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Estimation of hourly averaged solar irradiation: evaluation of models

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Hourly solar radiation data are required in many building services applications. These are also reported in the Chartered Institution of Building Services Engineers Guides A & J. Data from 16 locations in the UK were used to evaluate the so called Liu and Jordan model[1] for monthly averaged hourly solar irradiation. Individual data sets spanned periods from 12 to 26 years between 1968 and 1994, and overall, provided data from practically the full range of latitude of the UK (50.22°N–58.13°N). For hourly estimation, the model only slightly underestimated both global and diffuse radiation before noon and overestimated, again only slightly, after noon. In addition, a discrepancy was observed between the measured data and the model's predictions at low sunset angles. Following earlier research work, an attempt was made to further improve the Liu and Jordan model. However, it was found that at least for the UK data set, any such attempts were futile. This behaviour was attributed to the highly random nature of UK's solar climate.

Practical applications: Most meteorological stations report solar radiation data on a daily averaged basis. However, most building energy simulation software requires hourly radiation. Research studies have confirmed that the well-known Liu and Jordan model, which enables the above conversion, performs well for locations in the US. This paper evaluates the above model for locations in the UK and compares it with previously studied Indian locations. According to the evaluation, the average accuracy of the model to estimate hourly radiation from its daily counterpart is 85%.

Nomenclature

$\overline{G}$ monthly averaged daily global irradiation (kWh/m²)

$\overline{E}$ monthly averaged extraterrestrial radiation (kWh/m²)

$\overline{g}$ monthly averaged hourly global irradiation (Wh/m²)

$\overline{G}_{\text{clear}}$ average clear day global irradiation (kWh/m²)

$\overline{D}$ monthly averaged daily diffuse irradiation (kWh/m²)

$\overline{d}$ monthly averaged hourly diffuse irradiation (Wh/m²)

$\overline{K}_{\text{T}}$ monthly averaged clearness index

a, b site-specific coefficients

$c', c_0, c_{01}, c_{02}, c_1, c_{11}, c_{12}$ equation coefficients

$d', d_0, d_{01}, d_{02}, d_1, d_{11}, d_{12}$ equation coefficients

DEC   solar declination (degree)

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Figures 7–10 appear in color online: http://bse.sagepub.com

LAT	latitude (degree)
n	average daily hours of bright sunshine (h)
N	astronomical day length (h)
r_{D}	ratio of hourly to daily diffuse radiation
r_{DC}	ratio of computed hourly to daily diffuse radiation
$r_{\text{D\_LJ}}$	r_{D} predicted by Liu and Jordan's regression model
r_{Dn}	r_{D} predicted by proposed new model
$r_{\text{Dc,am}}$	ratio of computed hourly to daily global radiation before noon
$r_{\text{Dc,ave}}$	average ratio of computed hourly to daily global radiation
$r_{\text{Dc,pm}}$	ratio of computed hourly to daily global radiation after noon
$r_{\text{Dm,am}}$	ratio of measured hourly to daily diffuse radiation before noon
$r_{\text{Dm,ave}}$	average ratio of measured hourly to daily diffuse radiation
$r_{\text{Dm,pm}}$	ratio of measured hourly to daily diffuse radiation after noon
r_{G}	ratio of hourly to daily global radiation
r_{GC}	ratio of computed hourly to daily global radiation
$r_{\text{Gc,am}}$	ratio of computed hourly to daily global radiation before noon
$r_{\text{Gc,ave}}$	average ratio of computed hourly to daily global radiation
$r_{\text{Gc,pm}}$	ratio of computed hourly to daily global radiation after noon
$r_{\text{Gm,am}}$	ratio of measured hourly to daily global radiation before noon
$r_{\text{Gm,ave}}$	average ratio of measured hourly to daily global radiation
$r_{\text{Gm,pm}}$	ratio of measured hourly to daily global radiation after noon

Greek letters

ε	percentage error (%)
ω	hour angle (degree)
ω_{s}	sunset hour angle (degree)

1   Introduction

Concerns about energy efficiency in building design and the sustainable generation of electricity from solar energy have led to the need for accurate estimates of solar irradiation. Meteorological measurements available from locations around the world can be used as the basis for such estimates but are severely limited in the detail they can provide. The majority of stations, for example, do not collect solar data and those that do usually only provide daily measurements, whereas many current applications require estimates by hour or even by minute. Climate simulation systems, such as the weather generator described by Kilsby et al.[2] require at least hourly data to validate their output. Liu and Jordan's model fills gaps in the sparse data available by enabling the estimation of both beam and diffuse hourly irradiation from its daily counterpart.

