The Automation of Quality Control for Large Irradiance Datasets

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Abstract
The automation of quality control (QC) for large irradiance datasets is presented in this article. A three-step QC procedure is presented that includes an automatic elimination process of erroneous irradiance measurements and a novel empirical formulation for automatically identifying measurement tracking errors. The first step is a time-series visualisation, the second step is the automatic removal of missing and duplicate values, and the third step is an automatic flagging and elimination step to identify erroneous data. Two South African case studies were used to illustrate the practical application of the automatic QC procedure. The automatic QC procedure successfully removes the night-time data points as well as the tracking errors. An initial flagging procedure for reviewing data was also included as part of the QC procedure; however, these data points were found to consist of closure test flags. Upon further investigation, the flagged data did not indicate that the measurements were faulty, and therefore the automated elimination process shows adequate performance in removing data without this manual review process. The automatic process proves to be a time-efficient method to remove erroneous data and is therefore recommended as a minimum QC procedure for large irradiance datasets.

Keywords: quality control, irradiance, radiation, data

1. Introduction

Good-quality solar radiation data is needed to ensure profitable designs of photovoltaic (PV) systems (Muneer & Fairooz, 2002). The amount of total available solar energy, the relative magnitudes of irradiance components, and the availability patterns require long-term data. Various measurement equipment is used to record data which is then used for the design, modelling and monitoring of PV systems.

Diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) are measured with pyranometers, and direct normal irradiance (DNI) is measured with a pyrheliometer. GHI is measured with a hemispherical view and mounted horizontally. The pyranometer that measures DHI is shaded from the direct sunbeam. The pyrheliometer has a narrow view that only measures the beam directly from the Sun and is usually a sun tracker for greater accuracy (Sengupta, et al., 2021).

Real-time performance monitoring and energy yield forecasting also require accurate irradiance measurements. Data-driven applications have seen a rapid increase in usability, with irradiance measurements providing the pathway to improving the design, modelling and monitoring of PV systems. It is therefore vital to ensure that the quality of large irradiance datasets is acceptable for use by applying quality control (QC) procedures to the dataset.

QC procedures are broadly categorised into four sections, namely: range tests, across-quantities relationships, model comparison, and geographical analysis (Ohmura, et al., 1998). Usually, QC procedures flag data points which do not conform to one or more of the categories and leave the decision up to the user (Urraca, et al., 2017).

Large datasets, though ideal for PV system applications, must be preprocessed to ensure the quality of the data is appropriate. Forecasting, weather classification, monitoring, modelling and development of empirical models for relationships (transposition, decomposition, technology, corrections) require these data to be as accurate as possible. Gueymard and Ruiz-Arias (2016) states that there is no definitive, ideal, or widely accepted procedure for QC of irradiance data and usually institutions develop their own QC methodology. Furthermore, the possibility of low-quality periods and erroneous measurements is always extremely high. Erroneous measurements can be caused by instrumental errors, maintenance deficiencies or environment-related issues (Forstinger, et al., 2021; Muneer & Fairooz, 2002; Younes, et al., 2005).

Manual QC processes are a time-consuming and laborious exercise as irradiance datasets become larger. Automated QC is, in essence, a method of automatically eliminating erroneous data using either a comparison metric or an empirical formula. This reduces the assessment time that would have been needed to review the data, while ensuring that the quality of the data is of a high standard. Adequate QC procedures can reduce data storage space and ensure higher data quality, resulting in more accurate design, modelling, and monitoring of PV systems.

2. Quality Control of Large Irradiance Datasets

The QC methodologies aim to quantify steps to identify missing data, duplicate data and faulty data, usually using empirical formulae to achieve this.

