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# Comparison of two sensor technologies for solar irradiance measurement in a desert environment

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ABSTRACT

Using 24 months of 1-min radiometric measurements conducted at two remote arid sites in Kuwait, the impact of sensor technology (thermopile vs. photodiode with rotating shadowband) on the magnitude of the three components of solar irradiance (global, direct and diffuse) is analyzed. The deviations (photodiode minus thermopile) are typically affected by both sun zenith angle and irradiance magnitude. For the global and direct components, most deviations (91% in the case of GHI, 87–91% in the case of DNI, depending on site) are within ± 5%, and can thus be considered satisfactory. Larger deviations in direct and global irradiance are typically found under low zenith angles (summer conditions). The main source of concern is the negative bias and intricate pattern found in the diffuse deviations, most of the time. Only 46–61% of the deviations (depending on site) are within ± 5%. The diffuse issue seems to be caused by an insufficient spectral correction of the diffuse reading. The so-called "cat ear" angular issue (a sudden spike in sensitivity for an angle of incidence ≈80°, combined with a sudden drop in sensitivity beyond ≈85°) is also still present in the direct and global irradiance measurements under clear conditions. The present results underline the imperfect nature of the empirical corrections typically applied to photodiode instruments to improve their irradiance estimates. Nonetheless, the deviations observed here are sufficiently low in general to guarantee good resource assessments, even under harsh and variable desert conditions, to the condition that the photodiode instruments are properly calibrated on site during periods whose atmospheric conditions are representative of the whole year, and their readings are duly corrected with the best possible algorithms.

## 1. Introduction

Accurate measurements of solar irradiance are important in many applications—most particularly those related to the development, deployment, and operation of solar technologies such as photovoltaic (PV), concentrating PV (CPV), or concentrating solar power (CSP) systems. High-quality measurements are also necessary for the development and validation of radiation models typically used in solar resource assessments and energy simulations (e.g., Gueymard, 2012; Gueymard and Ruiz-Arias, 2015). The measurement of solar radiation typically relies on radiometers having either a thermopile or photodiode sensor, thus providing a wide range of cost and performance characteristics. The two types of sensors have advantages and drawbacks, which make their proper selection difficult, depending on the deployment climate and environment, accuracy requirements, or budget limitations (Sengupta et al., 2017). Typically, thermopile radiometers may achieve the lowest uncertainty under most conditions, but cost more, and require significant power for solar tracking. Additionally, they require frequent cleaning under arid conditions due to rapid dust soiling (Bachour et al., 2016; Geuder and Quaschning, 2006). The latter factors explain why photodiode sensors are often installed at remote desert locations for solar resource prospecting. Conversely, for long-term monitoring at sites where power and manpower are available, thermopile radiometers are typically preferred for their lower uncertainty and proven long-term reliability.

Considering the high accuracy requirements of bankable data, particularly for CSP or CPV, it is important to evaluate whether photodiode sensors can provide low-uncertainty data under harsh environments over periods long enough to conduct a meaningful assessment of the solar resource, which typically includes a site adaptation of long-term satellite-derived data (Gueymard et al., 2012; Polo et al., 2016). Considering the dependence of the solar industry on measurements obtained by photodiode sensors, the qualification of their performance under field conditions has attracted a lot of interest in recent years, and is now actively investigated by experts participating in Task 16 of the International Energy Agency Photovoltaic Power Systems Programme

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(IEA-PVPS). This ongoing platform follows on the tracks of a previous IEA-sponsored effort (Wilbert et al., 2015).

The field characterization of photodiode sensors requires side-by-side comparisons, which can rarely be done in practice because most stations (specially in harsh environments) are equipped with one type of sensor only. This explains why, so far, this kind of study has been conducted at only a few prominent research stations. For instance the recent investigation by Vuilleumier et al. (2017) evaluated two specimens of three different types of silicon-based sensors used in a rotating-shadowband irradiometer (RSI) configuration. Based on its original concept (Wesely, 1982; Michalsky et al., 1986), an RSI alternatively senses global horizontal irradiance (GHI), when the sun is unshaded, and diffuse horizontal irradiance (DIF) when the sun is shaded by the shadowband. The corresponding direct normal irradiance (DNI) is derived through calculation from the difference between GHI and DIF, using the fundamental closure equation relating the three components, and some refinements (Vignola et al., 2012).

To compensate for the deviations caused by three major effects (temperature dependence, spectral mismatch, and cosine error), different empirical corrections are applied to the raw signal, depending on manufacturer. These corrections have evolved over time, thus complicating the issue (Augustyn et al., 2004; Geuder et al., 2008, 2010, 2016; Vignola, 2006; Vignola et al., 2017; Wilbert et al., 2015). Moreover, these corrections cannot be perfect under all possible atmospheric and environmental conditions, and are thus sources of error. Long-term analyses are necessary to evaluate the overall performance of RSI instruments in field conditions. For instance, the reliability and accuracy of an RSI was evaluated against thermopile radiometers at Albuquerque, New Mexico (a very clear site) during a 12-month test (Rosenthal and Roberg, 1994). Even though the reliability of the instrument was found excellent and its accuracy adequate for general-purpose solar resource assessment spanning long integration periods, the applicability of the instrument for precise monitoring over short periods was questioned.