This paper reports on a comparison of measured hourly data from 16 UK locations with values calculated using Liu and Jordan's model. Various researchers have carried out similar evaluations as described in the next section, and certain weaknesses have already been identified. However, a rigorous evaluation has not been performed previously using data from the UK. The present aims are therefore as follows:

(1) to identify discrepancies between measured and calculated values for the UK data set and, therefore, to suggest possible approaches to improvement if at all possible.
(2) to evaluate the applicability of the Liu–Jordan model to a northern European location in comparison to similar studies carried out at lower latitudes.

2   Previous work

Solar radiation incident on any given surface can be decomposed into two components, the

direct or beam component emanating from the sun, and a diffuse component that results from multiple reflections and scattering due to particles in the atmosphere. The diffuse component may also include reflections from the ground and local surroundings, where the surface in question is sloped rather than horizontal. Differentiating between the two components is vital for accurate calculations in most solar energy applications; however, a number of steps may be required to arrive at realistic estimates at an appropriate level of detail for a given location depending on the basic data available. Where no actual measurements of solar irradiation are available, for example, the calculation scheme would involve the steps shown in Figure 1. As stated above for the sake of generality, Figure 1 shows the computational flow for any general surface, that is, one which may have a given orientation and slope. With each successive step, errors would be conflated, and the accuracy of each individual stage is therefore crucial.

Many locations around the world record sunshine duration, and this parameter may reliably be used to obtain monthly averaged daily irradiation. The second step would then incorporate the Liu and Jordan model presently under discussion to obtain hourly irradiation as indicated in Figure 1. Original work by Ångström[3] on the estimation of daily
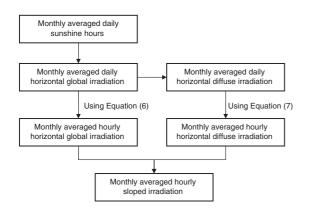

Figure 1 Calculation scheme for monthly averaged hourly sloped irradiation

global irradiation was based on a comparison of monthly averaged daily values with a clear sky figure. This method was refined by several other researchers[4–11] all of whom developed models of the form shown in Equation (1):

$$\overline{G} = \overline{E}[a + b(n/N)] \quad (1)$$

where $\overline{G}$ is the monthly averaged daily global irradiation; $\overline{E}$ is the monthly averaged extraterrestrial radiation; a, b are the site-specific constant coefficients; n is the average daily hours of bright sunshine; N is the day length and n/N is the fractional possible sunshine. N in the above formula is derived from the sunset hour angle using the following equations:

$$\omega_s = \cos^{-1}(-\tan \text{LAT} \tan \text{DEC}) \quad (2)$$

$$N = (2\omega_s/15) \quad (3)$$

where ω_s is the sunset hour angle, LAT is the latitude and DEC is the declination (angular position of the sun with respect to the equatorial plane at solar noon).

The sunset hour angle, given in degrees, is a measure of the rotation of the earth between solar noon and sunset. $2\omega_s$, therefore precisely describe the length of a given astronomical day. Some simple mathematics shows that a rotation of $15°$ of arc corresponds to 1 h.

The success of models of the form of Equation (1) relies on the compilation of appropriate coefficients for different locations; however, Suehrcke[12] has proposed an alterative relationship, which eliminates this additional overhead. Using the notion of a clearness index $\overline{K}_T = (\overline{G}/\overline{E})$ and a corresponding reference value for clear sky conditions $(\overline{G}_{\text{clear}}/\overline{E})$, Suehrcke's formulation is as shown in Equation (4):

$$\overline{G}/\overline{E} = (n/N)(\overline{G}_{\text{clear}}/\overline{E}) \quad (4)$$

Arguing that since $\overline{G}_{\text{clear}}/\overline{E}$ varies only within the very limited range of 0.65–0.75, Suehrcke proposed using a single constant value of 0.7

making Equation (4) applicable in any location given the single local value of n, the average daily hours of bright sunshine. Work by Driesse and Thevenard[13] has demonstrated the validity of this approach using 70 000 data points from 700 worldwide sites. The latter authors demonstrated a root mean square variation of 12% around the relationship predicted by Suehrcke. The 'universal' model can therefore provide acceptable estimates of monthly averaged daily global irradiation in the absence of site-specific coefficients.

Addressing the problem of decomposing global irradiation into its components, Liu and Jordan[1] developed a model similar to that shown in Equation (5) in which the ratio of monthly averaged daily diffuse irradiation ($\overline{D}$) to monthly averaged daily global irradiation ($\overline{G}$) is expressed as a function of $\overline{K}_T$. Two sets of coefficients for Equation (5) are available, one by Page[14] for use in temperate climates, and one for desert and tropical locations by Hawas and Muneer.[15]

$$\overline{D}/\overline{G} = 1.00 - 1.13\overline{K}_T \qquad (5)$$

$a = 1.00$, $b = 1.13$; Page[14]
$a = 1.35$, $b = 1.61$; Hawas and Muneer[15]

Using Equations (1)–(5), it is thus possible to obtain $\overline{G}$ and then $\overline{D}$ from monthly averaged sunshine data. In the remainder of this article, the subject of discussion shall be the progression of hourly, horizontal irradiation estimation.

