Loughborough University

This item was submitted to Loughborough's Research Repository by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Evaluation of uncertainty sources and propagation from irradiance sensors to PV energy production

PLEASE CITE THE PUBLISHED VERSION

http://www.pvsat.org.uk/

PUBLISHER

© The Solar Energy Society

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Mariottini, Francesco, Thomas R. Betts, Jiang Zhu, and Ralph Gottschalg. 2019. “Evaluation of Uncertainty Sources and Propagation from Irradiance Sensors to PV Energy Production”. figshare. https://hdl.handle.net/2134/33092.

Evaluation of Uncertainty Sources and Propagation from Irradiance Sensors to PV Energy Production

Francesco Mariottini*, Thomas R. Betts, Jiang Zhu, Ralph Gottschalg
(CREST), Wolfson School
Loughborough University
Loughborough, UK
F.Mariottini@lboro.ac.uk

***Abstract*— This work quantifies the uncertainties of a pyranometer. Sensitivity to errors is analysed regarding the effects generated by adopting different time resolutions. Estimation of irradiance measurand and error is extended throughout an annual data set. This study represents an attempt to provide a more exhaustive overview of both systematic (i.e. physical) and random uncertainties in the evaluation of pyranometer measurements. Starting from expanded uncertainty in a monitored pyranometer, the study concludes with an evaluation of its impact on the estimation uncertainty in the performance of a photovoltaics (PV) solar farm.**

Keywords- Pyranometer; Radiometer Calibration; Global Horizontal Irradiance; Uncertainty Evaluation; Data Availability

I. INTRODUCTION

Uncertainty in short timescale solar irradiance data can range from 4.7% to 25.3% [6]. However, few studies have quantified the generation and propagation of uncertainties from pyranometer measurements to PV performance. Uncertainties are often addressed with statistical methods only [1]. A better understanding of systematic and random effects on irradiance sensors may significantly contribute to the ongoing debate.

A crucial aspect when assessing PV performance through monitored data is to ensure enough reliability and validity of measurements in line with the objectives. The economic value of a PV system is required for a period of 25 years while there are cases of systems which have been running for more than 30 [2]. If we consider an overall profit margin of 7% for commercial-scale PV systems [3], uncertainty calibration becomes a crucial factor to the PV industry since it heavily affects the bankability of the PV project itself.

Previous studies have estimated the combination of uncertainties of measurements and modelling between 3% and 12% [4-5] which agrees weakly with the uncertainty in solar irradiance data presented in other studies ranging from 4.7% to 25.3% [6]. Both different time resolutions (and temporal averaging) [7] and environmental conditions have a role in explaining this difference.

High quality input data are crucial for any irradiance evaluation, since the input data can be a greater contributor to overall uncertainty than the choice of the model itself [8]. Quality of irradiance data depends strongly on the data source, and how data are processed (formatted, filtered and modelled, e.g. to fill data gaps) [9].

Uncertainty in pyranometer measurements depends on the following [10-11]: pyranometer design and quality of manufacturer, the performed calibration procedure, measurement conditions and maintenance, environmental conditions and exposure-related degradation. Overall a measurement uncertainty of 5% and 8% seem achievable targets respectively for daily and hourly irradiation [12] while some protocols can achieve uncertainties as low as 2% for daily irradiation [12].

I. METODOLOGY

Based on a previous formulation [13], uncertainty in global irradiance measurements is first evaluated for a pyranometer monitored at CREST in different environmental conditions and temporal averaging.

The expanded uncertainty was then adapted to a pyranometer at a commercial solar farm to estimate the impact of uncertainty on the evaluation of the energy production

A. Hypotheses

The analysis focus is on “almost clear-sky days”. Expanded uncertainty is defined through two different input data sources. In one case data is extracted and evaluated from a calibration certificate. For the reference pyranometer, datasheet and standards are used instead.