Usually, a data point is flagged using a boolean system (meaning 1 is true, 0 is false) which is then easily identifiable to eliminate from the entire dataset. el Alani, et al. (2021) states that flagging a data point does not give any insight into why the point is rejected and does not solve the potential problem. The literature recommends a visual inspection before eliminating the data point (el Alani, et al., 2021; Forstinger, et al., 2021; Ntsangwane, et al., 2019). Missing timestamps can occur during a data logger reset or data acquisition failure. Forstinger, et al. (2021) suggests replacing it with "not a number" to provide a continuous flow of information. The total number of missing data points then provides an overview of the station's dataset completeness.

Table 1 summarises the accepted domains for GHI, DHI, and DNI of commonly referenced QC methodologies. GHI, DHI, and DNI are in W/m^2 and the K-definitions are unitless. I_{0n} refers to extraterrestrial irradiance on a normal surface, θ_Z denotes the solar zenith angle, I_{SC} denotes the solar constant (usually 1367 W/m^2), and G_{0h} refers to horizontal extraterrestrial irradiance.

NREL SERI QC software was developed by Maxwell, et al. (1993). The software compares measured versus expected values as part of the QC process. It defines

$$\sum = K_t - K_n - K_d$$

would be zero in a perfect component closure, where K_n is the direct beam transmittance, K_d is the diffuse transmittance, and K_t is the clearness index (Maxwell, et al., 1993). Thus, a nonzero value indicates an error in the instruments, which is then flagged. The methodology does not indicate which component(s) of the irradiance is the problem. The range boundaries must be site specific to be accurate, where Sengupta, et al., (2021) and el Alani, et al., (2021) argue that the exact upper GHI and DHI limits are difficult to define for a specific location.

The Daylight research team presented the QC methods according to the European Commission Daylight I, 1993 (Jacovides, et al., 2006) and the Commission International de l'Eclairage (CIE) tests are sorted into five categories (Tregenza, et al., 1994) (see Table 1).

Table 1: Summary of commonly referenced QC methodologies

Author	Valid domain	Comments
The European Commission Daylight research team (Jacovides, et al., 2006)	$K_d \leq 1.1$	
	$K_t \leq 1.2$	
	$DHI \leq 0.8 \cdot G_{0h}$	
	$GHI \geq 5$	
	$GHI - DHI \leq G_{0h}$	
	$K_d \geq 0.90$ for $K_t < 0.20$	
	$K_d \leq 0.90$ for $K_t > 0.60$	
Commission International de l'Eclairage tests by (Tregenza, et al., 1994)	$0 < GHI < 1.2 \cdot I_{SC}$	
	$0 < DHI < 0.8 \cdot I_{SC}$	
	$0 < DNI < I_{SC}$	
	$GHI = (DNI \cdot \cos\theta_Z + DHI) \pm 15\%$	Accepted range up to 25%
	$DHI < GHI + 10\%$	Allowance for ring shading when DNI is unavailable
BSRN recommendations by (Long & Dutton, 2002)	$-4 < GHI < 1.5\, E_{0n} \cos^{1.2}\theta_Z + 100$	BSRN physically possible limits
	$-4 < DHI < 0.95\, E_{0n} \cos^{1.2}\theta_Z + 50$	
	$-4 < DNI < E_{0n}$	
	$-2 < GHI < 1.2\, E_{0n} \cos^{1.2}\theta_Z + 50$	BSRN extremely rare limits
	$-2 < DHI < 0.75\, E_{0n} \cos^{1.2}\theta_Z + 30$	
	$-2 < DNI < 0.95\, E_{0n} \cos^{0.2}\theta_Z + 10$	
	$abs(Closr) < 8\%$ for $\theta_Z < 75°$ and $GHI > 50$	BSRN closure tests
	$abs(Closr) < 15\%$ for $93° > \theta_Z > 75°$ and $GHI > 50$	
	$DHI/GHI < 1.05$ for $GHI > 50$ and $\theta_Z < 75°$	BSRN comparison procedures
	$DHI/GHI < 1.10$ for $GHI > 50$ and $\theta_Z > 75°$	
Long and Shi recommendations (Long & Shi, 2008)	$0 < GHI < C_1\, E_{0n} \cos^{1.2}\theta_Z + 50$	C_1, C_2 and C_3 is station-specific parameters}
	$0 < DHI < C_2\, E_{0n} \cos^{1.2}\theta_Z + 30$	
	$0 < DNI < C_3 E_{0n} \cos^{0.2}\theta_Z + 10$	
	$DHI/GHI < 0.85$ for $GHI/GHI_{clear} > 0.85$ and $DHI > 50$	
	$DHI > R_L - 1.0$ for $DHI/GHI < 0.8$ and $GHI > 50$	

