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The effect of soiling on energy production for large-scale photovoltaic plants

A. Massi Pavan [a,b,*], A. Mellit [c,1], D. De Pieri [b]

[a] Department of Industrial Engineering and Information Technology, University of Trieste Via A. Valerio, 6/A – 34127 Trieste, Italy
[b] Q.Cells International Italia S.r.l. Via G. Nicotera, 29 – 00195 Roma, Italy
[c] Department of Electronics, Faculty of Sciences Engineering, LAMEL, Jijel University, Ouled-Aissa P.O. Box. 98, Jijel 18000, Algeria

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Abstract

This work aims to evaluate the effect of soiling on energy production for large-scale ground mounted photovoltaic plants in the countryside of southern Italy. Since the effect of pollution can seriously compromise the yield of solar parks, the results obtained in this study can help the operation and maintenance responsible in choosing the proper washing schedule and method for their plants and avoid wasting money. In order to determine the losses due to the dirt accumulated on photovoltaic modules, the performances at Standard Test Conditions (STC – Irradiance: 1000 W/m^2; Cell temperature: 25 °C; Solar spectrum: AM 1.5) of two 1 MW$_p$ solar parks before and after a complete clean-up of their photovoltaic modules have been compared. The performances at STC of the two plants have been determined by using a well-known regression model that accepts as an input two climate data (the in-plane global irradiance and the photovoltaic module temperature), while the output results in one electrical parameter (the produced power). A regression model has been preferred to a common performance ratio analysis because this latter is too much influenced by the seasonal variation in temperature and by the plant availability. The results presented in this work show that both the soil type and the washing technique influence the losses due to the pollution. A 6.9% of losses for the plant built on a sandy soil and a 1.1% for the one built on a more compact soil have been found. Finally, these results have been used in order to compare the washing costs with the incomings due to the performance improvement.

Keywords: Large-scale photovoltaic plant; Soiling; Pollution; Performance; Produced energy

1. Introduction

With reference to Fig. 1, during the last 4 years the Italian photovoltaic market has been growing exponentially following a tendency already widely seen especially in Germany. This impressive growth has been driven by the introduction, at the end of 2005, of the feed in tariff mechanism which ensures satisfactory payback times and investment productivities to the investors. During 2009, the Italian photovoltaic market has been the second one for installed power all around the world.

As reported in Table 1, during 2009 the Italian installed power has grown at a rate of 165% with respect to 2008. Since the major part of the Italian market (69.5%) is focused on large size plants, this work investigates the operations of two 1 MW$_p$ photovoltaic systems.

The accumulation of dirt on solar panels (“soiling”) can have a significant impact on the performance of PV systems. Much of the information available is applicable only

* Corresponding author at: Department of Industrial Engineering and Information Technology, University of Trieste Via A. Valerio, 6/A – 34127 Trieste, Italy. Tel.: +39 040 5587970.
E-mail address: apavan@units.it (A. Massi Pavan).
[1] Abdus Salam International Centre for Theoretical Physics (ICTP), Strada Costiera, 11 – 34151 Trieste, Italy.

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Nomenclature

AC	alternating current
A, *B*, *C*, *D*	polynomial coefficients
CAN	controller area network
DC	direct current
H_i	in-plane global solar irradiance (W/m^2)
I_{DC}	current produced by the photovoltaic strings (A)
MPPT	maximum power point tracker
PV	photovoltaic
STC	standard test conditions (Irradiance: 1000 W/m^2; Cell temperature: 25 °C Solar spectrum: AM 1.5)
T_{mod}	photovoltaic module temperature (°C)
V_{DC}	direct current bus voltage (V)

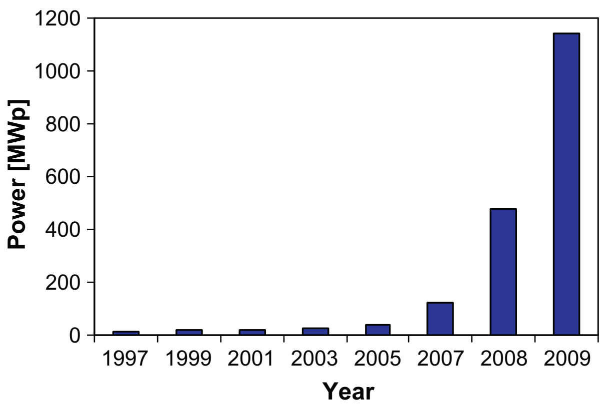

Fig. 1. Italian overall installed PV power.

Table 1
Italian installed PV power for power classes during years 2008 and 2009.

