

Communication

# Proposal for an Experimental Methodology for Evaluation of Natural Lighting Systems Applied in Buildings

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**Abstract:** This work has the objective of developing a methodology for the evaluation of indoor natural lighting systems, which, with speed and practicality, provides from real conditions of use a reliable result about the quality and performance of the proposed system. The methodology is based on the construction of two real-size test environments, which will be subjected to a natural light system through reflexive tubes made from recycled material, and to a commercial system already certified and consolidated, creating the possibility of comparison. Furthermore, the data acquired in the test environments will be examined in light of the values of solar radiation obtained from a digital meteorological station, such that it is possible to stipulate the lighting capacity of the systems at different times of the year.

**Keywords:** solar energy; solar radiation; skylight; solar energy harvesting; green energy; measurement

## 1. Introduction

According to data from the Energy Research Company, the consumption of electric energy in Brazil will be growing by 3.7% per year by 2030. For this reason, it is necessary to constantly increase the energy supply and development of systems with higher efficiency to accompany the increased consumption of electrical energy. Besides this indicator, it is observed that the Brazilian territory is geographically between the line of the Equator and the Tropic of Capricorn, and, therefore, presents high solar incidence throughout the year [1].

Brazil has territorial characteristics that contain a solar incidence of around 8 to 22 mega joules per square meter [2], this solar radiation is superior to the majority of Europe, where the solar system is used for residential lighting. Germany applies the use of solar energy in the generation of electricity on a large scale, although it presents solar radiation indices around 40% lower than those in the Southern Region of Brazil, which has the worst index, indicating a great potential for solar exploitation in Brazil [3,4].

Analyzing the structure of electricity consumption among the classes, it is observed that the commercial class shows the highest growth in the period 2015–2020, at 4.4% per year, followed by other classes (4.0% per year), residential class (3.8% per year) and industrial (2.5% per year) [3]. The evolution of residential electricity consumption in Brazil in the last decade can be seen as the combined effect of an average growth of 2.5% per year in the number of new consumers connected in the electricity grid. This has occurred due to investments in infrastructure promoted by the government, social programs and an average growth of 1.3% per year in consumption per residential consumer [3]. The residential sector represents a significant portion of total electricity consumption in the country. The sector represents 25% of total electricity consumption, according to the latest National Energy Balance, behind only the industrial sector [4].

Another relevant impact of residential consumption on the interconnected system of Brazilian electricity is due to the change in consumption peaks during the summer, changing the peaks from 6:00 p.m. to 3:00 p.m., approximately. This change is due to two main aspects, related to the lighting systems and the significant increase of climatization of residential environments. In this scenario, studies aimed at efficiency, reduction of lighting consumption and new sources of clean energy are essential to avoiding, in the medium and long terms, electricity rationing and/or the collapse of the electricity supply system [4,5]. Among the possible solutions for application in homes and commercial environments is the capture of sunlight and its redirection to interior environments as an alternative to the use of lamps. However, the efficiency of lighting through solar radiation is linked to climatic conditions [6].

The conventional solution for the use of natural lighting through window openings, when used alone, results in uneven distribution in indoor environments, causing excessive illumination near the aperture—and, consequently, glare problems—and insufficient levels of illumination at distant points. This conventional method generates overheating at places near the opening and results in an increase in the consumption of electric energy in the building for cooling [7]. To solve these problems, systems have been developed that take better advantage of natural light, mainly devices that redirect light, such as prismatic materials, light shelves, light ducts, etc. Simple systems for harnessing solar radiation for indoor lighting are called zenith systems. The use of lighting through zenith openings allows a greater uniformity of distribution of natural light compared to lateral illumination and, importantly, allows higher levels of illumination on the work plane. Among the devices that comprise this solution are the translucent tile, skylights, shedé, lanternin and domes [8].

Advanced natural lighting systems have emerged as a means of reducing the negative effects of natural lighting and improving the performance of buildings in terms of natural daylight and energy efficiency, while at the same time gaining greater control of the direct solar radiation input. In the devices that make up advanced systems, the reflexive tube responsible for the redirection of the natural light to poorly-illuminated zones, and for the improvement of visual comfort, stands out.

