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# THE ASSESSMENT OF THE ACCURACY OF DIFFUSE IRRADIATION MODELS AND THEIR POTENTIAL IMPACT ON BUILDING SIMULATION

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## ABSTRACT

A study was undertaken to verify the performance of five different models used to separate global horizontal radiation measurements into constituent diffuse and direct components. Model predictions were compared with measured data for ten locations in the UK , US and Japan.

The study showed that there are significant differences in the accuracy of available diffuse/direct radiation models. Their performance has been shown to vary depending on location, time of year and the clearness of the sky. The accuracy of these models has been shown to have a significant impact on the hourly demand profile of a typical building in the UK.

Pervious studies used statistical analysis of the accuracy of modeled diffuse radiation component to determine the most suitable model for a location. In this study the accuracy of each model was determined for each of three sky conditions: overcast, partially cloudy and clear. Using building simulation with both modeled and measured data, it was determined that accurate representation of clear sky conditions has the greatest impact on simulation performance. This was used as the determining factor in recommending models.

This study concludes that when using diffuse ratio models for building simulation, Maxwell's model is the most accurate for sites based in the UK, Reindl's for American sites and Muneer's model for any other world location where a geographically specific model is not available.

## INTRODUCTION

Building simulation software commonly use weather files compiled from data provided by meteorological stations as environment input variables. Assuming the weather file is representative of future conditions, local weather conditions, including wind speed, direction, diffuse and direct solar radiation allow simulations to provide predictions of future building performance.

Accurate solar irradiance data is essential for accurate prediction of thermal performance of buildings. Measured global, diffuse and direct normal irradiation data from a local monitoring station, or ideally at the building itself, offer the most representative picture of the building's solar radiation environment. Modern building simulation software such as EnergyPlus, IES Apache Sim or ESP-r require separate diffuse, direct normal and horizontal global irradiation data to perform energy calculations. Geographically local meteorological stations may often only record global horizontal irradiance; consequently models are used to estimate the diffuse and direct normal irradiance components. Measured and modeled radiation data are often used with other environmental data to produce a complete local weather file.

Several models have been developed to perform this split, including those developed by: Udagawa (Udagawa 1978), Erbs (Erbs 1982), Watanabe(1983) Muneer (Muneer 1986), Perez (Perez et al., 1986), Reindl (Reindl et al., 1990), Maxwell (1998), Clark (2007) and Zhang (Zhang 2007).

These models vary in their geographical applicability and accuracy when compared with measured experimental data. Previous studies have shown the importance of the accuracy of the diffuse direct ratio split in calculating slope irradiation.

*"Using abbreviated analysis it may be shown that for UK latitudes a 10% error in the diffuse correction factor may lead to a 15% error in slope irradiation."* (Muneer 2003)

Several previous studies have assessed the accuracy of the diffuse ratio when compared to measured data. Perez et al. (Perez 1990) reviewed the performance of global (on a horizontal surface) hemispherical to direct beam conversion models available at the time, and concluded that the most accurate was the Maxwell DISC model, giving the smallest error compared to measured data, MBE (25 W/m2) and RMSE (85 W/m2) under all conditions.

Since then there have been several additions to the armoury of models to choose from. This study compares the accuracy of some of these most recent models with experimentally measured ratios of diffuse to direct radiation taken from various cities in Europe, Asia and the US.

HOURLY CLEARNESS INDEX

Given existing hemispherical data, one approach to obtaining direct beam estimates is to develop a relationship between the hourly clearness index denoted by $K_T$ and the diffuse ratio given by $K_{DS}$. The hourly clearness index is a measure of the ratio of global horizontal irradiance Ig to the incident extraterrestrial irradiance, Ie (Muneer 2004).

$$K_T = {I_G}/{I_E} \quad (1)$$

This dimensionless parameter was first proposed by Liu and Jorden (Liu 1960). A simplified model for $K_T$ is based on the geometry of the earth where:

$$K_T = I / (I_0 \sin \theta_{sa}) \, (2)$$

Where $I_0$ is the solar constant of 1353 w/m3

$K_T$ can also be calculated using an estimation of the hourly extraterrestrial radiation E, based on the solar day number and the solar altitude (Muneer 2004).

$$K_T = {I_G}/{I_E} \; (3)$$

$$I_E = I_0[1 + 0.033\cos((\pi/180) \times 360 \times DN/365.25)] \times \sin(\pi/180 \times \theta_{sa}) \; (4)$$

Where $\theta_{sa}$ is the solar altitude in degrees, and DN is the day number, number of days passed in that year.