Power	2008 MW_p	2009 MW_p	%	$\Delta_{2008–2009}$
(1–3) kW_p	40.6	86.7	7.5	+113%
(3–20) kW_p	112.7	262.9	23.0	+133%
>20 kW_p	278.2	792.7	69.5	+185%
Total	431.5	1142.3	100	+165%

to the specific location in which the testing was conducted (Kimber et al., 2006). The most impressive result found in literature shows that about 8–10% of the power loss registered can be removed by cleaning the arrays (Haeberlin and Graf, 1998). Soiling losses in thermal solar collectors were studied by Biryukov et al. (Biryukov et al., 1999) and by Garg (Garg, 1974). The effect of soiling in concentrator photovoltaics was studied recently (M. Vivar et al., 2010)."

This work deals with the effect of soiling on the energy production of big solar parks installed in the countryside of southern Italy. Does the dirt on PV modules have an impact on their capacity to produce energy in this region? If yes, how much does the pollution decrease their efficiency? Answers to these questions are essential both to predict PV plants performance (Hammond et al., 1997) and to calculate a reasonable cash flow analysis (Lughi et al., 2008). This latter is a fundamental issue in a country like Italy where, as incentives to the investment in grid connected photovoltaic plants are given through a feed in tariff mechanism, the produced energy plays a fundamental role because of its strong relation with the payback (PB) time and the investment productivity (IP) (Mellit and Massi Pavan, 2010a). Moreover, correct estimates of losses due to the pollution effect on a given PV plant also enable technicians to provide reliable yield calculations that are required for developing dispatch plans. Indeed, these latter have to be provided in order to well integrate the grid connected photovoltaic plants into the new distributed generation concept (Mellit and Massi Pavan, 2010b).

How the pollution affects the energy yield is the question which this study aims to answer. Consequently this research monitored the operations of two photovoltaic plants installed in Puglia before and after a complete clean-up of their PV modules. It should be noted that Puglia represents – both in 2008 with 53 MW_p and in 2009 with 214 MW_p installed – the first region in Italy for PV installations.

In order to predict the power produced at Standard Test Conditions (Irradiance: 1000 W/m^2; Cell temperature: 25 °C; Solar spectrum: AM 1.5, hereafter briefly STC) before and after the clean-up process, a regression model to represent the behaviors of the two PV plants has been used. The comparison between the power rates before and after that the PV modules have been washed is related to the soiling effect on the PV plants performances.

This article is organized as follows: the next section gives a short description of the two PV plants under study. The database used is presented in Section 3. The polynomial regression model used for determining the behaviors of the two systems is discussed in Section 4. Results and discussion are presented in Section 5 and, finally, conclusions are given in Section 6.

2. Photovoltaic plants description

The two solar parks under study have been ground mounted with the use of a certain number of rammed poles. The PV plants are connected to the distribution grid and implement a centralized conversion (Massi Pavan et al., 2007) since each of the two inverters has one MPPT. The low voltage inverter outputs are raised to 20 kV via a transformer allowing the connection with the medium voltage electrical grid. Climate and electrical data are stored in

Fig. 2. Geographical location of the two studied PV plants.

a data logger and made available via a server connected to the web.

2.1. Location and geometrical parameters

The two PV plants object of the present study are installed in the region of Puglia in the southern of Italy (latitude 41° 7′ 31″ N, longitude 16° 52′ 0″ E). Fig. 2 shows the geographical locations of the two PV plants that have been built in the countryside. Each plant is south exposed; the tilt angle is 25°, and the shading angle due to the presence of parallel rows of PV modules is 20°. Fig. 3 shows one of the two monitored plants.

2.2. Electrical architectures

A block scheme of the considered photovoltaic plants is depicted in Fig. 4.

The strings are made of 20 series connected PV modules, while groups of 16 strings are parallel connected into 16 DC boards where fuses prevent over currents into the strings. The DC boards implement also some surge protective devices for limiting over voltage due to lightning.

Two groups of eight DC boards are then connected to the DC side of two inverters that convert the direct currents produced by the PV strings into an alternating current which is compatible and synchronized with the grid.

Finally, the AC side of the two inverters is connected to a double primary transformer that converts the low voltage output of inverters (315 V) up to 20 kV corresponding to the nominal voltage of the electrical grid.

2.3. Photovoltaic modules

The PV plants are made with Q.Cells multi-crystalline silicon QC-C04 modules; their electrical data are reported in Table 2.

The nominal power of the PV modules has been chosen so that the total nominal power of each PV plant would be 0.99 MW_p.

These PV modules are made of 60 multi-crystalline silicon solar cells that are embedded in EVA (ethylene–vinyl-acetate) plastic which is resistant to UV radiation. The frame consists of a torsion-resistant, corrosion-resistant aluminum alloy. The front panel of the modules is made of thermally pre-stressed solar glass. This glass guarantees both a high degree of transparency and protection for the solar cells from external weathering influences such as hail, snow and ice. A Tedlar® polyester foil on the rear side guarantees a long life duration. The junction box on the rear side is equipped with bypass diodes.

Fig. 5 shows the effect of the pollution on some PV modules.