The study of Soto (2010) evaluated the capacity of natural light to be obtained and distributed through light tubes in order to generate adequate lighting in popular habitation. A result was obtained in which it could reach a savings of 38% in the economic cost of energy used in artificial lighting for the simulated days, in addition to a possible improvement in the environmental quality of low-cost habitation [9].

Li et al. (2010) developed a study in Hong Kong to determine the efficiency of a light tube. In this study, 10 light tubes were installed in the ceiling of a hall, the results showed that the system, when integrated with an adequate lighting control, can substantially reduce the energy consumption of lighting [10].

With the objective of evaluating the efficiency of solar tubes, a 1:1 scale solar tube model was developed to determine the efficiency of light conduction, taking into consideration the reflectance and transmittance of the elements and their materials. This study shows that the main contribution of this system is to provide light to the deeper and less illuminated areas of buildings, and significantly improve the visual comfort of people [11]. In addition, regarding the capture of solar radiation on the

roof of the building, the length of the reflective tube can be varied to provide illumination to the desired internal environment. This fact makes the study of the reflective tube relevant in the determination of implantation costs, since high value materials are generally employed in the fabrication of this mechanical component, and, consequently, it negatively affects the payback of the substitution of artificial lighting by natural lighting.

The use of solar tubes for ambient lighting began in 1986, when an Australian inventor presented an innovation in lighting the interior of environments. The invention was patented by the company SOLATUBE, which began to act in the commercialization of the product. The product has evolved over the years, reaching maximum possible yield [12]. Over the years, competing companies have come up offering similar products based on the original design, but with small changes in the materials used, as can be seen in Table 1.

**Table 1.** Commercial Reflective Tubes.

Manufacturer	Reflective Tube Material	Nominal Reflection
Espacio Solar (Spain)	Aluminum with silver coating	98%
Velux (Portugal)	Highly reflective aluminum	99%
Fakro (Portugal)	Aluminum with silver coating	98%
Natural light tubular skylights (USA)	Aluminum with silver coating	98%
SOLATUBE (Australia)	Aluminum with silver coating	99.7%
Chatron (Portugal)	Aluminum with silver coating	99.7%
Solarspot (Italy)	Highly reflective aluminum	99.7%

At the research level, there are some studies on tubular natural light systems, which are presented in Table 2.

**Table 2.** Research developed.

Title	Information
Cylindrical mirror light pipes [13]	Evaluation of reflectivity in solar tubes from integrative sphere analysis
Tubular guidance systems for daylight: Achieved and predicted installation performances [14]	Critical review of existing zenith lighting methods
Tubular light guidance systems as advanced daylighting strategy [15]	Evaluation of tubular lighting systems using SkyVision software and other software with the same function
Rectangular-section mirror light pipes [16]	Modeling of rectangular reflective systems with integrative sphere
Analytical solution for daylight transmission via hollow light pipes with a transparent glazing [17]	Modeling of light transmission in solar tubes
Splayed mirror light pipes [18]	Modeling of rectangular reflective systems
Transmission of mirror light pipes with triangular, rectangular, rhombic and hexagonal cross section [19]	Definition of expressions for calculation of light transmission in reflective, triangular, rhombohedral and hexagonal rectangular systems
Overview and new developments in optical daylighting systems for building a healthy indoor environment [20]	Overview of two optical natural lighting systems (tube light systems and mirror systems)
Light transmission efficiency of daylight guidance systems: An assessment approach based on simulations and measurements in a sun/sky simulator [21]	Characterization of the photometric performance of tubular light guidance systems in terms of light
Light Pipes Performance Prediction: inter model and experimental confrontation on vertical circular light-guides [22]	Modeling and experimental analysis of vertical solar tubes
Study of light-pipes for the use of sunlight in road tunnels: From a scale model to real tunnels [23]	Evaluation of the application of light tubes in tunnel lighting
Thermal analysis of light pipes for insulated flat roofs [24]	Thermal analysis of solar tubes used in roofs
Innovative daylighting systems challenges: A critical study [25]	Analysis of existing natural light utilization technologies
Research on energy saving analysis of tubular daylight devices [26]	Presentation of a model for evaluating the efficiency of tubular systems
Investigation of laminar natural convection heat transfer within tubular daylighting devices for winter conditions [27]	Experimental and numerical study on natural laminar convection in TDD for winter conditions
Passive Tubular Daylight Guidance System Survey [28]	Case study of the installation of a TDGS in Cluj-Napoca (Romania)
Study of tubular daylight guide systems in buildings: Experimentation, modelling and validation [29]	Proposition of a new model of analysis more precise to validate the TDGS in efficacies

This work describes the use of a test environment built for the validation of solar tubes using recycled polymers with internal aluminum vacuum metallization to ensure the necessary reflexivity. These tubes proposed for validation seek to present an alternative to commercial products that use as materials aluminum metallized with high-purity silver, which makes the production cost too high for large-scale application.