A popular QC methodology is the recommendations of the baseline surface radiation network (BSRN) by Long and Dutton (2002). The physically possible limits test compares the irradiance measurement with a lower and an upper limit (Urraca, et al., 2017). The lower limit is usually -4 or 0 W/m^2 (Long & Dutton, 2002; Hoyer-Klick, et al., 2008; Long & Shi, 2008), and the upper limit is based on a clearsky model (Geiger, et al., 2002; Journée & Bertrand, 2011; Hoyer-Klick, et al., 2008; Younes, et al., 2005). Naturally, a data point that deviates from the minimum and maximum theoretical values is expected to indicate an erroneous measurement. Rare limits are the next step. Not all authors immediately exclude a data point if they are not flagged within the conditions presented in (Long & Dutton, 2002) but rather suggest a review of the data before deciding whether to remove it (Ntsangwane, et al., 2019; Moreno-Tejera, et al., 2015). The rare data is associated with unusual weather conditions (Ntsangwane, et al., 2019) which is unlikely, but not impossible to occur.

Comparison procedures are also used as part of the QC methodology which utilises the closure error. The closure error ($Closr$) is defined as:

$$Closr = 100\,[(\,DNI \cdot \cos\theta_Z + DHI - GHI\,)\,/\,GHI\,]$$

Long and Shi (2008) proposes the QCRad methodology by first introducing climatological limits with station-specific parameters. Further, the authors presented climatological comparisons which utilises the Rayleigh limit (R_L) (Long & Shi, 2008).

Recommendations for decomposition model development are presented by Gueymard and Ruiz-Arias (2016). Long and Dutton (2002) recommend physically possible limits and comparison procedures. Long and Dutton (2002) recommend that θ_Z not be greater than $85°$, that is, solar elevation angles less than 5˚, while Tregenza, et al. (1994) recommends 4˚. Furthermore, it is recommended that the GHI and DHI be greater than zero, and the DNI be a minimum of zero or higher. There are thus contrasting views of the cut-off of GHI: (Tregenza, et al., 1994) recommends 20 W/m^2, (Gueymard & Ruiz-Arias, 2016) recommends 0 W/m^2 and Jacovides, et al. (2006) recommends 5 W/m^2 (Tregenza, et al., 1994; Gueymard & Ruiz-Arias, 2016; Jacovides, et al., 2006). Gueymard and Ruiz-Arias, (2016) also recommends using the elevation in m ($Elev$) to determine a valid domain for DNI and it is recommended that the closure error is less than 5% (Gueymard & Ruiz-Arias, 2016). The closure error does differ from Long and Dutton (2002).

K-tests were introduced by Geuder, et al. (2015). The two main tests for the K-tests were assessing the K_t-K_n-space and the K_t-K_d-space. Along with the K-tests, the extremely rare limits of the BSRN, the comparison procedures and closure tests are also implemented in (Geuder, et al., 2015).

Forstinger, et al. (2021) proposes a harmonised QC procedure, a combination of various available methods, including expert visual inspection. Forstinger, et al. (2021) suggests that a flagged timestamp must be considered with respect to its surrounding timestamps. A data point is declared usable if it passed all individual QC tests or if the tests could not be performed while all measured radiation components were available. It is also suggested to exclude an entire day if more than 30% of its daytime timestamps are flagged (Forstinger, et al., 2021).

