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Dust effects on the PV plant efficiency: A new monitoring strategy

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***Abstract* – As well known dust deposition on PV panels results in a decrease of the electrical power produced by the panel/photovoltaic system. In order to assess this decrease and carry out a long-term economic analysis, it is desirable to make an accurate prediction of the efficiency of the system and of the maintenance costs. Starting from this assumption, an economic model that takes into account the relationship between the losses in the energy production and the cost of maintenance is very useful. In this paper the losses due to the dust will be evaluated considering radiation data provided by public meteorological stations installed which are few kilometers far from the considered PV system.**

I. INTRODUCTION

Renewable energy systems are fairly reliable, but like every complex system, they may fail, and the effects of failures should be analyzed and taken into account. When focusing on photovoltaic (PV) systems, the panels are among the most reliable elements. The reliability issue becomes more complex when a combination of PV panels is considered [1]. In this case the reliability model has to include, in addition to the PV panels, several other components (by-pass diodes, string diodes, cables, connectors…). Despite some of these components increase the overall reliability and make the PV system fault-tolerant, they also make more difficult to detect any fault. For this reason, a continuous monitoring of the photovoltaic plant is mandatory in order to promptly detect the presence of any abnormal situation and for planning the maintenance operation.

In this scenario, it is fundamental to guarantee the functionality of both the plant and the PV panels but also, at the same time, the reliability and maintainability performances.

Among maintenance tasks, one of the least considered activities is the cleaning of the panel surface [2]. It is important to highlight that losses due to the dust have a very important impact in PV module and plant performances: the decrease in power production can be as high as 7% [2], [4], [5]. Despite of this, usually, cleaning is not a task covered by maintenance contracts and even when it is taken into account, often it is not accurately scheduled; usually the cleaning strategy for PV plant is preventive and not condition based.

In order to optimize the production of a photovoltaic plant also considering the maintenance conditions, the authors have proposed an economical model that takes into account the impact of dust and pollution in terms of efficiency reduction and economical energy loss evaluation [6], [7]. In the cited papers the authors assume that radiation data are provided by a measurement station located in the same place of the plant.

In order to overcome the technical problems related to the observation of every single panel installed in large plant, the monitoring system is based on the use of a reference panel together with the data provided by a public weather station, following the approach adopted in [8].

II. MONITORING SYSTEM

A. Introduction

In order to quantify the payback ratio and to evaluate the long-term system performances of a photovoltaic plant, an accurate prediction of the plant efficiency and of the maintenance cost is mandatory. In particular, not only the investment cost and the revenues should be taken into account in the business plan. In fact, in order to estimate the plant dependability and to estimate the energy production, loss factors must be accurately considered. This analysis is critical when the target is to define the maintenance operations for assessing the business plan of a PV plant.

The maintenance plan needs the knowledge of the state of the plant. This consideration puts the accent on the monitoring system architecture that could require lots of sensors, for environmental and electrical quantity, distributed on the plant.

So, the main drawback of a monitoring system of a large PV plant is represented by the cost and complexity

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in the management (in term of hardware and software) of a large number of measurement sections. In order to overcome this drawback it is important to define in a clear way the target of the monitoring system. A system devoted to energy monitoring can observe, for example, only the status of the strings of the plant by means the electrical quantities while a condition monitoring strategy requires, in addition, the knowledge of the panel temperature and solar radiation.

As mentioned in the previous section, even if losses due to the dust can reach the 7%, the cleaning is not considered by maintenance contract and this activity follows a preventive policy. In order to implement an effective condition based approach (CBA), able to monitor this kind of failure mode, the knowledge of the performances of the plant for different radiations and temperatures is required. The difference between the energy forecast, and the energy production, can be considered as a strong parameter in the definition of maintenance scheduling. In fact, when a reduced efficiency is registered, the cumulated losses can be economically evaluated in terms of profit reduction. Thanks to this evaluation, the maintenance operations can be planned more efficiently as discussed [6], [7].

Unfortunately, the instruments devoted to the evaluation of the solar radiation (pyranometers) also require the definition of a suitable maintenance policy. In fact pyranometers need accurate cleaning of the external surface and a control of the humidity inside the case of the instrument. Without a correct maintenance policy, measurement information can lose effectiveness. On the other hand, the measurement process of the electrical quantities cannot be considered a problem: it is possible to reach good accuracy in a cost effective way and usually the instrumentation devoted to the measurement of electrical quantities does not require the definition of strict procedures for a scheduled maintenance.

