Renewable Energy 63 (2014) 687–697

Contents lists available at ScienceDirect

Renewable Energy

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

Developing an improved global solar radiation map for Zimbabwe through correlating long-term ground- and satellite-based monthly clearness index values

T. Hove [a],[*], E. Manyumbu [b], G. Rukweza [c]

[a] Department of Mechanical Engineering, University of Zimbabwe, Harare, Zimbabwe
[b] School of Engineering Sciences and Technology, Chinhoyi University of Technology, Zimbabwe
[c] Mechanical Engineering Department, University of Zimbabwe, Zimbabwe

ARTICLE INFO

Article history:
Received 19 April 2013
Accepted 15 October 2013
Available online

Keywords:
Global radiation
Merging
Mapping
Interpolation correction
Cross-validation

ABSTRACT

Reliable knowledge of the spatio-temporal distribution of solar radiation is required for the informed design and deployment planning of solar energy delivery systems. In this paper an improved global solar radiation map for Zimbabwe is developed by merging ground-measured radiation data from a sparsely distributed station network, with less accurate satellite-measured data which have an almost continuous spatial coverage. Monthly clearness index values derived from ground-measured global radiation are correlated with those derived from satellite data to obtain a model for calibrating satellite-measured data at a specified grid interval. Two multiplicative factors are to then used to further correct the generated data; CF_m to cater for the inexactness of the regression fit and the other, IBCF to cater for the interpolation error. Contour maps of global solar radiation are then constructed using interpolation by the geo-statistical method of ordinary kriging. The accuracy of the maps in predicting observed (ground-measured) values was tested by evaluating error statistics; relative bias error (rBE), relative mean bias error (rMBE) and normalized root mean square error (NRMSE) in a "leave-one-out" cross-validation analysis. Results indicate that the maximum normalized root mean square error was 0.028 (about 3%), a significant improvement when compared to an earlier map, the H–G map with a normalized root mean square error (NRMSE) of 0.097.

1. Introduction

Accurate information on the spatio-temporal distribution of solar radiation is a prerequisite for the proper design and deployment planning of solar energy projects. There is need to complement global- scale efforts such as the construction of the global atlas for wind and solar energy by the International Renewable Energy Agency (IRENA) [1]. The basic information required to evaluate the solar radiation available on solar energy collectors of any type [2–4], is a measure of the beam and diffuse components of global (total horizontal plane) radiation. Since data on the apportionment of global radiation into its components is not widely publicized and may not be readily available globally in the foreseeable future, it is commonly accepted practice to rely for the time being on models based largely on the knowledge of global radiation only. Currently, the diffuse radiation is estimated from regionally appropriate correlations of the monthly average diffuse ratio of global radiation with clearness index (ratio of global radiation to extraterrestrial radiation), [5,6]. The monthly average hourly (or other time-step) variation of both global and diffuse radiation can be estimated by the ratio of monthly average hourly (or shorter time-step) radiation to daily values, [7]. The beam radiation is then calculated as the difference between the global and the diffuse radiation. Therefore, the monthly global radiation remains the basic important input radiation data required to evaluate the solar energy available to a collector.

The average daily spatial and temporal variations of global radiation depend on latitude and local atmospheric conditions. Reliable data of global solar radiation is not commonplace in the world with values at arbitrary points having to be interpolated from only a few sparsely spaced ground-measuring stations in most developing countries. Nowadays satellite measurements provide another source of data. While satellite radiation measurements are almost continuous in space and time, they are not precise in estimating ground solar radiation. All satellite based measurements are

---

[*] Corresponding author.
E-mail addresses: tawandahv@yahoo.co.uk, hove.tawanda@yahoo.com (T. Hove), manyumbu@cut.ac.zw (E. Manyumbu), rukweza_godfrey@yahoo.co.uk (G. Rukweza).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.10.032

Nomenclature

a	regression constant in linear equation relating $\overline{K}_{\mathrm{ground}}$ and $\overline{K}_{\mathrm{satellite}}$
b	regression slope coefficient in linear equation $\overline{K}_{\mathrm{ground}}$ and $\overline{K}_{\mathrm{satellite}}$
$\overline{K}_{\mathrm{ground}}$	monthly average clearness index computed from ground-measured global radiation data
$\overline{K}_{\mathrm{satellite}}$	monthly average clearness index computed from satellite-measured global radiation data
$\overline{H}_{\mathrm{ground}}$	monthly average ground-measured global radiation (kWh/m^2)
$\mathrm{CF_m}$	monthly multiplicative factor correcting $\tilde{H}$ for regression equation error
$\tilde{H}$	model-estimated value of monthly average global radiation (kWh/m^2)
$\overline{\Delta H}_{\mathrm{m}}$	monthly average relative deviation over all the stations of $\tilde{H}$ from $\overline{H}_{\mathrm{ground}}$
ΔIE	relative interpolation error at the station position
H_{map}	radiation value predicted by map (kWh/m^2)
$\tilde{H}_{\mathrm{map}}$	radiation value predicted by map when a station data is omitted from the dataset (kWh/m^2)
H_{o}	monthly average extraterrestrial solar radiation on a horizontal plane (kWh/m^2)
IBCF	monthly interpolation bias correction factor
IRENA	International Renewable Energy Agency
N	number of stations over which statistics are computed
NRMSE	normalized root mean square error
R^2	coefficient of determination
rBE	relative bias error
rBME	relative mean bias error