The BSRN's physically possible limits and extremely rare QC tests are used in various literature (see (Urraca, et al., 2017; Perez-Astudillo, et al., 2018; Ntsangwane, et al., 2019; Roesch, et al., 2011; Moreno-Tejera, et al., 2015; Forstinger, et al., 2021), as well as the comparison procedure (using $Closr$) are used in (Forstinger, et al., 2021; Roesch, et al., 2011; Moreno-Tejera, et al., 2015; Perez-Astudillo, et al., 2018). There are some discrepancies regarding the limit of the solar elevation angle in (Tregenza, et al., 1994; Gueymard & Ruiz-Arias, 2016; Urraca, et al., 2017; Younes, et al., 2005) and the GHI limit in (Tregenza, et al., 1994; Gueymard & Ruiz-Arias, 2016; Jacovides, et al., 2006).

Most of the QC methods discussed assume that at least two of the three irradiance components are available. Different authors suggested automated elimination for certain tests versus reviewing the flagged data prior to elimination. Visual aid and summaries provide additional input into the QC process, making the automatic process more of a semi-automatic process. Overall, the empirical formulae presented provide a blueprint for QC tests for large irradiance datasets. Based on the available literature, the following minimum procedures for QC of large irradiance datasets are recommended:

- Time-series visualisation;
- missing and duplicate values;
- a flagging process that includes an immediate (automatic) elimination step and a reviewing step.

3. Quality Control Recommendations

This section will discuss the three minimum steps for QC: a time-series visualisation for an initial inspection, removal of missing and duplicate values, and then finally a flagging procedure that removes erroneous data from a dataset. For the time-series visualisation, the GHI, DHI, and DNI are plotted against time. Obvious gaps or erroneous data, such as periods where DHI ≈ GHI and DNI ≈ 0 are usually obvious to spot. From this, data points with missing data as well as duplicate timestamps are then eliminated.

In Table 2***,*** the names, flag labels and domains in which a data point is valid are shown. If it does not fall within the domain, the table also indicates whether the flagging process results in immediate/automatic elimination or whether the data will be reviewed before being removed from the dataset. *BSRN* refers to the BSRN recommendations in (Long & Dutton, 2002), *Daylight* to the European Commission Daylight Research Team (Jacovides, et al., 2006), *K-tests* to the K-tests proposed in (Geuder, et al., 2015) and *Gueymard and Ruiz-Arias* to the QC methodology for the development of the decomposition model in (Gueymard & Ruiz-Arias, 2016). Some of the equations have overlapping properties, are encapsulated by another, or result in an equation becoming obsolete. Therefore, not all equations are included to eliminate redundancy and reduce unnecessary computational power.

The *BSRN*, *Daylight* and *K-tests* QC methodologies were found to be inadequate in flagging tracking error periods where the irradiance was relatively low, such as timestamps in the early mornings and late afternoons. Usually, these measurements will only be removed after a manual reviewing process by the user. A tracking error test is proposed to automatically flag these erroneous data, and thus Tracker refers to the tracking error flagging process in Table 2. In theory, the ratio of DHI and GHI should be less than 1 but can be "possible due to experimental uncertainty at low solar elevations and/or under low-irradiance conditions" (Gueymard & Ruiz-Arias, 2016). However, if the dataset has long periods of DHI ≥ GHI, with consistently low DNI levels, this is an indication that the measuring equipment is defective. Tracking failures can occur due to misaligned pyrheliometers, which will read zero, and the shading ball will no longer occlude the Sun such that DHI ≈ GHI and DNI ≈ 0 (Brooks, et al., 2015). Thus, the ratio of GHI and DHI (K_d) is close to 1, however, K_n is approximately zero.