## 2. Materials and Methods

The standards regulating internal lighting in residential and commercial environments that were applied in this study, ABNT NBR ISO-CIE 8995-1, have been in force in Brazil since 2013. This norm defines the levels of adequate illuminance within of the workplace in order to ensure the health and integrity of the users of the room, and thus allow them to perform activities such as writing, reading and drawing [30].

In the regulatory standard, it is possible to find the parameter definitions in order to perform a calculation mesh for the design of a lighting system and, with the aid of luminosity measurement equipment (lux meters), determine the average illuminance and the uniformity of the incident light [30].

In order to carry out the calculations, it is necessary to know the largest dimension of the surface to be measured. The room in question was rectangular and had dimensions of 3 wide by 4 long, so its largest dimension (D) is approximately 5 m. The mesh size (P) is determined based on Formula (1), in meters [30].

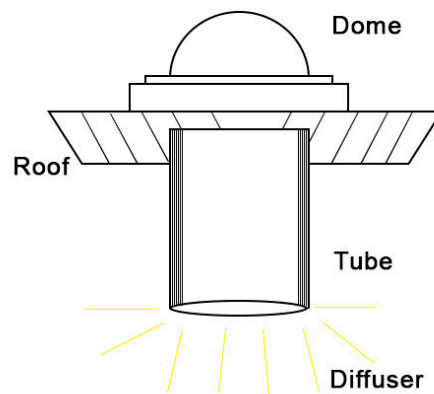
$$P = 0.2 \times 5 \log_{10} D \quad (1)$$

The number of points to be measured was determined through Equation (1), with 8 lux meters being required in each room, but during the period in which the study was performed only 6 were available. This, however, didn't interfere with the proportionality of measurement and data collection, since the equipment was evenly distributed on the surface and, consequently, the resulting illuminance of the environments could be obtained through the average data acquired through the devices.

### 2.1. Characteristics of Natural Lighting Systems

Advanced indoor natural lighting systems, as shown in Figure 1, are basically composed of three components. The dome is responsible for capturing the external solar radiation and for redirecting into the reflective tube, which has the function of conducting the luminosity to the desired location for illumination of the internal environment. Finally, the diffuser has the function of homogeneously distributing the illumination in the environment. Therefore, the test environment proposed in this study allowed the individual comparative tests of the three components applied in the use of natural light and, consequently, made it possible to evaluate the impact of each component related to the overall lighting efficiency of the system.

In order to evaluate the efficiency of the redirection of solar radiation by the proposed reflective tube compared to commercially available options, it was decided to use domes with Fresnel lenses in the two systems of capture of solar radiation. This allowed greater concentration of illumination, regardless of the position of the sun, and diffusers composed by prismatic lens in which the illumination is diffused homogeneously in the environment. Consequently, the comparative analysis was concentrated on the efficiency related to the performance of the tube, and the number of study variables was reduced.



**Figure 1.** Representation of a lighting system with reflective tube.

Because of the variety of solar tubes available on the market, and the manufacturing process of these products is an important factor in the impact of performance, we searched for lower-cost alternatives to manufacture the solar tubes. Therefore, the prototype of the tube was produced using a small plastic injection molding machine for large-scale production without burdening the design with the necessity for high-capacity equipment. The prototype of the tube has a total length of 1800 mm, being formed from tubes of 100 mm in length. Table 1 presents the main constructive characteristics of the two solar tubes implemented in the test environment, which have the purpose of evaluating the efficiency of the internal lighting of the environment compared to a commercial system.

