# Potential for Energy Conservation by a Hybrid Natural Lighting System with LED Illumination

Shih-Chuan Yeh[1,*] and Ju-Lin Lu[2]

[1]*De Lin Institute of Technology, Taiwan*

[2]*Taipei Municipal Wenhua Elementary School, Taiwan*

**Abstract:** In buildings, efficient lighting systems and excellent design of interior natural light illumination would contribute to energy saving by direct use solar energy for illumination. This paper propose a model of hybrid natural lighting system with LEDs illumination that would be improve the efficiency of solar energy use. The system is compounded by a prismatic daylight collector, a reflector for re-directing daylight into the room and a diffuse reflector for indoor illumination. The main emerged intensity distribution of the right-angle prismatic collector was investigated using matrix ray tracing model and edge ray principle. The directionality of main emerged light from hypotenuse of the prism is applied to effort the performance of natural light illumination systems by simply guiding design. In this paper, we propose that an efficient hybrid natural lighting system with LED which combined with the prismatic daylight collector can be realizable by a suitable tilted angle of the prismatic daylight collector for different daylight conditions. The reduced electrical energy consumption for using hybrid natural lighting system with LED illumination system can contribute to 70%, 61% and 40% compared to using T8 fluorescent, T5 fluorescent and LEDs, respectively.

**Keywords:** Hybrid natural light illumination, daylight collection.

## 1. INTRODUCTION

One of the most important factors that to lead to climate change and the environmental degradation is the abusive of fossil fuel. The evolution of renewable energy such as the use of solar energy not only reduces consumption of fossil fuel but also slow down the pace of global warming. Solar energy is one of the renewable energies that now providing the lowest cost options for economic and community development in rural regions around the globe. Utilization of solar energy, in addition to the use of solar cell and solar thermal application, indoor daylight illumination is also an important access to solar energy. The artificial lighting systems could account for 30% of the total power consumption in commercial buildings, efficient lighting systems and excellent design of interior natural light illumination would contribute to energy saving; furthermore, the natural light illumination system lead to a comfortable working environment and it has the potential to improve human health, mood, performance and productivity [1-4]. High energy performance building concepts have proposed, combines energy saving and energy recovery from local renewable resources [3, 6], the natural light illumination system can provide part building energy demand.

The natural light illumination system which is compounded by daylight collector, light guide and emission element, the possibility of controlling direct daylight by optical designed systems for comfort illumination or energy conservation has been reported by many authors in the past [7-10]. The prismatic elements can be part of daylight illuminate system that be located at the roof or façade of buildings used as the collectors to collect and guide illuminate daylight for reducing glare and saving energy [11-14]. One of the challenges of natural light illumination is the difficulty in getting a uniform illuminated condition during a day. The hybrid systems of natural light illumination coupled with artificial light source or solar cells are also developed for advanced illuminated condition and energy consumption over the past decade [15-18].

The detailed analysis of emerged light distribution would contribute to the performance of guiding daylight and is efficient to design natural light illumination systems [19]. In this paper, the main emerged intensity distribution of the right-angle prismatic collector was investigated using matrix ray tracing model and edge ray principle, we also proposed an efficient hybrid natural lighting system with LED which combined with the prismatic daylight collector can be realizable by a suitable tilted angle of the prismatic daylight collector for different daylight conditions..

## 2. RAY-TRACING MATRIX MODEL

In this paper a two-dimensional ray-tracing matrix model is used to calculate the propagated directions of rays for sunshine illuminate on the surface of a prism [12, 13]. The propagated direction of a ray is described

*Address correspondence to this author at the Ln. 380, Qingyun Rd, Tucheng Dist, New Taipei City 236, Taiwan (R.O.C); Tel: 886-222733567-388; Fax: 886-286866560; E-mail: yehsc@dlit.edu.tw

