CHAPTER 2

THEORIES

This chapter reviews the research literature relevant to the measurements and model developments of the luminous efficacy of daylight. This chapter also presents various technical definitions and terminology of solar irradiance and daylight luminance.

2.1 Solar Irradiance

Solar irradiance is the energy emitted by the sun from a nuclear fusion reaction. Solar irradiance is in the form of electromagnetic radiation with the wavelengths ranging from about 0.3 μm to over 3 μm covering ultraviolet (less than 0.4 μm), visible (0.4-0.7 μm), and infrared (over 0.7 μm) bands. About half of the irradiance is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. The spectrum of solar irradiance is close to that of a black body with a temperature of about 5800 K. Regarding to the spectral character, the *black body* is referred as the perfect absorber. The energy emitted for a blackbody was done by Planck's equation for black body radiation is given as:

$$E_{b\lambda} = \frac{c_1}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1\right)}, \qquad \text{Equation 2.1}$$

where $E_{b\lambda}$ is the monochromatic emissive power,
λ is wavelength,
T is the temperature of the emitting surface (K),
c_1 is the first Planck's constant (3.7405×10^{-16} W.m^2),
c_2 is the second Planck's constant (0.0143879 m.K).

The length of the radiation's path through the atmosphere is an important factor that determines how much irradiance reaches the earth's surface. The solar irradiance falls on the surface in two forms, *beam* (or direct) (E_{eb}) and *diffuse* (E_{ed}). The beam component comes directly as irradiance from the sun, while the diffuse component reaches the earth indirectly and is scattered or reflected from the atmosphere or cloud cover. The global irradiance on the surface (E_{eg}) is the sum of the two components.

The amounts of solar irradiance received at a location on the earth's surface are dependent on the state of the atmosphere and the location's latitude. Other influencing factors are the geographic location, time of day, season and local landscape. The *incident solar irradiance*, sometimes called insolation or the energy per unit time per unit area (or power per unit area), is typically measured in watts per square meter (W/m^2).

2.2 Daylight Illuminance

The *daylight illuminance* is the amount of light flux incident per unit projected area of the surface being illuminated with the unit of lumen per square meter (lm/m^2 or lux).

Obviously, the source of daylight is the sun. The average illuminance on a surface perpendicular to the sun's rays and lying just outside the earth's can be calculated as follows:

$$E_v = K_m \int_{380}^{760} V(\lambda) E_e(\lambda) d\lambda \qquad \text{Equation 2.2}$$

where E_v is the illuminance that is the visible-eye sensitivity-irradiance,
$E_e(\lambda)$ is the solar spectral irradiance (w/m^2)
K_m is a normalizing factor representing the number of lumens of light stimulus produced by one watt of electromagnetic radiation at a wavelength of 555 nm (683 lm/w).
$V(\lambda)$ is the values of C.I.E. photopic spectral sensitivity of the eye. This sensitivity has a maximum value of 1.0 at 555 nm and drops to zero at 380 nm and 760 nm [6].
λ is the spectral wavelength,

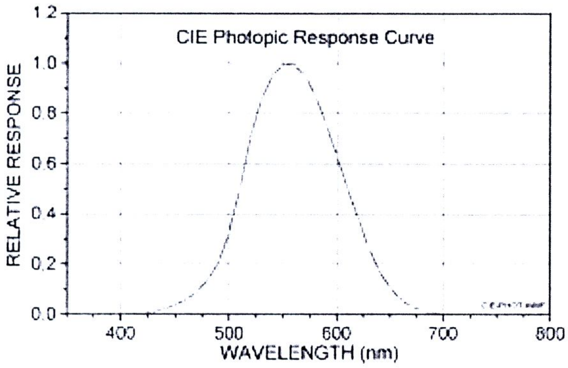

Figure 2.1: The C.I.E photopic curve of the eye response

Through the earth's atmosphere, the weather condition and local terrain on the ground surface make the overall distribution of daylight over the sky to scatter and reflect. In this scenario, the direct or beam and diffuse illuminance are provided in the sky dome and the total of these two components produce the global illuminance.