To provide a model to decompose averaged daily to averaged hourly values, Liu and Jordan[1] built on earlier work by Whillier[16] to develop a set of regression curves, which represent the ratio of hourly to daily global solar irradiation at a series of time intervals from solar noon. This approach was validated by Collares-Pereira and Rabl[17] who obtained Equation (6) using a least squares fit as follows:

$$r_G = \frac{\pi}{24}(a' + b'\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \qquad (6)$$

where $a' = 0.409 + 0.5016\sin(\omega_s - 1.047)$; $b' = 0.6609 - 0.4767\sin(\omega_s - 1.047)$ and r_G = ratio of hourly to daily global irradiation, $\overline{g}/\overline{G}$.

Liu and Jordan's theoretical model for the ratio of hourly to daily diffuse irradiation is given in Equation (7):

$$r_D = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \qquad (7)$$

where r_D is the ratio of hourly to daily diffuse irradiation, $\overline{d}/\overline{D}$.

Other methods for obtaining hourly irradiation figures, such as the 'daily integration model' described by Gueymard[18] have been proposed. However, Gueymard's model has been shown to produce very similar results to the Liu–Jordan model, at least in the case of Hawas and Muneer's Indian data. Weather generators such as the one described by Kilsby et al.[2] also use linear regressions to derive value for a range of meteorological variables including sunshine duration. They do not, however, attempt to model global and diffuse irradiation directly. The Liu–Jordan model therefore remains the object of study here.

Hawas and Muneer[15] compared measurements from 13 locations in India taken between 1957 and 1975 to the values predicted by the model and found a general agreement for the r_G model. Average values for r_G and r_D are shown in Figure 2 as points, while the solid lines indicate the values predicted by Equations (6) and (7) for 0.5, 1.5, 2.5, 3.5, 4.5 and 5.5 h from solar noon.

Notwithstanding the agreement with Liu and Jordan's model for global irradiation, Hawas and Muneer[15] found that the Indian data differed markedly from the values predicted by Equation (7) for diffuse irradiation. A compressed range of r_D is evident in Figure 3, where the average data points from the Indian recording stations are superimposed on Liu and Jordan's regression curves for the same time values as in Figure 2.
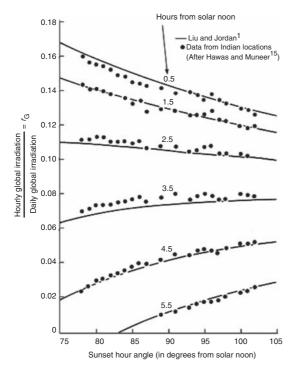
Hours from solar noon

—— Liu and Jordan[1]
• Data from Indian locations
(After Hawas and Muneer[15])

0.5
1.5
2.5
3.5
4.5
5.5

Hourly global irradiation = r_G / Daily global irradiation

Sunset hour angle (in degrees from solar noon)

Figure 2 Ratio of hourly to daily global irradiation

Plotting individual values of r_D rather than average values as a function of sunset hour angle for a particular displacement from solar noon (Figure 4) reveals how great the scatter is, and demonstrates that the Liu–Jordan diffuse model is not suitable for estimating individual, hour by hour diffuse irradiation. Hawas and Muneer attribute the discrepancy to local conditions, and the extent to which the Liu–Jordan model is applicable elsewhere is still an appropriate subject of investigation. This is underlined by Iqbal's[19] results, which show good agreement with the Liu–Jordan model for three Canadian locations. To summarise, therefore, it has been shown by previous researchers that the decomposition of daily to hourly global irradiation can be performed with a fairly high level of accuracy for long-term averaged data but not when hour-by-hour estimates are required.

Iqbal raised a further question in relation to Liu and Jordan's models for global and diffuse irradiation concerning the asymmetrical distribution of irradiation on either side of solar noon. At one of the Canadian sites in particular, a consistently lower level of global irradiation was observed in the morning compared to the afternoon. Similarly, Saluja and Robertson[20] reported differences in computed values of yearly averages of irradiation on east- and west-facing surfaces for Aberdeen, Easthampstead and Kew compared to other UK locations. Like the variations observed by Hawas and Muneer,[15] these observations suggest that local factors need to be taken into account when estimating hourly irradiation.