In order to define a flexible but easy monitoring architecture the authors have analyzed the opportunity of using the output collected by a reference panel. This architecture can support the energy production monitoring and can be used to analyze the failure mode represented by the dust deposition on the panel surface and the aging of the panel itself. If the reference panel has been chosen following a statistical approach, it could represent, with a given confidence level, the behavior of the PV plant in different conditions of dust deposition and aging [7].

The monitoring strategy that will be discussed in the following is based on three assessments:

- the use of an electrical model for the reference PV panel in order to forecast the behavior of the panel itself (the accuracy of the model will be analyzed in the following Section II.B);
- the use of weather data provided by a weather station located near or even quite far from the plant (the results will show that the choice depends by the target of the monitoring system). The analysis of the pros and con related to the use of data coming from a Public Weather Station (PWS) will be discussed in Section III;
- the use of an economic model that allows to assess maintenance activity for the plant. The method and a case study will be presented in IV.

B. Reference panel: model qualification.

The method herein proposed, is based on the use of a reference panel: its actual production is compared with the expected, obtained by means of a model of the PV panel. In [10] a simplification of the traditional single diode model has been presented and discussed. This innovative model is particularly suitable for the simulation of photovoltaic cells and panels which operate in the typical working conditions of a photovoltaic power plant. The definitional uncertainty of this model can be considered negligible if compared with the uncertainty of the measures of the environmental quantities.

The accuracy of the proposed model has been tested using two different kinds of module technologies, mono and poly crystalline, and comparing the values of the actual and predicted energy. Two PV panels, a 180 watt mono crystalline and a 5 watt poly crystalline module have been used by means of the measurement set-up shown in Figure 1.

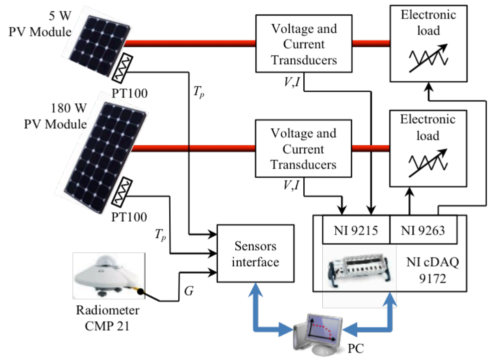

Fig. 1. Monitoring technique based on the comparison of the energy production.

Starting from the assumption that PV panels in the maximum power point, the Maximum Power (MP) Voltage and Current for the two panels have been evaluated in outdoor conditions and the results have been compared with the outputs of the proposed model.

The predicted energy W_{est} (*est* = estimated) is provided by computing solar radiation G and panel temperature T_p by means of the PV model [10]. Since the electronic loads (depicted in previously cited Figure 1) draws the MP from the panels under test, the power production can be estimated by means of the model equation which provides the MP point, in term of voltage V_{mp} and current I_{mp}, for each given environmental condition. The energy production can be estimated as:

$$W_{est} = \int_{t_1}^{t_2} V_{mp}(t) I_{mp}(t) dt \qquad (1)$$

The procedure for the estimation of the production has been tested for twenty days. The computation of W_{est} has been performed daily for a time range of 24 hours (t_1 corresponds to the midnight of a day and t_2 to the midnight of the following day). The electrical and environmental quantities have been acquired thanks to the measurement setup described in Figure 1 with a sampling frequency of 180 samples per hour. Processing these quantities by means of the proposed electric model and by applying (1), allows to estimate the energy production which can be compared to the actual one. A list of the analyzed days is reported in Table 1.

For all of them, the weather conditions, the produced energy and the error, estimated at the end of the day is synthesized (the data are related to the mono-crystalline panel reported in Figure 1).

In Figure 2 the daily actual production (of July 11th, 2011 in Milan) is also plotted with a blue line and then compared with the estimated one (the relative error, registered at the end of the day, corresponds to -1.08 %).