2.3 Luminous Efficacy of Daylight

Luminous efficacy is a figure to quantify the sun as a *light* source, rather than as an energy source. It provides a link between the two important quantities of daylight illuminance and solar irradiance. The efficacy (K) is defined as the ratio between daylight illuminance (E_v) and its corresponding solar irradiance (E_e). It is expressed in terms of lumen per watt (lm/W) and is defined mathematically by the following expression:

$$K = \frac{E_v}{E_e} = K_m \frac{\int_{380}^{760} V(\lambda) E_e(\lambda) d\lambda}{\int_0^{\infty} E_e(\lambda) d\lambda} \qquad \text{Equation 2.3}$$

where E_e is the total solar irradiance.

2.4 Insolation Parameters and Classification of Sky conditions

The amount of daylight available on a location depends on the condition of the prevailing sky. Insolation parameters have been established and employed as indicators to identify sky condition and also as input variables for mathematical models in solar and daylight calculation. Values of these parameters can be derived from measurement of daylight illuminance and solar irradiance at a station. Some parameters are presented in this section. Sky conditions can be classified by amount of *cloud cover* or alternatively *sky ratio* (or *diffuse fraction*), *k*. The cloud cover index is graduated in tenths and is employed to indicate the amount of cloud in the sky, with 0.0 for no cloud to 1.0 for full cloud. The sky ratio is obtained as the ratio of diffuse horizontal irradiance E_{ed} to global irradiance E_{eg}:

$$k = \frac{E_{ed}}{E_{eg}}. \qquad \text{Equation 2.4}$$

The Illumination Engineering Society of North America (IESNA) classifies sky condition into one of three types, as shown in Table 2.1 (Rea, 2000).

Table 2.1: Classification of sky condition

Sky condition	Cloud cover	Sky ratio
Clear	0.0 to 0.3	$k \leq 0.3$
Partly cloudy	0.4 to 0.7	$0.3 < k < 0.8$
Cloudy	0.8 to 1.0	$k \geq 0.8$

Source: The IESNA Lighting Handbook (9th edition)

The cloud cover index is obtained from human observation and is subject to uncertainty. The sky ratio is based on instrumented measurement and would not be subject to human judgment. However, this index possesses a drawback, which is that during sunrise and sunset, the value of the sky ratio approaches *one* no matter what the actual sky condition is.

There are other parameters employed for classifying sky conditions. In community research of solar energy, the *clearness index* (Liu and Jordan, 1960) has normally been used to identify the condition of sky. It is expressed as the ratio of the global irradiance to its corresponding extraterrestrial solar irradiance E_{e0} as shown below:

$$k_t = \frac{m \cdot E_{eg}}{E_{e0}}. \qquad \text{Equation 2.5}$$

The value of k_t varies from 0.0 to 1.0; the higher the value of k_t, the clearer the condition of the sky. It is noted that the present sky classification is more suitable for the professional community where practicality in determining sky condition is desirable. However, in the research community, more detailed classifications in terms of more gradation in sky types based on measurement records are often proposed.

Correlation between k and k_t has been well studied (Smietana, 1984; Skartveit, 1987; Spencer, 1982). Correlation of a parameter called *diffuse index*, k_d, that is a ratio of diffuse irradiance to its extraterrestrial irradiance, and k_t were also studied (Iqbal, 1980; Hollands, 1985; Vazquez, 1991; Garrison, 1985). These create more insight into the variations of sky condition and the values of the indices. Some studies illustrated that there exists variation of values of k_t with solar position even when the sky condition is invariant. Suehrcke (1988) presented a mathematical formula to correlate k_t with solar altitude α_s for clear sky. Perez (1990) described limitations of k_t in identifying sky condition as well as proposing possible solutions to improve its performance.

Perez (1990) suggested using two indices called Perez's clearness index (ε) and brightness index (Δ) for improving identification of a sky condition. The definition of clearness index as proposed by Perez differs from that used in solar energy research. With a later modification to the original Perez's clearness index, it is currently expressed as follows:

$$\varepsilon = \frac{(E_{ed} + E_{es}) / E_{ed} + 1.041\phi_s^3}{1 + 1.041\phi_s^3}, \qquad \text{Equation 2.6}$$

where E_{es} is the beam normal irradiance, (W/m^2),
ϕ_s is the zenith angle of the sun, radian.