A further feature of Hawas and Muneer's[15] analysis of the Indian data was to investigate potential relationships between r_D and $\overline{K}_T$. Where the Liu–Jordan model predicts a constant value for r_D at a given displacement from solar noon, Hawas and Muneer found a clear tendency for r_D to decrease with $\overline{K}_T$ as shown in Figure 5.

This study will evaluate the Liu and Jordan's regression curves for the UK taking into account the discrepancies discussed above.

3 Methodology

Computed values of r_D and r_G derived using Liu and Jordan's models are compared against measured data from 16 UK recording stations. Percentage error, calculated by Equation (8), is used to show the divergence of the Liu and Jordan model from the measured values:

$$\varepsilon = 100\frac{(c - m)}{m} \qquad (8)$$

where ε is the percentage error, c is the calculated value after Liu and Jordan and m is the measured value.

This work is based on the measured UK data set that was provided by the UK Meteorological Office to the CIBSE Guide J[21]
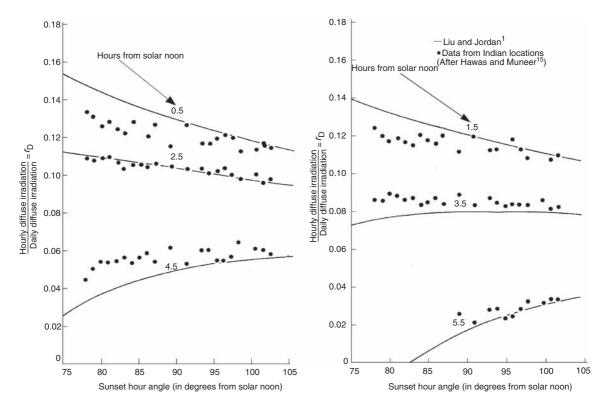
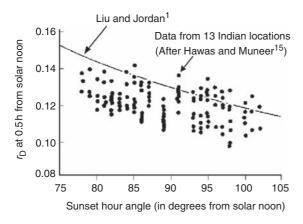**Figure 3** Ratio of hourly to daily diffuse irradiation

Figure 4 Individual values of r_D at 0.5 h from solar noon

panel members. Muneer led the work of solar radiation group under the overall coordination of Levermore. Note that the above data set contained measured hourly radiation and other climatic parameters for a total of 20
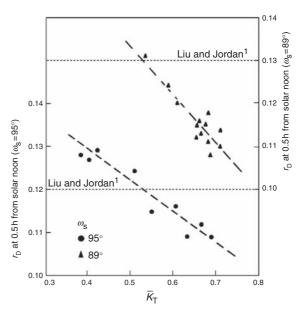

Figure 5 r_D at 0.5 h from solar noon for two fixed values of ω_s

Table 1 Details of the data used in the present study and their sources

Station	No. of years data	Latitude	Missing/ Erroneous hours	Total hours	Missing hours (%)
Camborne	13 (1982–1994)	50.37	444	62842	0.71
Crawley	13 (1980–1992)	51.08	334	62808	0.53
Bracknell	20 (1975–1994)	51.38	223	100307	0.22
London	20 (1976–1995)	51.52	*	93830	0
London (wcb)	20 (1975–1994)	51.52	1455	89774	1.62
Aberporth	20 (1975–1994)	52.13	650	92298	0.70
Hemsby	15 (1981–1995)	52.25	613	61153	1.00
Manchester	13 (1982–1994)	53.47	*	61424	0
Finningley	12 (1983–1994)	53.48	107	56724	0.19
Aughton	13 (1982–1994)	53.55	548	61326	0.89
Aldergrove	26 (1968–1994)	54.65	3984	112634	3.54
Edinburgh	17 (1976–1992)	55.85	*	79591	0
Mylnefield	19 (1975–1993)	56.45	186	87485	0.21
Dunstaffnage	20 (1975–1994)	56.47	102	91945	0.11
Aberdeen	20 (1975–1994)	57.17	12	97191	0.01
Stornoway	13 (1982–1994)	58.22	769	54304	1.42

*Completed data for these locations were produced by the CIBSE Solar Data Task Group.

stations, of which only three (Bracknell, Manchester and Edinburgh) were selected for inclusion in CIBSE Guide J. Muneer was also responsible for undertaking the quality control for the solar radiation data. The reader is referred to Muneer and Fairooz[22] for further details. The time periods covered by the station subsets range from 12 to 26 years. Table 1 shows the list of the data that have presently been used.

Percentages of missing or erroneous hours were calculated for the stations in Table 1 by dividing the total missing hours by the total recorded hours with global and diffuse values at the location. The station with the highest number of missing hours was Aldergrove with 3.54% and the lowest was Aberdeen with just 0.01%. Only 3 out of 16 stations were missing more than 1% of data.