The commercial lighting system used for the comparative study was a SOLATUBE model 160DS (SOLATUBE, Spokane, WA, USA), 250 mm in diameter, constructed of 99% aluminum and metallized internally with silver of high purity. The prototype as mentioned above was developed with recycled polypropylene, internally metallized with aluminum through the process of vacuum metallization by the magnetron sputtering process. As can be seen in Figure 2, due to the limitations of the metallization process, it was necessary to construct the tube in parts, in this case semi-tubes by the injection process, so that they could be metallized internally and subsequently form the reflective tube. After the metallization of these semi-tubes, rings were constructed which were then joined to the tube in the desired length.



**Figure 2.** Prototype of the proposed system.



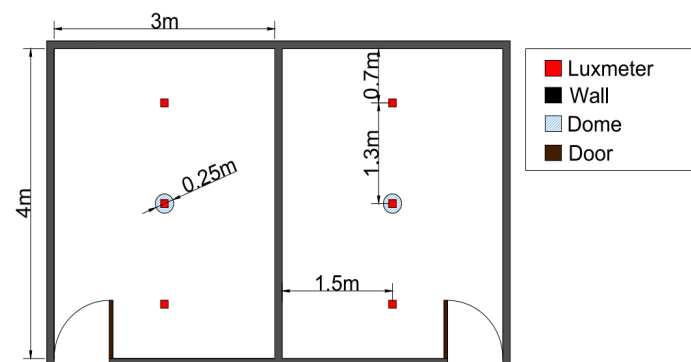
The Table 3 presents a comparison between the proposed system and a commercial luminaire.

**Table 3.** Main features of reflective tubes.

	Characteristics of Reflexive Tubes				
	External Material	Internal Material	Diameter (mm)	Length (mm)	Weight (Kg)
Commercial (Solatube 160DS)	Aluminum 99%	High-purity silver (Vacuum Metallization)	250	1800	2.2
Prototype	Recycled polypropylene	Aluminum (Vacuum Metallization)	250	1800	2.9

## 2.2. Validation System

The proposed experimental model consists of two rectangular rooms of the same dimensions, completely enclosed so that there is no interference of unwanted solar radiation, thus ensuring that the results come exclusively from the objects of study. Figure 3 shows the layout of the lux meter, dimensions, diffusers and their respective diameters.



**Figure 3.** Representational layout of the elements that make up the test environment.

Figure 4 shows the installation of the reflective tubes responsible for directing the illumination captured through collectors located on the roof of the test environment, and distributed inside the rooms through diffusers located in the center of each room.



**Figure 4.** Arrangement of the reflective tubes in the test environment.

This constructive way of fixing the reflective tubes allows a quick and convenient replacement of the tubes to make other comparisons in order to identify materials that present a higher reflection index and, consequently, helps to raise the internal illumination indices to meet the current norms.

### 2.3. Data Acquisition

In order to acquire the data concerning the internal lighting of the two rooms that make up the test, MLM-1020 lux meter (Minipa, São Paulo, Brazil) was used, which was designed with a basic precision of 3 percent, and a datalogger system with a capacity of 2044 data. Data for global solar radiation was obtained through the Digital Vantage Pro 2 meteorological station (Davis Instruments, Hayward, CA, USA), in the period between January and December, 2016. The meteorological station was installed in the college SATC (Criciúma, Brazil), and made it possible to analyze the global radiation in the south of state of Santa Catarina (Brazil) at the following coordinates: 28.4° S 49.12° W and 32 m above the sea level.

### 3. Results and Discussion

The station performed data recording throughout the 24 h of the day, and due to this characteristic, it was defined that the daily period of analysis will include the interval from 8:00 a.m. to 8:00 p.m. Data on sunlight outside this time interval were found to be irrelevant for the purposes of this study. Through the analysis of the obtained values, the efficiency of the reflective tubes that make up the test environment was verified and, consequently, a comparative analysis between the two systems was realized, making it possible to define the rate of transmission of the external luminosity to the interior for the developed recycled tube in comparison to the commercial tube.

With the help of the data obtained by the digital meteorological station during 2016, it was possible to be aware of the variation of the solar radiation incidence during the year, as well as to stipulate a characteristic day of each month, as demonstrated below in Figure 5, which represents an average day that characterizes all solar incidence of the year of 2016.

The main reason for developing a systems validation methodology in a testing environment is to obtain the quality of the product in question accurately and under real conditions, and to gain an approximate understanding of how the room will behave during the year when compared with values previously obtained from the solar station. For this, with the lux meters proportionally distributed at the height of the work plane, data of illuminance in lux were collected and analyzed. It is noteworthy that the data acquisitions were carried out during the summer, over ten days, at the end of January and beginning of February.

