ESTIMATING ENERGY SAVINGS IN ARTIFICIAL LIGHTING PROVIDED BY THE USE OF A SOLAR LIGHT PIPE PROTOTYPE

Gandhi Escajadillo Toledo[1], Alexandre Vieira Pelegrini[1,2]
[1]Postgraduate Program of Design (PPGDesign),
Federal University of Parana (UFPR), Curitiba, Brazil
[2]Academic Department of Industrial Design (DADIN),
Federal University of Technology - Paraná (UTFPR), Curitiba, Brazil

ABSTRACT
In Brazil, few studies investigate the savings in energy consumption using solar light pipes technologies within the national context. This paper aims to estimate the electricity consumption savings provided by the use of a solar light pipe prototype installed in a test house, located in the city of Curitiba/PR, Brazil. An estimation of savings in energy consumption using this system was calculated. An increase of natural illumination indoors up to 50 % was measured under partially covered sky conditions. The lowest Percentage of Natural Lighting Utilization (PALN) was estimated for the month of June, at 32 %. The maximum PALN was estimated for the month of November, at 45 %. The annual hours that artificial lighting could be substituted was estimated to 1182 hours.

KEYWORDS: *Renewable energy, Electricity consumption saving, Solar light pipe.*

I. INTRODUCTION

In the current context of increasing energy demand, the use of technologies that contribute to reduce electricity consumption is an asset. Advanced daylighting systems are an alternative that contribute to the reduction of energy spent on lighting, while they also mitigate carbon emissions associated with artificial lighting systems [1], [2].

Despite that Brazil receives more solar irradiation than many countries that are in the forefront of utilizing solar energy technologies, there are currently few projects that utilize the power of sunlight in applications of technologies that enhance natural lighting. Most projects are focused on the generation of artificial lighting, and do not consider natural lighting as an alternative to reduce energy consumption [3], [4].

One natural illumination technology is the solar light pipe. There is a substantial number of research articles showing that this technology can considerably increase lighting levels in indoors environments, and significantly contribute to reduce the use of artificial lighting in daytime [5], [6], [7]. In the international context, there are several studies that investigate the development and evaluate the performance of solar light pipes under different geometric and environmental parameters [1], [2], [6], [8]. It is noticed that in Brazil there are only a few published studies on the use and integration of these systems and other natural lighting systems in buildings [9]. Hence, in order to investigate the performance of solar light pipes in the Brazilian context, this paper aims to analyse and estimate savings in energy consumption from a solar light pipe prototype installed in a test house, located in the city of Curitiba/ PR, Brazil.

The next sections of this paper are divided as follows: Section II presents a brief review of related works; Section III describes the applied methods, explaining how the lighting performance analysis and estimated energy savings were conducted; Section IV shows the main results, including the lighting performance of the prototype and also the calculated annual saving on artificial lighting; and Section V presents the conclusions. Suggestions for future works are briefly presented in Section VI.

II. RELATED WORKS

Li et al. [6], evaluate energy savings using light pipes in Hong Kong, in a non-commercial building. The analysis results indicate that the system provided with lighting controls can substantially reduce the power consumption spent on lighting. Also, was found that energy savings depends directly on the availability of external lighting. Using on-off and high frequency dimming controls, energy expenditure were respectively 54% and 42% of the energy consumed without any lighting control and light pipe [6]. The energy savings using hybrid solar systems in different locations around the world has been investigated by Mayhoub & Carter [7]. Solar light pipes have a better cost-benefit relationship, despite not having a sophisticated technology. The electric savings generated in non-commercial buildings was up to 55% [7].

In Brazil, one of the few research on electric energy savings using light pipes was developed by the Electric Power Company named Light. The study was conducted in a gym in Rio de Janeiro [10]. The main result was an 86% lower consumption of energy spent on lighting, in this case the payback will be achieved in approximately five years.

III. METHODS

The light pipe prototype developed for this research was installed in a test house, located at the Polytechnic Campus of the Federal University of Paraná (UFPR), in the city of Curitiba/PR, Brazil. The latitude and longitude of this city is -25.51º and -49.27º. The azimuth of the test house is 21º.

