Solar Energy 169 (2018) 425–433

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Improved quality control protocols on solar radiation measurements

Daniel Perez-Astudillo*, Dunia Bachour, Luis Martin-Pomares

Qatar Environment and Energy Research Institute (QEERI), HBKU, Qatar Foundation, Doha, Qatar

ARTICLE INFO

Keywords:
Solar measurements
Quality control

ABSTRACT

This article presents a proposed set of comprehensive quality control tests on solar radiation measurements (global horizontal, direct normal and diffuse horizontal components) that allow for the automated identification of incorrect measurements. The proposed set is a combination of existing tests from different sources, chosen, and some adapted, to identify most problems in the collected data at one-minute temporal resolution, and are applied here to values measured with high-precision stations at two different sites, to derive quality flags for each entry in order to assess whether these tests are able to identify problems in the measured data, i.e., to point out data of dubious quality. The results show that this set of tests is able to spot issues which may be otherwise unidentified by the widely used BSRN set of tests, impacting calculated yearly-averaged irradiances by sometimes small, but not negligible, amounts, of as much as 4% even in a well-maintained station.

1. Introduction

Great efforts are being made around the world in order to collect accurate measurements of solar radiation at ground level. Since the largest spatial coverage is provided by satellite observations, which present their own inaccuracies in the derivation of solar radiation at ground level, direct (ground-based) measurements provide the means to site-adapt the results derived from satellite data, thus allowing for more reliable historical and widespread data. However, errors in the direct measurements can occur, due to external factors, and instrument or operation issues particular to each site. It is, therefore, critical to have means to assess the accuracy of the measurements coming from different sites and instruments, in order to understand the reliability of the measurements and allow for comparisons between different data sets, ensuring uniformity for use in site adaptation and in all kinds of studies.

One of the most used methodologies for quality control (QC) of solar radiation data has been proposed (Long and Dutton, 2002; also in Roesch et al., 2011) by the Baseline Surface Research Network (BSRN, Ohmura et al., 1998), a world-wide project of the World Meteorological Organisation's World Climate Research Programme. Other known set of tests is NREL's SERI QC programme (NREL, 1993), and several groups of tests have been used or proposed by, for example, Long and Shi (2008), the Commission Internationale de l'Eclairage (Kendrick et al., 1994), Younes et al. (2005), Moradi (2009), the Royal Meteorological Institute of Belgium (Journee and Bertrand, 2011), the Indian SRRA Network (Schwandt et al., 2014), or Pashiardis and Kalogirou (2016). Regarding the measurement of global, direct or beam, and diffuse radiations, all methodologies have in common a basic set of tests to ensure that measurements do not exceed physically possible upper and lower limits dictated by the available radiation coming from the sun, and some consistency checks; also found are checks on different sky clearness conditions (usually empirical, in terms of bands of acceptance determined from historical data), checks against clear-sky models and, less frequently used, sunshine durations and comparison against data from nearby locations.

The BSRN-recommended quality tests are widely applied not only in stations incorporated to the BSRN network, but also in many independent stations, since they provide an automated and standardised method of assessing the correctness of measurements. Although these recommended tests are able to identify most of the issues that could occur in measured irradiances, it is possible to find scenarios in which the checks fail to point out problems, that is, some entries may be able to pass the QC checks and yet be erroneous; also, in conditions where the tests are not applicable, it is still desirable to have an automated way to assess the validity of the measured values. In this work, a combination of different tests is proposed, based mainly on the BSRN tests and modified versions of some of the tests proposed by Long and Shi, showing results of the application of these tests with three 1-year datasets, from two sites.

2. Methodology

This study focuses exclusively on daytime values, using 1-min

* Corresponding author.
E-mail address: dastudillo@hbku.edu.qa (D. Perez-Astudillo).

https://doi.org/10.1016/j.solener.2018.05.028
Received 24 September 2017; Received in revised form 19 April 2018; Accepted 7 May 2018

averages of the three solar irradiance components most commonly measured at the earth's surface: the total or global horizontal (G), the beam or direct normal (G_b) component, and the diffuse horizontal (G_d) component. The three are related by the formula

$$G= G_b*\cos(\Theta_z) + G_d, \quad (1)$$

where Θ_z is the solar zenith angle (angular position of the sun measured from the vertical overhead) at the considered time. By independently determining these three irradiances, a basic consistency test can be performed, i.e., the compliance with this formula.

The BSRN-recommended tests include this consistency check, as well as comparisons against physically possible values (minimum and maximum) for each variable, checks against values which are 'extremely rare' but physically possible (also minimum and maximum), and a test on the so-called diffuse ratio (G_d/G), which should be below a certain maximum at all times. Due to considerations of the usual uncertainties in the sensors, these tests allow for some deviations from the exact values, and under some conditions (low irradiances, low solar elevations) some of the tests are not applicable. If a variable fails its tests at a given time, it is highly probable that the measurement is incorrect.

The set of tests proposed here comprises 19 checks. Some of them use only one of the variables (G, G_b or G_d), and some use two or all three of them. For each test, a QC flag is defined, called here flag0, flag1, … , flag18. If a test was not applicable, or if the test was successful, the corresponding flag is given a value of zero; if the test fails, the flag is set to one; thus, a flag value of one indicates that the variables involved in that test are erroneous, or at least suspect.