The solar altitude can be calculated from the solar declination angle ($\theta_d$), the absolute solar time (AST), the equation of time (EOT), and the latitude(LAT).

$$\theta_{sa} = \arcsin(\sin(\pi * \mathrm{LAT}/180) * \sin(\theta_d) - \cos(\pi * \mathrm{LAT}/180) * \cos(\theta_d) * \cos(\pi * \mathrm{AST}/12) \quad (5)$$

Where:

$$\mathrm{AST} = \mathrm{localtime} + \mathrm{EOT} \pm (STM - LONG) \quad (6)$$

The solar declination angle and the EOT are derived using Yallop's algorithm (Yallop 1992).

## DIFFUSE RADIATION MODELS

The diffuse ratio $K_{DS}$ is defined as the ratio of the horizontal diffuse radiation to the global horizontal radiation.

$$K_{DS} = {I_D}/{I_G} \quad (7)$$

WATANABE

The Watanabe approach defines two expressions for the diffuse ratio $K_{DS}$ representing separate conditions for clear and overcast skies, and was derived from East Asian measured data. Rather than using a constant to differentiate sky type Watanabe uses an estimate for the clearness index under a clear sky, $K_{TClear}$, to determine which diffuse ratio to use.

$$K_{TClear} = 0.4268 + 0.1934 \times \sin \theta_{sa} \quad (8)$$

$$K_{DS} = K_T - (1.107 + 0.03569 \times \sin \theta_{sa} + 1.681 \times \sin^2 \theta_{sa})(1 - K_T)^3 \quad (9)$$

when $K_T \geq K_{TClear}$

$$K_{DS} = (3.996 - 3.862 \times \sin \theta_{sa} + 1.540 \times \sin^2 \theta_{sa}) K_T^3 \quad (10)$$

when $K_T < K_{TClear}$

$$DH = I_0 \times \sin \theta_{sa} \times K_{DS}(1 - K_T)/(1 - K_{DS}) \quad (11)$$

$$SH = I_0 \times \sin \theta_{sa}(K_T - K_{DS})/(1 - K_{DS}) \quad (12)$$

$$DirectN = I_0 \times K_{DS}(1 - K_T)/(1 - K_{DS}) \quad (13)$$

Where:

DH = direct solar radiation on the horizontal surface in $W/m^2$

SH = diffuse radiation in $W/m^2$.

DirectN = direct normal radiation.

MUNEER

Based on regression curves from a global data set of measurements, Muneer (1987) proposed the following expression.

$$K_{DS} = 1.006 - (0.317 \times K_T) + (3.1241 \times K_T^2) - (12.7616 \times K_T^3) + 9.7166 \times K_T^4 \quad (14)$$

CLARKE

This model seeks to improve the accuracy of prediction by use of monthly $K_{DS}$ regressions. The hourly diffuse ratio given by $K_{DS}$ is calculated from $K_T$ using regressions given below, where coefficients are given for each month in table 1 below. Lkt and Ukt are the lower and upper limits of $K_T$ substituted in the equations.

