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Algorithm for modelization and control of solar total radiation, using the derivative

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Abstract

Detailed knowledge of the solar resource is important for its possible applications in solar use, design of buildings and biological effects, among others. In this paper, we present an algorithm for the calculation of global solar irradiance based on a parametric model, which allows us to obtain global solar irradiance, at any geographical location and time of day. Also, we present a new algorithm using the derivative. Results were compared with measurements taken with a solar radiometer, supporting our arguments. We found percentage of discrepancy of 1.6% to 6.8% in days of May, 2007). Another very useful application of the algorithm is to determine the threshold levels of solar irradiance for Rosario and Concepción del Uruguay, Argentina. The algorithm produces an alert signal that is transmitted when an error happens. We present applications of the algorithm, which allow modifying the incorrect measurements in near real time, giving more confidence to the published data.

Keywords: *algorithm, model, solar radiation, data control*

Introduction

At the global level, there are few stations of measurement of solar radiation, and less still with the necessary maintenance. For example, Gaztelumendi (2003) reported that in 2002, 160 error warnings were registered in the Automatic Weather Stations (AWS) network of the Basque Country, Spain. These include 5% failure in communication, 5% failure of the booster station, 20% general failure of the station and 70% detected errors in the measurement of meteorological variables (of which there were 8% in the sun irradiation), i.e. the errors in the sun irradiation were 5.6% of the total error warnings. Thus, it is imperative to use the automatic control method for counting the data.

Data analysis makes it possible to identify factors that produce errors or systematic deviations. In the latter case, along with the hardware maintenance, it is necessary to take into account the location of the weather station (WMO, 1996).

The measurements recorder with instruments exposed to the elements are subject to a large number of possible failures/errors, which can be due to internal and external causes. Among the former the measurement of negative values may be mentioned: sensor or protective cover deterioration, peak voltage (Cede, 2004), time mismatch in the computer or acquisition system with respect to the real time. Some of the external causes for failures/errors are depositions of matter that obstruct the entry of radiation in the exterior dome, and the extreme winds that modify the tilt of the instruments.

The basic idea is to perform data control detecting the suspected values produced by an abnormal solar radiation distribution. If the data have an error then the program must send a signal about the failure to the support staff, and do the automatic correction.

The main issue, in relationship to the data provided by instruments exposed to the elements, is constant checking and verification. Consequently, the present work proposes the development of a methodology, supported by efficient algorithms, which would allow a constant systematic verification. This will significantly reduce the frequent data problems of external sensors.

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1.1 Analysis of data errors

An antecedent to this work, is the one realized by the Basque Service of Meteorology (BSM) which has more than 25 pyranometers (model CM11), complementing the measurements of atmospheric variables with its net of Automatic Weather Stations (AWSs) (Hernandez et al., 2003a, 2003b; Gaztelumendi et al., 2003). The AWSs of the BSM is a net located in about a 100 places of the Basque country in Spain and its validation procedure of values was based on a series of rules (Hernández et al., 2003a).

The validation rules are:

1- Data must be consistent with the technical specifications defined by the pyranometer.

2- Data must be consistent, i.e. they must satisfy the physics laws of the variable. Therefore

→ No solar irradiance during the night;

→ Daily evolution of solar irradiance under clear skies is characteristic, its graph being very similar to the Gaussian bell, symmetric with respect to the solar noon;

→ Solar irradiance values can exceed a certain percentage of the solar irradiance for clear sky conditions.

It is important to emphasize that the BSM considers the consistency of the solar irradiance essential for the meteorological variables (the graph must show the cloud progress; under clear sky conditions, the temperature develops in correlation with the solar radiation, although with a temporal delay).

3- Data must be coherent with the information of the nearest stations.