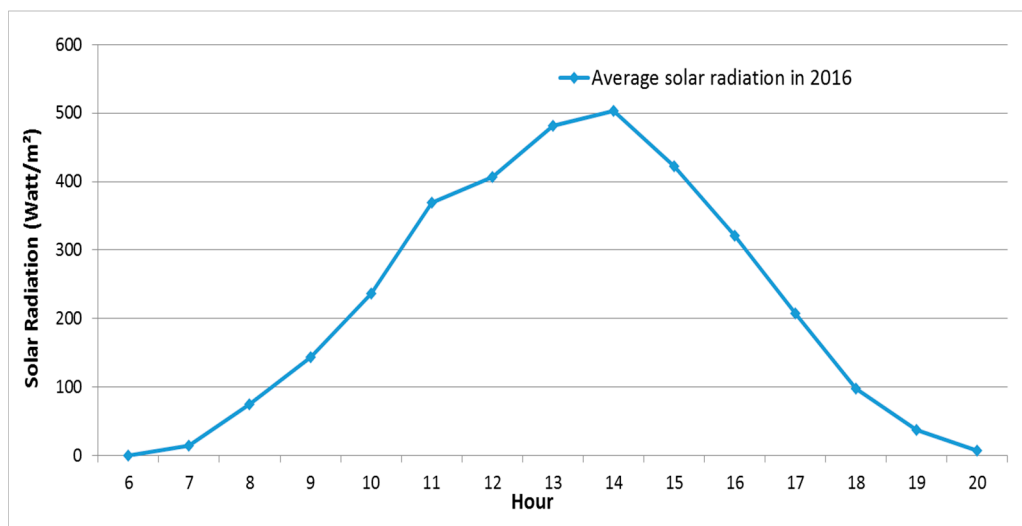


Figure 5. Annual average global radiation of 2016, from 06:00 to 20:00 h.

Throughout the period of tests and measurements, there was no interference from users inside the room, with natural light being the only source of incident light captured in the environment. From

Tables 4 and 5, it is possible to verify the average data acquisition for each hour during the ten days, both from the rooms with the commercial system and the prototype system, measured in lux, and of the meteorological station, measured in Watt/m<sup>2</sup>.

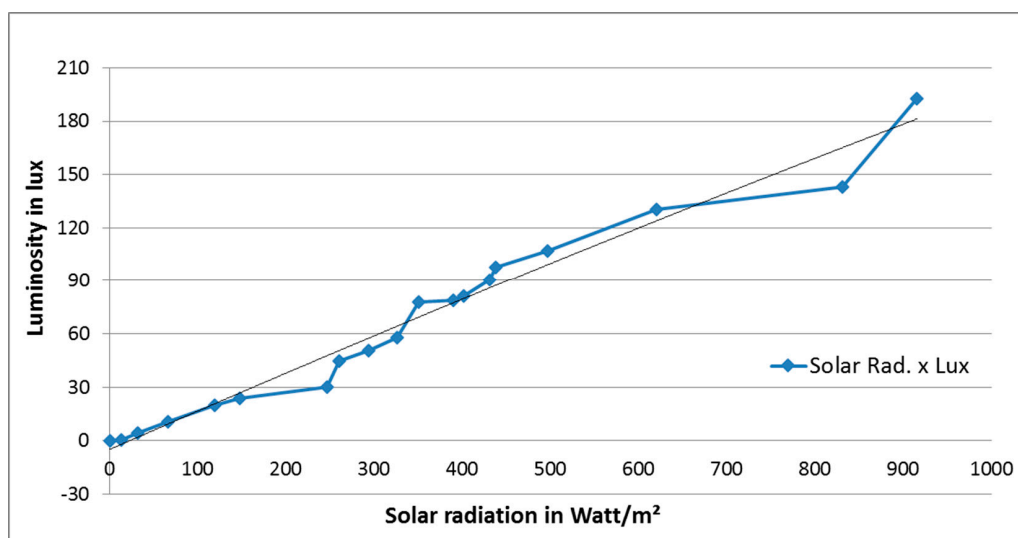
**Table 4.** Values obtained from the analysis of the luminosity in the test environments and in the meteorological station—Part 1.