Fig. 3. One of the two monitored PV plants.

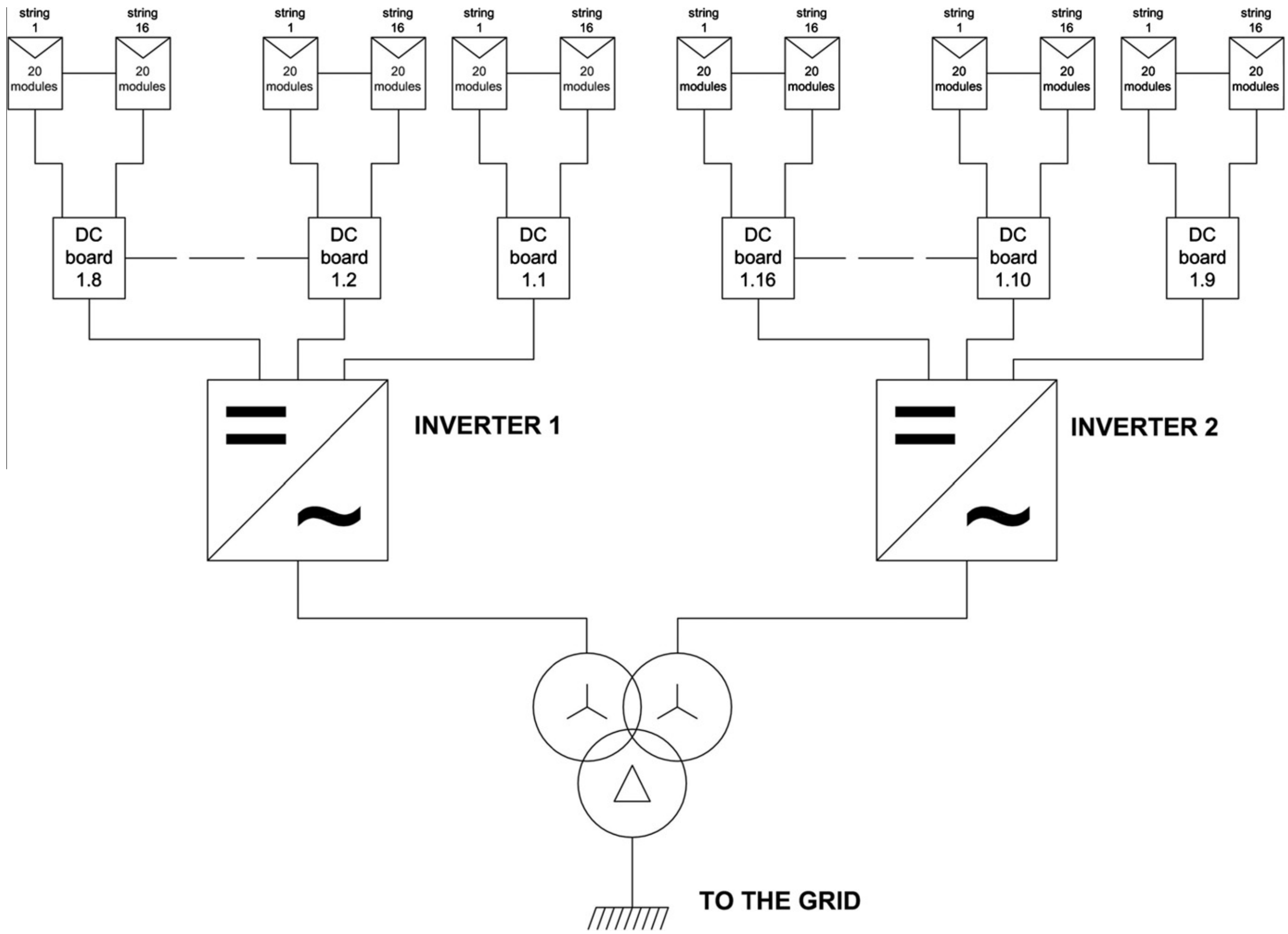

Fig. 4. Blocks scheme for the considered PV plants.

Table 2
STC electrical data for Q.Cells QC-C04 PV modules.

Power class	210	215	220	225	230	235
Nominal power (W)	210	215	220	225	230	235
Short circuit current (A)	8.10	8.20	8.30	8.40	8.45	8.55
Open circuit voltage (V)	35.90	36.10	36.25	36.35	36.40	36.50
Current at maximum power point (A)	7.45	7.55	7.65	7.75	7.85	7.95
Voltage at maximum power point (V)	28.30	28.60	28.80	29.00	29.20	29.40
Current/temperature coefficient (%/K)	+0.05					
Voltage/temperature coefficient (%/K)	−0.37					
Power/temperature coefficient (%/K)	−0.47					

2.4. Monitoring system

The monitoring system which has been used consists in:

- an acquisition board installed in each DC board which logs the current produced by a couple of strings and the DC bus voltage;
- a radiation sensor, shown in Fig. 6a, which is a reference solar cell installed in-plane with the PV modules;
- a Controller Area Network Bus interface;
- two temperature sensors for module and ambient temperature acquisition which are of the type Pt1000 and shown in Fig. 6b and c respectively;
- a data logger produced by Skytron® Energy named Skylog®;
- a server for the storage of the acquired dataset. This equipment, named Skyserv®, is connected to the web and also calculates the produced power and energy for each plant.