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**Table 1: The Nomenclature in Ray Tracing Matrix Model**

| Nomenclature | |
|---|---|
| Θ | the component of vertical angle of a vector in spherical coordinate |
| ψ | the component of horizontal angle of a vector in spherical coordinate |
| $\hat{r}_i$ | the unit vector of the incident ray |
| $\hat{r}_r$ | the unit vector of the reflective ray |
| $\hat{r}_t$ | the unit vector of the refractive ray |
| $\hat{N}$ | the unit vector of the normal incident ray |
| $\alpha_i$ | the incident angle |
| $\alpha_r$ | the reflective angle |
| $\alpha_t$ | the refractive angle |
| $\delta_{ir}$ | the angle between the rays of incidence and reflection |
| $\delta_{it}$ | the angle between the rays of incidence and refraction |
| $\hat{N}_p$ | the unit vector of the normal plane of incidence |
| θ | the component of polar angle of a vector in polar coordinate |
| $\theta_i$ | the polar angle of the incident ray |
| S1 | the top surface of the prism in 2-D |
| S2 | the hypotenuse of the prism in 2-D |
| S3 | the opposite surface of the apex of the prism in 2-D |
| $\alpha_A$ | the apex angle of the prism |
| $\theta_{2min}$ | the minimum incident polar angle that transmitted light of S1 would also transmitted the hypotenuse |
| $\varphi_P$ | The tilted angle of the prismatic daylight collector |

by the polar angle $\theta$ of a unit vector of this ray in 2D ray-tracing matrix model; Table **1** is the nomenclature in ray tracing matrix model, Figure **1a** shows an illustration of the unit vectors of incident ray, reflective ray, refractive ray, and the angles $\delta_{ir}$ and $\delta_{it}$; Figure **1b** shows an illustration of the polar coordinate. The geometric structure of the prism and positions where rays intersect with the surfaces is determined by a constant coordinate; and temporary coordinates are defined to determine the propagated direction of rays for all of the positions where rays intersect the element in this model.

The components of a unit vector of the propagated ray are defined in Eqns. 1a and 1b such that they correspond to the polar coordinates and the Cartesian coordinate system, respectively:

$$\hat{r} = \mathrm{r}\hat{e}_r + \theta\,\hat{e}_\theta, \quad r = 1, \quad 0 \le \theta \le 2\pi \tag{1a}$$

$$\hat{r} = \mathrm{c}_x\ \hat{e}_x + \mathrm{c}_y\ \hat{e}_y \tag{1b}$$

The unit vectors of the propagated directions of the incident ray $\hat{r}_i$, reflective ray $\hat{r}_r$, refractive ray $\hat{r}_t$ and the normal incident ray $\hat{N}$ are defined in terms of Cartesian coordinates in Eqns. 2a-2d:

$$\hat{r}_i = i_x\hat{e}_x + i_y\hat{e}_y \tag{2a}$$

$$\hat{r}_r = r_x\hat{e}_x + r_y\hat{e}_y \tag{2b}$$

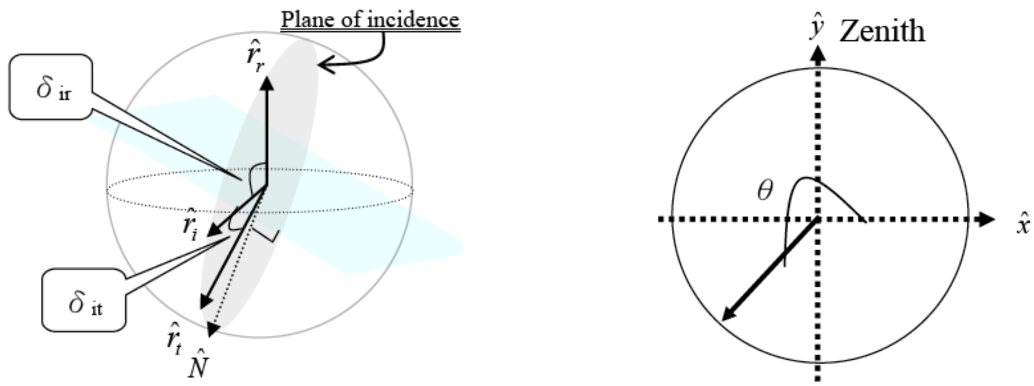
$$\hat{r}_t = t_x\hat{e}_x + t_y\hat{e}_y \tag{2c}$$

$$\hat{N} = N_x\hat{e}_x + N_y\ \hat{e}_y \tag{2d}$$

The components of the unit vectors of the propogate rays can be determined by the scalar poroduct equations in Eqns. 3a-3c, where $\alpha_i$, $\alpha_r$ and $\alpha_t$ are correspond to the angles of incidence, reflection and refraction, respectively.

