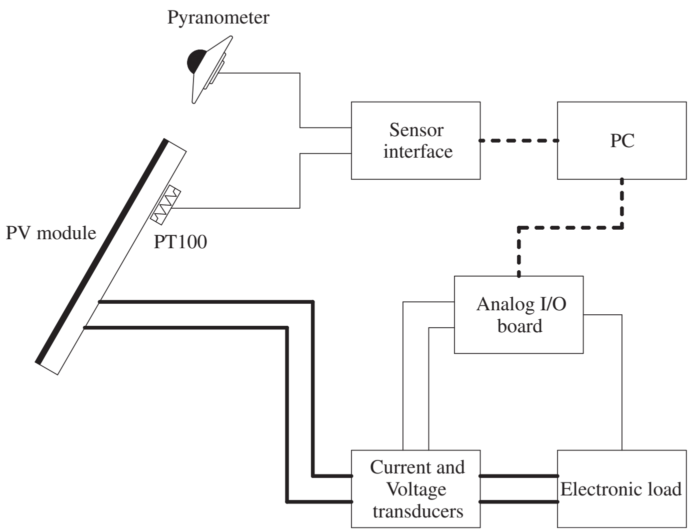


**Fig. 3.** Experimental setup.

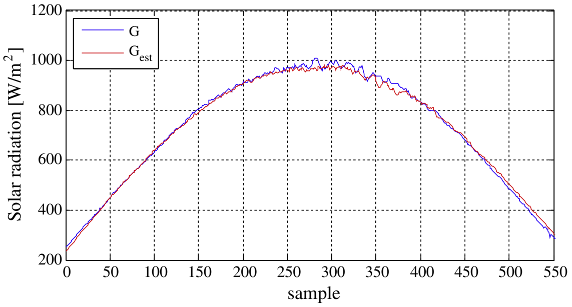


**Fig. 4.** Solar irradiance on the panel: measurement from a nearby radiometer and estimation from the data provided by the weather station over a typical clear day.

**Table 1**
Coefficient for predicting the maximum power obtained using $G$ and $G_{est}$.

| Parameter | Using $G$ | Using $G_{est}$ |
|---|---|---|
| $C_0$ ($m^2$) | −0.0474 | −0.0307 |
| $C_1$ ($m^2$/°C) | $-6.54 \times 10^{-6}$ | $-5.97 \times 10^{-6}$ |
| $C_2$ ($m^2$) | 0.0166 | 0.0113 |
| $C_3$ ($m^2$) | $-1.27 \times 10^{-3}$ | $-8.52 \times 10^{-4}$ |

difference is lower than 35 W/m$^2$ when the solar radiation is about 1000 W/m$^2$. It should be noticed that it has the same order of magnitude as the uncertainty of the employed radiometer.

The data acquired during the first five sunny days of the considered period have been extracted, and the samples where the solar radiation is greater than 200 W/m$^2$ have been employed to compute the constants $C_0 \ldots C_3$ both using $G$ and $G_{est}$ by means of a least square fitting. The results are reported in Table 1 and the corresponding functions which allows predicting the maximum power from the panel temperature and solar radiation are plotted in Fig. 5. As expected, the two functions are very similar, especially in the range of temperature and solar radiation which has been covered by the data employed during the fitting. In particular, the maximum difference of the predicted maximum power is about 0.1 W considering a temperature in the range (280–340) K and a solar irradiance level between 200 and 1100 W/m$^2$.

After the parameters computation, it is now possible to test the accuracy of the proposed method. The data corresponding to the sunny days which have not been employed during the fitting and with a solar radiation greater than 200 W/m$^2$ have been considered and the predicted maximum power (using both $G$ and $G_{est}$) have been compared to the measurement. To this aim, the threshold on the solar radiation has been introduced in order to consider just the intervals where the energy production is significant. The results of the comparison on a typical sunny day are shown in Fig. 6. Fig. 7 reports the error of the predicted maximum power both using the local measurement of the solar irradiance and the estimation using the data provided by the weather station. Both the predictions are quite good, since the maximum errors are 0.16 W and 0.27 W using $G$ and $G_{est}$ respectively. It should be noticed that the maximum error in estimating the maximum power using the data from the weather station drops to 0.11 W if two outliers were removed from the data. A significant indicator of

