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Task 16 Solar Resource for High Penetration and Large Scale Applications

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Solar Energy

SolarStations.org — A global catalog of solar irradiance monitoring stations

April 2025

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COVER PICTURE

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

SolarStations.org— A global catalog of solar irradiance monitoring stations

IEA PVPS Task 16
Solar Resource for High Penetration and Large Scale Applications

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Data article

SolarStations.org—A global catalog of solar irradiance monitoring stations

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ABSTRACT

Ground-based measurements remain the most accurate method for determining solar surface irradiance despite continuous improvements in satellite-derived and reanalysis models. However, identifying and accessing high-quality irradiance measurements is challenging, largely due to incomplete information on available stations. Consequently, many studies use low-quality data or have poor geographical coverage, reducing the scientific outcomes. To address this issue, a global catalog of multi-component solar irradiance monitoring stations has been created, streamlining the identification of relevant stations. Each station entry includes the following metadata: station name, location, elevation, owner, network, period of operation, data availability, instrumentation, and climate zone. The station catalog and an interactive map are available for free at www.SolarStations.org. As of April 2025, the catalog contains information on 808 stations, of which 440 are currently active. Only half of the active stations share data freely, highlighting a widespread issue of data availability. The catalog and website are developed openly on GitHub and welcome community contributions.

1. Introduction

To obtain solar surface irradiance data, three main sources are presently available: ground-based measurements, satellite-derived estimates, and numerical weather prediction modeled data [1]. The highest accuracy can normally be achieved with ground-based measurements, though achieving this requires rigorous maintenance practices and careful quality assessment of the data. Thanks to their potentially high accuracy, long-term ground-based measurements remain critical for high-quality applications such as developing solar radiation models, benchmarking modeled datasets, or quantifying Earth's radiation balance [2–4]. In parallel, short-term measurement campaigns are necessary to evaluate the solar resource for large solar energy projects with low uncertainty and thus maintain financial risks at a minimum [1,5].

High-quality solar radiation datasets typically include at least the following three standard observations:

- Global horizontal irradiance (GHI): total solar irradiance incident on a horizontal surface, including both direct and diffuse irradiance.
- Direct normal irradiance (DNI): direct/beam irradiance received at normal incidence from a small solid angle centered around the sun disk.
- Diffuse horizontal irradiance (DHI): irradiance scattered in all directions by the atmosphere, measured on a horizontal surface.

Although global tilted irradiance (GTI) is of interest for evaluating solar energy systems, it is not considered a standard observation because of the infinite number of possible orientations. Furthermore, GTI can be estimated from the standard observations with acceptable accuracy for most applications [1,6,7].

The three standard observations are related by the *closure equation*:

$$\mathrm{GHI} = \mathrm{DHI} + \mathrm{DNI} \cdot \cos(\theta_z) \tag{1}$$

where θ_z is the solar zenith angle. Whereas GHI is made up of two independent irradiance components, DHI and DNI, it is common practice to also refer to GHI as a component. For example, comparisons involving GHI, DHI, and DNI are usually called three-component checks. In what follows, those stations that observe at least any two of GHI, DHI, or DNI are referred to as multi-component stations.

As shown by the closure equation, observing two of the three reference components makes it possible to calculate the third component. Moreover, measuring all three components provides a means of independently assessing whether closure is actually achieved. This opens the possibility to perform a much more elaborate quality assessment, which is ultimately conducive to higher confidence in the measurements. Lowering the measurement uncertainty in the irradiance components is a key aspect of solar resource assessments [8].

Despite the importance of ground-based measurements in general, most meteorological stations in the world do not provide irradiance

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measurements, and if they do, the measurements are often single-component and of relatively poor quality. The few high-quality multi-component monitoring stations whose data can be shared are typically operated by national meteorological institutes, universities, or public research organizations. The scarcity of these stations is largely caused by the high investment and operation costs, as well as the labor-intensive maintenance requirements.

Unfortunately, many of the high-quality stations that do exist are often not used in research studies because either they are simply unknown to the scientific community or there are barriers to their public data access. In the authors' opinion, this accessibility issue constitutes an even greater problem than the scarcity of stations. As an example, the largest global benchmark of satellite-derived irradiance estimates recently undertaken in Ref. [3,9] analyzed data from 161 stations, whereas if the SolarStations.org catalog had been available, more than 400 stations could potentially have been used.