$$N_x \cdot i_x + N_y\ i_y = \cos\alpha_i \text{, where } \alpha_i = \theta_i - \theta_N \tag{3a}$$

$$N_x \cdot r_x + N_y\ r_y = \cos\alpha_r \text{, where } \alpha_r = \theta_r - \theta_N \tag{3b}$$




(**a**) (**b**)

**Figure 1:** (**a**) An illustration of the interface of mediums, plane of incidence and unit vectors, the angles $\delta_{ir}$ and $\delta_{it}$. (**b**) The definition of polar angle of a ray. (Whang et. al., 2013).

$$N_x \cdot t_x + N_y\ t_y = \cos\alpha_t \text{, where } \alpha_t = \theta_t - \theta_N \tag{3c}$$

The angle $\alpha_t$ can be determined by Snell's law; and it can be shown that $\alpha_r = \pi - \alpha_i$, based on the law of reflection. The angle $\delta_{ir}$ is defined as the angle between the rays of incidence and reflection. It can also be shown that $\delta_{ir} = \pi - 2\alpha_i$; and $\delta_{it}$ is defined as the angle between the rays of incidence and refraction $|\alpha_i - \alpha_t|$, as illustrated in Figure **1a**. The scalar product of $\hat{r}_t$ and $\hat{r}_i$ is shown in Eq. 4:

$$\hat{r}_i \cdot \hat{r}_t = \cos(\delta_{it}) \tag{4}$$

The 2D matrix of reflection and the matrix of refraction are described as follows:

$$\begin{bmatrix} \mathrm{N_x} & \mathrm{N_y} \\ \mathrm{i_x} & \mathrm{i_y} \end{bmatrix} \begin{bmatrix} r_x \\ r_y \end{bmatrix} = \begin{bmatrix} \cos\alpha_r \\ \cos(\delta_{ir}) \end{bmatrix} \tag{5a}$$

$$\mathrm{M}_{in} M_R = M_{PR} \tag{5b}$$

$$\begin{bmatrix} \mathrm{N_x} & \mathrm{N_y} \\ \mathrm{i_x} & \mathrm{i_y} \end{bmatrix} \begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} \cos\alpha_t \\ \cos(\delta_{it}) \end{bmatrix} \tag{6a}$$

$$\mathrm{M}_{in} M_T = M_{PT} \tag{6b}$$

Based on the matrix analysis, the reflective vector $M_R$, the refractive vector $M_T$ and propagated direction of reflective and refractive rays of external incidence of the element can be determined.

### 2.1. Transmitted Intensity Distribution

When parallel light is incident onto the surface of a prism as well as sunshine falling on a prism, the transmitted light of S1 may be divided into two parts to strike different areas of the prism. Figures **2a** and 2b illustrate sunshine illuminate on S1 of the prismatic daylight collector during afternoon in a day, in the region 270°≤ $\theta_i$ <360°. All of the transmitted light beam from S1 reaching S2 for the externally incident onto S1 in the region of incident polar angles 270°≤ $\theta_i$ <360°as illustrate in Figure **2a**; and the distribution of transmitted light from S1 can be determined by the edge ray principle. The position E in Figure **2a** is the limited position of transmitted light S1, the transmitted light beam illuminating S2 in the area where $x > x_E$.

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The value $x_E$ and edge ray of the transmitted light can be determined by Eq. 7, and the relative area where the emerged light from S2 also can be determined by the edge ray principle for parallel light beam illuminate on S1 in the region 270°≤$\theta_i$<360°

$$\frac{\overline{AE}}{W} = \frac{\sin(\alpha_{mt})}{\sin(\alpha_{Ed})} \tag{7}$$