3. The used datasets

In order to determine the behavior of the two PV plants at STC, for each system two datasets of electrical and climate data have been collected: the first corresponding to

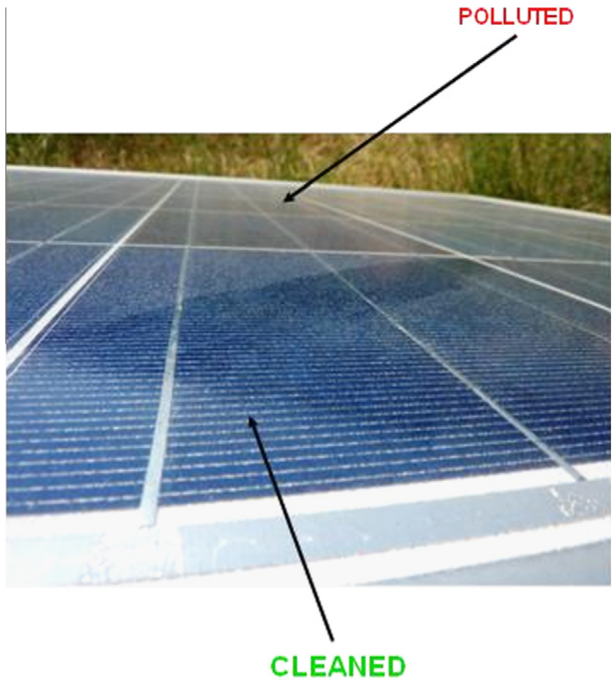

Fig. 5. Pollution effect on the PV modules.

soiled PV modules and the second to cleaned ones. It must be noted that the PV modules have been operating for approximately one year before that the clean-up was performed.

Two different washing procedures have been adopted for the two plants. In both cases the PV modules have been squirted with under pressure distilled water, while the PV modules of plant number 1 have also been brushed.

The first acquisition period goes from June 21st to August 15th 2010, while the second one is from September 1st to October 21st 2010.

For each plant, and for each of the two periods of operation, the following measures have been used:

– the current produced by two couples of parallel connected PV strings I_{DC};
– the DC bus voltage V_{DC};
– the module temperature T_{mod};
– the in-plane global irradiance H_i.

Fig. 7 shows the collected data for both sites (here after named plant number 1 and plant number 2) during period June 21st–30th 2010; the sampling time is 15 min. The power values shown in Fig. 7 have been calculated multiplying the DC bus voltage V_{DC} by the current I_{DC}.

4. Polynomial regression model

The IEC standard 61724 defines three performance parameters for assessing the overall operation of a PV system: the reference yield Y_r (hours), the system yield Y_f (hours) and the performance ratio PR (dimensionless).

An evident limitation for purposes of this work is that the above parameters are clearly influenced by weather (Marion et al., 2005):

– Y_r is the ratio between the total in-plane irradiance and the reference irradiance – has a month-to-month and year-to-year weather variability;
– Y_f is the ratio between the produced energy and the nominal power of the PV generator – is influenced by solar radiation;
– PR – the ratio between the system yield and the reference year – is influenced less by the weather as its value is normalized with respect to solar radiation, but it is still influenced by seasonal variations in temperature and by plant availability.

In order to make results independent from weather, other parameters for performance characterization have been proposed in literature:

– PVUSA rating method (Whitaker et al., 1997) which assumes that the array current is dependent on irradiance, while the voltage on array temperature. The model needs the following climate data: irradiance on the array plane, ambient temperature and wind speed;
– SANDIA array performance model (Whitaker et al., 1997) which uses a set of equations for determining the power at maximum power point at arbitrary conditions.