Results show that when the solar radiation and the temperature are measured locally, the prediction of the production is accurate: by comparing the model output with the actual one for the reference panel, it is possible to estimate, day by day, the energy reduction related to the dust deposition on the panel surface or, in clean condition, the aging effect.

Table 1 Actual energy production and estimation error using a local pyranometer

Day (2011)	Weather	Produced Energy [MJ]	Estimation error
July 9th	Rainy	1.24	-1.95 %
July 10th	Partly Cloudy	2.51	-1.18 %
July 11th	Sunny	3.26	-1.08 %
July 12th	Rainy	2.30	0.10 %
July 13th	Rainy	0.60	-2.69 %
July 14th	Partly Cloudy	2.33	-1.51 %
July 15th	Partly Cloudy	3.05	-0.44 %
July 16th	Partly Cloudy	1.30	-2.14 %
July 17th	Rainy	0.88	-2.06 %
July 18th	Sunny	3.27	-1.06 %
July 19th	Rainy	1.13	-2.29 %
July 20th	Sunny	3.51	0.71 %
July 21st	Sunny	3.47	0.46 %
July 22nd	Sunny	3.40	0.43 %
July 23rd	Partly Cloudy	2.36	-1.05 %
July 24th	Sunny	3.33	0.53 %
July 25th	Partly Cloudy	3.18	0.54 %
July 26th	Rainy	2.69	0.92 %
July 27th	Partly Cloudy	1.92	-1.08 %
July 28th	Partly Cloudy	2.77	-1.01 %

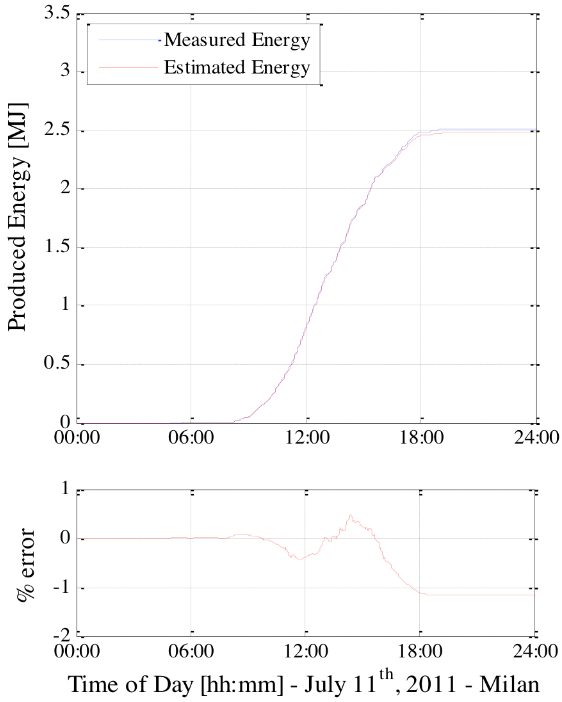

Fig. 2. Comparison between measured and predicted energy production.

The bottleneck of this approach is represented by the pyranometer: it is an expensive instrument that requires, as just recalled in the previous Section, a strict maintenance policy.

III. DATA COLLECTED BY PUBLIC WEATHER STATION

In order to overcome the problem related to the use of a pyranometer installed in the plant, it is possible to evaluate the effect on the prediction when the radiation data are collected by a public weather station. The advantage of this approach is a fairly accurate radiation measurement is ensured. However, it is important to highlight that this solution shows few drawbacks which are mainly related to the time resolution of the provided data and to the distance between the PV panel and the weather station.

In order to verify the effect of the time resolution it is possible to evaluate the energy production by means of the electric model and by using data of solar radiation with different time resolutions. In Figure 3 the effect on energy production, which has been estimated for two different situations, is shown: clear day and mostly cloudy day. In this figure, the data of solar radiation has been obtained as average on different time windows of measurements collected near to the PV panel with a sampling period of 20 s. The error has been computed with respect to the output of the model fed with no averaged data.