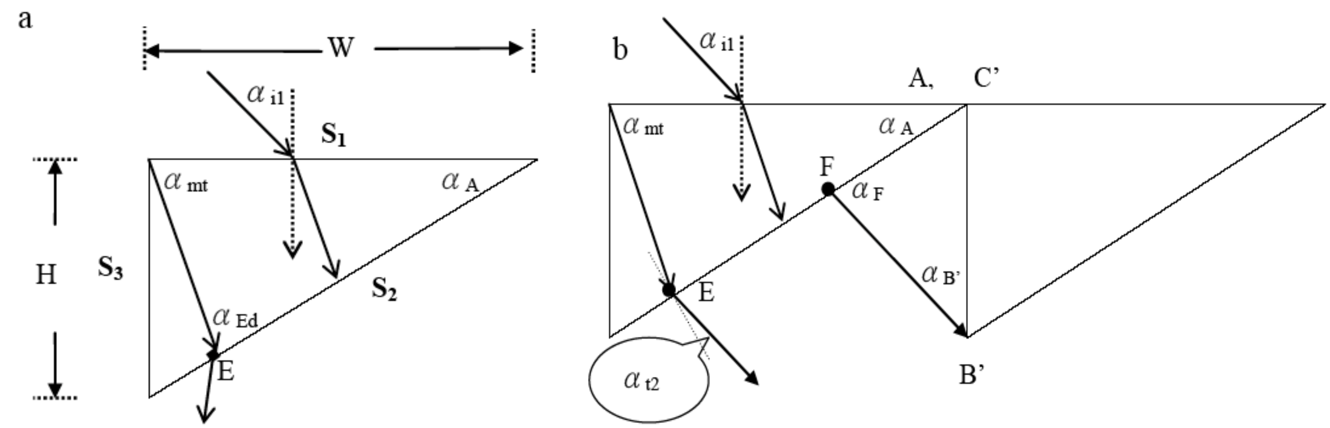



**Figure 2:** (**a**) The illustrations of sunshine illuminate on S1 of the prismatic daylight collector at 270°≦θi<360°, (**b**) The illustration of emerged light from S2 would illuminate space and re-illuminate S3 of the adjacent prism of prismatic daylight collectors at 270°≦θi<360°. (Whang et al., 2013).

Where, $\alpha_{Ed} = \frac{\pi}{2} + \alpha_t - \alpha_A$

Assuming daylight light is unpolarized; the values $T_m(\theta)$ and $R_m(\theta)$ are the transmittance and reflectance of the *m*-th interface for light initially incident onto S1 at the polar angle-$\theta$, respectively; these value were calculated based on Fresnel equations. The intensities of transmission $I_{T,m}(\theta)$ and reflection $I_{R,m}(\theta)$ can be determined by Eqns. 8a-c:

$$I_{i,m}(\theta) = I_{R,m-1}(\theta),\ for\ \ m > 2$$
$$I_{i,m}(\theta) = I_{T,m-1}(\theta),\ for\ \ m = 2 \quad (8a)$$

$$I_{R,m}(\theta) = R_m(\theta) \cdot I_{R,m-1}(\theta) \quad (8b)$$

$$I_{T,m}(\theta) = T_m(\theta) \cdot I_{R,m-1}(\theta) \quad (8c)$$

We set the intensity of incidence $Io$ equal to 1 to more easily describe the characteristics of the main emerged light; the normalized illuminated intensity and the intensity of emerged light are defined as $I_{i,1}(\theta)$ and $Iem$, respectively.

$$I_{i1}(\theta) = Io \times Cos\alpha_i(\theta) \quad (9)$$

$$I_{em}(\theta) = A_i(\theta) \times T_{em}(\theta) \quad (10)$$

Furthermore, the prismatic daylight collector can be compounded by n numbers of prismatic elements, and the percentage of emerged light illuminate the adjacent prism of emerged light from the prism is vary with the polar angle of the incident daylight. Figure **2b** shows an illustration of emerged light from S2 would illuminate space and re-illuminate S3 of the adjacent prism for incident polar angle in the region 270°≦θi<360°. The emerged light would illuminate space and illuminate the adjacent prism for the emerged light that was