Prior to the present analysis, the raw data files were preprocessed using a series of computer programmes written in Visual Basic for Applications (VBA), which also made use of the processing features of Microsoft Excel. On completion of a stage of preprocessing, results were saved in a new file to minimise file size and to prevent accidental data loss. The preprocessing consisted of the steps shown in Figure 6.

The first filtering stage simply removed unwanted meteorological data from the files. The second stage identified and removed erroneous secondary values for global or diffuse radiation. Several criteria were used in this step including the following:

- the value for diffuse radiation greater than that for global radiation,
- missing radiation data and
- negative or zero radiation values

After the second filter, calculated values were added to the data, which was then stored in an Excel file for later analysis. Equations (6) and (7) were used to calculate monthly averaged hourly global and diffuse irradiation.

The operation of the VBA programmes was cross-validated using another statistical software package (SPSS version 14).

4   Results and discussion

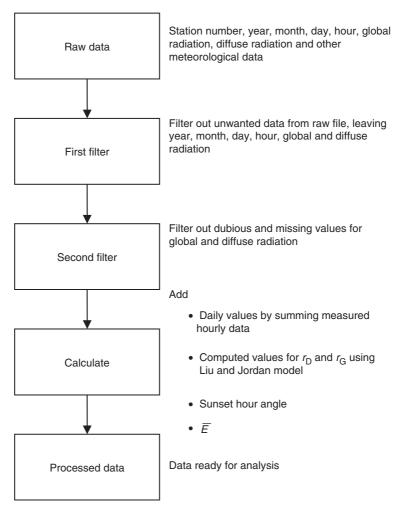Having calculated the appropriate figures for monthly averaged global and diffuse radiation,

```
┌─────────────────────┐
│                     │     Station number, year, month, day, hour, global
│      Raw data       │     radiation, diffuse radiation and other
│                     │     meteorological data
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│                     │     Filter out unwanted data from raw file, leaving
│     First filter    │     year, month, day, hour, global and diffuse
│                     │     radiation
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│                     │     Filter out dubious and missing values for
│    Second filter    │     global and diffuse radiation
│                     │
└─────────────────────┘
          │                 Add
          │
          ▼                    • Daily values by summing measured
┌─────────────────────┐          hourly data
│                     │
│      Calculate      │        • Computed values for r_D and r_G using
│                     │          Liu and Jordan model
└─────────────────────┘
          │                    • Sunset hour angle
          │
          ▼                    • $\overline{E}$
┌─────────────────────┐
│                     │     Data ready for analysis
│    Processed data   │
│                     │
└─────────────────────┘
```

Figure 6 Flow chart for the preprocessing of raw solar radiation data

percentage error was used to show the deviation of the measured values from those predicted by the Liu and Jordan model. Better agreement was found for global radiation than for diffuse radiation for all 16 locations. Since a similar trend was observed in all 16 cases, two stations Bracknell and Stornoway were selected to illustrate the differences. Bracknell used to be the UK Meteorological Office Headquarters, with higher quality data recorded than elsewhere and is also in close proximity to London. Stornoway is one of the most northerly of the UK stations.

An examination of the percentage error at Bracknell (Figure 7) shows a reasonably good fit between the measured data and the Liu–Jordan model for global radiation. At Bracknell, the error is normally distributed around zero, with 38.7% points lying in the ±10% range, and 66.9% of the data in the ±20% range. At Stornoway, 80% of the percentage data lies in the range of −10% to −30% (Figure 8) showing that the Liu–Jordan model consistently underestimates global radiation for this location.
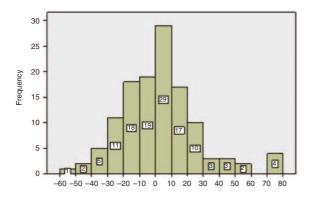
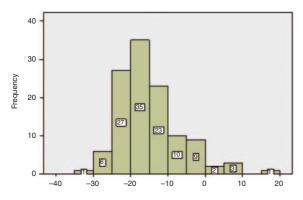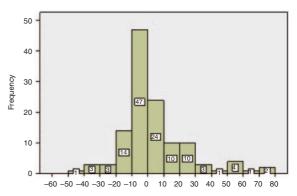**Figure 7** Histogram of percentage error of global radiation for Bracknell

Figure 9 Histogram of percentage error of diffuse radiation for Bracknell

Figure 8 Histogram of percentage error of global radiation for Stornoway

Figure 10 Histogram of percentage error of diffuse radiation for Stornoway

In the case of diffuse radiation, Figure 9 shows that 77.2% of the data population for Bracknell lies in the ±20% error range. A negative shift in comparison with the plot for global radiation (Figure 7). The error for Stornoway shown in Figure 10 exhibits the same trend as the global radiation data where the data population is once again skewed towards negative errors. Around 94% of the error lies in the error range of −30% to 0%.