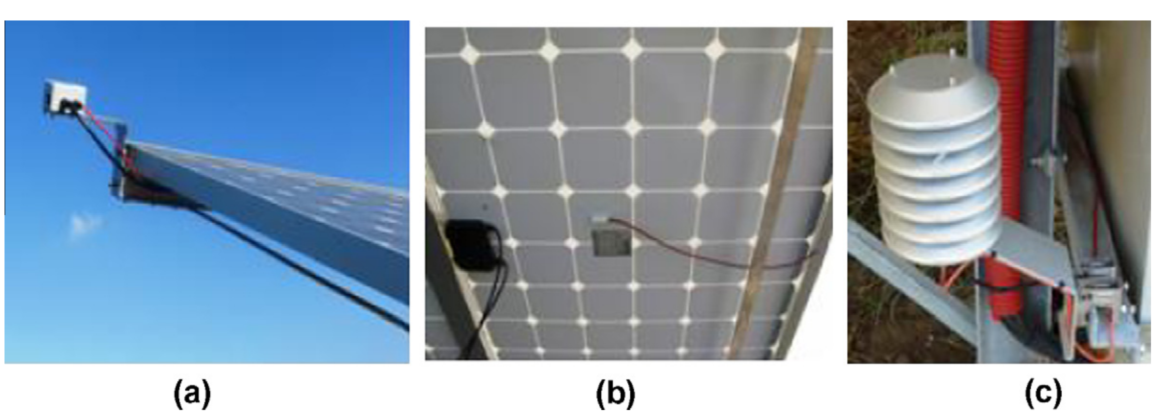

Fig. 6. Reference cell (a), module (b) and ambient temperature (c) sensors.

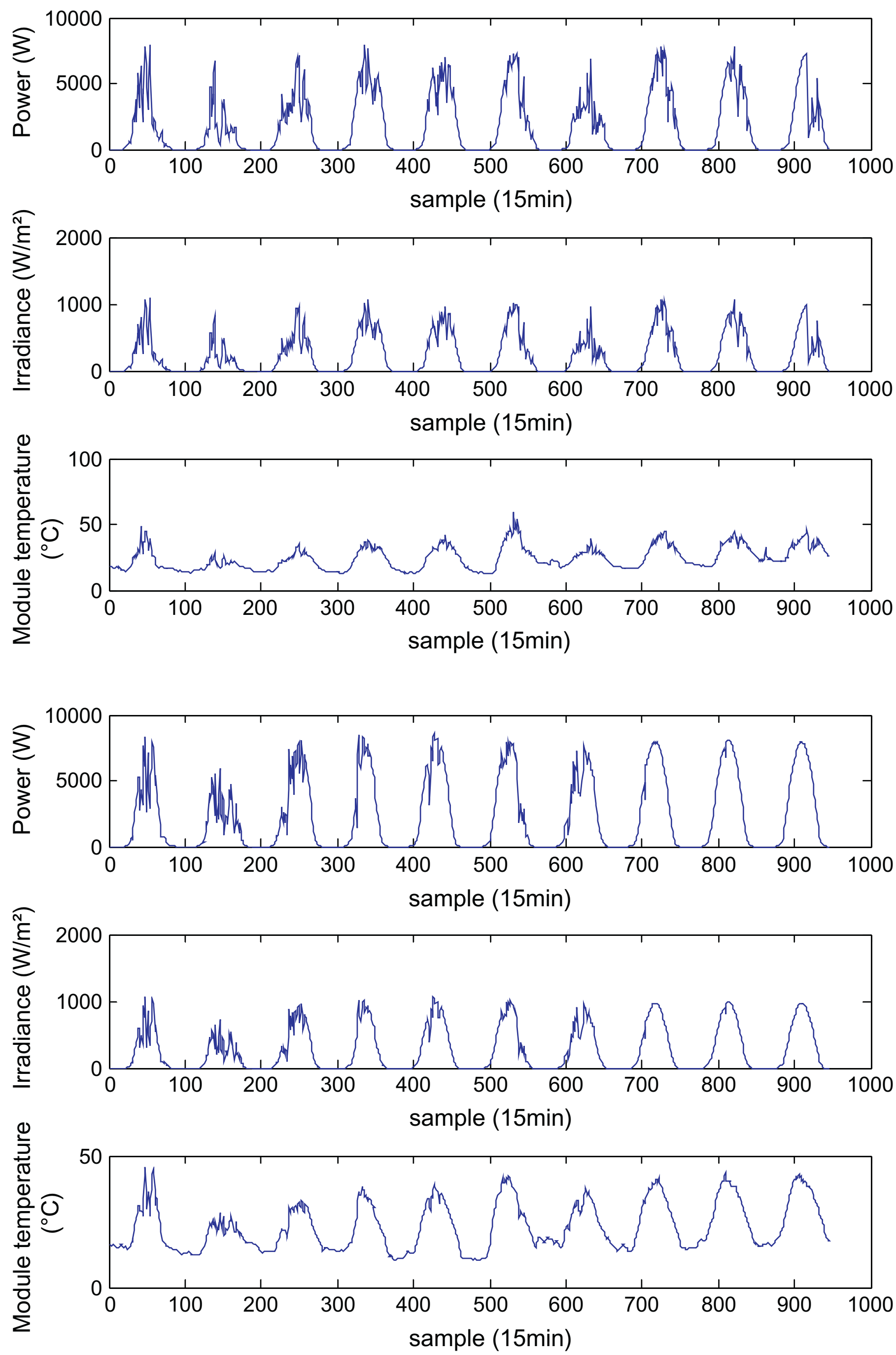

Fig. 7. DC power, in-plane global irradiance, and module temperature for the two PV plants before that the modules have been cleaned (period June 21st–30th 2010).