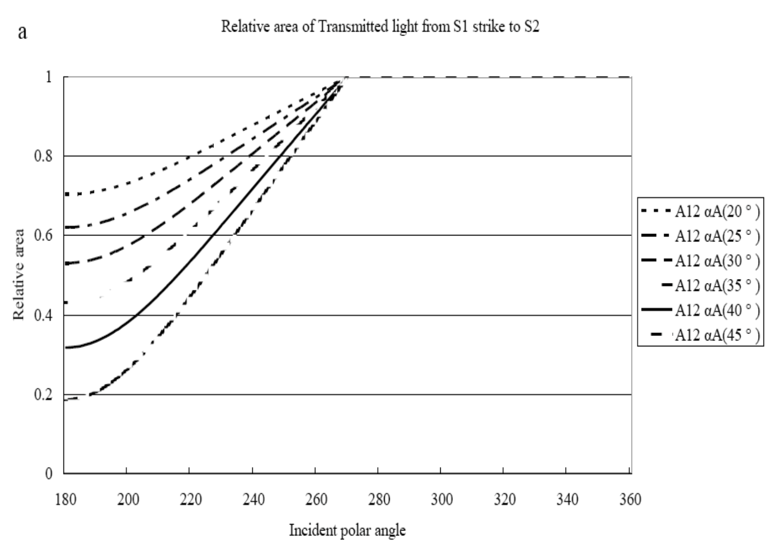



**Figure 3:** The Percentage of area that transmitted light would strike to S2.

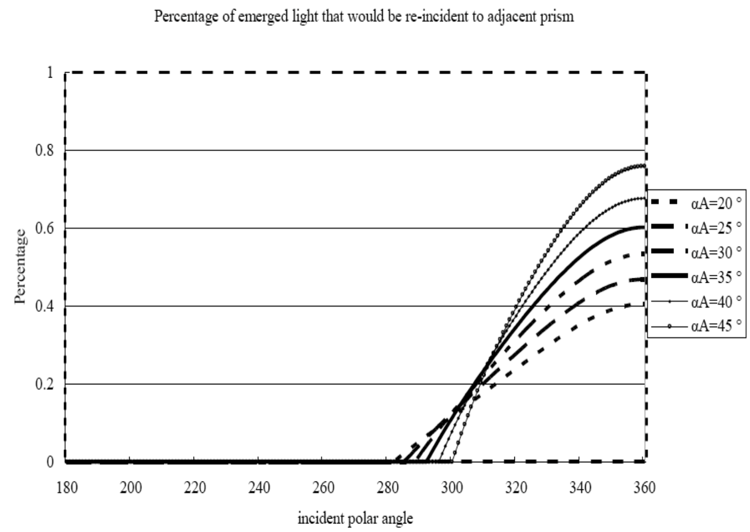



**Figure 4:** The percentage of emerged light from S2 that would strike to surface-S3 of the adjacent prism.

corresponding to emerge from the region of EF and AE, respectively.

## 3. INTENSITY DISTRIBUTION OF THEORETICAL MAIN EMERGED LIGHT

We calculated the main emerged light for sunshine illuminate on the surface of the prismatic daylight collectors which is made of polycarbonate with the refractive index n=1.5836 according to the probability directions; the characteristics of the main emerged light of the prismatic elements with different apex for sunshine illuminate the prism during the day using this matrix model and the edge ray principle.