$$I_D / I_G = a_1 + a_2 K_T + a_3 K_T^2 + a_4 K_T^3 \quad (15)$$

For $K_T$ < lower limit, $K_{DS} = a_0$

For $K_T \geq$ lower limit and $K_T$ < upper limit

For $K_T \geq$ upper limit, $K_{DS} = a_5$

| | a0 | a1 | a2 | a3 | a4 | a5 | Lkt | Ukt |
|---|---|---|---|---|---|---|---|---|
| J | 0.98 | 0.8379 | 2.359 | -8.5929 | 6.0447 | 0.4 | 0.2 | 0.65 |
| F | 0.98 | 0.8234 | 2.5252 | -8.6825 | 6.2551 | 0.47 | 0.2 | 0.72 |
| M | 0.98 | 0.842 | 2.1475 | -7.7183 | 5.2648 | 0.33 | 0.2 | 0.82 |
| A | 0.98 | 0.8788 | 1.7881 | -6.7321 | 4.5419 | 0.33 | 0.2 | 0.83 |
| M | 0.98 | 0.8925 | 1.4524 | -4.899 | 2.7294 | 0.25 | 0.2 | 0.85 |
| J | 0.98 | 0.8798 | 1.7195 | -6.1193 | 3.8769 | 0.3 | 0.2 | 0.88 |
| J | 0.98 | 0.8656 | 1.8013 | -6.3287 | 4.052 | 0.31 | 0.2 | 0.85 |
| A | 0.98 | 0.86 | 1.8965 | -6.9659 | 4.7367 | 0.32 | 0.2 | 0.82 |
| S | 0.98 | 0.8533 | 1.9973 | -7.42 | 5.049 | 0.32 | 0.2 | 0.75 |
| O | 0.98 | 0.7895 | 2.8158 | -10.052 | 7.4404 | 0.38 | 0.2 | 0.63 |
| N | 0.98 | 0.8469 | 2.4528 | -9.7624 | 7.5419 | 0.38 | 0.2 | 0.7 |
| D | 0.98 | 0.8168 | 2.3577 | -9.2841 | 7.3998 | 0.46 | 0.2 | 0.64 |

**Table. 1 Clarke monthly regression parameters.**

## MAXWELL

Based on data from 14 US and European sites, Maxwell's approach again uses two sets of expressions again for clear or overcast skies.

$$I_{B,n} = I_{max0}\{K_{nc} - [A + B \times \exp(\frac{C}{\mathrm{Sin}(\theta_{sa})})]\}$$

(16)

Where

$$I_{max0} = I_0[1 + 0.033\cos((180/\pi) \times 360 \times DN/365)] \times \sin(180/\pi \times \theta_{sa})$$

(17)

$$K_{nc} = 0.866 - 0.122 \times \frac{1}{\mathrm{Sin}(\theta_{sa})} + 0.0121 \times (\frac{1}{\mathrm{Sin}(\theta_{sa})})^2 - (0.000653 \times (\frac{1}{\mathrm{Sin}(\theta_{sa})})^3) + 0.000014 \times (\frac{1}{\mathrm{Sin}(\theta_{sa})})^4 \quad (18)$$

Where for $K_T > 0.6$

$$A = 0.512 - 1.56 \times K_T + 2.286 \times K_T^2 - 2.222 \times K_T^3$$
$$B = 0.37 + 0.962 \times K_T$$
$$C = -0.28 + 0.932 \times K_T - 2.048 \times K_T^2$$

Where for $K_T < 0.6$

$$A = -5.743 + 21.77 \times K_T - 27.49 \times K_T^2 + 11.56 \times K_T^3$$
$$B = 41.4 - 118.5 \times K_T + 66.05 \times K_T^2 + 31.9 \times K_T^3$$
$$C = -47.01 + 184.2 \times K_T - 222 \times K_T^2 + 73.81 \times K_T^3$$

REIDL

Reindl used data from five European and North American locations to develop diffuse ratio correlations based on four parameters: $K_T$, solar altitude ($\theta_{sa}$), dry-bulb temperature ($T_{db}$) and the relative humidity fraction ($\phi$). Reindl developed three expressions, covering the complete range of possible values of $K_T$.

$$K_{DS} = 1.0 - 0.232 \times \mathrm{Kt} + 0.0239 \times \sin(\theta_{sa}) - 0.000682 \times T_{db} + 0.0195 \times \varphi \quad (19)$$

Interval: $K_T \leq 0.3$, constraint: $I_D / I_G \leq 1.0$

$$K_{DS} = 1.329 - 1.716 \times \mathrm{Kt} + 0.267 \times \sin(\theta_{sa}) - 0.00357 \times T_{db} + 0.106 \times \varphi \quad (20)$$

Interval: $0.3 < K_T < 0.78$, constraint $0.1 \leq K_{DS} \leq 0.97$

$$K_{DS} = 0.426 \times \mathrm{Kt} - 0.256 \times \sin(\theta_{sa}) + 0.00349 \times \mathrm{T_{db}} + 0.0734 \times \varphi \quad (21)$$

Interval: $K_T \geq 0.78$, constraint: $K_{DS} \geq 0.1$

## SKY CONDITION DEFINITION

Previous work on identification of sky types has shown that when using individual climatic parameters to determine sky type, cloud cover (CLD) and Kt produce acceptable agreements with measured data (Li 2004). Kt was used in the classification of measured data into basic sky types.