As climate parameters, this model needs the array plane irradiance and the cell temperature. The model also needs the knowledge of used PV module parameters as short circuit current at STC, open circuit voltage at STC, voltage, current and power temperature coefficients, etc. Finally, some empirical relationships used to compensate the influences of the solar spectrum and solar angle of incidence are also used;

– A generic polynomial regression model to simulate the performance of a selected PV system described in Eq. (1).

$$P = A + B \cdot T_{mod} \cdot H_i + C \cdot H_i + D \cdot H_i^2 \quad (1)$$

where T_{mod} is the PV module temperature; H_i is the in-plane global irradiance; A, B, C and D are polynomial constants.

First of all, the simulation procedure requires the calibration of the model to the system under study in order to obtain A, B, C and D that best represent the behavior of the system. Once the model is well adjusted, the same constants are used along with new temperature and

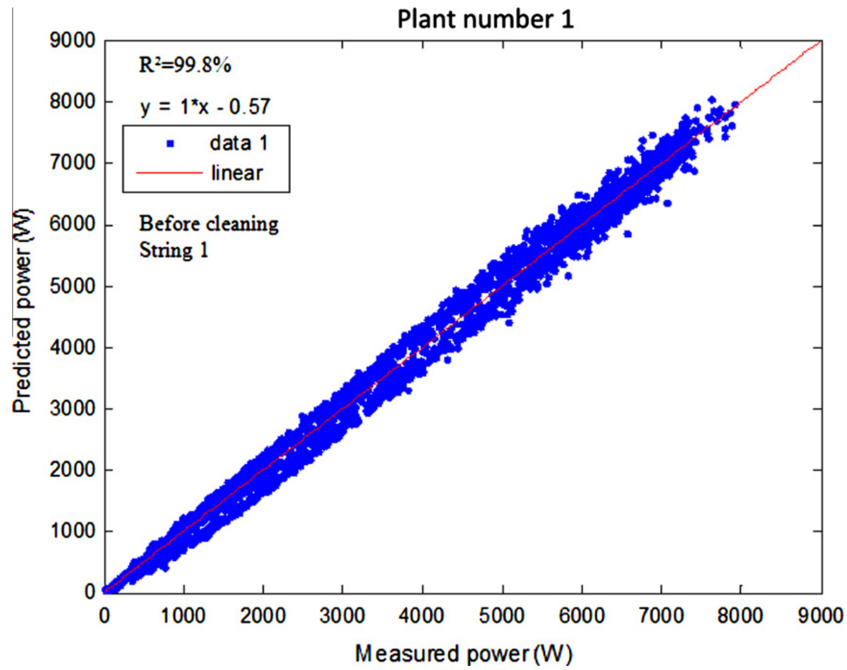

Fig. 8a. Measured and predicted powers before that the PV modules of plant 1 have been cleaned.

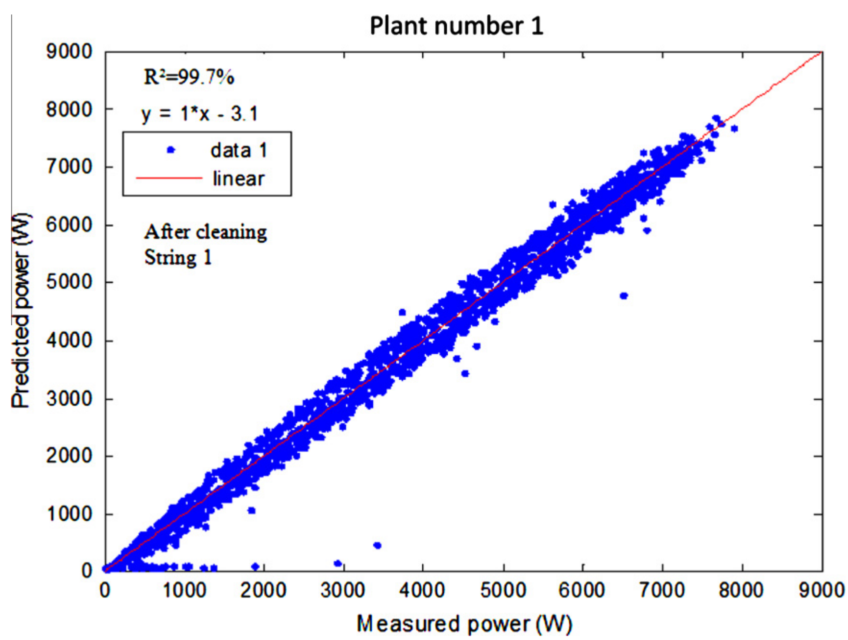

Fig. 8b. Measured and predicted powers after that the PV modules of plant 1 have been cleaned.

irradiance inputs to predict the power generated by the system (Mayer et al., 2008).