3.1 Lighting Performance Analysis

The solar light pipe prototype is divided into three main parts, named as: the collector, the transportation system (light pipe) and the internal lighting control system. The prototype's upper part, the collector, was cut at an angle of 30º in order to optimize the entrance of direct sunlight. The collector and diffuser parts were made of polycarbonate (PC) with UV protection, with about 89% transmittance in the visible spectrum. The aluminium light pipe was internally coated with a Mylar® sheet with 98% reflectance. The light pipe ratio diameter/length was 1:3, with a length L = 0.75 m and a diameter Ø = 0.25 m. The lighting control system allows the light entering the room to be adjusted in accordance to the user needs (Fig. 1a). In a totally open setting, it allows maximum transmitted light to enter the room (Fig. 1a). When the device is closed with a light diffuser, all light is blocked (Fig. 1b).

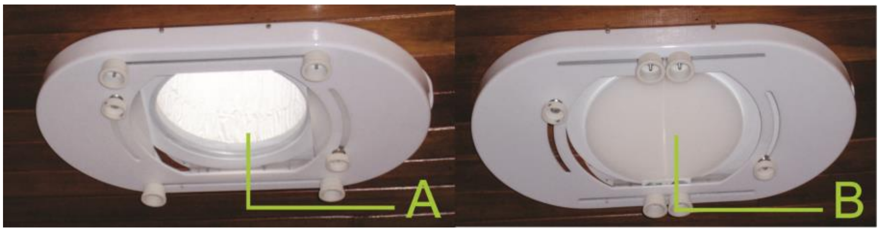

Figure 1. Control lighting system with diffuser opened and closed.

The room where the measurements were carried out had the following dimensions: (3.82 x 2:40 x 2.60) meters (m), and the percentage of window area on the facade was about 30 %. Other variables that had an influence in the lighting distribution inside the room are: the floor reflectance (45%); the ceiling reflectance (25%); the walls reflectance (70 %); and the window transmittance (88%). The central axis of the prototype is located at 2.82 m from the window in y-axis and at 1.2 m with respect to the x-axis. Four measurement points were established, located at 0.75m from the floor level (Figure 2). Four lux meters (model LX1330B) were positioned at each measurement point (P1, P2, P3 and P4), as shown in Figure 2. As expected, the solar light pipe had a higher lighting efficiency at points 1 and 2. Lighting levels at points 3 and 4 receive more lighting coming from the window [3]. For this reason, zone 1 (Fig. 2) was chosen for the analysis of energy savings.

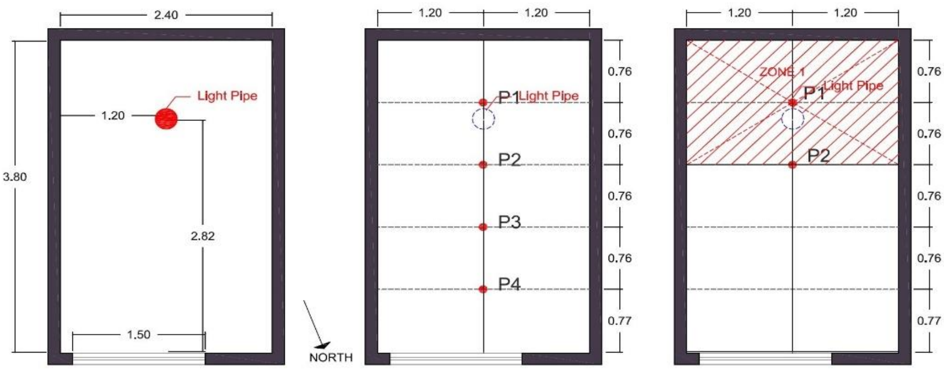

Figure 2. Room Dimensions and analysis points

The measurements were carried out between 7 am and 4 pm, from June 2013 to August 2013. These months correspond to winter season in Brazil. As explained earlier, two situations were analyzed: (1) illumination with the clear diffuser and (2) illumination with the diffuser closed, where the room received natural lighting through the window only. Results were organized according to three types of sky: clear sky, partially covered sky and overcast sky.