B. Subjects

A manufacturer-calibrated Kipp & Zonen (KZ) CMP21 pyranometer was selected from the CREST monitoring facility. The pyranometer is facing south and is mounted in the horizontal. The pyranometer is installed inside a KZ CVF3 ventilation unit. A raw dataset was data mined for the deployed generic pyranometer (south-oriented, tilt equal to 30° degree). As a conservative hypothesis, it was assumed to be also a CMP21 model but with unknown specifications (in reality, it is more likely a lower specification model). Data from 3/6/15 to 3/1/16 were analysed.

C. Location

The CREST outdoor test facility (52°46’N,1°,12W) is located within four degrees in longitude and two degrees in latitude of the selected photovoltaic farm. This reduces additional cross-site uncertainties due to different climates.

D. *Data Quality Management*

Data quality procedures employed are based on the ISO standard [14-15]. To assess data completeness, pyranometer disconnections were analysed against the expected sun path (as a proxy for day length), as plotted in Figure 1. The assessment is applied to a CREST pyranometer for the period of Jun 2015 to Jan 2016. Flagged disconnections were excluded from further analysis.

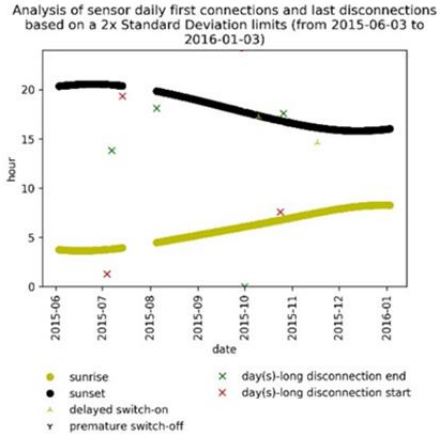


Figure 1. Outcomes of data completeness assessment for CREST pyranometer.

E. *Identification of "almost clear days"*

The focus here is on clear-sky days due to the impact on energy production and zero off-set type A uncertainty [10].

Due to scarce recurrence of "perfect" clear-sky conditions for the selected locations, initial clear-sky conditions criteria are progressively and gradually loosened through iteration. The starting requirements are:

- Maximum diffuse fraction (cloud ratio) of 0.20.
- Maximum Pearson correlation coefficient of 0.95 (daily). Due to high correlation values usually found during the research.
- Maximum irradiance (and irradiation) deviation from a clear-sky model of 5%.

F. *Formulation of Uncertainty*

The uncertainty formulation follows Konings and Habte [13] who defined type B uncertainties [16].

$$u_c(E) = \sqrt{\left(c_V^2 u^2(V) + c_S^2 u^2(S) + c_E^2 u^2(E)\right)} \quad (1)$$

The original formulation (1) was integrated with information extracted from the calibration certificate of the CMP 21 pyranometer and experience at CREST.

By using simple interpolation techniques on the certificate data, both temperature and directional response are considered as systematic effects on measurements. Then for each data point, the pyranometer sensitivity is corrected to compensate.

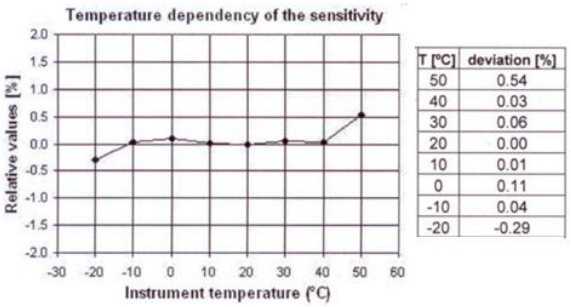


Figure 2. Temperature dependency of the sensitivity from the calibration of the KZ CMP21 [17]

Absorption and refraction of light on pyranometer glass dome thickness may vary depending on the longitude and latitude axes due to the imperfect manufacturing process (and consequently measurement of irradiance as well). To estimate the directional dependency of irradiance for different azimuth and zenith angles, linear interpolation techniques were applied on values provided in the calibration certificate.