Ground stations which are part of a network are generally easier to identify and thus see much greater usage. Examples of well-known regional and national networks include MIDC by NREL [10], SOLRAD and SURFRAD by NOAA [11,12], SRML by the University of Oregon [13,14], and SAURAN in southern Africa [15]. On a global scale, two networks stand out. The first (and oldest) is the Baseline Surface Radiation Network (BSRN) [16,17]. The BSRN was instituted by the World Climate Research Programme (WCRP) in 1992 and is still the only global long-term solar and longwave irradiance network. The second is the ESMAP network of short-term campaign stations in the Global South [18] sponsored by the World Bank.

The aforementioned networks account for only a fraction of the existing radiometric stations but represent the primary source of ground-measured irradiance data used by the scientific community. That is because they provide free and unrestricted access to multi-component observational data. Even though many other stations do exist, these are often not easy to identify or access, leaving potential users to rely on datasets of lower quality and/or deficient geographical representativeness, thus affecting the accuracy and reliability of their findings. Moreover, there is an apparent entrainment effect that has permeated the various scientific communities involved in solar radiation modeling or forecasting. In essence, many publications have presented validation work based on BSRN data, almost exclusively, giving the false impression that *only* BSRN data are of high quality.

Another aspect of this situation is that, in many instances, the existing observations are used to postprocess (or "site adapt") modeled datasets, particularly those based on satellite observations, reanalysis, or forecast models [19–22]. A fair evaluation of such improved data requires independent observations from many stations not used for model development, which is currently challenging.

Recognizing the need for reliable and geographically diverse solar irradiance ground measurements, this paper presents SolarStations.org, a global catalog of multi-component solar irradiance monitoring stations. The main goal of the catalog is to provide users with the necessary information to make informed decisions on the best irradiance data to use, particularly including lesser-known stations. This provides assistance to address questions such as: Where is the nearest monitoring station to a point of interest? What measurements are available from a specific station? Is data freely available, and if yes, for which period?

The catalog is part of the *AssessingSolar* initiative [23], which was launched through the International Energy Agency's expert task on solar resource assessment PVPS Task 16 [24]. Within the field of solar irradiance, there are two related initiatives that deserve attention. The first is the Global Energy Balance Archive (GEBA) [25], which contains monthly-mean irradiance fluxes from thousands of stations of varying quality. The second is the in-situ measurements dataset in Ref. [26] (partly based on [27,28]), which can be accessed at https://viewer.webservice-energy.org/in-situ/. Both of these are databases of measured data and thus are limited to stations that can provide shareable data to third-party platforms. In comparison, the SolarStations.org catalog contains metadata for all qualifying stations (regardless of data availability), and thus provides a much more comprehensive overview, although no measurement data is actually provided.

2. Methods

2.1. Identifying stations

The SolarStations.org catalog was conceptualized after growing frustration among solar resource experts during the collection of data for the global irradiance benchmarking study in [3]. The study was carried out by a group of experts in the International Energy Agency's PVPS Task 16 and included data from 129 multi-component stations, the largest benchmarking study to date.

Identifying these stations was non-trivial, and many were based on word-of-mouth or personal contacts, highlighting the need for a comprehensive overview of available stations. Starting from the list in [3], the SolarStations.org catalog was expanded by meticulously searching through scientific reports, publications, presentations, benchmarking studies, and the world wide web, as well as soliciting input from the scientific community. Notably, the most significant contribution of stations was made by the fourth co-author, who over several years, had maintained a curated list of high-quality stations.

2.2. Station classification

Solar irradiance monitoring stations employ different types of instruments with varying levels of uncertainty. Additionally, the irradiance components measured at each station differ depending on the instrumentation used. It should be noted that this catalog includes only multi-component stations, i.e., stations that measure at least two of the three standard components. This restrictive criterion is introduced here in part because multi-component stations have the important advantage of providing the necessary basis to conduct more exhaustive and effective quality assessments. This also prevents the over-representation of thousands of low-quality stations measuring GHI only (usually as part of meteorological or agricultural networks), with almost no opportunity for satisfactory quality assessment. Low-quality irradiance measurements or insufficient quality assessment make them unfit for model validation purposes, in particular. This stems from the fact that, under clear-sky conditions in particular, the uncertainty of the best radiation models approaches that of high-quality reference measurements [29]; it is thus conceivable that such models might have a lower uncertainty than low-quality measurements.