The most common data failures/errors are:

a- *Station failure*: when the station´s normal functioning has been interrupted (see Figure 1);

b- *Transmission failure*: communication problems;

c- *Storage failure*: the data disc or storage capacity is full;

d- Data failure: the station and the computer it connects to, communicate, but they are not synchronized (time and date) and the assigned data have incorrect time.

e- Zero positive shifts: when the sensor does not absorb the solar radiation (wavelengths in the spectral range of the instrument) it must indicate zero voltage. This error appears with positive values during the darkness periods, or during the day as well. There is a minimum threshold to be considered in the interpretation of the records. Some authors think that these values should be corrected to zero for night values and taken off for the diurnal values. Grossi Gallegos (2009) claims that the parasitic signal received (f.ex. artificial lighting, radio station or electric generator) in the sensor, or in the connecting cable, should be detected. In the case of a constant signal it is possible to correct the records only eliminating the false nocturnal values.

f- *Zero negative shifts:* this error is normally present when the internal dome has a different temperature to the cold connections of the sensor. For more data about this phenomenon, see the Kipp&Zonen web site (2007).

h- Sensor fail: since the sensor is outside, it could sometimes measure incorrectly during the day and due to other effects. The most common failures are moisture in the dome interior, lightning striking the sensor, problems in cabling and pyranometer break down.

i- Fault in calibration of the sensor: if the calibration factor is wrong, the signal is multiplied by a constant that does not belong to the sensor. These data will be higher or lower than they should be.

j- Wrong location of the sensor: the environment can produce shadows on the pyranometer (vegetation, buildings, its own station, etc.) (see Figure 1).

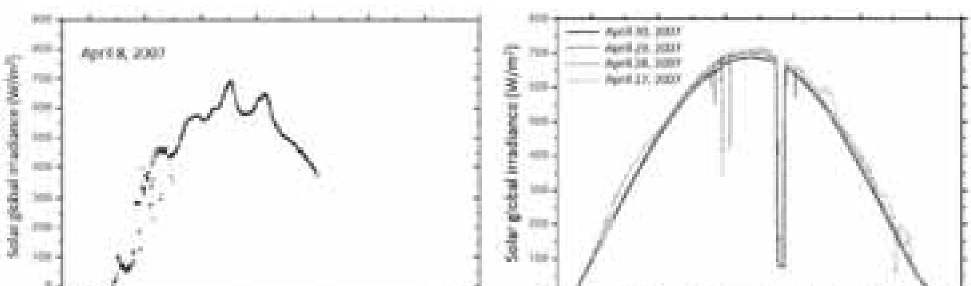

Fig.1. Solar data with failures in solar irradiance acquisition in Concepción del Uruguay, Argentina, in 2007. Left: Loss of data due to electrical failure in the station. Right: Wrong location of the sensor causing shadow from a water pipe.

k- Cosine error: the incident radiation on a horizontal plane has a value proportional to the cosine of incidence radiation at the zenith.
The errors listed above can occur randomly and simultaneously. According to Rudel (2003), the new stations, recording data simultaneously, do not generally verify their proper functioning.

1.2 Significant atmospheric events

Significant atmospheric events are exceptional manifestations of nature with significantly different values of the atmospheric variables from the average values. They usually are not caused by failures of the measuring system, and require more data and complementary equipment to evaluate the correct values. An example is the enhancement caused by the *edge effect* in the cloud, where the solar irradiance is similar or superior to the solar irradiance at top of the atmosphere (solar constant). This phenomenon was registered in Puna in the Atacama Desert and in the city of Recife (Brazil) by Piacentini et al. (2003 and 2010).
Furthermore, cloud effects, like the attenuation or increase of the radiation, are considered significant atmospheric events.
One of the rules when measuring solar radiation is that the value must be greater than the expected minimum under prevailing cloud cover (Hernández et al., 2003a). For the development of the present algorithm, the case of solar radiation values greater the extraterrestrial radiation has been taken into consideration. These values are not considered as errors as they could have been caused by some significant event like *cloud border effect* or *multiple scattering* in the cloud plane.

1.3 Solar radiation models

There are several models of total solar (or global) radiation: models based on meteorological data (Gul et al., 1998), cloud observations (Ehngerg and Bollen, 2005), isotropic sky models, with or without considering horizon brightening (Loutzenhiser, 2007), among others.
Usually, modelling of the radiative transfer is performed in different ways:
a) An integro-differential equation that describes the incidents of the direct and diffuse components at a given point, or
b) by using parametric semi-analytical models that are based on algebraic functions obtained by adjusting the solutions of the radiative transfer equations and mathematical formulae for these parameters.
Iqbal (1983) proposed three models (A, B and C), chosen for their simplicity and accuracy. For the present algorithm, we use the model C of Iqbal, based on studies by Bird and Hulstrom (1980) that developed a transmittance expression for the different attenuation processes in the atmosphere. The model needs three input parameters: water vapor column, broadband aerosol optical depth, and ozone and carbon dioxide column values.
When solar radiation enters the atmosphere, a portion of the incident energy is removed through scattering and absorption. Both considerably influence the spectrum, modifying the extraterrestrial spectral energy that passes through the atmosphere. The scattered radiation is called *diffuse radiation*. A portion of this scattered radiation goes back into space and a portion reaches the Earth's surface. The radiation that hits the Earth's surface in a straight line from the solar disk is called *direct radiation* (Iqbal, 1983).