His clearness index reduces the zenith angle dependence by normalizing k_t with respect to a standard clear sky global irradiance. A brightness index (actually diffuse index) is defined equivalently to clearness index k_t, and is given by

$$\Delta = \frac{m \cdot E_{ed}}{E_{e0}}. \qquad \text{Equation 2.7}$$

The variation of ε expresses the transition from a totally overcast sky to a clear sky as shown in Table 2.2. The variation of Δ reflects the opacity, or thickness, of the cloud. Brunger (1993) also used two indices to identify sky conditions similar to k_t and k. Other insolation parameters which are used less are turbidity index and sunshine duration.

Table 2.2: Classification of sky condition by Perez's clearness index.

Bin number / Sky condition	Lower bound	Upper bound
1. Overcast	1.000	1.065
2.	1.065	1.230
3.	1.230	1.500
4.	1.500	1.950
5.	1.950	2.800
6.	2.800	4.500
7.	4.500	6.200
8. Clear	6.200	Higher

Source: Perez et al., 1990

2.5 Development of Luminous Efficacy Models

This section compiles the luminous efficacy models proposed by various authors. From the review, it was found that the models were developed separately for the three irradiance components: global, diffuse horizontal and beam normal. Some models were developed just for a particular condition e.g. clear sky or overcast sky. These models have been adopted from time to time for evaluation of their performance against the daylight and irradiance data in different, as well as specific, locations.

a) Global Luminous Efficacy Models

Littlefair [7] employed the observed data in Southern England to develop two models of the global luminous efficacy: one for clear sky and the other one for overcast sky. Regarding the model, the global efficacy under clear sky is dependent only on solar altitude angle while efficacy under overcast sky is related to brightness condition of the sky. Both of the models are in the form of second degree polynomial equation.

$$K_{gcl} = 91.2 + 0.70\alpha - 0.0063\alpha^2 \qquad \text{for clear sky,}$$

$$K_{gov} = K_{gcl}\left(1.22 - 1.091\Delta + 1.494\Delta^2\right) \qquad \text{for overcast sky.}$$

Muneer and Kinghorn [14] developed a global efficacy model based on measurements from several locations in UK. Different from that of Littlefair, Muneer and Kinghorn employ a single model to characterize the global efficacy for all sky conditions. The model is in the second degree polynomial function of the clearness index (k_t). From the model, the global efficacy is invariant with solar altitude angle.

$$K_g = 136.6 - 74.541k_t + 57.3421k_t^2$$

Ruiz and Robledo [17] also developed a luminous efficacy model for all sky conditions. Solar altitude and clearness index are the input parameters of the model. As shown in the Equation below, the model is in a form of power function.

$$K_g = 104.83 \cdot sin\alpha^{0.026} \cdot k_t^{-0.198}$$

It seems that Robledo and Soler [15] adopted the same concept of Littlefair to develop the global efficacy model for Italy. Two models with different functions were used to characterize the global efficacy; the one for clear sky and the other one for overcast sky. Under clear sky conditions, the value of global efficacy varies only with solar altitude angle.

$$K_{gcl} = 129.46 sin\alpha^{0.122} e^{-0.0029\alpha} \qquad \text{for clear sky,}$$

The Following expression was employed to characterize the global efficacy under overcast sky. The brightness index was included as the model input

$$K_{gov} = K_{gcl(Ro)}(1.361 - 1.091\Delta + 1.0334\Delta^2) \qquad \text{for overcast sky.}$$

Chung [25] presents the same equation as Littlefair, but with the local coefficients for Hong Kong. In this work, a model of the global luminous efficacy was proposed for intermediate sky condition using the diffuse fraction (k) as the input parameter.

$$K_{gin} = (125.9 - 7.96k)k + (82.5 + 0.997\alpha - 0.0089\alpha^2)(1 - k)$$

A more sophisticated and complicated functional form of luminous efficacy model proposed by Perez [9] included four basic model inputs expressed as below:

$$F(\varepsilon, W, \phi_s, \Delta) = a_i(\varepsilon) + b_i(\varepsilon) f(W) + c_i(\varepsilon) g(\phi_s) + d_i(\varepsilon) h(\Delta)$$