Whether a radiometric station should be considered for a given application depends on the acceptable level of uncertainty and the number of components required. Thus, it is helpful to categorize the stations into classes (hereafter, "tiers") to aid users in identifying suitable stations. The categorization is based solely on the instrumentation of the station and not the quality of the data. Attempting to evaluate data quality is difficult and can be subjective to some extent [9]. That process would also be contingent on having access to the actual data and performing stringent quality control processes. Furthermore, data quality cannot be summarized by a single attribute because it often varies from year to year with changing equipment or maintenance practices.

2.2.1. Tier-1 stations

Tier-1 stations are made of top-of-the-line research-grade stations and are defined as stations that meet all of the following criteria:

- Measurement of GHI with a spectrally flat Class-A thermopile pyranometer
- Measurement of DNI with a Class-A thermopile pyrheliometer mounted on a solar tracker
- Measurement of DHI with a spectrally flat Class-A thermopile pyranometer shaded by a shading ball or disk attached to a solar tracker.

Class A refers to the radiometer categorization stipulated in standard ISO 9060:2018. Tier-1 stations require a high investment cost since they utilize a solar tracker and high-performance thermopile instruments. All stations in the BSRN network are examples of Tier-1 stations.

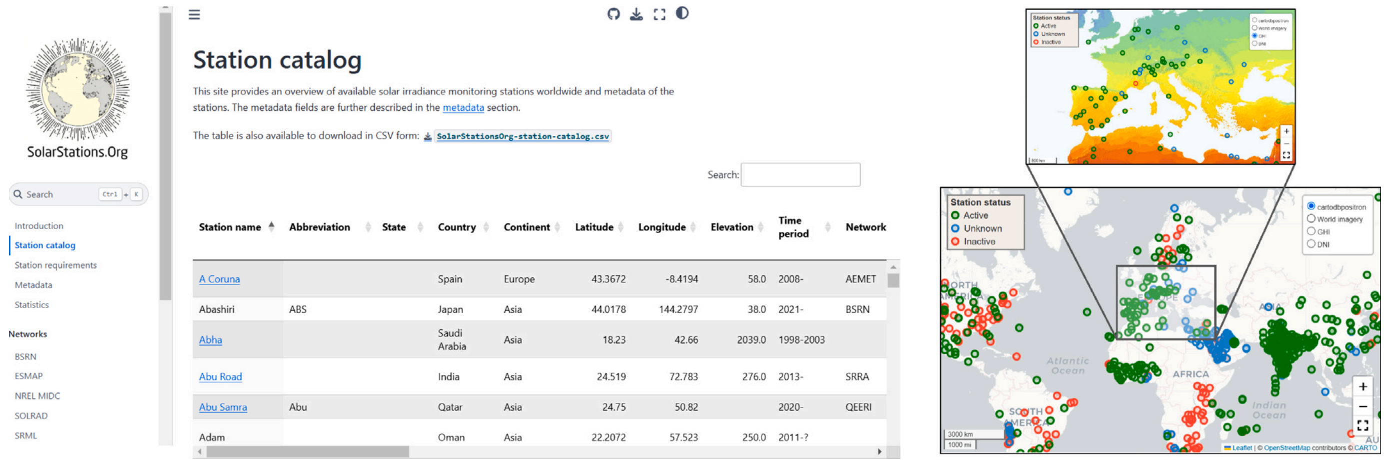

Fig. 1. Screenshots of the interactive station catalog (left) and map (right) from the SolarStations.org website. The inset map shows a zoomed-in view with the annual average GHI background activated.

2.2.2. Tier-2 stations

Tier-2 stations utilize lower-quality equipment or only monitor two of the three components. The stations that are categorized as "Tier 2" have to meet only one of the following criteria:

- Meet two of the three requirements of Tier-1 stations
- Observe GHI and DHI using a rotating shadowband pyranometer or a 2-component pyranometer, such as the Delta-T SPN1.

Even though the measurement uncertainty of Tier-2 stations is typically higher than that of Tier-1 stations, they might still be very useful in various applications. Moreover, including these types of stations significantly increases the geographical coverage of high-quality data.