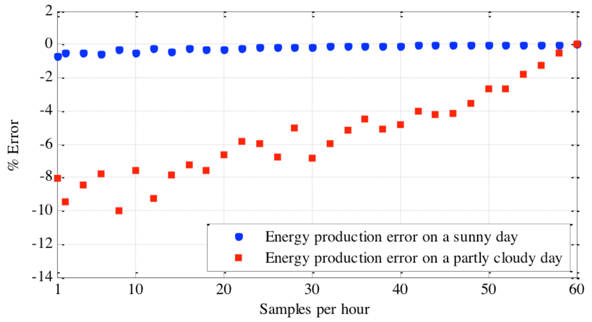

Fig. 3. Effect of the time resolution of the data on the error of the predicted energy production [11].

Figure 3 clearly shows that the error is low as far as the time resolution is fairly high. However, low time resolutions do not introduce significant error in the energy estimation when it is computed for sunny days. In fact, as well shown, it is not possible to find a strict correlation between the error and the number of samples per hours. The evaluated energy production error increases in cloudy days, while it remains practically constant in sunny days. Another factor which could impact significantly on the estimation of the energy production is represented by the distance between the weather station and the PV panel under test.

Assuming that the weather station is close to the panel under consideration (on the order of few kilometers) the apparent position of the Sun with respect to these two points can be reasonably considered the same.

The only phenomenon which can introduce a relevant error is represented by the assumption that the solar radiation measured by the weather station is the same of that at the place where the PV panel is installed. In fact, this statement is not verified for each weather condition, since for non-uniform cloud coverage of the sky, the irradiation of the ground can vary significantly in the range of few hundreds of meters. In order to verify the effect of the distance between the PV panel and the weather station the solar radiation measured in two different locations has been compared. In clear condition, the maximum error in the evaluation of the daily solar energy radiation using data acquired by a weather station placed 2 km far from the PV panel has been evaluated and it is in the range ± 5%.

In order to separate and quantify the effects due to the time resolution and those due to the distance, the solar radiation acquired locally has been averaged and resampled with time steps of 6 samples/h and 1 sample/h. The application of these two different resolutions impact on the error in the energy estimation, which have been called ε_{loc6} (6 samples/h) and ε_{loc1} (1 sample/h) respectively. Successively, the energy has been computed by using the data provided by the PWS. The obtained estimation errors, in this case, have been called ε_{ws6} (6 samples/h) and ε_{ws1} (1 sample/h).

Table 2 Error in predicting the energy production.

Days	ε_{loc6} %	ε_{loc1} %	ε_{ws6} %	ε_{ws1} %
Sunny	-0.12±0.67	-0.72±0.65	2.41±0.54	2.91±0.55
Cloudy	-4.1±2.2	-8.3±4.7	-3.9±6.3	-4.4±6.6
Rainy	-6.9±4.8	-11±6.3	-12±4.8	-15±7.1

In Table 2 the results of all the considered 20 days are, finally, reported considering three different weather conditions.

This result is a further confirmation of what has already been mentioned, *i.e.* in case of sunny weather the error in the estimation of energy production is slightly affected by the sampling frequency (at least in the field of explored values). The data also clearly shows the effect of the spatial resolution of the environmental parameter measurements. During cloudy days, the use of data collected by the weather station causes the error to rise. The minimum errors have been achieved in estimating the energy production during sunny days. In this condition, the PV panel model is more accurate, and both the spatial and the time resolutions of the environmental data are less influential. On the contrary, in cloudy days, the errors are larger. This is mainly due to the high variance of the solar radiation intensity that cannot be considered by using data with low time resolution.

However, non-clear days still participate to the evaluation of the reduction in energy production when a time period longer than a single day is considered. In this case, according to the fact that a low power output is expected for cloudy/rainy weather conditions, the overall error is slightly influenced by the high uncertainty reported for these days. In fact, even considering that most of the considered 20 days are not completely clear, the error of the estimated total energy production is still low, as deductible from values given in the Table 3.

Table 3 Errors in predicting the energy production over 20 days.

	ε_{loc180} %	ε_{loc6} %	ε_{loc1} %	ε_{ws6} %	ε_{ws1} %
Over 20 days	-0.75	-2.62	-5.44	-2.51	-3.01

Starting from these results, it is possible to use the radiation data provided by a PWS if we accept to use this information not day by day but along a longer time window.