Zenith angle	Azimuth angle				
	-180	-90	0	90	180
80	1.24	3.21	2.02	-0.48	1.24
70	0.49	1.27	0.80	-0.19	0.49
60	0.18	0.48	0.30	-0.07	0.18
40	0.21	0.23	0.07	-0.05	0.21

Table 1. Assumed percentage cosine errors for different Zenith angles and Azimuth angles.

For the CREST pyranometer, specification limits were initially extracted from the Kipp & Zonen calibration certificate and instruction manual. The same specification limit for the datalogger was kept having verified that its accuracy is similar to the one used at CREST.

Following the description of the calibration procedure, reference irradiance is put equal to 500 Wm^{-2}. For the considered sources of uncertainty, this results in a combined standard uncertainty of 4.66 Wm^{-2}. The calculated expanded uncertainty (coverage factor 2) is 9.32 W m-2, or 1.86%.

For the PV farm monitoring pyranometer, specification limits for a generic Kipp & Zonen CMP 21 are considered. In this case a sensitivity of 10.5 µV $W^{-1}m^2$ was assumed as average of the extreme values provided. The resulting combined standard uncertainty and calculated expanded uncertainty are 7.95 Wm^{-2} and 15.90 Wm^{-2}, respectively.

II. RESULTS

A. *Deviation of irradiance for almost clear-sky days in Loughborough*

Table 2 demonstrates the quantification of how much the expanded uncertainties vary in the entire considered dataset of almost clear days. Data with time resolutions of 60s and 3600s were used in the calculation respectively. Uncertainty increases when data with 3600s time resolution is used.

Input data	Time resolution [s]	Irradiation lower limit [kWh/m2]	Irradiation upper limit [kWh/m2]	Percentage deviation [%]
calibration-based	60	116.16	120.94	± 2.01
	3600	116.34	121.51	± 2.18
datasheet-based	60	114.39	122.72	± 3.51
	3600	114.41	123.44	± 3.79

Table 2. Overview of absolute and relative variation of irradiance for the 20 selected almost clear-sky days.

Percentage deviation increased from +/-2.01% to +/-3.51% for 60s resolution data and from +/-2.18% to +/-3.79% for 3600s resolution data, almost doubled when using datasheet-based input data instead.

B. *Impact of irradiance uncertainty on the evaluation of PV performance*

The estimated uncertainties of irradiance measurements are applied to the monitored values of a pyranometer at a PV solar farm. The identified almost clear days at CREST were used also a sample for this case.

Input data	Time resolution [s]	Percentage deviation [%]	Average expanded uncertainty [W/m2]
datasheet-based	60	± 2.87	13.83
	3600	± 3.07	13.83

Table 3. Overview of irradiance and related uncertainty for the solar farm pyranometer.

The results of the expanded uncertainty calculation were used to assess the impact on the solar farm energy production for an entire year (from 10/8/2015 to 10/8/2016). An average system efficiency of 11.25 was estimated based on monitored energy production (by string inverters) and irradiance (by pyranometer), assuming an inverter efficiency of 97% based on Danfoss Triple Lynx 15 KW datasheet and a AC/DC ratio of 0.85 (from system data).

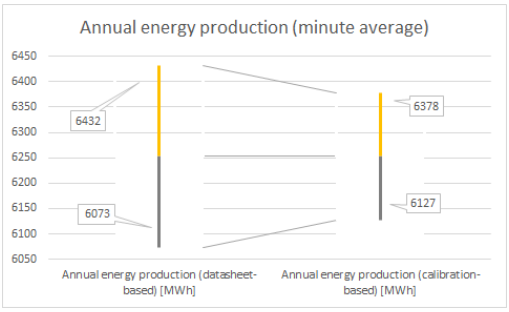


Figure 3. Effects of expanded uncertainty on estimated energy production in a PV solar farm of 7389 kW (peak).

Estimated energy production ranges from 6.13 GWh to 6.38 GWh. If only datasheet-based information is used the additional uncertainty is ± 54 MWh.