2.2.3. Tier-3 stations

Stations measuring solar irradiance that do not qualify as Tier-1 or Tier-2 stations are categorized as Tier 3. This includes stations that sense DHI using a manually adjusted shadow band. Such measurements have substantial uncertainty because of the necessity to manually adjust the shadow band every few days, which is prone to errors. Tier-3 stations are not included in this catalog because of their low accuracy and/or lack of satisfactory quality assessment, and thus, have limited interest in solar energy research.

2.3. Station metadata

As of April 2025, the catalog contains 808 known stations, 440 of which are active. Each station entry is defined by the following primary metadata:

- Station name
- Country and state if applicable
- Location (latitude and longitude)
- Elevation
- Time period of operation
- Owner or contact
- Network (if applicable)
- Data availability
- Instrumentation

The instrumentation field denotes what instruments are used at each station: *G* denotes an unshaded thermopile pyranometer measuring GHI, *B* denotes a thermopile pyrheliometer measuring DNI, and *D* denotes a thermopile pyranometer shaded by a tracking shadow ball or disk measuring DHI. Additional options include: *IR* (pyrgeometer), *UV/UVA/UVB* (UV radiometers), *PAR* (photosynthetic active radiation sensor), and *RSR/RSI/RSP* for a rotating shadowband radiometer/irradiometer/pyranometer. Wherever possible, there is also a hyperlink to the station or network's website. Additionally, known issues or supplementary information, if available, is mentioned in a comment section. A screenshot from SolarStations.org of the current station catalog is shown in Fig. 1.

Furthermore, the catalog has been enriched with additional derived metadata enabling more informed decisions and statistical analyses of the existing stations. The derived metadata for each station includes:

- Continent
- Köppen–Geiger classification and climate zone
- Station tier (based on instrumentation; see above)
- Annual climatological irradiance (GHI, DNI, and DHI)

The Köppen–Geiger classification is determined at a resolution of 100 arc seconds using the *kgcpy* Python package based on data from [30]. For each station, the mean annual irradiance was obtained from the NASA POWER Project's Climatology 2.4.2, which was current as of 2024-10-29.

2.4. Station catalog

The information included in the SolarStations.org catalog can be freely downloaded as tabulated data in CSV format. This includes both the primary and derived metadata upon which the website's *Statistics* section is built. It is emphasized that the catalog does not provide a way for users to directly download the solar irradiance data from each station. In most cases, it points to the website from which the data can be downloaded, or offers information on possible contacts. However, for some networks, users can download data using the data retrieval functions (pvlib iotools) described in [31], which are part of the pvlib python package [32]. The pvlib iotools provide a standardized way to download irradiance data from BSRN, MIDC, SOLRAD, SRML, and SURFRAD. Details on the implementation of the catalog is described in Section 4.

2.5. Statistics

The SolarStations.org catalog can also be used to conduct statistical analyses regarding solar irradiance stations. For example, of the 808 identified stations, 440 were active in April 2025, whereas only 14 of these were in continuous operation before 1993 (~3%). Additionally, 76% and 24% of the identified stations were classified as Tier 1 and Tier 2, respectively. Fig. 3 displays the number of active stations per continent. It is clear that Asia has by far the highest number of stations.