The variation of the above function occurs by the climatic condition and composition of the atmosphere. Therefore, to approach the characteristic of this model, the *sky clearness* ε, the *solar zenith angle* ϕ_s, the *sky brightness coefficient* Δ and the aerosol act as the parameter to control the quantity of daylight illumination.

b) Diffuse Luminous Efficacy Models

At the same time of the model's development for the global efficacy, Muneer and Kinghorn [14] also proposed a model for the diffuse efficacy for the UK. From this model, the diffuse efficacy is only a function of clearness index (k_t). The models are in the form of the second degree polynomial.

$$K_d = 130.2 - 39.828 k_t + 49.979 k_t^2$$

where K_d is the diffuse luminous efficacy.

Ruiz and Robledo [17] adopted the same functional form of their global efficacy model to develop a model of luminous diffuse efficacy model. In order to describe sky condition, the brightness index was used instead of the clearness index. The following equation expresses the model function of the diffuse efficacy:

$$K_d = 86.68 \cdot \sin \alpha^{0.034} \cdot \Delta^{-0.266}$$

Chung [25] presents a rather simple equation for the diffuse efficacy. The diffuse efficacy model is a linear function of the cloud ratio. The following equation was formulated for the diffuse efficacy for Hong Kong:

$$K_{dcl} = 135.3 + 25.7CR$$

where K_{dcl} The diffuse luminous efficacy for clear sky.

c) Beam Luminous Efficacy Models

The best polynomial fit of Aydinli and Krochman [18] and Ullah MB [19] by a fourth and fifth degree polynomial model respectively, with the solar altitude as the only independent variable,was developed for direct luminous efficacy and clear sky conditions. The original coefficients are:

$$K_{bcl} = 17.2 + 4.4585\alpha - 8.7563 \times 10^{-2} \alpha^2 + 7.3948 \times 10^{-4} \alpha^3 - 2.167 \times 10^{6} \alpha^4 - 8.4132 \times 10^{-10} \alpha^5$$

$$K_{bcl} = 5.36139 + 7.55407\alpha - 0.199068\alpha^2 + 0.0227639 \times 10^{-2} \alpha^3 - 0.958058 \times 10^{-5} \alpha^4$$

Chung [25] also presented a model of beam luminous efficacy for Hong Kong. The model is in a form of second degree polynomial function of solar altitude angle:

$$K_{bcl} = 48.5 + 1.67\alpha - 0.0098\alpha^2$$

where K_{bcl} is beam luminous efficacy for clear sky.

$$F(\varepsilon, W, \phi_s, \Delta) = a_i(\varepsilon) + b_i(\varepsilon) l_w + c_i(\varepsilon)\cos(\phi_s) + d_i(\varepsilon)\ln(\Delta)$$

The variation of the above function occurs by the climatic condition and composition of the atmosphere. Therefore, to approach the characteristic of this model, the sky clearness ε, solar zenith angle ϕ_s, sky brightness coefficient Δ and the aerosol act as the parameter to control the quantity of daylight illumination. The *precipitable water* is based on Reitan's formulation as follows:

$$l_w = \exp(0.07DPT - 0.075)$$

where *DPT* is the dew-point temperature

The a_i, b_i, c_i and d_i coefficients are given in Table 2.3, for the results by R. Perez [11].

Table 2.3 : Coefficients for Perez et al. luminous efficacy model.

Bin number / Sky condition	a_i	b_i	c_i	d_i
(a) Global luminous efficacy				
1.	96.6251	-0.4703	11.5010	-9.1555
2.	107.5371	0.7866	1.7899	-1.1892
3.	98.7277	0.6972	4.4046	-6.9483
4.	92.7210	0.5591	8.3579	-8.3063
5.	86.7266	0.9763	7.1033	-10.9361
6.	88.3516	1.3891	6.0641	-7.5967
7.	78.6240	1.4699	4.9305	-11.3703
8.	99.6452	1.8569	-4.4555	-3.1465
(b) Diffuse luminous efficacy				
1.	97.2375	-0.4579	11.9962	-8.9149
2.	107.2129	1.1508	0.5840	-3.9490
3.	104.9660	2.9605	-5.5334	-8.7793
4.	102.3945	5.5890	-13.9510	-13.9052
5.	100.7100	5.9400	-22.7500	-23.7400
6.	106.4200	3.8300	-36.1500	-28.8300
7.	141.8800	1.9000	-53.2400	-14.0300
8.	152.2300	0.3500	-45.2700	-7.9800