Table 2: Label and valid domains for the proposed QC procedure

Name	Flag label	Domain	Automatic/Review
BSRN	1a	$-4 < \text{GHI} < 1.5\,\text{I}_{0\text{n}} \cos^{1.2}\theta_Z + 100$	Automatic
	1b	$-4 < DHI < 0.95\,I_{0n} \cos^{1.2}\theta_Z + 50$	Automatic
	1c	$-4 < DNI < I_{0n}$	Automatic
	1d	$-2 < GHI < 1.2\,I_{0n} \cos^{1.2}\theta_Z + 50$	Review
	1e	$-2 < DHI < 0.75\,I_{0n} \cos^{1.2}\theta_Z + 30$	Review
	1f	$-2 < DNI < 0.95\,I_{0n} \cos^{0.2}\theta_Z + 10$	Review
	1g	$abs(Closr) < 8\%$ for $\theta_Z < 75°$ and $GHI > 50$	Review
	1h	$abs(Closr) < 15\%$ for $93° > \theta_Z > 75°$ and $GHI > 50$	Review
	1i	$K_d < 1.05$ for $GHI > 50$ and \$ $\theta_Z < 75°$	Automatic
	1j	$K_d < 1.10$ for $GHI > 50$ and $\theta_Z > 75°$	Automatic
Daylight	2a	$K_t < 1.2$	Review
	2b	$DHI < 0.8 \cdot G_{0h}$	Automatic
	2c	$GHI > 5$	Automatic
	2d	$GHI - DHI < G_{0h}$	Automatic
K-tests	3a	$K_n < K_t$	Review
	3b	$K_n < 0.8$	Automatic
	3c	$K_d < 0.96 \; for \; K_t > 0.6$	Automatic
Gueymard and Ruiz-Arias	4a	$\theta_Z < 85°$	Automatic
	4b	$DNI < 1100 + 0.03\,Elev$	Automatic
	4c	$Abs\,(Closr) < 5\,\%$	Review
Tracker	5a	$0.8 < K_d < 1.2$ and $K_n < 0.01$	Automatic

4. Case Study

Two datasets are used for this case study and are indicated by the black dots in Figure 1. The first dataset (referred to as Dataset 1) is from the Stellenbosch University (SUN) station, which is located in Stellenbosch, South Africa. The coordinates of the station are (33.9281° S, 18.8654° E) and the altitude is relatively low (119 m). The station measures, among other measurements, the GHI, DNI, and DHI over a minute interval, which is aggregated into hourly measurements. The GHI is measured using an unshaded Kipp & Zonen CMP11 unshaded pyranometer, the DNI is measured with a Kipp & Zonen CHP1 on a SOLYS tracker and the DHI is measured with a Kipp & Zonen CMP11 under a shadow band (Brooks, et al., 2015; SAURAN, 2022).

The second dataset (referred to as Dataset 2) is from the University of Zululand (UNZ) station, which is located in KwaDlangezwa, South Africa. The station's altitude is relatively low (90 m), and the coordinates of the station are (28.8529° S, 31.8516° E). The measuring system is similar to SUN (SAURAN, 2022). For this study, hourly data is used from 2019 to 2021 for both datasets.

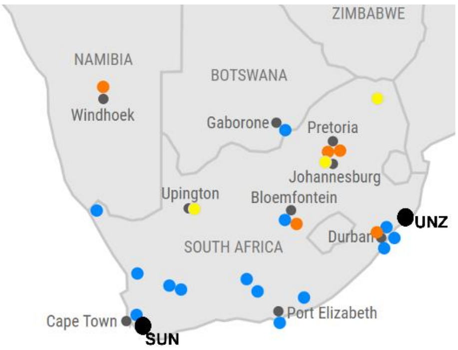

Figure 1: Datasets used for this study

4.1. Time-series visualisation and the removal of duplicate and empty data points

Figures 2 and 3 show the SUN and UNZ data from the SAURAN network, respectively. The datasets include the removal of repeated timestamps and missing data. For both datasets, there are clear periods where no data is recorded. There also appears to be a tracker error during late 2020 for a short period for the SUN dataset and a clear tracking error in the UNZ dataset (where GHI ≈ DHI and DNI ≈ 0 at the start of 2019 and also from July 2019 onwards).