IV. DUST EFFECT MONITORING: AN ECONOMIC POINT OF VIEW

A. Economic model.

In order to optimize the PV plant maintenance policy, it is important to study the relationship between the losses in the electricity production and the cost of the maintenance operations. This reduction in efficiency can be translated into a voice of "induced cost" due to lack of electricity production. The approach is based on the fact that Maximum Power Point (MPP) is strictly connected to the presence of the dust on the panel (such as previously described in literature). Starting from this point of view, it is easy to understand that there is an interesting correlation between the energy losses (W_{losses}) defined as the difference between the energy theoretically available (W_{th}) and the energy actually produced (W_{act}) and the "induced cost".

In order to evaluate the efficiency reduction of the plant, two parameters can be considered:

- C_S is the value of saving (cost saving) per produced energy unit;
- C_{INC} is the value of the economic incentives per produced energy unit.

The cost of the PV plant due to the lack of the energy production denoted in the following as cost of the production losses, C_{PL}, between two consecutive maintenance operations can be estimated with the following expression [6]:

$$C_{PL} = \left(C_S + C_{INC}\right) W_{losses} \tag{2}$$

C_{PL} is a time dependent parameter.

Another important parameter to take into account is the maintenance activity costs, C_{MA}, related to a single cleaning operation. It is approximately given by the sum of the costs of material, C_m, used for cleaning and the cost of the workforce, C_{wf}:

$$C_{MA} = C_m + C_{wf}\,. \tag{3}$$

It is well known concept that the maintenance activity has to be performed when the monitoring shows that the following inequality is no longer verified:

$$C_{PL} \le C_{MA}\,. \tag{4}$$

Therefore, with (2), when

$$\left(C_S + C_{INC}\right) W_{losses} \le C_{MA}\,. \tag{5}$$

Figure 4 shows the qualitative trend of the cost due to the lack of the energy production (in red) and the costs of the maintenance operation (in blue in the mentioned figure).

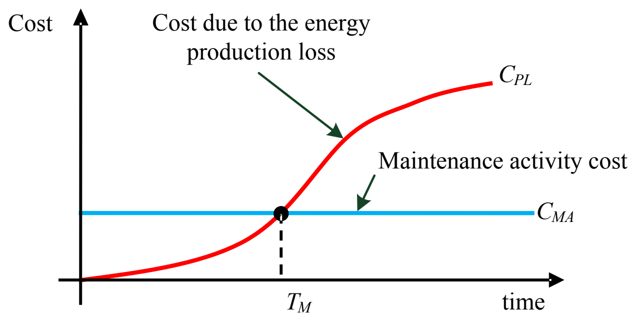

Fig. 4. Trend analysis (qualitative).

The intersection of these two curves represents the optimal instant in which the maintenance activity should be performed (Maintenance Time denoted in the following as T_M).

The economic model requires the knowledge of the energy loss due to the dust deposition. Starting from the results presented in Section III, the W_{th} estimation can be performed considering solar radiation data acquired both with local and public weather station.

So, in order to evaluate the economic model, in Equation (2) W_{losses} can be computed as the difference between the actual energy evaluated by means of the reference panel and the output of the model computed considering the radiation provided by the weather station (local or public).

As shown in the previous section, the best accuracy is reached when the solar radiation measurement is performed in the same place where the reference panel is installed. It is possible to use data coming from a remote station increasing the measurement rate (requesting the data to the Public Station Manager) or accepting a rougher estimation of T_M since the electrical model is fed with data that are not collected in the same place of the reference panel.

B. A Case Study

At this point it is useful, in order to verify the applicability of the presented method, to analyze a typical case study.

The data are related to a plant with a rated power of 20 kW in Standard Test Condition (STC). The plant has been characterized in clean conditions for three years by means of a continuous monitoring activity, so, starting from the collected data, it is possible to define an average monthly production profile.

In order to verify if it is possible to determine T_M , even if the weather data are provided by PWS, we hypothesized: an energy loss of 5% on the expected value and, starting from the consideration reported in Table 3, ε_{ws6} overall model contribution.

This error takes into account both panel model error and weather station location considering a number of samples in an hour commonly acquired in public weather station.

Considering an average cost for cleaning of € 170.00 and considering (C_s+C_{inc}) equal to 0.443 €/kWh, it is possible to evaluate the losses in economic terms. As shown in Figure 5, T_M depends on the amount of the economic losses evaluated cumulating their value monthly. The use of local (blue line) instead of the PWS data (red line) has a minor impact in the evaluation of T_M.