**Table. 2 Sky type as defined by clearness index range**

| Sky type | Kt range |
|---|---|
| Overcast | $K_T \leq 0.3$ |
| Partly cloudy | $0.3 < K_T < 0.5$ |
| Clear | $K_T \geq 0.5$ |

## EXPERIMENT

The radiation data used was collected from various sources. All UK and Japanese data came from Muneer's book Windows in Buildings 2000, with no additional meta data. US data was provided by the five institutions. (NREL 2008). A total of ten sites were used in the study.

**Table.3 Contributing sites and their longitude and latitude.**

| Site name | Longitude, latitude, STM |
|---|---|
| Fukuoka, JP | 33.6 ° N, 130.4° E, +9 |
| Solar Radiation Research Lab, Colorado, US | 39.74° N 105.18° W, -7 |
| Bluefield State college, West Virginia, US | 37.27° N, 81.24° W, -5 |
| University of Nevada, Las Vegas, Nevada, US | 36.06° N, 115.08° W, -8 |
| Atmospheric Radiation Measurement Program, Okalahoma, US | 35.93° N, 84.31° W,-5 |
| Elizabeth City State University, North Carolina, US | 36.28° N, 76.22° W, -5 |
| Napier University, Edinburgh, UK | 55.92° N 3.24° W, 0 |
| Sheffield University, UK | 53.5 ° N, 1° W, 0 |
| University of Manchester, UK | 53.30° N, 2.30° W, 0 |
| Garston, UK | 51.75° N, 0.47° E, 0 |

Where data sets did not contain explicitly measured direct normal irradiation, measured global and diffuse irradiation data from each set was used to produce a direct normal component using subtraction. Also the data sets were not used in the development of any of the test models; this would likely have skewed the comparisons of the models.

For each site location, simulated direct normal data was generated from the measured global horizontal data and, in the case of the Reidl model, environmental conditions such as temperature and humidity. Direct normal irradiation data derived from measured results were compared with predicted direct normal data using each of the five candidate models. Figure 1 shows a comparison between derived measured data and simulated modeled data, for a sample clear day.

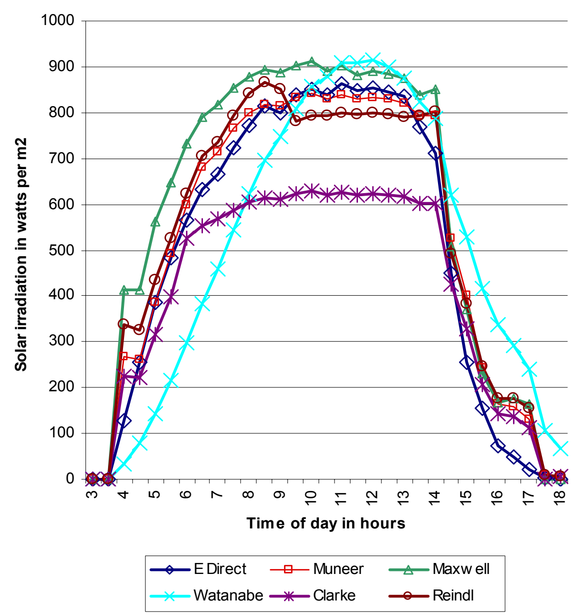


**Fig. 1 Comparison between models and data from sample clear day.**

When measured and simulated data is compared for each complete data set, the results can be summarized by Table 4, which shows the square of Pearson correlation coefficients for the simulated and real data. RSQ is a common statistical measure of the correlation between data sets, where a RSQ of 1 means a perfectly positive linear relationship between measured and simulated data.