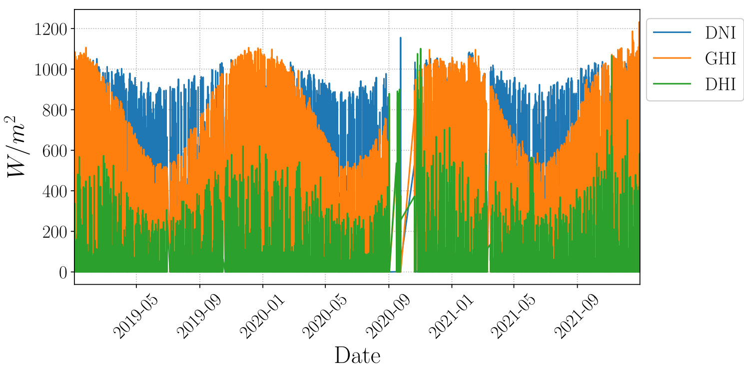

Figure 2: Dataset 1 - After the removal of duplicate and empty data points

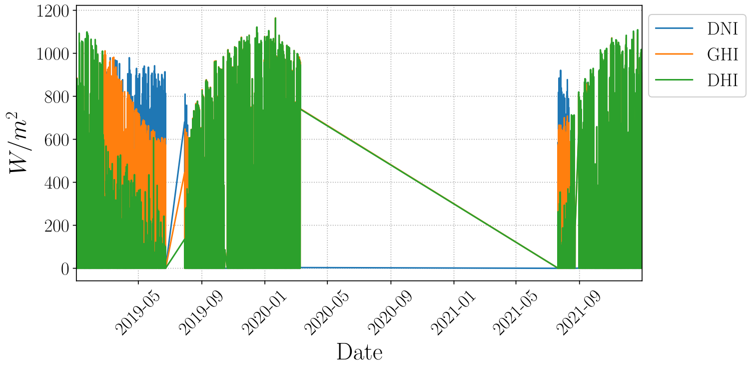

Figure 3: Dataset 2 - After the removal of duplicate and empty data points

4.2. Flagging process

Figures 4 and 5 show the distribution of the number of data points flagged using the automated process as previously described. From a visual inspection, the BSRN is flagged by 1g, Daylight by 2c, K-tests by 3a and 3c, and Gueymard and Ruiz-Arias by 4a and 4c. The tracking error (Tracker 5a) is significantly flagged for Dataset 2. The dataset goes through two elimination processes: an automatic elimination process and then a reviewer-based inspection/elimination process.

After the data undergo the automated QC procedure step, there are still flags that must be reviewed. The automatic elimination process removes 61.4% and 90.2% from Datasets 1 and 2, respectively. These metrics make sense considering the removal of nighttime values and tracking errors (such as the tracking error noticeable in Figure 3). The nighttime flags (2d and 4a) remove 53.6% of the original data from Dataset 1 and 51.7% from Dataset 2. Dataset 1 has 23.5% of the original number of data points flagged for review and Dataset 1 has 5.6% of flagged data points. The closure tests comprise approximately 99.9% of the total reviewable flagged data points.