During a 15-month test period under the temperate (and somewhat cloudy) climate of Payerne, Switzerland, Vuilleumier et al. (2017) found that the RSI correction functions appeared as if they had been purposefully optimized to lower the error in DNI—which, with an extended range of error distribution of ± 40 W/m$^2$, was still about twice or more as that of a good-quality thermopile pyrheliometer. For GHI and DIF, the observed deviations from reference instruments were about ± 25 W/m$^2$ and ± 20 W/m$^2$, respectively. Interestingly, the deviations were stronger and more dependent on solar zenith angle under clear-sky conditions. The latter result is perplexing, since a lot of solar resource prospecting is undertaken with RSI instruments in very sunny areas with strong potential for intensive solar energy development, including concentrating technologies.

In parallel, the need for correction functions complicates the calibration of RSIs, particularly because some of these functions are proprietary. Calibration factors become essentially indissociable from a software-based correction method, which has a number of implications. In particular, this situation imposes the need for special calibration methods, e.g. involving unusually long periods (Jessen et al., 2016). Another concern is the risk of sensitivity drift due to changes in either the detector or the diffuser, particularly under harsh desert conditions. This requires studies of the long-term accuracy of RSIs under such conditions (Geuder et al., 2014). Thermopile radiometers are also subject to sensitivity drift. Nevertheless, based on the accumulated experience of various institutions that have maintained pyrheliometers and pyranometers for decades, it is argued here that their construction prevents the occurrence of rapid or large drifts, even after 20 or more years of continuous service.

In this context, the present study compares irradiance data from two research stations located in remote desert areas of Kuwait. At each station, one thermopile pyrheliometer and two thermopile pyranometers sense the three components (DNI, GHI and DIF) separately. They are collocated with a photodiode-based RSI for redundancy. A first goal of this investigation is to quantify irradiance differences in the two sensor technologies and help understand their origin, particularly considering the harsh desert conditions under which they operate. By comparing long time series of irradiance data from the two types of instruments, a second goal is to evaluate the impact of using RSI instruments on solar resource assessments at the seasonal and annual time scales.

Section 2 provides details on the data available for this investigation, including their calibration and quality control. Section 3 describes the methodology, particularly regarding the management of outliers. The results are analyzed in Section 4 from different standpoints. Section 5 provides long-term aggregated results and a discussion on the measurement uncertainty. Finally, Section 6 provides a general discussion and conclusion.

## 2. Data sources

The Kuwait Institute for Scientific Research (KISR) is developing and maintaining a solar measurement network in support of achieving a sustainable energy mix for Kuwait (Al-Rasheedi et al., 2014). Two of the five operational stations have reported 1-min irradiance data since 2012, using Kipp & Zonen thermopile radiometers (CHP1 pyrheliometers and CMP21 pyranometers) and a photodiode-based RSI (4G model). The latter instrument was developed by Reichert GmbH in collaboration with Solar Millennium AG, based on the LI-COR LI-200 silicon detector and the original design by Michalsky et al. (1986). In Kuwait, this instrument was installed, calibrated, and software-corrected by CSP Services GmbH (hereafter, CSPS), using proprietary corrections developed (or adopted) by CSPS.

A detail of the experimental setup is shown in Fig. 1. The station's design, instrumentation, calibration, and maintenance program follow the best practices (Sengupta et al., 2017). It is stressed that the cleaning and maintenance of all radiometers are routinely done (and documented photographically) *seven days per week* at each of these stations, barring adverse conditions. Such adverse conditions might be related to (i) the local weather (dust storms, fog, or rain); (ii) temporary station shutdowns; (iii) the unavailability of maintenance personnel; or (iv) exceptional circumstances, such as military exercises. Fig. 2 provides the number and description of major causes of disruption of the daily maintenance schedule at Shagaya during the 24-month experimental period discussed here. Overall, that station was serviced daily more than 90% of the time. This remarkable achievement under remote desert situations is a unique feature of the KISR network. Using the extensive daily photographic record of before/after cleaning pictures, Fig. 3 shows examples of soiling on a pyranometer dome. Experience showed that rain—a rare event in Kuwait—can actually increase the dust soiling effect, which is somewhat counterintuitive.

A preliminary calibration period of all radiometers was initially done at the Plataforma Solar de Almeria, Spain, before deployment. For


**Fig. 1.** Detail of the experimental setup, pictured at sunrise, showing an RSI (left) and thermopile radiometers mounted on a sun tracker with shading-ball attachment (right). The backside of PV solar panels (needed to power such an autonomous station) appears in the bottom right part of the picture.