**Table 4 RSQ comparison between real and simulated direct normal.**

| Location/ Year | Muneer | Mawell | Wat. | Clarke | Reindl |
|---|---|---|---|---|---|
| Fukuoka, JP | 0.928 | 0.889 | 0.685 | 0.936 | 0.925 |
| Colorado, US | 0.844 | 0.844 | 0.844 | 0.844 | 0.844 |
| W. Virginia, US | 0.884 | 0.902 | 0.575 | 0.909 | 0.906 |
| Nevada, US | 0.816 | 0.818 | 0.493 | 0.793 | 0.813 |
| Okalahoma, US | 0.875 | 0.913 | 0.554 | 0.876 | 0.903 |
| N.Carolina, US | 0.698 | 0.731 | 0.438 | 0.692 | 0.722 |
| Napier, UK | 0.867 | 0.863 | 0.579 | 0.870 | 0.869 |
| Sheffield, UK | 0.917 | 0.922 | 0.571 | 0.916 | 0.883 |
| Manchester, UK | 0.757 | 0.781 | 0.520 | 0.779 | 0.757 |
| Garston, UK | 0.863 | 0.864 | 0.659 | 0.863 | 0.863 |

## EFFECT OF MODELLED RADIATION DATA ON BUILDING SIMULATION

A weather file was produced using a combination of measured global horizontal data and simulated direct and diffuse radiation components using Muneer's model. EnergyPlus was used to perform simulations of a typical elementary school building, using a weather file containing all measured data, and then repeated using the hybrid weather file. The building simulation was based on a real building built to 2002 building codes in the UK. Predicted heating loads for a winter and summer month for each weather file can be seen in table 5.

**Table.5: Total gains for building for one month in winter and summer**

| | | Percent difference |
|---|---|---|
| January heating loads using simulated data using Muneer's model. | 19648 kwh | |
| January heating loads using measured data. | 19623 kwh | 0.128% |
| July heating loads using simulated data using Muneer's model. | 6370 kwh | |
| July heating loads using measured data. | 6376 kwh | 0.098% |

From table 5 the disparity between predicted heating loads, when using simulated weather data, appears negligible when considering the impact over long time frames. A more detailed study into the building's hourly solar gains was performed differentiating between clear, partially cloudy and overcast skies shown here in figure 2. Summer hourly solar gains data reveals a peak difference of approximately 1.8 kw, where delta gains are gains using real weather data minus gains using simulated weather data. This represents about an 8% difference between solar gains in the building at those times.

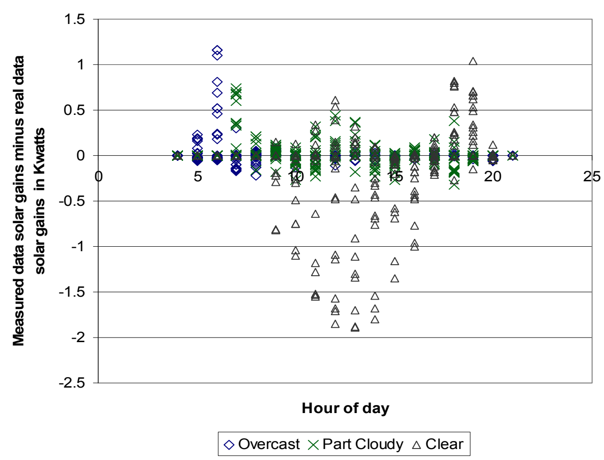


**Fig.2 Hourly difference between building solar gains using modelled and measured direct radiation, over July.**

The impact of these differences in solar gains on the simulation results can best be seen on its resultant impact on temperature in the building, shown in figure 3. The largest differences in temperature occur during the winter month with 17 working hours of the month having a difference greater than 0.3 degrees, all of these periods during occupied times.

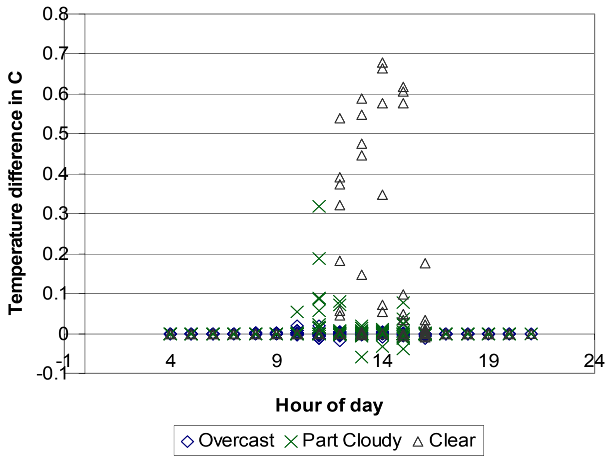


**Fig.3 Hourly difference in degrees C between building temperatures in winter using modelled and measured direct radiation.**

Differences in temperature over 0.3 degrees where seen on four separate days, corresponding to days with clear skies.