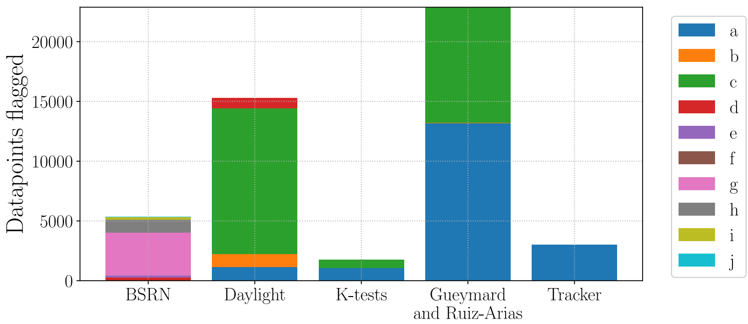

Figure 4: Dataset 1 - Flagged data

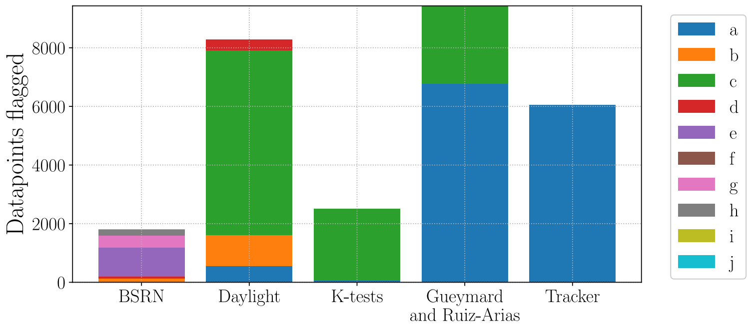

Figure 5: Dataset 2 - Flagged data

The days with the most flags were identified from each dataset and are shown in Figures 6 and 7. Tables 3 and 4 show the hourly GHI, DNI, and DHI measurements, as well as the $Closr$ percentage, and the checkmark (✓) indicates that the timestamp has been identified with a specific flagging procedure. Flags 1d to 1f and 2a were not flagged for either of these days.

In Figure 6, the clear sky bell curve is visible; however, Table 3 shows that most closure tests have been flagged. For example, at 07:00, 1h and 4c are flagged. The closure percentage is 16.69%, which is less than the specified 15% for 1h and 5% for 4c. Then also, at 08:00, 1g, 3a and 4c are flagged which are the closure tests ($abs(Closr) = 22.57\% > 8\%$ as well as $abs(Closr) = 22.57\% > 5\%$) and the K-test ($K_n = 0.56 > K_t = 0.54$). The historical weather of that day states that it rained the previous night and cleared up in the morning, resulting in a clear day (Stellenbosch Weather, 2022). Similarly to Table 4 and Figure 7, a clear sky bell curve is observed. The closure tests are also flagged, as well as K-tests when $K_n > K_t$. Historical weather data from Richard's Bay indicated that it was a clear, hot, and sunny day (World Weather, 2019).

After reviewing the data, the authors of this paper reject the flagged data and assume the data presented is usable and not faulty after the automatic elimination process. The automatic elimination is sufficient as a minimum suggested QC procedure for irradiance datasets. The review-based part of the QC procedure is there for the user's discretion and based on the application of the data.

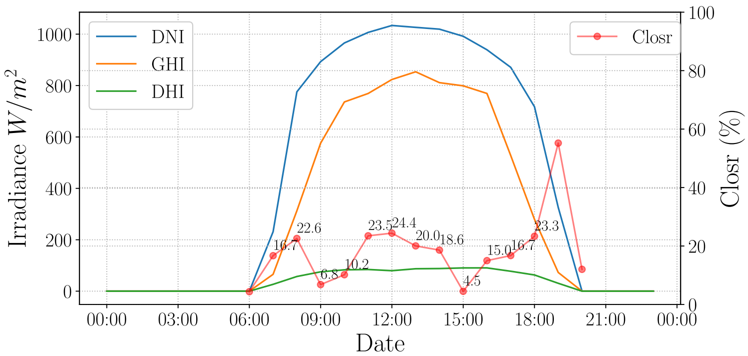

Figure 6: Dataset 1 - Review of a flagged day (21 October 2020)