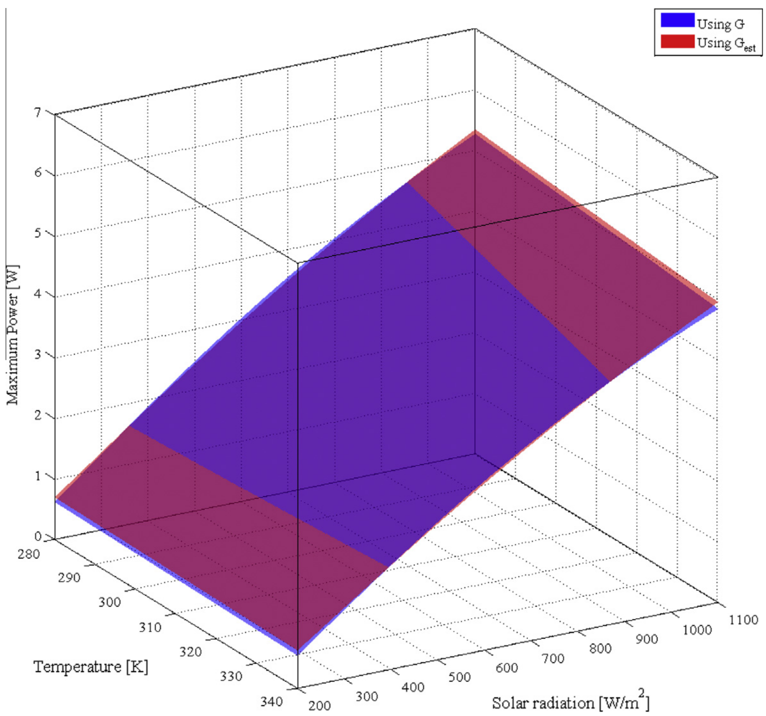


**Fig. 5.** Plots of the functions allowing the estimation of the maximum power using the direct measurement of the solar irradiance and the data provided by a weather station.

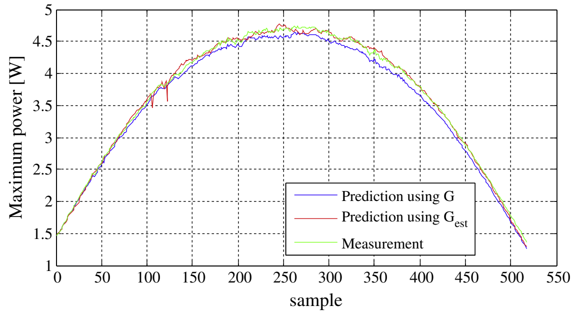


**Fig. 6.** Comparison between the measured and the predicted maximum power over a typical clear day.

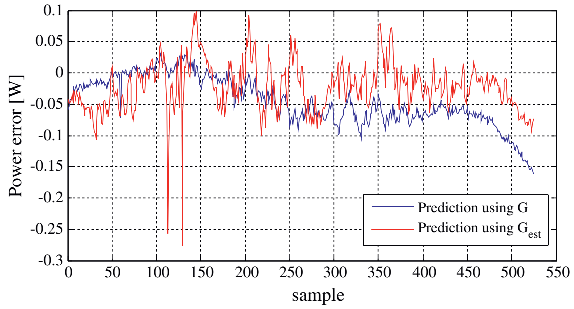


**Fig. 7.** Error in predicting the maximum power using the local measurement of solar irradiance and the data provided by a weather station during a typical clear day.

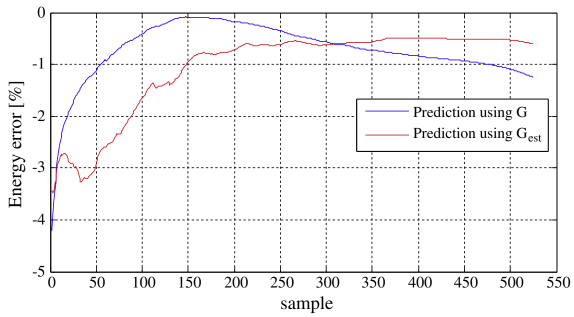


**Fig. 8.** Error in predicting the energy production using the local measurement of solar irradiance and the data provided by a weather station during a typical clear day.

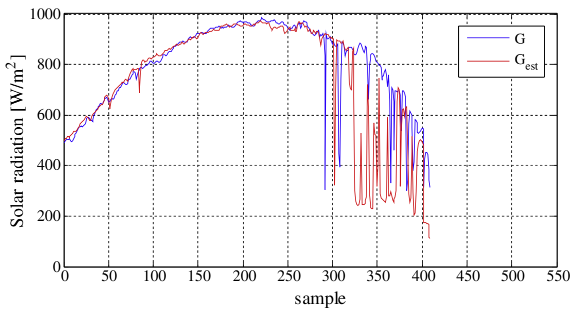


**Fig. 9.** Solar irradiance on the panel: measurement from a nearby radiometer and estimation from the data provided by the weather station over a cloudy day.