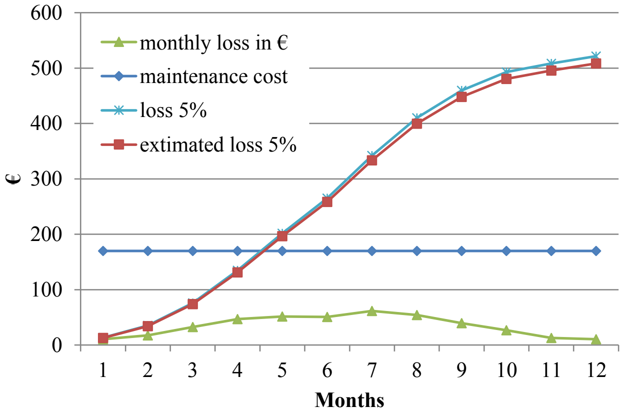

Fig. 5. Losses vs time.

V. CONCLUSION

In order to define a maintenance policy based on an economical model of the PV plant, in this paper the authors have evaluated and discussed the pro e cons of using environmental data provided public weather stations located few kilometers away from the PV system itself. A discussion about the influence of the distance between public weather station and the PV system is given. Furthermore, the effect of the time resolution is also discussed. Finally, some considerations about the error introduced in the time to maintenance estimation using radiation data obtained by PWS have been also presented.

REFERENCES

[1] M. Mani, R. Pillai, “Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations”, *Renewable and Sustainable Energy Reviews*, vol. 14, Dec. 2010, pp. 3124-3131.

[2] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni,” Electrical performances optimization of Photovoltaic Modules with FMECA approach”, *Measurement*, vol. 46, Dec. 2013, pp. 3898-3909.

[3] A. Detrick, A. Kimber, L. Mitchell, “Performance Evaluation Standards for Photovoltaic Modules and Systems,” *IEEE 31st Photovoltaic Specialists Conference*, Lake Buena Vista, FL, USA, 2005, pp. 1581-1586.

[4] E.L. Meyer, E.E. van Dyk, “Assessing the reliability and degradation of photovoltaic module performance parameters”, *IEEE Transactions on Reliability*, vol. 53, no.1, March 2004, pp. 83-92.

[5] V. Sharma, S.S. Chandel, “Performance and degradation analysis for long term reliability of solar photovoltaic systems: a review”, *Renewable and Sustainable Energy Reviews*, vol. 27, Nov. 2013, pp. 753-767.

[6] L. Cristaldi, M. Faifer, M. Rossi, M. Catelani, L. Ciani, E. Dovere, S. Ierace “Economical Evaluation of PV System Losses Due to the Dust and Pollution”, *IEEE International Instrumentation and Measurement Technology Conference*, Graz, Austria, 2012, pp. 614-618.

[7] L. Cristaldi, M. Faifer, M. Rossi, L. Ciani, M. Lazzaroni, S. Toscani, “Photovoltaic Plant Efficiency Evaluation: A Proposal”, *12th IMEKO TC10 Workshop on Technical Diagnostics*, Florence, Italy, 2013, pp. 260-265.

[8] L. Cristaldi, M. Faifer, M. Rossi, S. Toscani, M. Catelani, L. Ciani, M. Lazzaroni, “Simplified method for evaluating the effects of dust and aging on photovoltaic panels”, *Measurement*, vol. 54, Aug. 2014, pp. 207-214.

[9] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, M. Rossi, “Characterization of photovoltaic panels: The effects of dust”, *IEEE International Energy Conference and Exhibition*, Florence, Italy, 2012, pp. 45-50.

[10] L. Cristaldi, M. Faifer, M. Rossi, S. Toscani “A simplified model of photovoltaic panel”, *IEEE International Instrumentation and Measurement Technology Conference*, Graz, Austria, 2012, pp. 431-436.

[11]L. Cristaldi, M. Faifer, M. Rossi, F. Ponci, “A Simple Photovoltaic Panel Model: Characterization Procedure and Evaluation of the Role of Environmental Measurements”, *IEEE Transactions on Instrumentation and Measurement*, vol. 61, Oct. 2012, pp. 2632-2641.