## ANALYSIS

Each data item in each set was then classified according to whether the sky was overcast, partially cloudy or clear, based on the hourly clearness index. The diffuse ratio was then calculated from each model for each sky condition. The route mean squared of the direct normal estimations and measured direct normal were then calculated for each sky condition, giving a picture of how accurately each model represents each of the three basic sky conditions. By averaging the results of all US and UK separately, a measure of which model predicts which sky type most accurately for each country can be seen. Figure 4 and 5 shows the variation in accuracy of the models between sky types for the US and UK respectively. The column named *combined* represents the RSQ of all days regardless of sky type.

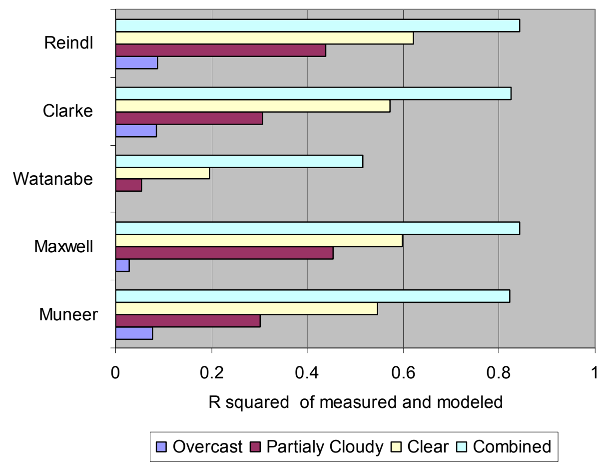


**Fig.4 Averaged US RSQ difference between modelled and measured direct radiation for each model by sky condition.**

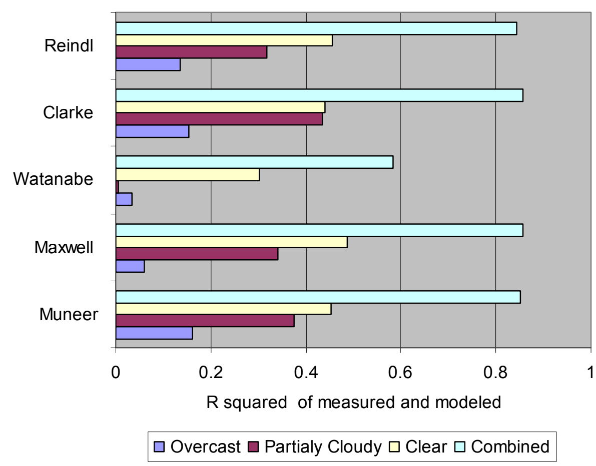


**Fig.5 Averaged UK RSQ difference between modelled and measured direct radiation for each model by sky condition.**

## CONCLUSIONS

The building simulation study showed that using radiation data generated using an appropriate diffuse ratio model allows for accurate prediction of annual building heating loads when compared to results using measured radiation data. However hourly heating loads and zone temperatures predicted using simulations with measured data can vary significantly from results obtained using modeled radiation data, with temperature differences of over 0.3 degrees seen for 10% of working hours in January.

By simulating only one type of building in one location, no broader conclusions can be drawn about the absolute value of any increase in simulation error as a result of using either diffuse ratio model. However, the building simulation study confirmed the logical assumption that the accuracy of the diffuse ratio model has its greatest impact on building performance prediction during periods of peak solar activity on clear days.

For sites in the UK, Clarke's and Maxwell's models provide estimations of the diffuse ratio that differ least from the measured data, with an RSQ value of around 0.857. As this study showed, when diffuse radiation models are used to perform building simulation, accuracy during clear periods is preferable. A more detailed analysis of the data shows that the Clarke model performs noticeably better in overcast conditions and Maxwell's model is more accurate when predicting clear skies. Therefore this study concludes that Maxwell's model is preferable when performing building simulation of sites in the UK.