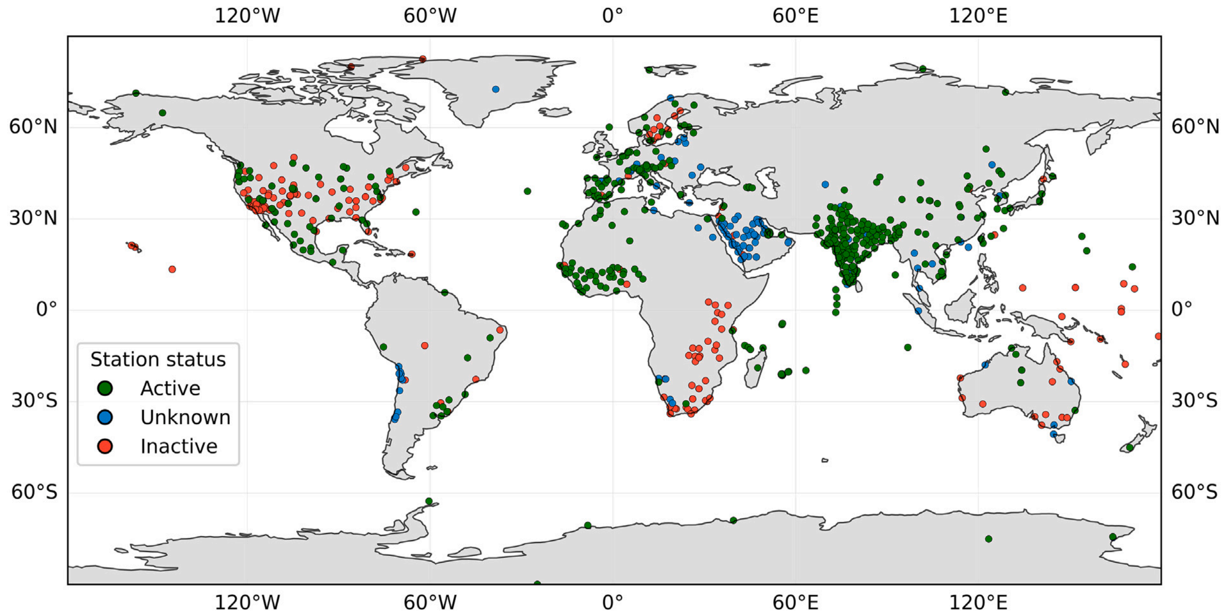

Fig. 2. Map of the irradiance monitoring stations from the SolarStations.org catalog.

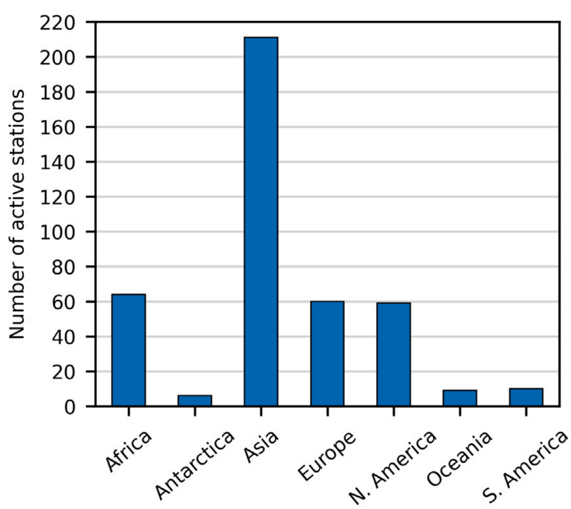

Fig. 3. Number of active stations per continent as shown in the Statistics page of SolarStations.org.

In contrast, the continent with the highest density of stations is Europe, with ~6 stations per million km^2.

More plots are presented on the *Statistics* page of the website, such as the total number of stations per country, Köppen–Geiger climate zone, elevation, or latitude.

2.6. Limitations

Based on the station map in Fig. 2, it is clear that there are very few known stations in Russia, Western Asia, central Africa, or the northern part of South America. This is probably in part caused by the incompleteness of the catalog, as it is very unlikely that there are not more stations in those regions. In general, it has been less challenging to identify stations in Western countries than elsewhere

Additionally, information concerning inactive stations is expected to be less complete than it is for active stations. In most cases, the historical stations that are included in the catalog belong to networks whose websites have been preserved. It is known that, unfortunately, historical databases have been lost because of computer issues or other factors. In parallel, stations that are not part of a network are harder to identify and thus are relatively less frequent than stations in networks.

Overall, the presented catalog is still under development and does not pretend to be exhaustive. It can thus be assumed that there exist many multi-component stations that are not part of the catalog. It is expected that the more the website becomes known at large (and not just by the solar energy community), new stations will be identified and added. In that process, contributions to the station catalog are highly welcome (see Section 4). Nevertheless, it is expected that most existing Tier-1 stations in service have been listed. It is therefore unlikely that users would be easily able to retrieve data from stations not currently cataloged.

3. Use cases

To demonstrate the usefulness of the catalog, this section presents three example use cases. Each use case illustrates a different aspect of how the SolarStations.org catalog can be used, although the possible use cases extend far beyond the ones described.