As the monitoring system available for the studied systems does not provide a dataset for the wind speed and the empirical compensation relationship for solar spectrum and solar angle are unknown, the latter method has been chosen for determining the powers at STC for the cleaned and polluted systems.

The two datasets for each plant are related to eight (when the PV modules were polluted) and seven weeks (after that the clean-ups have been performed) of operation that represent an adequate time span to determine the regression coefficients A, B, C and D with the non-linear least squares. The large-scale algorithm has been chosen; this algorithm is a subspace trust region method and is based on the interior-reflective Newton method described in (Coleman and Li, 1994). Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG).

Table 3a
Polynomial coefficients as calculated for the two couples of strings of plants number 1 and number 2.

	Couple of string # 1	Couple of string # 2
PV plant # 1		
Dirty modules	$A = -2.2743$	$A = -3.3700$
	$B = -0.0058$	$B = -0.0049$
	$C = 8.4705$	$C = 8.3658$
	$D = -9.0960E\text{-}4$	$D = -8.8777E\text{-}4$
Cleaned modules	$A = -1.5452$	$A = -3.0104$
	$B = -0.0179$	$B = -0.0159$
	$C = 9.0827$	$C = 8.8061$
	$D = -6.9031E\text{-}4$	$D = -5.6264E\text{-}4$
PV plant # 2		
Dirty modules	$A = 8.8497$	$A = 8.5022$
	$B = -0.0145$	$B = -0.0142$
	$C = 9.2233$	$C = 9.1693$
	$D = -0.0011$	$D = -0.0010$
Cleaned modules	$A = -4.9301$	$A = -3.4658$
	$B = -0.0120$	$B = -0.0110$
	$C = 9.0477$	$C = 9.0888$
	$D = -8.6800E\text{-}4$	$D = -9.6359E\text{-}4$

Table 3b
STC powers before and after that the PV modules inserted into the strings of plant number 1 and 2 have been cleaned.

	Couple of string # 1	Couple of string # 2	Average
PV plant # 1			
STC power for dirty modules (kW)	7.4124	7.3528	7.3826
STC power for cleaned modules (kW)	7.9431	7.8423	7.8927
STC power difference (%)	7.2	6.7	6.9
PV plant # 2			
STC power for dirty modules (kW)	7.7731	7.7784	7.7758
STC power for cleaned modules (kW)	7.8741	7.8479	7.8610
STC power difference (%)	1.3	0.9	1.1

Table 4
Economical index overview.

	Plant # 1	Plant # 2
Cash inflow (€/year)	600.000,00	600.000,00
Losses due to pollution (%)	6.9	1.1
Money lost because of the pollution (€/year)	41.400,00	6.600,00
Washing cost (€)	2.500,00	2.500,00
Average hidden washing cost (€)	1.644,00	1.644,00
Total washing cost (€)	4.144,00	4.144,00

For each plant, the first dataset has been used in order to obtain the polynomial constants (A, B, C and D) representing the polluted PV strings of the two plants. By imposing to Eq. (1) a cell temperature of 25 °C and an irradiance of 1000 W/m^2, the STC powers for the polluted PV strings have then been obtained.

The same procedure has then been applied to the second dataset in order to determine the STC powers for the washed PV strings.

5. Results and discussion

As described in the previous Section, Eq. (1) has been used in order to determinate the STC powers for both plants before and after that the cleaning had been performed. Fig. 8a and b show the correlation between the measured powers and the ones that have been predicted by using the regression model for plant number 1 before and after that the PV modules have been washed. As can be seen, a good agreement is obtained as the correlation coefficient is more than 99%.

Tables 3a and 3b report the calculated coefficients A, B, C, D and the STC powers for both couples of the two considered strings for plants number 1 and number 2 respectively. The percentage differences between the powers before and after the modules cleaning are also reported. With reference to Table 3b, the average benefit due to the cleanness is 6.9% and 1.1% for plant number 1 and number 2 respectively.

According to (Kimber et al., 2006), the noticeable difference between the two sites is related to the following reasons:

– site number 1 is more sandy than site number 2 where the ground is more compact so that the effect of pollution is smaller. The mean STC power for dirty modules, greater for the PV plant number 2 (7.78 kW versus 7.38 kW), points out this fact.
– the two PV plants have been cleaned with two different methods. The PV modules of plant number 2 have only been squirted with under pressure distilled water, while the ones of plant number 1 have also been brushed. This difference seems to have had a direct effect on the STC powers of the cleaned PV modules: the mean STC power of PV plant number 1 is bigger than plant number 2 (7.89 kW versus 7.86 kW).