1.4 Developed algorithm

The implemented algorithm has two important parts: A- the implementation of the C model; and B- the analysis of the dataset. The first part should determine the theoretical values of solar irradiation (at all times): global, direct and diffuse. In addition, it calculates the times of sunrise, noon and sunset. These values are obtained by implementing the C model for the entry parameters. The second part implies the reading of the text file and the searching of the real values (noontime, sunrise and sunset, and the values outside the range). Figure 2 describes the algorithm flow diagram.

1.4.1 Implementation of the C model

Input values must be read before the calculations. These values are:
A- The latitude, longitude and difference to the GMT. The algorithm calculates the sunrise, noon and sunset times.
B- The date, latitude, total ozone and carbon dioxide columns, precipitable water, atmospheric pressure, visibility, albedo and single scattering albedo. The algorithm calculates the solar irradiance values for each minute.

One advantage of this model is the possibility to count the total, direct and diffuse components, for posterior analysis.

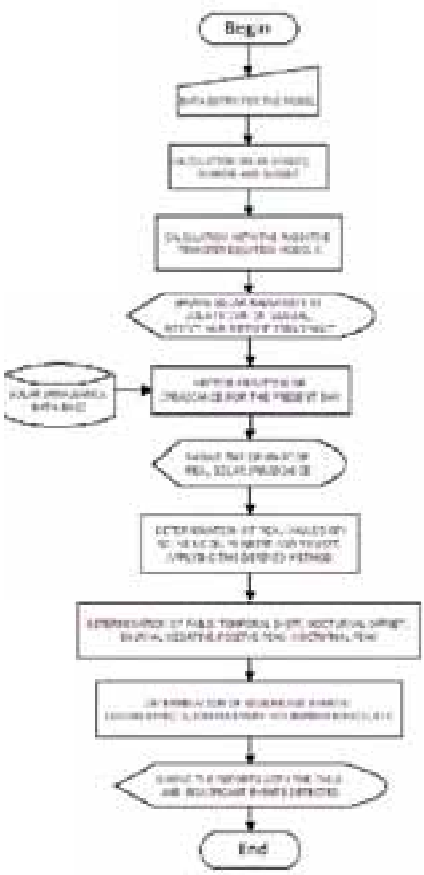

Fig. 2. Detection algorithm.

1.4.2 Search of real values

Once the data file has been copied as a vector, the present algorithm looks for the solar noon applying the derivative method.
The derivative method (proposed here) consists in the calculation of the slope for the global solar irradiance, data by data, as follows:

$$slope\ (i) = \left[\frac{data(i) - data(i-1)}{\Delta t}\right] \quad \text{(eq. 1)}$$

where Δt=1 minute. For this reason, the slope is just the difference between the current data and the previous data.
As can be seen in Figure 3, when midday occurs (maximum value of solar global irradiance, in red), the slope values pass from positive to negative (blue line).
Once noontime is found, the algorithm uses the theoretical data of the hours of sunshine for calculating the sunrise and sunset. From then on, the *derivative method* will be used for searching slopes steeper than the normal bell's slope.
In Figure 3, the global solar radiation data measured with the indicated pyranometer under clear skies (red line) and its slope (blue line) are drawn showing the signals, but not to scale. In Figure 4, the representation of some solar global irradiance data and the corresponding slope can be seen. There is a peak (see (i) in fig.4) of the solar global irradiance data and therefore a slope with positive data and negative in the case of (i +1), returning then to the value of the slope if there are no peaks.