3.2 Estimated Energy Savings

To estimate the energy savings, the method PALN (Percentage of Natural Lighting Utilization) was applied [11]. This method estimates the amount of energy savings through the use of natural lighting [11]. The PALN is obtained through the period of time when natural lighting is enough to perform a specific task in an indoor environment, including supplement artificial lighting. In this case, the PALN was calculated by substitution, where the saving factor depends on the ratio between the number of hours that the daylight illuminance is higher than the project illumination and the total number of hours (n) of using the room. The PALN was calculated using the following equation:

$$PALN = \frac{\sum_0^n E_{\ln} \geq E_p}{n} \quad (1)$$

Where Eln is the illuminance average provided by daylight; Ep is the project illuminance and n is the number of hours analysed. To calculate the PALN for each time, the Probability of Occurrence of Sky Types for every month was used, as shown in equation 2:

$$PALN_P = (PALN_{CC} \cdot \rho_{CC}) + (PALN_{CP} \cdot \rho_{CP}) + (PALN_{CE} \cdot \rho_{CE}) \quad (2)$$

Where $PALN_P$ is the considered percentage of natural lighting utilization [%]; $PALN_{CC}$ is the percentage of natural lighting utilization under clear sky conditions [%]; $PALN_{CP}$ is the percentage of natural lighting utilization under partially covered sky conditions [%]; $PALN_{CE}$ is the percentage of natural lighting utilization under covered sky conditions [%]. P_{CC} is the Probability of Occurrence of Clear Sky Type; P_{CP} is the Probability of Occurrence of partially covered Type; P_{CE} is the Probability of Occurrence of covered Type.

TRY (Test Reference Year) weather data files for Curitiba city were analysed. The probability of Occurrence of Sky Type for all months was considered to estimate the solar light pipe performance [12]. Test Reference Year (TRY) is a source of weather data of a typical year used in performance simulations. In this case this weather data was used just as a reference to organize the occurrence of sky type in the city of Curitiba. Table 1 shows the process and data that was used to calculate the percentage of natural lighting utilization and the hours to replace artificial lighting per year.

Table 1. Process to calculate PALN and replacement of artificial lighting

Steps	Process	Data
1	Analysis of measurement results	Measurement Values
2	PALN for each sky type	Measurement Values
3	Final PALN	Probability of Occurrence of Sky Types in Curitiba and PALN for each sky type
4	Hours to replace artificial lighting	PALN per year

In this study, the general PALN, which includes the lighting percentage considering lighting from the window and Solar Light pipe, was not calculated. The PALN was obtained by calculating the increase of lighting levels considering just the solar light pipe, when minimum illumination level is achieved due to the presence of the system. In this work, it was considered the minimum illumination value of 300 lux, recommended by the Brazilian Technical Standard NBR 8995, as a standard reference for the residential test room [13].

IV. RESULTS

4.1 Lighting Performance Analysis

In this study it is important to emphasize that the presence of a window in the room is an important factor influencing the analysed results, contributing to high illuminance levels [3]. However, this natural lighting will typically also be the case if the system is applied in normal settings.

An average of illuminance values was calculated based on the data measured from the prototype. The average corresponds to each type of sky: Clear, partially covered and covered. In graphs shown in Fig.3, Fig.4 and Fig.5, the values marked with green line indicate illuminance values in the room with closed diffuser, and red lines indicate illuminance values with open diffuser.

For the overcast sky context, the increase in illuminance levels was 72% when the room received natural lighting from the solar light pipe in comparison with the room with the diffuser closed (Fig.3). This increase was during peak sun hours. For partially covered sky, the increase also corresponds to peak sun hours; with 58% (Fig.4). For measurements under the clear sky, an increase of about 49% was observed (Fig.5).