III. CONCLUSIONS

The study focused on uncertainty in irradiance measurement. By applying information contained in calibration certificates instead of information from manufacturer datasheet, the percentage deviation decreased from +/-3.51% to +/-2.01% for 60s resolution data and from +/-3.79% to +/-2.18% for 3600s resolution data. On the other hand, different temporal averaging did not show considerable variations.

Future independent calibrations and measurements of pyranometers at CREST will help to better define and validate measurements dependency on environmental parameters (systematic sources of uncertainties) and different conditions from almost clear days. Data quality, including data completeness, should be integrated into uncertainty formulation during future studies. Another important research aspect will be the propagation of uncertainty in irradiance measurements directly into power measurements.

IV. ACKNOWLEDGEMENTS

This study has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 721452.

V. REFERENCES

[1] D. C. Jordan and S. R. Kurtz, "The dark horse of evaluating long-term field performance-Data filtering," IEEE J. Photovoltaics, vol. 4, no. 1, pp. 317–323, 2014.

[2] D. C. Jordan, S. R. Kurtz, K. VanSant, and J. Newmiller, "Compendium of photovoltaic degradation rates," Prog. Photovoltaics Res. Appl., vol. 24, no. 7, pp. 978, 980, 2016.

[3] R. Fu et al., "U.S. Solar Photovoltaic System Cost Benchmark : Q1," NREL, September, 2017.

[4] C. P. Cameron, W. E. Boyson, and D. M. Riley, "Comparison of Pv System Performance-Model Predictions With Measured Pv System Performance," pp. 2–7, 2008.

[5] J. Freeman, J. Whitmore, N. Blair, and A. P. Dobos, "Validation of multiple tools for flat plate photovoltaic modeling against measured data," 2014 IEEE 40th Photovolt. Spec. Conf. PVSC 2014, no. August, pp. 1932–1937, 2014.

[6] B. Goss, R. Gottschalg, and T. R. Betts, "Uncertainty analysis of photovoltaic energy yield prediction," Sol. Energy Soc., no. April, pp. 157–160, 2012.

[7] K. Gibson, I. R. Cole, B. Goss, T. R. Betts, and R. Gottschalg, "Compensation of temporal averaging bias in solar irradiance data," IET Renew. Power Gener., pp. 1–7, 2017.

[8] M. Sengupta and P. Gotseff, "Evaluation of Clear Sky Models for Satellite-Based Irradiance Estimates," no. December, p. 42, 2013.

[9] N. Geuder et al., "Screening and Flagging of Solar Irradiation and Ancillary Meteorological Data," Energy Procedia, vol. 69, pp. 1989–1998, 2015.

[10] ISO, "ISO 9060 Solar energy - Specification and classification of instruments for measuring hemispherical solar and direct solar radiation." 1990.

[11] M. Krawczynski, M. Strobel, and R. Gottschalg, "Intercomparison of pyranometers for distributed measurement system," 5th Photovolt. Sci. Appl. Technol. Conf., no. November 2015, 2009.

[12] World Meteorological Organization, Guide to Meteorological Instruments and Methods of observation, vol. I & II, no. 8. 2017.

[13] J. Konings and A. Habte, "Uncertainty evaluation of measurements with pyranometers and pyrheliometers," no. November, pp. 8–12, 2015.

[14] BSI, "BS ISO 8000-8:2015 Data quality Part 8 : Information and data quality : Concepts and measuring," 2015.

[15] BSI, "Draft BS ISO 8000-61 Data quality Part 61: Information & data quality management process reference model," vol. 44, no. 0, 2016.

[16] Joint Committee for Guides in Metrology, "Evaluation of measurement data — Guide to the expression of uncertainty in measurement," Int. Organ. Stand. Geneva ISBN, vol. 50, no. September, p. 134, 2008.

[17] Kipp & Zonen, "Calibration certificate CMP21 090318." 2009.