Considering that the operations of each of the two studied plants guarantee to the investors a cash inflow of ca. 600.000,00 €/year, and that a complete washing takes one day and costs € 2.500,00, Table 4 reports some economical index gathered from the losses given above. The money lost because of the pollution have simply been calculated by multiplying the year cash inflows by the noticed losses. The average hidden washing costs have been obtained dividing the year cash inflows by the number of days in a year since during the washing operation the plants must be switched off.

6. Conclusions

In this work, in order to determine the effect of soiling, the STC powers for some strings of the two 1 MW$_p$ photovoltaic plants built in the countryside of southern Italy have been evaluated. A regression model applied to the collected datasets before and after a complete clean-up has been used in order to determine the behavior of the two plants. The correlation coefficients between measured powers and the predicted ones with the regression technique demonstrated the effectiveness of the model used. It must be noted that a performance ratio analysis, which is usually adopted in order to determine the behavior of a PV plant, has not been performed as too much influenced by seasonal variation in temperature and by plant availability.

The results obtained show that the soiling effect is strongly dependent on both the soil type and the washing technique. For the first plant, built on a quite sandy site, the losses due to pollution were 6.9%, while for the second plant, built on a more compact ground, they were 1.1%. In the first case the PV modules have been squirted with under pressure distilled water and brushed in order to remove all layers of soil, while in the second one the PV modules have only been squirted.

Finally, the economical index shown in Table 4 can certainly help operation and maintenance responsible in choosing the cleanliness schedule. Nevertheless, a more detailed analysis will be conducted in a future work in order to create a method for understanding when and how many times it is advisable to wash a due PV plant and for how long will the benefits hold. In order to obtain this result, more than one dataset per year will be analysed and different washing techniques will be applied to the same PV plant.

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References

Biryukov, S., Faiman, D., Goldfeld, A., 1999. An optical system for the quantitative study of particulate contamination on solar collector surfaces. Solar Energy 66, 371–378.

Coleman, T.F., Li, Y., 1994. On the convergence of reflective newton methods for large-scale nonlinear minimization subject to bounds. Mathematical Programming 67 (2), 189–224.

Garg, H.P., 1974. Effect of dirt on transparent covers in flat-plate solar energy collectors. Solar Energy 15, 299–302.

Haeberlin, H., Graf, J.D., 1998. Gradual reduction of PV generator yield due to pollution. In: Second World Conference on Photovoltaic Solar Energy Conversion, Vienna, Austria.

Hammond, R., Srinivasan, D., Harris, A., Whitfield, K., Wohlgemuth, 1997. Effects of soiling on PV module and radiometer performance. In: Twenty-sixth IEEE Photovoltaic specialist conference, Hawaii, USA.

IEC 61724 photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis.

Kimber, A., Mitchell, L., Nogradi, S., Wenger, H., 2006. The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest region of the United States. Fourth IEEE World Conference on Photovoltaic Energy Conversion, Hawaii, USA.

Lughi, V., Massi Pavan, A., Quaia, S., Sulligoi, G., 2008. Economical analysis and innovative solutions for grid connected PV plants. Nineteenth IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Ischia (NA), Italy.

Marion, A., Adelstein, J., Boyle, K., Hayden, H., Hammond, B., Fletcher, T., Canada, B., Narang, D., Shugar, D., Wenger, H., Kimber, A., Mitchell, L., Rich, G., Townsend, T., 2005. Performance parameters for grid-connected PV systems. Thirty-first IEEE Photovoltaics Specialist Conference and Exhibition, Lake Buena Vista, Florida.

Massi Pavan, A., Castellan, S., Quaia, S., Roitti, S., Sulligoi, G., 2007. Power electronic conditioning systems for industrial photovoltaic fields: centralized or string inverters? First IEEE International Conference on Clean Electrical Power, Capri (NA), Italy.

Mayer, D., Wald, L., Poissant, Y., Pelland, S., 2008. Performance prediction of grid-connected photovoltaic systems using remote sensing. Report IEA-PVPS T2-07:2008, pp. 18.

Mellit, A., Massi Pavan, A., 2010a. A 24-hours forecast of solar irradiance using artificial neural network: application for performance prediction of a grid-connected PV plant at Trieste, Italy. Solar Energy 84, 807–821.

Mellit, A., Massi Pavan, A., 2010b. Performance prediction of 20 kWp grid-connected photovoltaic plant at Trieste (Italy) using artificial neural network. Energy Conversion and Management 51, 2431–2441.

Vivar, M. et al., 2010. Effect of soiling in CPV systems. Solar Energy 84, 1327–1335.

Whitaker, C.M., Timothy, U., Townsend, T.U., Newmiller, J.D., King, D.L., Boyson, W.E., Kratochvil, J.A., Collier, D.E., Osborn, D.E., 1997. Application and validation of a new PV performance characterization method. Twenty-sixth IEEE Photovoltaics Specialist Conference and Exhibition, Anaheim, California, USA.