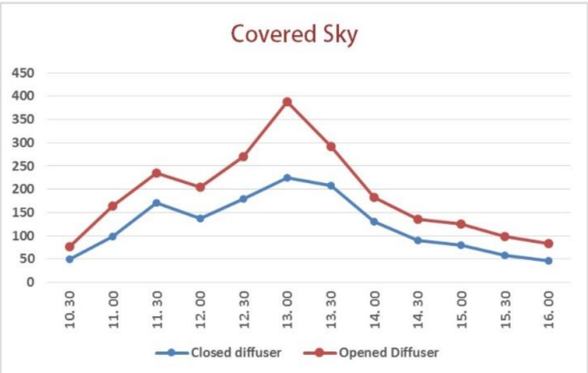

Figure 3. Comparison of illuminance values in the room between opened and closed diffuser, for covered sky.

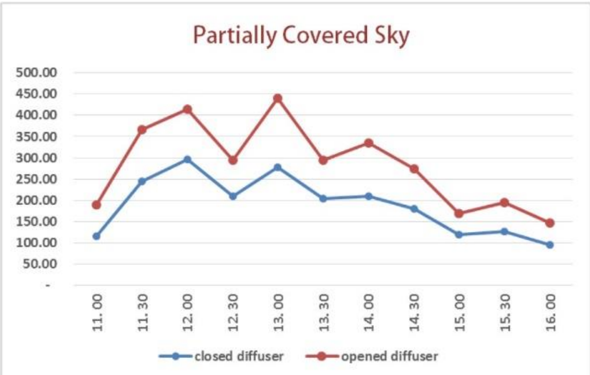

Figure 4. Comparison of illuminance values in the room between opened and closed diffuser for partially covered sky.

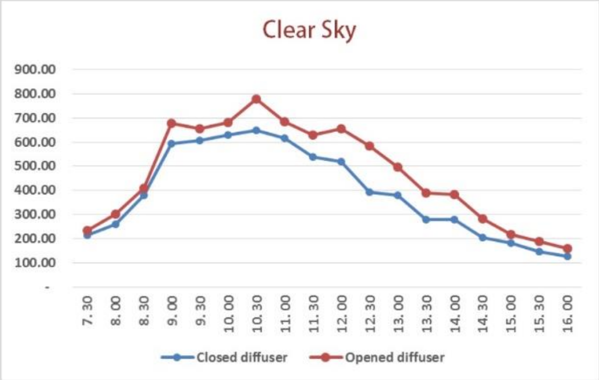

Figure 5. Comparison of illuminance values in the room between opened and closed diffuser for clear sky.

As expected, the average lighting in the room was higher under the clear sky conditions, due to direct solar irradiation, characteristic of this sky type. For covered sky type, general lighting is lower because external illumination is lower and due to diffuse skylight [2]. Based on the data the best performance is achieved during partially covered sky conditions, when natural lighting levels provided by the solar light pipe, most of the time, is sufficient to achieve minimum illumination recommended by the Brazilian Technical Standard NBR 8995 [13]. However, it should be emphasized that under the covered sky conditions, natural lighting levels also increased considerably, although not enough to reach the minimum recommended value of 300 lux.

4.2 Estimated Energy Savings Results

To estimate the possible energy savings resulted from the use of the solar light pipe, the Probability of Occurrence of Sky Types in the city of Curitiba was considered [12]. The percentage of calculated natural lighting utilization is shown in Table 2. These values correspond to PALN, considering only natural lighting from the solar light pipe. As explained in methods, total natural lighting in the indoor environment was not considered.

Table 2. Percentage of natural lighting utilization (PALN) estimated for each sky type.

Sky Type	Percentage
Clear	28 %
Partially Covered	50 %
Covered	30 %

Based on the calculated percentages for the three sky conditions, it was estimated the possible electricity savings (watt-hours) for a period of one year (Table 3). Table 2 shows the results for annual percentage of lighting utilization and the equivalent hours for substituting artificial lighting in daytime. Table 2 shows the numbers of hours related to the hours per month that can possible be substituted by artificial lighting using any kind of lamp. Fig. 6 presents the percentage values from calculated PALN in relation with the number of hours when artificial lighting is not needed. This relationship is according to each month of the year.

