PASSIVE TUBULAR DAYLIGHT GUIDANCE SYSTEMS ENERGY SAVING POTENTIAL FOR THE RESIDENTIAL BUILDINGS IN ROMANIA

Calin **CIUGUDEANU**, Dorin **BEU,**
Lighting Engineering Laboratory, Technical University of Cluj-Napoca, Romania
calin.ciugudeanu@insta.utcluj.ro

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Abstract*: Traditional vertical window can provide adequate daylight within about six meters of the window. Daylight levels decrease asymptotically with distance from the window so that a disproportionate amount of daylight/solar gain must be introduced into the front of the room to achieve small increases in daylight at the back. Tubular daylight guidance systems (TDGS) are linear devices that channel daylight into the core of a building. These consist of a light transport section with, at the outer end, some device for collecting natural light and, at the inner end, a means of distribution of light within the interior. The nature of the systems and the factors influencing the costs and various benefits that contribute value are identified. Lighting systems in residential buildings, lit by electric lighting and daylight guidance, were surveyed. Data on the physical characteristics of the systems and lighting conditions achieved were collected. The results formed the input to a cost and value analysis which permitted the economic limits of the systems to be evaluated. Some estimations were made about the energy savings and the environmental benefits of those lighting systems.*

1. GENERAL OVERVIEW

The visual effect of lighting is an important part of the total living or working environment. Although every building has different functions, it is compelling to use daylight as a primary or a secondary light source for the benefits of energy, productivity, and health [1]. Although it is becoming increasingly difficult to provide the light required for various activities from daylight alone due to the increased building density, partial use of daylight can still significantly reduce lighting and cooling loads and improve occupants' preferences, visual relief, and pleasing effects [2].

The most effective daylighting strategies could be to optimize building orientation and form as well as to optimize window size and placement. Due to overcrowded urbanization, however, it is increasingly difficult to use strategies that let natural light penetrate deep into the interior space. Fortunately, emerging technologies are available that allow sunlight into the core interior of multistore buildings, although optical sun lighting systems as a remote illumination source can be traced back as far as the late 1800s [3]. Several recent developments in optical lighting systems offer renewed opportunities for reliable optical daylighting sources with broad applicability and high effectiveness. And due to developments in renewable materials, the use of optical daylighting systems for active lighting control can be simple, reliable, and relatively inexpensive.

A few systems exist to redirect daylight into areas of buildings that cannot be lit by conventional glazing. One major generic group is known as 'beam daylighting' - redirects sunlight by adding reflective or refracting elements to conventional windows. The second major group is known as 'tubular daylight guidance systems TDGS.

Tubular daylight guidance systems are linear devices that channel daylight into the core of a building. They consist of a light transport section with, at the outer end, some device for capturing natural light and, at the inner end, a means of distribution of light within the interior. The light capture device may be located at roof level of a building enabling light from the zenithal region of the sky to be gathered. Alternatively, light may be gathered from a device mounted on the building facade. Zenithal openings allow intensive use of daylight but may cause glare or overheating due to penetration of direct solar radiation especially during summer. For a horizontal aperture the quantity of solar flux entering through a facade mounted collector depends on facade orientation and season and these systems are more likely to be influenced by external obstruction than zenithal systems. Collectors may be either mechanical devices that actively focus and direct daylight (usually sunlight) or be passive devices that accept sunlight and skylight from part or whole sky hemisphere. The transport element is usually a tube lined with highly reflective or prismatic material or may contain lenses or other devices to redirect the light. Light is distributed in an interior space by output components, commonly diffusers, made of opal or prismatic material.

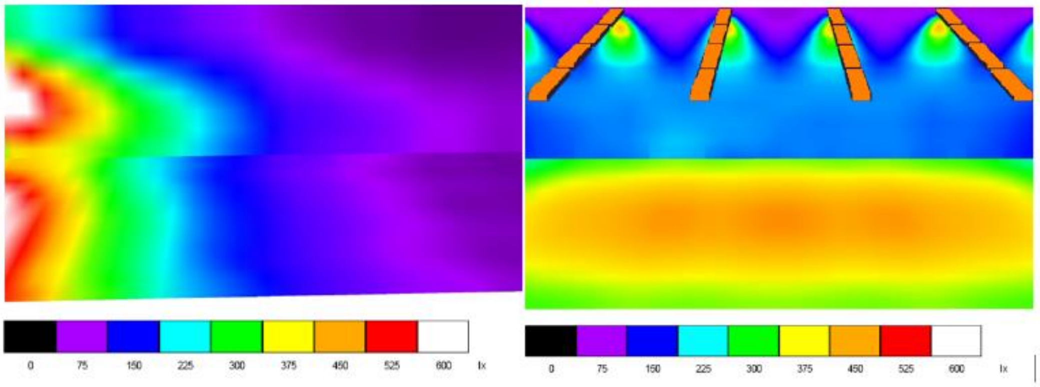
There has been a considerable research effort on TDGS over the last decade. Initially, this concentrated on light transport materials and devices, but latterly, a number of methods of predicting light delivery and/or distribution within a building interior have been developed. They form the basis of CIE173:2006 Tubular Daylight Guidance Systems – technical report. The report describes mostly the passive zenithal systems. These are, by far, the most commercially successful types of tubular daylight guidance, being manufactured and installed in large numbers in numerous countries. The design methodology presented in this report relates to passive zenithal systems only. The Report includes reviews of the technology of all generic types of daylight guidance systems and includes case-studies. The sections on performance indices, photometry of components and systems, design methods, cost and benefits, human factors and architectural issues relate to passive zenithal systems [4].