In summary, weaknesses in the Liu–Jordan model are obvious for higher latitudes. Table 2 summarises the distribution of error in the total data set.

Further analysis was done to evaluate the expression of r_G and r_D derived by Liu and Jordan. Measured values for r_G and r_D before

Table 2 Summary of percentage error in the total data set

Error band (w/m²)	Percentage of total data population, global radiation	Percentage of total data population, diffuse radiation
±10	22.5	54.9
±20	50.7	95.8
±30	64.8	100

and after solar noon were plotted against sunset hour angle. Values of r_G from Equation (6) and r_D from Equation (7) for 0.5, 2.5 and 4.5 h from solar noon were superimposed on the same graphs for comparison. Figures 11–16 therefore contain three sets of points for each time value. Note that in
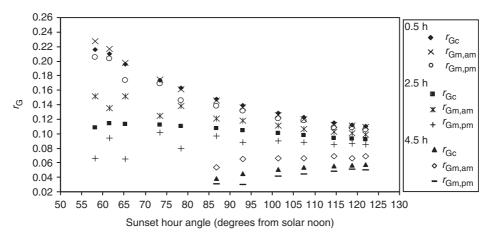
Figure 11 Ratio of measured hourly to daily total global radiation for different hours of the day vs sunset hour angle for Bracknell station
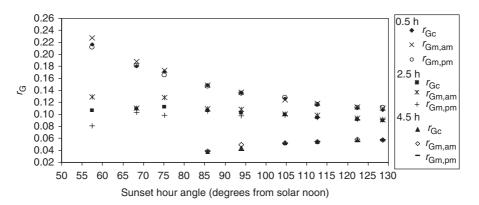

Figure 12 Ratio of measured hourly to daily total global radiation for different hours of the day vs sunset hour angle for Stornoway station
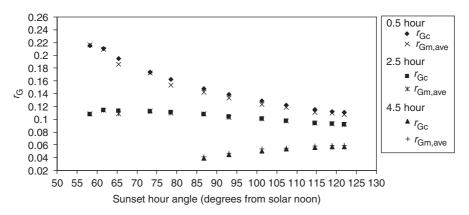

Figure 13 Average ratio of measured hourly to daily total global radiation for different hours of the day vs sunset hour angle for Bracknell station
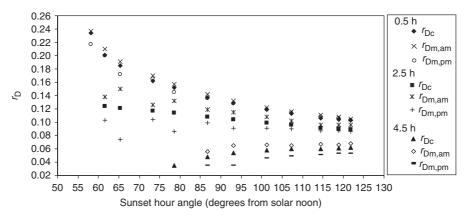
Figure 14 Ratio of measured hourly to daily diffuse radiation for different hours of the day vs sunset hour angle for Bracknell station
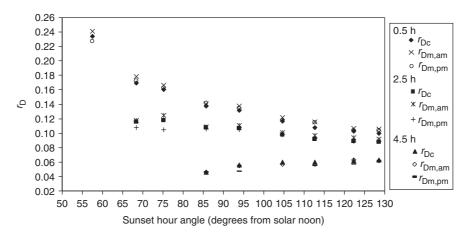

Figure 15 Ratio of measured hourly to daily diffuse radiation for different hours of the day vs sunset hour angle for Stornoway station
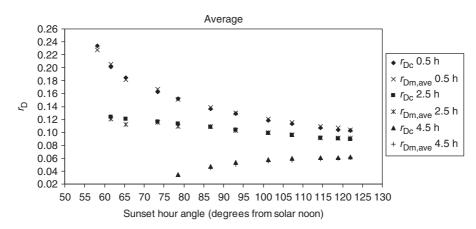

Figure 16 Average ratio of measured hourly to daily diffuse radiation for different hours of the day vs sunset hour angle for Bracknell station

Figures 11–16, r_{GC} is the ratio of computed hourly to daily global radiation, and r_{DC} is the ratio of computed hourly to daily diffuse radiation. Furthermore, in Figures 11, 12, 14 and 15, the variation of measured forenoon and afternoon values is compared against the computed ratios.

Figure 11 shows that for Bracknell, the expression for r_{GC} underestimates the global radiation before noon and overestimates after noon for displacements of 2.5 and 4.5 h. At 0.5 h from solar noon, the expression of r_{GC} agrees well with the measured values with slightly less accurate estimates at low sunset angles.