Table 3. Percentage of natural lighting utilization (PALN) and estimated hours to replace artificial lighting

Month	PALN	Hours
January	40%	124 hours
February	39%	112 hours
March	36%	124 hours
April	37%	120 hours
May	34%	93 hours
June	32%	90 hours
July	34%	93 hours
August	34%	93 hours

September	33%	90 hours
October	35%	93 hours
November	45%	150 hours
December	38%	124 hours

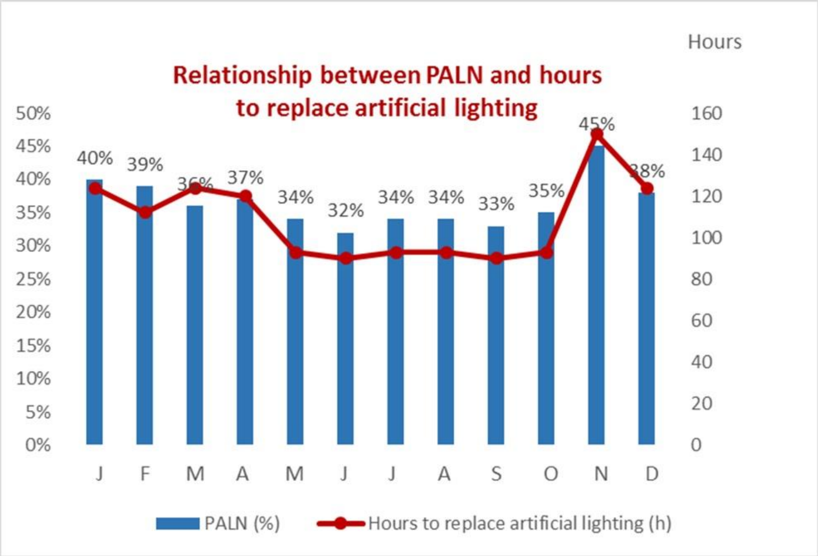

Figure 6. Relationship between PALN and estimated hours to replace artificial lighting.

It is important to notice that the annual savings (in kWh) may vary depending on what type of lamp is used in a room, and where the solar light pipes are installed. After determining the number of hours that artificial lighting can be replaced, final calculations of savings depend on the lamp type. For example, to estimate the annual saving in kWh (Kilowatts hours) using a 40 watts lamp bulb, annual savings of 47.2 kWh can be estimated. This savings can vary dramatically if a calculation was carried out considering a lamp with different power: with a 9 watts lamp, the annual savings are 10.6 kWh. Higher efficiency was estimated for the spring and summer season and lowest efficiency is in months of winter season. In this study, the lowest PALN was for June, with 32 %. The maximum PALN was for November with 45 % (Table 2).

V. CONCLUSIONS

In this paper, the estimated energy savings achieved from the use of a solar pipe prototype system in a residential sector of the city of Curitiba/PR was presented. The presented calculations correspond to environmental conditions of the test house.

The highest measured performance of the tested system was during partially-covered sky conditions, where the percentage of lighting utilization is higher, reaching up to 50 % and lighting values could be increased up to 164 lux. This performance is considered significant, despite the tests were conducted during the winter season in Brazil. The integration of the solar light pipe with natural light from a window can decrease the power consumption associated with lighting with up to 47.2 kWh per year.

The results indicate that artificial lighting could be substituted by natural illumination during around 1182 hours per year. In addition to the possible energy saving, the solar light pipe system also provides a more sustainable lighting solution.

VI. FUTURE WORK

As a recommendation for future studies, it would be interesting to further investigate the annual consumption savings integrated with an artificial lighting control system. These savings could possibly be monitored by digital technologies, such as smart grids. Artificial lighting could be provided by a short solar panel located next to the collector; in this case, new research on monitoring different electronic boards for the activation of artificial lighting, could be conducted.