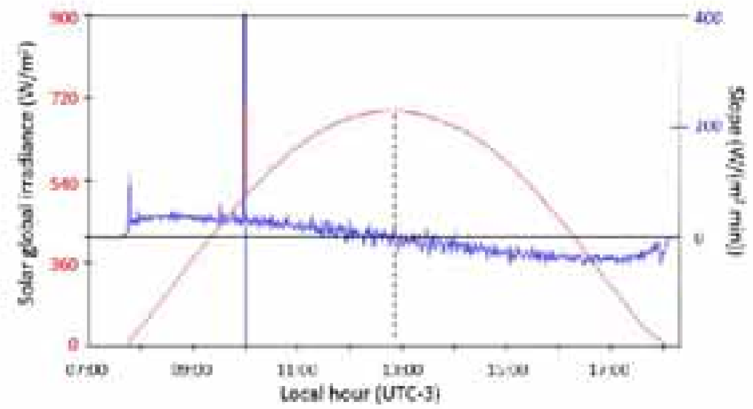

Fig. 3. Graph of example of solar global irradiance measured with a Kipp&Zonen pyranometer (red line) as a function of the local hour and superimposed the variation of the slope, data to data (blue line) (adapted from Salum et al., 2008).

The factor used to detect positive and negative peaks was found experimentally after working on several global solar radiation records. To find the peak this factor must be at least 1.3, i.e. the current data are 30% larger than the previous one.

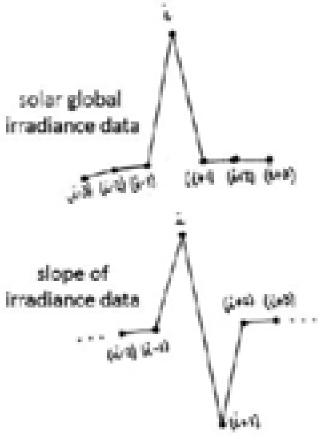

Fig. 4. Top: Scheme of positive peak in solar global irradiance. Bottom: Scheme of the slope (data to data) resulting from these values.

1.4.3 Detection of failures/errors

The software checks for failures/errors:

- *Systematic search for a nocturnal nonzero (or offset) value*

The algorithm searches nonzero values overnight, which is defined as the period from the end of twilight (about 45 minutes after sunset) until the beginning of the dawn (about 45 minutes before the sunrise). These values are averaged and shown in the report on the output screen.

- *Search for values that exceed the normal values*

This search consists in finding a threshold value above which the value is anomalous. The value chosen was 1528 W/m^2, which is one of the maximum values recorded and published internationally up to the present. This value was measured with a precision pyranometer at the peak of Tres Cruces, at 3900 m above sea level, in the high altitude intertropical desert of Puna de Atacama, in December 1997 (Piacentini et al., 2003).

- *Search for abnormal diurnal positive/negative peaks*

With the irradiance and slope data, the algorithm performs the scanning in compliance with the following rules:
a) The value of the current data must exceed the previous data value multiplied by a certain factor, and then returned to the previous value,
b) the current value of the slope is to be positive,
c) the posterior value of the slope must be negative, and
d) the phenomenon last less than three minutes (corresponding to three data) (see Figure 4).
If complying to these rules, the data is labeled a positive diurnal peak.
There are similar rules for negative peaks, but the slope is first negative and then positive.

- *Time shift*

The delta parameter (time shift) is calculated as the difference between the *actual solar noon time* and the *theoretical one*. The time shift is calculated and then the algorithm alerts this value. Furthermore, it automatically corrects the data and stores them in a data file (corrected solar radiation).

1.4.4 Combination of theoretical and real values

First, the algorithm applies the model C to the calculation of solar total irradiance, minute by minute. In figure 5, the graph of the real data (red line) and the model data (white line) is seen.