1. The accuracy of model-derived irradiance datasets (e.g., satellite-derived or reanalysis) can be assessed by comparing modeled data with high-quality ground measurements. Benchmarking studies can only have global relevance if they have a large geographical coverage. Such studies can, with great benefit, use the SolarStations.org catalog as a starting point for selecting suitable stations. For instance, a new global irradiance benchmark is ongoing within the IEA PVPS Task 16, which used the catalog to identify potential stations.
2. Quality control checks are often developed to be valid for a wide range of climatic conditions; e.g., [33]. When developing new quality-assessment algorithms, it is important to include data from stations that experience unusual climatic or environmental conditions, such as high turbidity or humidity, equatorial, polar, or high-elevation situations, high surface albedo, etc. A Task 16 working group recently used the catalog for an ongoing effort aimed at improving data quality assessment algorithms. Specifically, a number of mountain stations were selected by sorting the interactive table by elevation and considering stations located above 3000 m.

3. In a recent study [7], a key objective was to investigate the behavior of a transposition model (used to derive tilted irradiance from the three standard components) regarding circumsolar brightening at consistently high solar elevations. To make such a comparison, it was necessary to obtain irradiance measurements from a site near the equator with high annual direct irradiance. Using the interactive map with the irradiance background enabled, it was seamless to identify a suitable station with freely available data, namely the Darwin Met Office BSRN station in Australia.

For each of the above use cases, the station catalog provided a list of stations that complied with the selected criteria, as well as critical information regarding data availability. Consequently, for use cases 1 and 2 above, relying on the station catalog resulted in the use of a larger number of stations and, consequently, more generalizable scientific results.

4. Implementation

The station catalog consists of metadata that is stored in a comma-separated values (CSV) file with columns corresponding to the primary metadata fields (see Section 2.3). The CSV file format is selected because the data amount is low and CSV files have important features: they are easy to distribute and edit, they are software agnostic, they are human-readable, and they make tracking changes seamless.

Whenever major changes are made to the catalog, a new file containing the primary and derived metadata is uploaded to the free open science repository, Zenodo. The most recent version has the following DOI: 10.5281/zenodo.14223818. When referring to the catalog in published work, it is suggested to use the version specific DOI.

The SolarStations.org website is developed using the Jupyter Book framework [34]. All interactive maps and tables are made using the Folium and ITables Python packages, respectively. The content is stored on the collaborative platform GitHub (https://github.com/AssessingSolar/solarstations). The webpage is automatically updated every time a new change is made to the repository. Contributions to keeping SolarStations.org up to date, or to expand its scope, are highly welcome.

5. Conclusions and outlook

This paper presented SolarStations.org, a global list of active and historical radiometric stations, along with their metadata. The catalog aims at enabling users to (i) find available high-quality stations close to any location of interest, (ii) provide sufficient information to determine if a station is of interest, and (iii) connect to websites from which additional information and data can be obtained. With this development, it is hoped that the catalog will gain greater visibility, which, in turn, is expected to lead to feedback from various scientific communities about missing stations, corrections, or additions, ultimately making the dataset even more useful.

Regarding future work, the authors plan to maintain the catalog, continuously updating the status and number of stations. The catalog is expected to support diverse studies related to the activities of various IEA tasks, such as PVPS Task 16, and help the solar energy industry in general, as well as the climate and remote sensing communities.

While the catalog provides information on most of the world's existing irradiance monitoring stations, there remain significant barriers to accessing data from most stations. Accessing data from stations that do not provide public data access is typically a time-consuming process, most often requiring correspondence with station personnel or some administration (e.g., for confidential data or data that must be purchased). Even when a dataset is freely available, its usage too often implies two difficult steps: (i) processing of non-standardized data formats, and (ii) dealing with insufficient documentation about instrumentation, calibration history, maintenance, time stamp definition, etc. Moreover, the operational status of 14% of the stations in the catalog is unknown due to a lack of publicly available information. For these reasons, it is concluded that more resources should be dedicated to the dissemination of data (preferably with public access), and efforts should be made to develop a standardized file format for solar irradiance data. Establishing a network for independent research stations, similar to BSRN, could also be an important step in reducing data access barriers.

CRediT authorship contribution statement

Adam R. Jensen: Writing – original draft, Software, Methodology, Conceptualization. **Ioannis Sifnaios:** Writing – original draft, Visualization, Investigation, Data curation. **Kevin S. Anderson:** Writing – review & editing, Software. **Christian A. Gueymard:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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