For Stornoway in contrast, the expression for r_{GC} gives a good estimate of global radiation for all three displacements from solar noon as shown in Figure 12. The problem of over- and underestimating global radiation still occurs at low sunset angle as in Figure 11 for Bracknell.

The over- and underestimation of global and diffuse radiation that is evident in Figures 11 and 12 disappears when pre- and postnoon values are aggregated as shown in Figure 13. The errors cancel each other out, and the impression is one of a good fit. However, since we are interested in accurate values for any given hour, this is misleading.

The corresponding plot of the hourly ratio of diffuse radiation for Bracknell in Figure 14 follows a similar pattern to that for r_G in Figure 11. The expression of r_{DC} for 0.5 h from solar noon correlates well with the measured values except for a small over- and underestimate at low sunset hour angle, while at 2.5 and 4.5 h from solar noon, the expression for r_{DC} underestimates before noon and overestimates after noon. For Stornoway, the expression for r_{DC} provides good estimation for all the hours as shown in Figure 15.

The effect of plotting the average of the measured values for r_D against sunset hour angle conceals the differences before and after solar noon as for r_G and gives the impression of a good fit with the calculated values as exemplified in Figure 16 for the Bracknell station. This suggests that the Liu–Jordan model needs to be refined to take account of this asymmetry.

Location-specific effects are evident in the charts above, with a more marked spread of measured values for r_D at Bracknell, for example, than for Stornoway, and the extent of the local effect can be illustrated using a similar approach to Hawas and Muneer[15]. Plotting individual values of r_D at Bracknell rather than averages against sunset hour angle for a particular displacement from solar noon clearly shows an unacceptable degree of scatter in Figure 17.

5   Possible improvement

Given the observation by Hawas and Muneer[15] that r_D tended to decrease as a function of $\overline{K}_T$ for the Indian locations studied, the authors suggested that a systematic relationship between r_D and $\overline{K}_T$ might exist. An attempt was carried out to improve the Liu and Jordan's r_D regression model by taking into consideration the effect of $\overline{K}_T$.

Starting from the standard form of Liu and Jordan's model for r_D as shown in Equation (7), a further term was introduced as in the Liu and Jordan model for global radiation shown in Equation (6). The proposed model is shown in Equation (9):

$$r_D = \frac{\pi}{24}(c' + d' \cos \omega) \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \omega_s \cos \omega_s}, \quad (9)$$

where

$$c' = c_0 + c_1 \sin(\omega_s - 1.047) \quad (10)$$

$$d' = d_0 - d_1 \sin(\omega_s - 1.047) \quad (11)$$

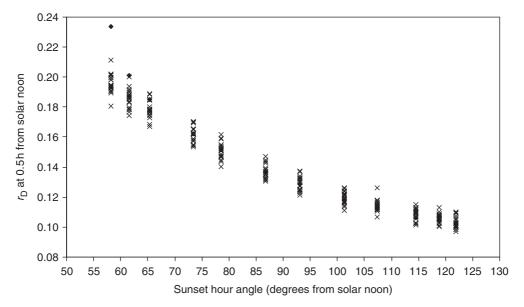Crucially, the coefficients c' and d' are not constants but are themselves functions of $\overline{K}_T$

Figure 17 Individual (not averaged) values of r_D at Bracknell station before noon at 0.5 h from solar noon

derived by linear regression as shown in Equations (12)–(15):

$$c_0 = c_{01} + c_{02} \overline{K}_T \qquad (12)$$

$$c_1 = c_{11} + c_{12} \overline{K}_T \qquad (13)$$

$$d_0 = d_{01} + d_{02} \overline{K}_T \qquad (14)$$

$$d_1 = d_{11} + d_{12} \overline{K}_T \qquad (15)$$

Using SPSS 14, the values of the further coefficients were derived, and the values are shown in Table 3.

The derived coefficient values were then substituted to Equations (10) and (11) to get the value of c' and d'. The performance of the proposed refinement (r_{Dn}) compared to Liu and Jordan's original model (r_{D_LJ}) was carried out by plotting the calculated values from both models against measured values of r_D.

The R^2 value of the r_{D_LJ} plot as calculated by SPSS 14 is 0.976, and for the r_{Dn} plot, R^2 is 0.979 as shown in Figures 18 and 19, respectively.

The difference between the two models is negligible, and the proposed inclusion of $\overline{K}_T$

Table 3 Coefficient values for new r_D regression model

Coefficient	Value
c_{01}	−51.780
c_{02}	914.039
c_{11}	−0.072
c_{12}	0.078
d_{01}	6.972
d_{02}	−119.682
d_{11}	0.029
d_{12}	0.076

cannot, therefore, be said to bring any additional precision to the estimates produced. This was further checked by performing a similar comparison to that done by Hawas and Muneer[15] for the Indian data. Measured values of r_D were plotted against $\overline{K}_T$ for two fixed values of ω_s. The results are shown in Figure 20.