Hour	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Standard Tube	0.00	4.11	19.85	44.45	57.82	81.18	97.99
Recycle Tube	0.00	1.55	5.70	12.75	17.91	27.94	38.39
Solar Rad.	0.60	31.70	119.30	260.80	326.30	350.90	390.10

**Table 5.** Values obtained from the analysis of the luminosity in the test environments and in the meteorological station—Part 2.

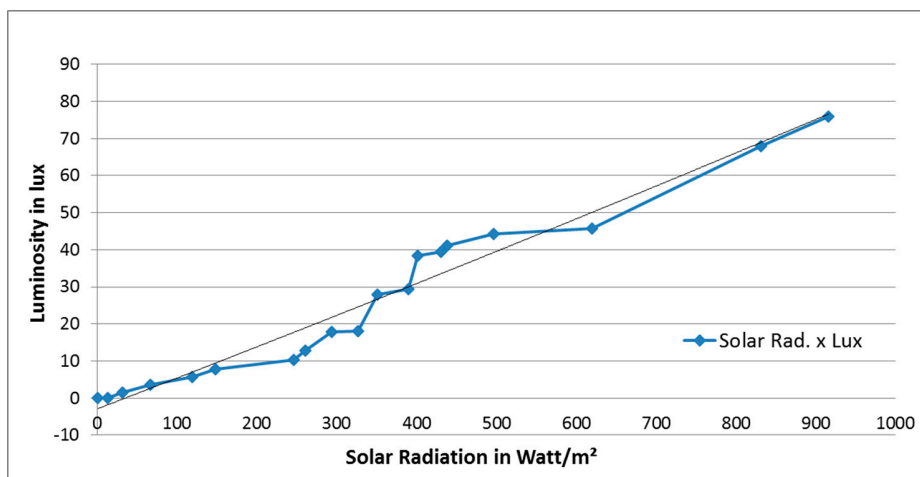
Hour	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Standard Tube	77.60	90.57	78.64	50.62	29.89	23.97	10.43	0.46
Recycle Tube	41.02	39.50	29.32	18.05	10.24	7.70	3.61	0.16
Solar Rad.	430.90	438.30	401.70	294.20	246.40	147.90	66.50	13.50

Based on studies performed previously, and on the table developed, it is possible to relate the values obtained in the two environments, and deduce with certainty that the tube produced with recycled material has an efficiency of approximately 40% when compared to the commercial tube (in which it presents 99% reflection), as shown in Tables 4 and 5. However, with the objective of simulating the annual lighting curve of 2016 that the two environments were supposed to have, two graphs which relate the incidence of solar radiation to the variation of illuminance inside the test environment were produced. It is known that within the spectrum of sunlight, a large portion represents visible light (between 370 and 750 nm), which will be used in the system to illuminate the internal environment [31], and that global solar radiation is not directly connected to internal environment illumination but, as determined through the measurements shown in Figures 6 and 7, that the variations of these physical quantities are proportional; i.e., when the solar radiation increases, the visible luminosity is also greater.