The initial results of the US data show that overall; Maxwell's model performs slightly better than the other four models, with an average US RSQ figure of 0.8434. However, when US data is classified by sky type, Reidl's model significantly out performs the Maxwell model for clear sky conditions.

When applied to a Japanese data set Muneer's and Clarke's models gave the highest RSQ measure of around 0.93. With only one site, no firm conclusions can be drawn from this result. However, Muneer's model is the only model to be derived from a global set of measurements, and is likely to be preferable when considering sites from outside the UK or US.

Future work will include a comparison of the simulated building loads and solar gains, using data generated using each of the five radiation models. Extending the study to include more locations would also improve the work.

## NOMENCLATURE

$K_T$ hourly clearness index

Ig global horizontal irradiance

Ie incident extraterrestrial irradiance

$I_0$ solar constant of 1353 w/m3.

E hourly extraterrestrial radiation

$\theta_{sa}$ solar altitude in degrees.

DN number of days passed in that year.

$\theta_d$ solar declination angle.

AST absolute solar time.

EOT equation of time.

LAT latitude.

LONG longitude.

SMT the standard time meridian, (longitude of the location being considered).

I global solar radiation on the horizontal surface in W/m2

DH direct solar radiation on the horizontal surface in $W/m^2$

SH diffuse radiation in $W/m^2$.

$T_{db}$ dry-bulb temperature and the

$\phi$ relative humidity fraction

MBE mean bias error

RMSE root mean square error

RSQ square of Pearson correlation coefficient

## REFERENCES


Clarke et al 2007: An investigation of possible improvements in accuracy of regressions between diffuse and global solar irradiation, *Building Service Engineering.*2007; 28: 189-197

Erbs 1982, D.G., Klein, S.A. and Duffie.: Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly-Average Global Radiation, Solar Energy, Vol.28, No.4, pp.293-302, 1982

EL Maxwell 1998, RL George, SM Wilcox .A Climatological Solar Radiation Model,1998 Annual Conference-American Solar Energy Society, 1998

D.H.W. Li 2004, Standard skies classification using common climatic parameters. - August 2004 –Volume 126, issue 2 pp 964-957

Liu BYH 1960, Jordan RC. The interrelation and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy 1960;4(3):1–19

Muneer 2003, Sky luminance and radiance distributions: a comparison based on data from Bahrain, Israel, Japan and Europe Lighting Res. Technol. 35,1 (2003) pp. 11–17

Muneer and Saluja, 1986 T. Muneer and G.S. Saluja, Correlation between hourly diffuse and global solar irradiation for the UK, *Building Services and Engineering Research and Technology* **7** (1986), pp. 37–43.

T. Muneer, 2000, Windows in Buildings, Architectural Press.

T. Muneer, 2004, Solar Radiation and Daylight Models for the Energy Efficient Design of Buildings, 2nd edition, Butterworth-Heinemann.

Perez et al., 1986 R.S. Perez, C. Arbogast, R. Seals and J. Scott, An anisotropic hourly diffuse radiation model for sloping surfaces: description, performance validation, site dependence evaluation, *Solar Energy* 39 (1986), pp. 487–497.

Perez R, et al. 1990. Climatic evaluation of models that predict hourly direct irradiance: prospects for performance improvements. Solar Energy 1990;44(2):99–108.

Reindl et al., 1990 D.T. Reindl, W.A. Beckman and J.A. Duffie, Evaluation of hourly tilted surface radiation models, Solar Energy 45 (1990), pp. 9–17.

Udagawa, M. and Kimura K.: Estimation of Direct Radiation from Observations of Horizontal Solar Radiation, Transactions of AIJ, No.267, pp.83-89, 1978

Watanabe, T., Urano, Y., and Hayashi, T. 1983. Procedures for Separating Direct and Diffuse Insolation on a Horizontal Surface and Prediction of Insolation on Tilted Surfaces¡± (in Japanese), Transactions, No. 330, Architectural Institute of Japan, Tokyo, Japan.

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