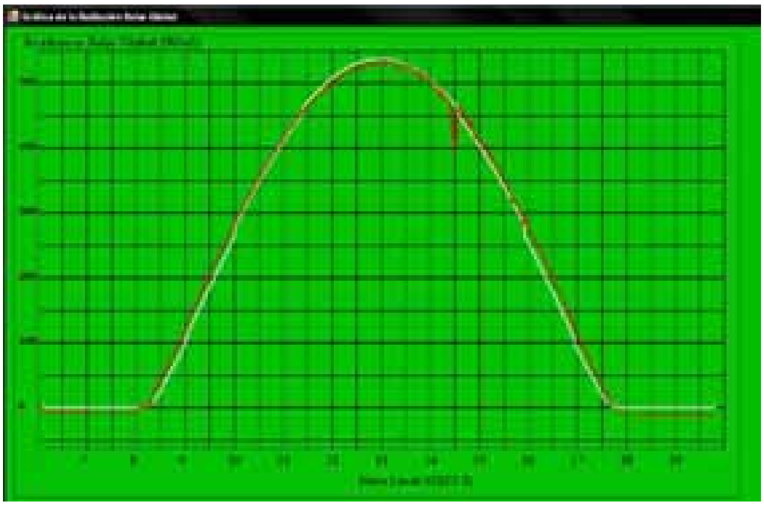

Fig. 5. Sample of the screen that shows the graph of the real data (red line) and the model data (white line).

3. Results

To implement the detection of daily features (solar noontime, the rising and setting of the Sun - dusk and dawn) and the positive and negative peaks of the acquired data, calculate the derivative, data by data, for the whole day

Figure 6 shows the first screen shot of the developed software for May 8, 2007. Here, the user enters the necessary parameters for the algorithm of the solar model for clear sky. Furthermore, it shows the solar radiation at noontime: total radiation is 629.99 W/m^2, the diffuse one is 239.21 W/m^2, and direct solar one is 580.64 W/m^2. The real value of the total solar irradiance at local noon is 640 W/m^2, resulting in a percentual difference (or percentage of discrepancy) for this day of 1.6%.

Fig. 6. Example of the initial screen and model results report for May 8, 2007.

On the left in Figure 7 below is the screenhot of the real data acquired (top) and the report of failures and significant events for May 8, 2007 (at the bottom). There was a peak at 10:00 am local hour, which was added to the real set of data (fictitious value of 900 W/m^2) in order to evaluate the algorithm. This peak turned out to be adequate. The data has a nocturnal offset (see fig.7) of -8.42 W/m^2. In addition, Figure 7 shows a time drift of 9.46 minutes.

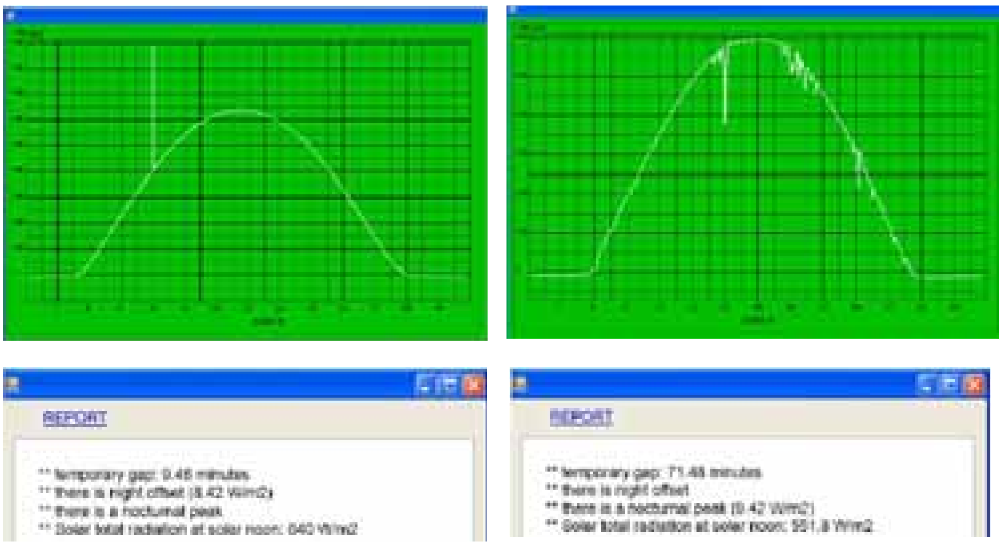

Fig. 7. Top: Graph of the real solar radiation data for: May 8, 2007 (left) and May 17, 2007 (right). Bottom: Reports corresponding to the days above.

For May 17, 2007, the software calculated the theoretical solar noon radiation at 592.13 W/m^2, diffuse radiation: 233.66 W/m^2, and direct radiation: 561.29 W/m^2. The real values of solar total irradiance at local noon was 551.8 W/m^2, resulting a porcentual difference of 6.8%. In Figure 7 Right, there are the graph screen of the real data acquired and the report of fails and significant events for this day. In the graph of data it was seen that and some of nocturnal offset. The report says that the nocturnal offset was of -9.41 W/m^2.