**Figure 6.** Relation between solar radiation and internal luminosity of the test room in which it has commercial pipe.



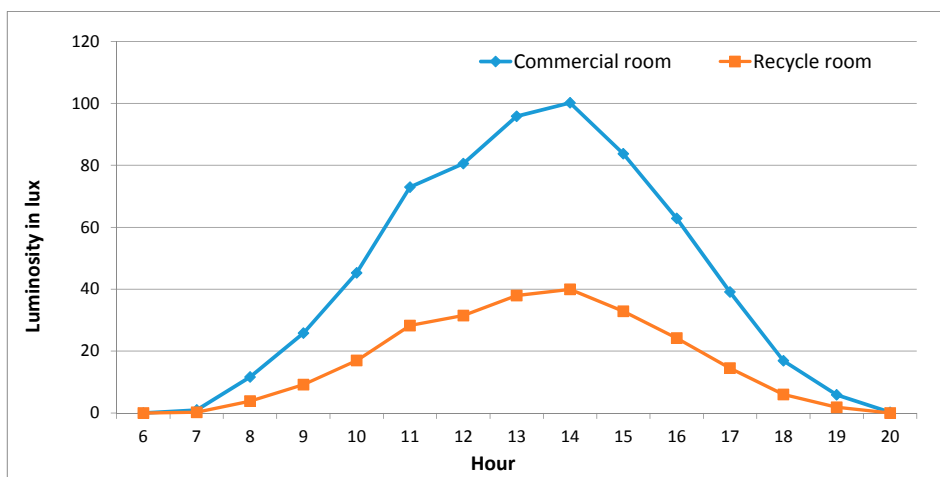


**Figure 7.** Relation between solar radiation and internal luminosity of the test room in which it has prototype pipe.

Based on the graphs above, a mathematical conversion function was developed, responsible for transforming solar radiation values as read by the meteorological station into lux values that will illuminate the test rooms. With this, it was possible to represent the illumination of the rooms during the year, ensuring a wide system analysis from a few days of testing. It is known that such a methodology will not be completely accurate, since it does not consider the natural wear and tear that the systems would have. Furthermore, no luminosity data collection tests were performed during the winter to verify or not the real proportionality of the solar radiation in relation to the illumination. We intend to perform new comparisons over larger periods and at different times of the year.

Despite the limitations of evaluation of the methodology developed, it is possible, as shown in Figure 8, to safely promote the representation of the daily performance that the system will usually provide. It is emphasized that the average global radiation in the afternoon period is significant, and is in agreement with the peaks of electricity consumption during the summer. This fact represents the initial viability for the implementation of a natural light system composed of reflective tubes.

It was observed through thermal readings with a pyrometer that the internal test environments with both tubes did not contribute to the heating of the test room, and consequently did not negatively impact the thermal comfort of the environment. This fact is attributed to the characteristics of the material applied in the confection of the domes that present ultraviolet protection.



**Figure 8.** Luminosity expected for the test environments in 2016, from 06:00 to 20:00 h.

#### 4. Conclusions

The purpose of this study was to evaluate, in a practical and fast way, the feasibility of new indoor lighting projects, especially regarding the use of natural light as a source of light in hybrid systems, in order to save electricity. It was then possible to establish a situation of real conditions, and to simulate the behavior of the system when compared to products already marketed, as well as to relate the two solutions to the meteorological station of the institution.

In this conception, we reduced the inputs involved in the possible formulation of the recycled materials, which present better characteristics of light energy targeting, looking for gains in the performance of the hybrid lighting system. Thus, it was possible to estimate the quality of the system in the test phase, and to compare it with a product that had already been validated, contemplating the proposed changes with less onerousness and greater agility in obtaining the results.

Sunlight is present only during one period of the day, and even then, in some cases, it is covered by clouds. Therefore, it is necessary to use artificial light to either replace or complement natural light. Even so, the system is fully feasible for residential environments because, as previously mentioned, the natural lighting coming from windows and doors can bring problems of excess heat and also great glare. The system is even more interesting for commercial, industrial, classroom, sports gymnasiums and others. In these cases, artificial light supplementation during the day is necessary, given the inefficiency of natural zenith lighting. It is concluded, therefore, that tubular illumination ensures adequately distributed illumination within the environment by reducing the consumption of electricity, and if applied on a large scale, will represent a considerable reduction in overall energy consumption and support preservation of natural resources.

The proposed luminaire can be enhanced with photovoltaic systems and artificial lighting with LEDs. In this case, a photovoltaic panel carries a battery during periods of sunshine and in periods of absence of the sun, the battery provides electricity to the LEDs incorporated into the luminaire diffuser. In this case, the system could be totally off-grid, not needing the consumption of electrical energy, making the product even more attractive economically.

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**Author Contributions:** A.D.S. Research on the plastic materials for the substrate and the type of material for the metallization, participated in the writing of the paper; J.M.N. Design and design of the infrastructure and methodology for validation, participated in the writing of the paper; L.D.B. Design and manufacture of reflective tube matrices, participated in paper writing; O.H.A.J. Research on the plastic materials for the substrate and the type of material for metallization; Participated in the writing of the paper; G.P.D.F.N. Writing paper; Application of data validation and treatment methodology; R.D.S.G. Application of data validation and treatment methodology; Participated in the writing of the paper; M.V.F.D.S. Participation in project design and technical feasibility; C.D.F.M. Consulting in the area of metallic and plastic materials for tube design.

**Conflicts of Interest:** The authors declare no conflict of interest.

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