In contrast to the Indian data shown in Figure 5, the plots for Bracknell do not show a consistent decreasing trend for r_D as a function of $\overline{K}_T$. Both are much flatter, and in the case of a sunset hour angle of 101.3°, r_D actually increases with $\overline{K}_T$.
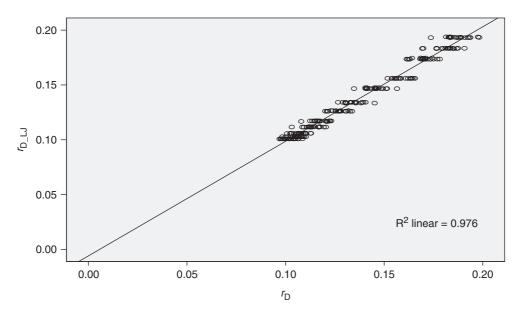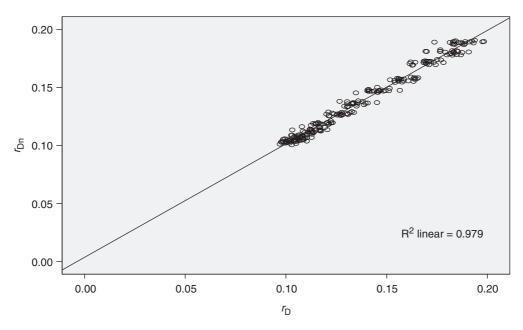
Figure 18 Liu and Jordan r_{D_LJ} regression model against measured r_D value

Figure 19 New proposed regression model r_{Dn} against measured r_D value

The strong correlation seen by Hawas and Muneer could be explained by the consistency of the solar climate in India compared to the much more unpredictable distribution of clear weather in the UK. These climatic differences are illustrated in Figures 21 and 22 by plotting frequencies of K_T for India and the UK.
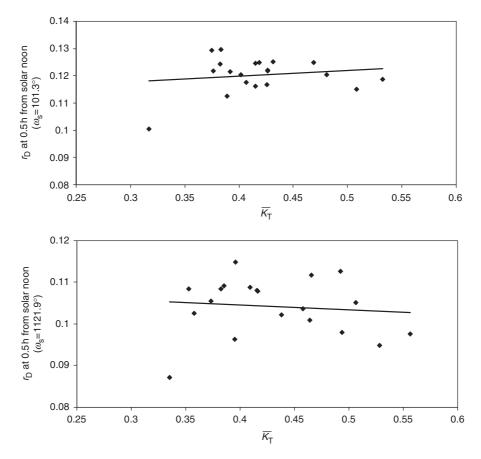
Figure 20 r_D at 0.5 h from solar noon for two fixed values of ω_s for the Bracknell station
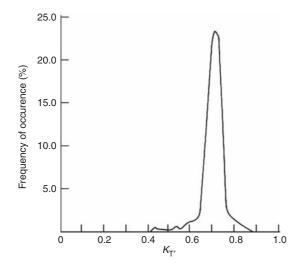

Figure 21 Frequency of occurrence of K_T for an Indian location

6 Conclusions

From the evaluation work presented here, it can be concluded that the Liu–Jordan model performs well for estimating the average hourly global and diffuse radiation. At the individual hourly level, however, a number of problems were observed. At low sunset angles, the values predicted by the model were less reliable. Given the low absolute solar energy available at such angles though, this was not seen as a major defect.

Local meteorological conditions appear to have an effect as demonstrated by the investigation of the effect of $\overline{K}_T$ on the calculated values. A consistent effect of $\overline{K}_T$ was not
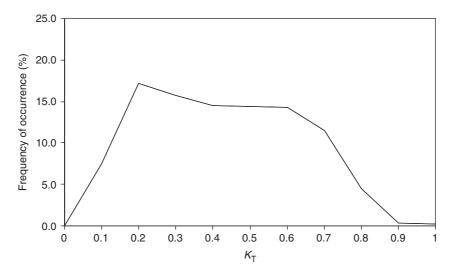
Figure 22 Frequency of occurrence of K_T for a UK location (Bracknell)

evident from the UK data in contrast to earlier findings from other locations.

A general weakness, however, was the model's inability to take account of the asymmetric distribution of radiation across solar noon. Because of this, it underestimates global and diffuse radiation before noon and overestimates after noon for most of the UK locations. These observations are in agreement with Hawas and Muneer[15] who were using data from recording stations in India. This particular weakness of the Liu–Jordan model cannot, therefore, be assumed to be location specific since it is evident in data from such widely different climates.

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