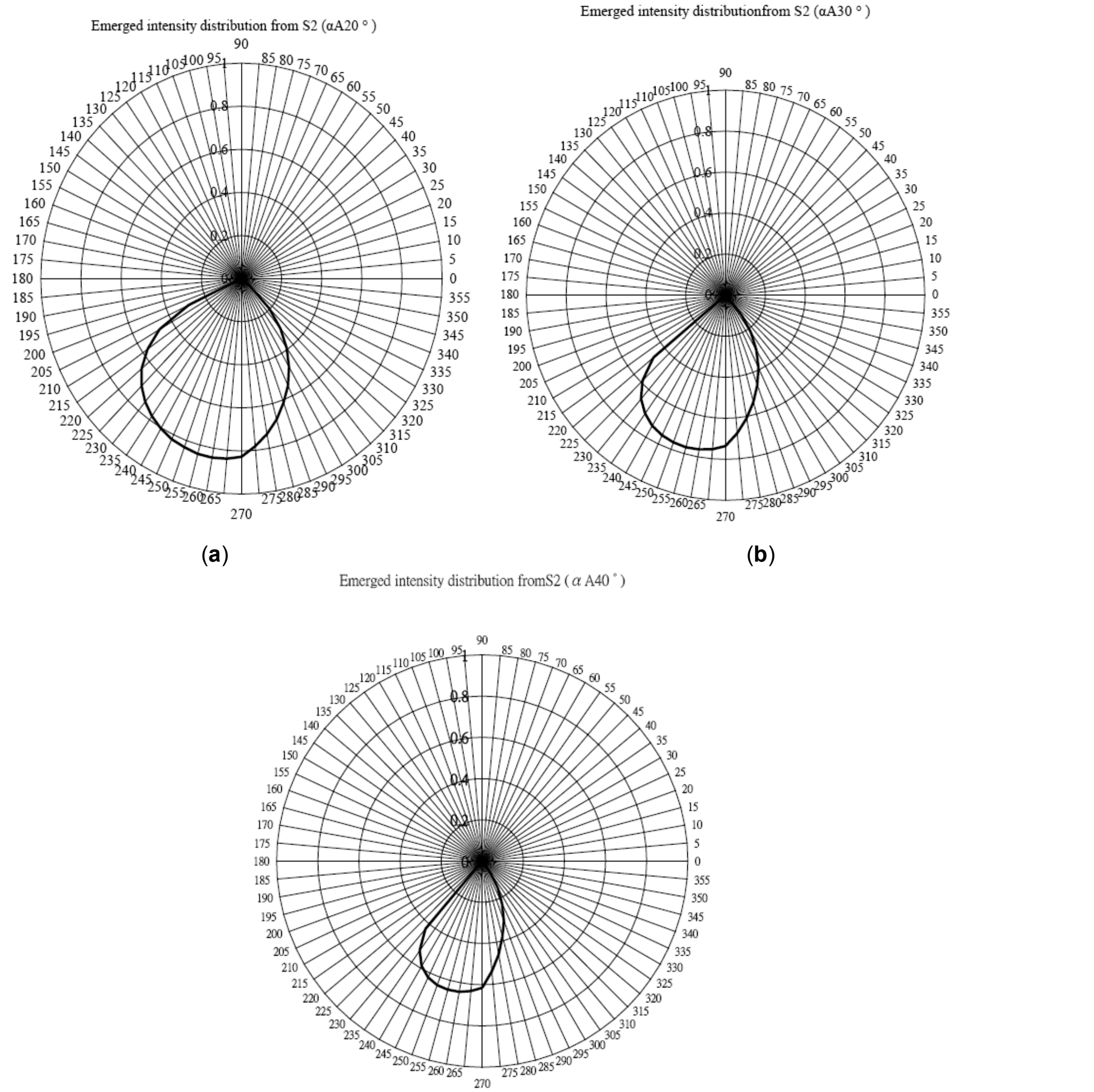
Figure **3** shows the relative area where the transmitted light would be strike to S2 is increasing as the incident polar angle is becoming larger until $\theta_i = 270°$, and the percentage is varied with the apex angles of prisms. Although, most of the transmitted light of S1 would first intersect S2, light rays can have internal reflections inside the prism before the greatest intensity emerges out from the prism; the probability of emerged light from S2 is also varied with the apex angles of prisms. Since, the transmitted light would be total internal reflected for larger incident polar angle; the percentage of emerged light from S2 is larger for the prism with sharper apex.

The transmitted light from S2 may be reaching surface-S3 of the adjacent prism for $\theta_{t2} > 270°$; meanwhile, it decreasing the relative flux of emerged light that illuminate space. The percentages of the emerged light from S2 that would be reaching S3 of the adjacent prism for daylight illuminate the prismatic daylight collectors which with different apex angles are plotted in Figure **4**; they show that the percentage of emerged light would be reaching the adjacent prism increases with increasing the polar angle of incidence and apex. In addition to the emerged light from S2, parts of the transmitted light will be totally internal reflected at S2, and strike to S1 or S3. The figures show that the majority of reflective light from S2 will strike to S3 for the prism with larger apex angle. Figures **5a-5c** show the intensity distribution curve of emerged light that illuminate space for sunshine illuminate on the surface of the prismatic daylight collectors with apex angles 20°, 30° and 40°.

## 4. ESTIMATION OF ENERGY CONSUMPTION

Yeh proposed a model of open natural light illumination system which compounded by a tilted prismatic daylight collector, a reflector and a diffuser for interior daylight illumination [14]. The main emerged light from S2 is redirected by a reflector into the indoor scattering diffuser for natural light illumination by reflector. The open natural light illumination system can be realizable by detailed analysis the characteristics of emerged light from S2 for sunshine illuminate on the surface of the prismatic daylight collector.