Table 3: Dataset 1 - 21 October 2020 summary

Hour	GHI	DHI	DNI	$Closr$	θ_Z	1g	1h	3a	4c
	W/m^2			%	°				
07:00	65.6	26.6	231.3	16.7	77.5		✓		✓
08:00	312.6	57.1	775.5	22.6	65.1	✓		✓	✓
09:00	575.8	75.3	893.0	6.8	52.8				✓
10:00	736.2	83.0	965.7	10.2	41.1	✓			✓
11:00	769.2	84.3	1006.8	23.5	30.7	✓		✓	✓
12:00	823.6	79.7	1033.8	24.4	23.9	✓		✓	✓
13:00	853.6	87.2	1026.5	20.0	24.1	✓		✓	✓
14:00	811.3	88.0	1019.5	18.6	31.0	✓		✓	✓
15:00	799.0	90.5	991.8	4.5	41.4				
16:00	769.3	90.6	939.2	15.0	53.1	✓			✓
17:00	527.8	77.5	870.9	16.7	65.4	✓			✓
18:00	279.6	63.1	717.6	23.3	77.8		✓		✓

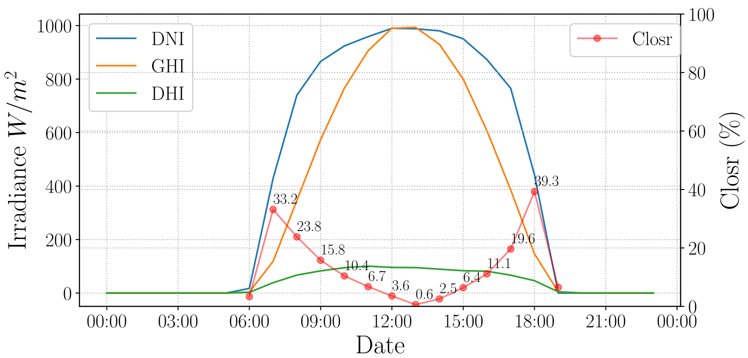

Figure 7: Dataset 2 - Review of a flagged day (26 February 2019)

Table 4: Dataset 2 - 26 February 2019 summary

Hour	GHI	DHI	DNI	Closr	θ_Z	1g	1h	3a	4c
	W/m^2			%	°				
07:00	118.9	38.8	429.1	33.2	73.8	✓		✓	✓
08:00	346.6	67.3	739.8	23.8	60.7	✓		✓	✓
09:00	573.5	82.9	866.0	15.8	47.9	✓		✓	✓
10:00	766.2	95.0	924.0	10.4	35.6	✓			✓
11:00	906.3	100.7	958.8	6.8	25.3				✓
12:00	990.0	95.9	989.8	3.6	20.1				
13:00	993.3	95.3	988.1	0.6	23.8				
14:00	930.0	89.5	980.5	2.6	33.6				
15:00	800.2	83.7	950.7	6.4	45.6				✓
16:00	606.6	81.7	873.1	11.1	58.4	✓			✓
17:00	385.7	66.9	765.6	19.6	71.5	✓			✓
18:00	146.3	46.4	442.3	39.3	84.5		✓		✓

5. Conclusion

For this paper, an extensive review of QC procedures for large irradiance datasets is discussed. A three-step methodology is proposed, which includes a time series visualisation, removing missing and duplicate data entries, and a flagging QC process. The flagging process consists of two parts: automatically eliminating data that do not conform to specified domains and flagging data for review. A case study of two datasets is presented which provides a practical application of the proposed procedure. The review part of the QC methodology is specifically to assess uncommon but not unlikely occurrences, as well as to understand why certain irradiance measurements can occur.

Approximately 50% of the original datasets are flagged for night-time values where PV power production is zero. The QC method successfully removes tracking error data points from the datasets automatically. The majority (99.9%) of flagged-for-review data points consisted of data not conforming to the closure tests; however, further investigation showed that the flagged data points are not erroneous. Thus, the proposed automated QC process is sufficient as a minimum procedure for basic applications, such as modelling and monitoring of PV systems, to remove the majority of erroneous irradiance measurements.

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