For May 18, 2007, the model solar noon values were 588.62 W/m^2, 233.08 W/m^2, and 559.27 W/m^2, for total, diffuse and direct radiation respectively. The real values of solar total irradiance at local noon is 575.8 W/m^2, resulting a porcentual difference of 2.2%.

For May 19, 2007 the model solar noon values were 585.18 W/m^2, 232.51 W/m^2, and 557.29 W/m^2 for total, diffuse and direct radiation respectively. The real value of total solar irradiance at local noon was 551.8 W/m^2, resulting in a percentual difference of 5.7%. Figure 8 (left) is screenshot of the real data acquired and it shows the failures and significant events for this day. We can see a fictitious peak in the afternoon, which was added to the real set of data (of 9000 W/m^2). The search for the peak was successful. It shows a day without clouds and the nocturnal offset. The report says that the nocturnal offset was -8.70 W/m^2 and a time drift of 4.48 minutes.

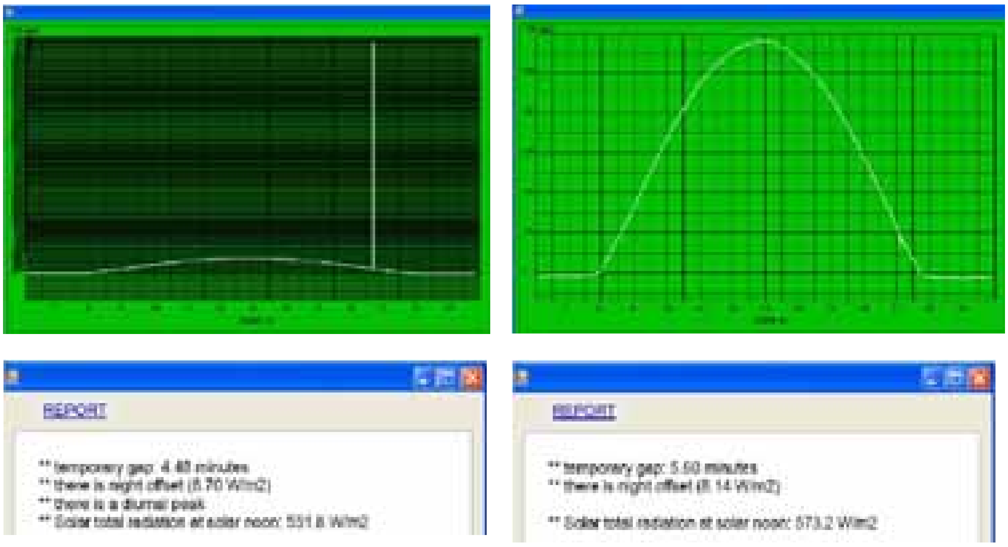

Fig. 8. Top: Graph of the real solar radiation data for May 19, 2007 (left) and May 25, 2007 (right). Bottom: Reports corresponding to the days above.

For May 25, 2007 the model solar noon values were 566.35 W/m^2, 229.33 W/m^2, and 546.19 W/m^2 for total, diffuse and direct radiation respectively. The real value of solar total irradiance at local noon is 573.2 W/m^2, resulting a porcentual difference of 1.2%. In the right of figure 8, there is a screenshot of the real data acquired and the failures and significant events for this day. The algorithm reports that the nocturnal offset was of -8.14 W/m^2 and a time drift of 5.60 minutes.

3. Conclusions and future perspectives

Data transmission, data storage, zero positive shifts, sensor failures, fault in calibration of sensor, wrong location of the sensor and cosine error are some of the failures that can be detected with the present algorithm. It proves that it is reliable for solar radiation data validation, resulting in a percentage of discrepancy values (percentual difference) of 1.6%, 6.8%, 2.2%, 5.7% and 1.2% for the total irradiance at local noon May 8, May 17, May 18, May 19 and May 25, 2007, respectively. For the days with peaks (diurnal and nocturnal), the detection was successful, as well as those for the time shift and the night offsets.

Some future perspectives are the extension of the algorithm (for solar radiation data) to other types of data that need a continuous monitoring of meteorological and air quality data.

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