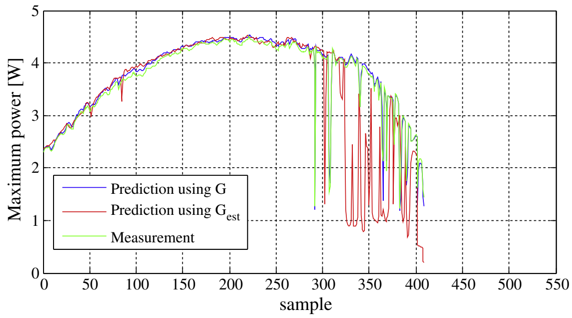


**Fig. 10.** Comparison between the measured and the predicted maximum power over a partly cloudy day.

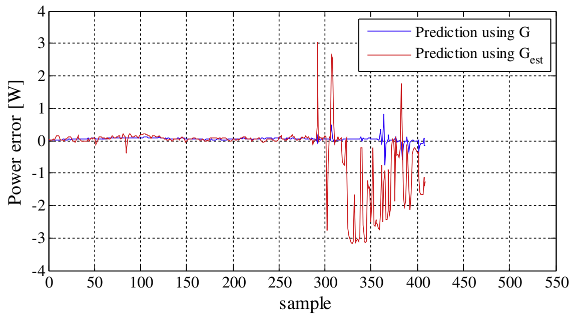


**Fig. 11.** Error in predicting the maximum power using the local measurement of solar irradiance and the data provided by a weather station during a partly cloudy day.

the quality of the estimations is the root mean square error, which is 0.035 W using the local measurement of solar radiation and 0.028 W if the data from the weather station is employed. Therefore, it can be deduced that using the radiation measurement of a weather station does not affect the prediction of the maximum power noticeably, thus avoiding the cost of a dedicated radiometer.

The difference between the energy actually produced by a PV panel and the energy produced at the beginning of its operating life is key for the condition monitoring and for the planning of the maintenance activities. The focus of this paper is not discussing the effect of the quantization on the estimation of the energy production (this aspect has been investigated in [12]) but the possibility of employing the maximum power predicted by the proposed techniques. Therefore it is interesting to compare the time integration of the maximum power predicted by the proposed method (both using $G$ and $G_{est}$) with the integral of the measured maximum power, which have been sampled with the same frequency. The integration has been performed by using the trapezoidal rule. Fig. 8 reports the percent error in predicting the energy production in a typical sunny day, both using $G$ and $G_{est}$. It always remains below 1.7% in both cases; therefore a dedicated radiometer is not needed for planning an effective maintenance strategy [5].

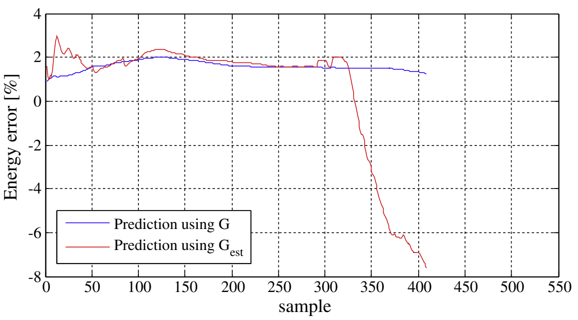


**Fig. 12.** Error in predicting the energy production using the local measurement of solar irradiance and the data provided by a weather station during a partly cloudy day.

During cloudy days, and in general with variable weather, it is not possible to obtain an accurate estimation of solar irradiance on the module using the data provided by the weather station, as shown in Fig. 9. The estimation is quite precise before sample 280 (which has been acquired at about 2 pm) when the sky was clear. After that $G$ is noticeably different than $G_{est}$ because of the effect of the clouds. Therefore, in these conditions the error in predicting both the maximum power and the energy production using $G_{est}$ is not acceptable once the sky had become cloudy, as depicted in Figs. 10–12. However, the employment of a dedicated radiometer allows a good prediction even in these conditions.

Moreover it must be noticed that from the point of view of the maintenance activity this error is not so key. In fact, in cloudy days energy production is quite low, therefore the percentage error in the evaluation of the total energy over a medium/long period of time is low even when public weather station data are employed [13].

## 7. Conclusions

In the paper a method allowing estimating the reduction of the energy production of a PV module due to the aging or the presence of dust on its surface has been presented. The approach is based on the use of a reference panel and a simple model allowing the prediction of the generated power. It has also been shown that this technique is also effective when the measurement of the solar radiation is performed by a public weather station and not measured by a dedicated pyranometer, thus reducing the cost. In this case, the error in predicting the energy production does not increase noticeably during sunny days, and the good accuracy permits the implementation of the maintenance strategies proposed by the authors in a previous paper.

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