Table 2.4: Summary of relevant research on luminous efficacy

Authors	Model description	Model parameter	Model Development	Model Evaluation	Development & Evaluation	Location of Data	Year of publication
P.J. Littlefair [7]	Formed the model by best curve fitting with second degree polynomial	Mainly dependent on the solar altitude.			✓	Southern England	1985
Navvab et al. [8]	A semi-empirical model for a range of turbidities and produce a relationship	Solar altitude angle.	✓			San Francisco, California	1986
Perez et al. [9]	The luminous efficacy depended mainly on four parameters	The solar zenith angle θ_z, the sky's brightness Δ, the sky's clearness ε and precipitable water.	✓			Albany, New York	1987 and 1990
J. Wright et al. [10]	Direct luminous efficacy depended on insolation and moisture conditions	Atmospheric precipitable water		✓		Albany, New York	1989
S. Pohlen et al. [12]	Follows model of Perez et al.	The solar zenith angle θ_z, the sky's brightness Δ, the sky's clearness ε and precipitable water.		✓		Paraparaumu Beach, New Zealand	1996
B. Molineaux et al. [13]	The model accounted for the atmospheric turbidity	Optical air mass, water vapor contain and Angstrom's turbidity.		✓		Albany, USA and Geneva, Switzerland.	1995
Muneer [14]	A Polynomial functional	Clearness index		✓		United Kingdom	1997
Robledo and A. Soler [15-16]	The direct or beam luminous efficacy was developed from the experiment data	Mainly dependent on the solar altitude and clearness index.			✓	Madrid, Spain	2000-2002
Riuz et al. [17]	Power function of sine	Solar altitude and clearness index.	✓			Madrid , Spain	2001
J.C. Lam and D.H.W. Li [20]	The second degree polynomial	Solar altitude angle.	✓			Hong Kong	1996

Table 2.4: (Continued).

Authors	Model description	Model parameter	Model Development	Model Evaluation	Development & Evaluation	Location of Data	Year of publication
De Rosa and M. Cucumo [21]	Constant value of luminous efficacy	Observed illuminance and irradiance.		✓		Arcavacata (Italy), Geneva (Switzerland), Vaulx-en-Velin (France), Bratislava (Slovakia) and Osaka (Japan).	2008
T. Katerina [22]	Formed the model by best curve fit with binomial, trinomial and exponential	Solar altitude.		✓		Athens, Greece	2005
Gabriel Lopez et al. [23]	The artificial neural network was used for the atmospheric variable and the spectral radiative transfer model for	α_s and aerosol optical characteristics are the parameters for the model.		✓		Spain	2006
Chung [25]	Formed the model by best linear function of cloud ratio. Also, the second degree polynomial	Diffuse and global irradiance. Solar altitude	✓			Hong Kong	1992
M.Chanda [26]	Formed the model least square fit and polynomial of sine(Solar altitude)	Solar altitude		✓		Roorkee, India.	1996
J.A. Olseth, A. Skartveit [27]	Exponential function of the solar altitude	Solar altitude			✓	Norway	1989
De Rosa et al. [30]	Constant value of luminous efficacy	Observed illuminance and irradiance.			✓	Arcavacata, Italy	2004
S. Roberta and R. Luis [31]	Followed Robledo and A. Soler.	Mainly dependent on the solar altitude and clearness index.		✓		Florianopolis, Brazil	2008

The main parameters used for the development of the model are the solar position and the relative indices as the independent variable. The relative indices are the sky brightness, sky clearness and precipitable water.

Some researchers have extended upon previous studies while others developed new models. The authors of this study have both evaluated the existing model, and on the other hand, they also developed a new model.

The development of the luminous efficacy model is specific to certain locations. Most of the models have been developed in European countries. Only few have been developed in Asian countries, such as India and Hong Kong.