essentially made at the top of the atmosphere and require atmospheric models to estimate the solar radiation at ground level. Their accuracy depends on ground based input parameters such as the atmospheric turbidity, and on the ability of the model to differentiate between cloud- and ground-reflected radiation. A promising approach is to complement the few ground measurements by expertly merging them with satellite-derived measurements in order to build a comprehensive solar radiation database.

In Zimbabwe Hove and Gottsche [6] have previously produced monthly maps of global, diffuse and beam radiation based on available long-term ground-measured data with only a few points with satellite-derived data. The Hove and Gottsche (H–G) maps were made by interpolating data from only 35 points for the entire country. Further, the satellite data available to them was for two years only and they used this limited data to develop the correlation of ground radiation with satellite measurements. This paper presents an improvement to the H–G maps and describes an improved approach for calibrating satellite-measured data that is used to generate more grid data points for making the Zimbabwe global solar radiation map. The resulting map benefitted from utilising long-term data (31 years) for correlating ground-measured and satellite-measured data (21 years).

2. Materials and methods

2.1. Calibrating satellite-based measurements

The correlation between ground- and satellite-measured radiation parameters has to be established in order to generate approximate ground-truth global radiation values from satellite-measured data. This enables the determination of some calibration formula relating the two sets of data. Three different correlations can be chosen from;

1. direct relationship between satellite- and ground measured global radiation values as previously done by Refs. [6,8] and others;
2. correlating the clear-sky index (the global radiation normalized by the radiation on a clear sky) as inferred from satellite-measured data with the same index calculated from ground-measured data and
3. correlating the ground-measurement-based clearness index (the global radiation normalized by the extraterrestrial radiation) with its satellite-based counterpart.

The idea in all the three approaches above is to come up with a simple relationship (ideally linear) which can be used to deduce ground conditions from satellite measurements.

2.2. Data available for study

Satellite-measured solar irradiance data measured by the geostationary satellite Meteosat covering Africa and Europe can be obtained from the solar data acquisition web service SoDa, [9]. Monthly average values of global, clear-sky and extraterrestrial irradiance for the years 1985–2005 can be downloaded from the same website free of charge. The 21 year-records can be considered of long enough duration to represent the long-term solar radiation conditions. The long-term (1970–2000) ground-measured monthly average global irradiation data is also available for 21 stations in Zimbabwe. Additionally, monthly average long-term sunshine duration records over the same period are available at another 9 stations. The sunshine duration values can be converted to global radiation values by means of Angstrom-type correlations to give a total of 30 stations with ground-measured solar radiation information. This is the same ground-measured global radiation data that was available to Hove and Gottsche [6]. Clear-sky irradiation at a few of these stations can be computed from known values of the Linke atmospheric turbidity using the methods of Remund et al. [10] or Hove and Manyumbu [11] and interpolation could then be used to estimate clear-sky radiation values at arbitrary points.

2.3. Correlations of ground- and satellite-measured parameters

The correlations of ground- and satellite-measured parameters are examined in this section using the Harare station as a typical example for illustrative purposes. The scatter diagrams for the relationships: ground-measured *versus* satellite-measured global radiation; clear-sky index computed from ground-measured data *versus* clear-sky index computed from satellite-measured data and clearness index computed from ground-measured data *versus* clearness index computed from satellite-measured data are examined in Figs. 1–3, respectively. The best-fit lines, together with the coefficient of determination for each of the three relationships were computed and the closeness of regression lines to the scatter data assessed.

Considerable scatter can be observed for the direct relationship of ground-measured global radiation to satellite-measured global radiation on Fig. 1. The coefficient of determination (square of the coefficient of correlation), R^2 is about 0.71. The relationship between the clear-sky index computed from ground-measured data *versus* the clear-sky index computed from satellite-measured data in Fig. 2 shows less scatter and a higher coefficient of determination of about 0.9. An even better correlation ($R^2 = 0.96$) can be observed for the third relationship of *clearness indices*. This was the general