The percentage of emerged light about illuminate space and the adjacent prism not only related to apex angle of prism, but also related to the incident polar angle of incident light. The majority of emerged light that illuminate space would be shifted to cover the region $\theta_i$ > 270° which can be correspond to the direction of sunshine illuminate to the room that face sunshine.




(**c**)

**Figure 5:** The intensities distribution of emerged light from S2 Sunshine illuminate on the surface of prismatic collectors which with apex angles: (**a**) $\alpha_A$=20°, (**b**) $\alpha_A$=30° and (**c**) $\alpha_A$=40°.

The tilted prismatic daylight collector would contribute to cover the majority of emerged light for sunshine illuminate the classroom as well as efficient collect solar energy. However, one of the challenges of natural light illumination is the difficulty in getting a uniform illuminated condition during a day due to the variation of solar radiation following the altitude and azimuth of sun and cloudiness. The hybrid natural lighting system with LED illumination system for advancing the illumination intensity requirement during a day, and reduce the electrical energy consumption for using artificial lighting, Figure 6 is the illustration. Table **2** is the electrical energy consumption for using different lighting systems in classrooms of Taiwan elementary school, which the electrical energy consumption of daylighting and LED hybrid system is estimated by the average insolation duration is 4 hours in a day during 1/1/1981~12/31/2010 at Taipei city, Taiwan. The reduced electrical energy consumption for using hybrid natural lighting system with LED illumination system can contribute to 70%, 61% and 40% compared to using T8 fluorescent, T5 fluorescent and LEDs, respectively.

## 5. CONCLUSION

Prismatic elements are widely applied to daylight illumination systems for redirecting and collecting daylight; most of the evolutions of prismatic elements have been concerned with the properties of the total internal reflection of prisms. We investigated the efficiency of apex angle of the right-angle prismatic collector on the performance of main emerged light by using matrix ray tracing model and edge ray principle for sunshine illuminate on the surface of the prismatic daylight collector.

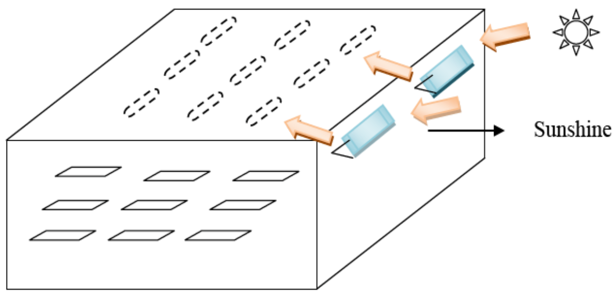



**Figure 6:** The illustration of illumination by the hybrid natural lighting system with LEDs in a classroom.

**Table 2: Energy Consumption of Different Lighting Systems**

| | T8 fluorescent | T5 fluorescent | LED tube | Daylighting and LED |
|---|---|---|---|---|
| Nominal length (ft) | 4 | 4 | 4 | 4 |
| Nominal power (W) | 40 | 28 | 18 | 18 |
| artificial lighting (set) | 22 | 22 | 22 | 22 |
| operating time (h/day) | 10 | 10 | 10 | 6 |
| energy consumption(kwh/day) | 8.8 | 6.16 | 3.96 | 2.38 |

In this paper the intensity distribution of emerged light when sunshine illuminate on the surfaces of right-angle prisms with different apex were detailed calculated, and clearly show that the characters of emerged light are vary with the apex of prism. The total internal reflection occur at S2 is related to the apex angle of prismatic elements, the time interval that the transmitted light of S1 would be total reflected at S2 is longer for larger apex angle. The intensity distribution of the main emerged intensities for sunshine illuminate on the surface of the prismatic collector show that the distribution can be shifted by changing the apex of the right prismatic collector.

A model of hybrid natural lighting system with LED illumination system which is compounded by a tilted prismatic daylight collector, reflector, diffuser was proposed and LEDs. The prismatic element used in the system not only as a canopy to contribute to reduction of indoor heating and glare, but also as a daylight collector to re-directed light for using to promote the efficiency of natural light illumination system, LEDs can contribute to advance the illumination condition during a day.

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