REFERENCES

[1]. KIM, G. & KIM, J., (2010) "Overview and New Developments in Optical Daylighting Systems for Building a Healthy Indoor Environment". Building and Environment, Vol. 45, n. 2, pp. 256–269.
[2]. KOMAR, L. & DARULA, S., (2012) "Determination of the Light Tube Efficiency for Selected Overcast Sky Types". Solar Energy, vol. 86, n. 1, pp. 157-163.
[3]. SOUZA, D. A., (2005), "Avaliação Teórica e Experimental do Desempenho de Duto de Luz, na Cidade de São Carlos – SP". Master dissertation, Dept. Civil Eng., Univ. São Carlos, São Carlos.
[4]. PURIM. C. A. "Desenvolvimento de um Coletor Solar para Iluminação Direta com Fibra Óptica". Master dissertation, Dept. Technology Development, Engineering Institute of Paraná, Curitiba, 2008.
[5]. MOHELNIKOVA, J., (2009), "Tubular Light Guide Evaluation. Building and Environment", vol. 44, n. 10, pp. 2193–2200.
[6]. LI, D. H. W., TSANG, E. K. W., CHEUNG, K. L., TAM, C. O, (2010), "An Analysis of Light-pipe System via Full-scale Measurements". Applied Energy, vol. 87, n.1, pp. 799–805.
[7]. MAYHOUB, M. & CARTER, D., (2012), "A Feasibility Study for Hybrid Lighting Systems. Building and Environment", vol. 53, pp. 83–94..
[8]. KOCIFAJ, M., KUNDRACIK, F., DARULA, S., KITTLER, R., (2012), "Availability of luminous flux below a bended light-pipe: Design modelling under optimal daylight conditions". Solar Energy, vol. 86, n.9, pp. 2753–2761.
[9]. TOLEDO, G. E., BUSCH, L., PELEGRINI, A.V., (2012), "Tecnologias e Benefícios dos dutos solares: Uma revisão estruturada da literatura visando identificar parâmetros de projeto e contribuir para o design sustentável". Proceedings of the 2012, IV SIMPÓSIO PARANAENSE DE DESIGN SUSTENTÁVEL, pp. 75 – 89.
[10]. LIGHT, (2011), "Luz Natural com Tecnologia Inovadora", Light-Energy Efficiency Magazine, n. 2, ago, 2011. Available: <http://www.light.com.br/web/institucional/eficiencia/pdf/revista-eficienciaenergetica2.pdf.>.
[11]. SOUZA, M. B., (2003), "Potencialidade de aproveitamento da luz Natural através da utilização de Sistemas automáticos de controle para Economia de energia elétrica". Doctor dissertation, Dept. Production Eng., Univ. Santa Catarina, Florianópolis.
[12]. LABEEE – Laboratory of Energy Efficiency in Buildings, (2013) TRY weather files from Curitiba. Available: http://www.labeee.ufsc.br/downloads/arquivos-climaticos/formato-try-swera-csv-bin.
[13]. ABNT–Associação Brasileira de Normas Técnicas (2013) – NBR 8995-ISSO-CIE – The Lighting of Workplaces, Rio de Janeiro.

AUTHORS

Gandhi Escajadillo Toledo graduated in Architecture at the Federico Villarreal University of Peru (2010). She has professional experience working in areas of Architecture and Urbanism. Gandhi received her master degree in Design from Federal University of Parana-Brazil, her graduated work focused on solar light pipes application in Brazilian context. Her research work is in renewable energy, advanced daylighting systems and sustainable architecture with emphasis on solar systems. In 2013 joined the research program of Sustainable Development in rural areas at the Ricardo Palma University in Peru.

Alexandre Vieira Pelegrini is a lecturer and researcher at the Academic Department of Industrial Design (DADIN), from the Federal University of Technology - Paraná (UTFPR). He also lectures and supervises students at the Postgraduate Program in Design (PPGDesign) from the Federal University of Paraná (UFPR), both located in the city of Curitiba, Brazil. He received his PhD from Brunel University, in London (UK), and also holds a master's degree in Mechanical Engineering (Federal University of Paraná / UFPR), and a bachelor's degree in Industrial Design (State University of Santa Catarina / UDESC).