G, G_b and G_d are the only measurements needed for these tests. Additionally, the following values have to be calculated for each minute at the location of the measurement:

- Θ_z, the solar zenith angle, and AM, the air mass. A fast and simple calculation of Θ_z can be obtained with the NOAA equations (NOAA, 2017) but higher-precision algorithms exist, and some online sites provide tables for any location; here, the SolPos v.2.0 method from NREL (SolPos, 2001) was followed, as well as the Kasten and Young formula (Kasten and Young, 1989) for AM.
- I_{ob}, the beam (normal) extra-terrestrial (ET) radiation at the top of the atmosphere; it is the product of the solar constant (I_{sc} = 1367 W/m^2) and an earth-sun distance correction factor; the horizontal ET radiation is I_{ob} multiplied by the cosine of Θ_z.
- $G_{b,cs}$ and G_{cs}, the maximum clear-sky beam and global irradiances; for the tests, these values are derived with the ESRA model (Rigollier et al., 2000), using a Linke Turbidty value of 1, since the goal is to determine upper limits to the measured values.
- A calculated G (c.f. Eq. (1)):

$$sum = G_b*cos\Theta_z + G_d \quad (2)$$

- The clearness index:

$$K_t = G/(I_{ob}*\cos\Theta_z) \quad (3)$$

- The modified clearness index of Perez et al. (1990), which has reduced dependency on zenith angle and therefore on air mass:

$$K_t' = K_t/(1.031*\exp(-1.4/(0.9 + 9.4/AM)) + 0.1) \quad (4)$$

The tests and their flag numbers are shown in Table 1. For any row in the table, if the condition is met then the test failed, and the corresponding flag is set to 1, and 0 otherwise. The flag is considered to affect all the variables listed in the third column; for instance, flag9 = 1 means that both G and G_d failed the test. The tests marked with "*" in the first column are the same as some BSRN tests. Table 2 shows a summary of the flags that indicate whether any given variable (G, G_b or G_d) is acceptable or not.

Table 1
Proposed set of quality control tests. If a listed condition is met, the corresponding flag is set to 1, and 0 otherwise, for the variable/s listed in the third column. Tests with "*" in the first column are the same as in the BSRN set.

Test/Flag No.	Failure condition	Applies to
0*	$G < -4$ W/m^2	G
1*	$G_d < -4$ W/m^2	G_d
2*	$G_b < -4$ W/m^2	G_b
3*	$G > I_{ob} * 1.50 * (\cos\Theta_z)^{1.2} + 100$ W/m^2	G
4*	$G_d > I_{ob} * 0.95 * (\cos\Theta_z)^{1.2} + 50$ W/m^2	G_d
5	$G_b > I_{ob}$	G_b
6	$G_b > G_{b,cs}$	G_b
7*	(only applicable for sum > 50 W/m^2 and $\Theta_z \le 75°$) G/sum < 0.92 or G/sum > 1.08	G, G_b, G_d
8*	(only applicable for sum > 50 W/m^2 and 75° < Θ_z < 93°) G/sum < 0.85 or G/sum > 1.15	G, G_b, G_d
9*	(only applicable for G > 50 W/m^2 and $\Theta_z \le 75°$) $G_d/G > 1.05$	G, G_d
10*	(only applicable for G > 50 W/m^2 and 75° < Θ_z < 93°) $G_d/G > 1.10$	G, G_d
11	$\lvert G_b * \cos\Theta_z - (G-G_d)\rvert > 50$ W/m^2	G, G_b, G_d
12	$G_d > 700$ W/m^2	G_d
13	$G_d/(I_{ob} * \cos\Theta_z) > 0.6$	G_d
14	$K_t < 0.2$ and $G_d/G < 0.9$	G, G_d
15	$K_t > 0.5$ and $G_d/G > 0.8$	G, G_d
16	(only applicable for $G_d > 50$ W/m^2) sum/G_{cs} > 0.85 and G_d/sum > 0.85	G_b, G_d
17	$K_t' > 1$	G
18	$(G - G_d)/\cos\Theta_z > G_{b,cs}$	G, G_d

Table 2
Relation between quality flags and each radiation component.

	Bad quality if any of these flags is 1
G	0, 3, 7, 8, 9, 10, 11, 14, 15, 17, 18
G_b	2, 5, 6, 7, 8, 11, 16
G_d	1, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18

It is proposed here that a measured value is not to be used, that is, should be treated as missing, if *any* of the tests in which it is involved has failed. Note that if flag6 is 1, flag5 is also 1, since the clear-sky G_b is lower than the ET beam value; therefore, flag5 might be redundant if, as proposed here, one decides to flag G_b as incorrect if any of these flags is 1, but flag5 has been kept in case more relaxed criteria are used. Flag11 is similar to flags 7 and 8, but instead of using variable limits, a constant value is used as maximum difference between measured and calculated G; this is a more strict check (than the BSRN one) at high radiation values, and less strict at low radiations. Flag16 expands on tests 9 and 10, and indicates a 'tracker-off' situation, that is, when the solar tracker is not working properly; indeed, if the calculated G, derived from G_b and G_d, is close to its clear-sky value, then G_d should not be very high. Flag18 compares the calculated beam radiation (from the G and G_d measurements) to a maximum clear-sky beam value.

For consistency, the same acceptance criterion was used for the BSRN set of tests: an entry was considered as bad quality if any of the tests in which it is present failed (the "extremely rare" limits were not tested, however, as their results are usually not considered conclusive). One must note that some BSRN tests (No. 7–10 in Table 1) are not done in some conditions; the corresponding measurements are then kept here if they pass the other tests; in other words, data are only marked as 'bad quality' if they actually fail an applied test.