Our previous research [5], [6] presents results of an experimental study on the performance of a passive tubular daylight system, under the climatic condition of Cluj-Napoca, Romania. A light pipe with flat collector and light-distribution diffuser was installed in a residential building. The performance of the light pipe was tested. The CIE173:2006 suggested methods of prediction are tested against measured data from the installation survey.

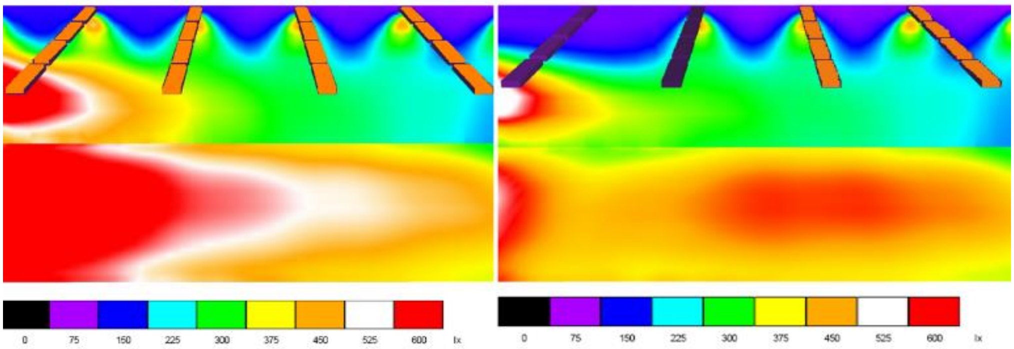
2. TUBULAR DAYLIGHT GUIDANCE SYSTEMS (TDGS)

Conventional vertical window can provide an adequate daylight within about six meters deep inside the room. Daylight levels decrease asymptotically with distance from the window so that a disproportionate amount of daylight/solar gain must be introduced into the front of the room to achieve small increases in daylight at the back. While this can increase energy savings over a larger room area by offsetting electric lighting energy, the corresponding increase in cooling due to solar heat gain, and/or heating due to structural heat loss, can negate these savings. The use of glazed areas on other parts of the building envelope including atriums, skylights and roof monitors may light some areas remote from windows but these are of limited use in lighting deep core areas 1.

The estimated lighting level was simulated with Dialux 4.6 Software for a room (6*12 m) situated in Bucharest. The room has the windows orientation NE on the 6 m wall [6]. In *fig. 1* it can be seen the limited amount of daylight inside a 12 m deep room. The same figure illustrates the lighting level when there are used fluorescent 36 W lamps. A dimmed artificial light scene was also simulated in order to obtain a better lighting uniformity.



Daylight Artificial



Daylight + Artificial Daylight + Dimmed Artificial

Fig.1. Lighting levels for a room (l=6 m, L=12 m, windows on the left side NE, simulation for a building situated in Bucharest, summertime).

TDGS consist of a light transport section with, at the outer end, some device for collecting natural light and, at the inner end, a means of distribution of light within the interior – *figure 2*.

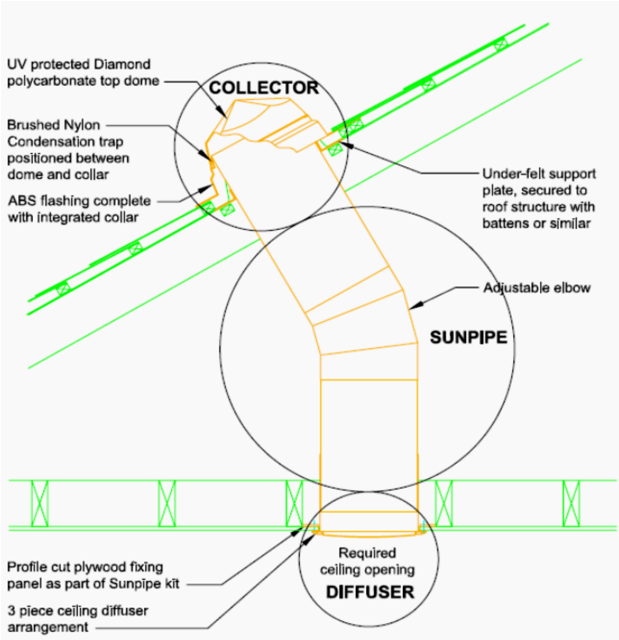


Fig. 2. Tubular daylight guidance system with passive collector [7]

Collectors may be mechanical devices that actively direct daylight (usually sunlight) or be passive devices that accept sunlight and skylight from part or whole sky hemisphere and may be located at roof level gathering light from the zenith sky or on the building façade. Zenith openings capture light from the brightest sky region but may cause glare or overheating due to direct solar penetration. Orientation is a major determinant of collection efficacy in façade mounted collectors. The transport element is usually a tube lined with highly reflective silvered or prismatic material and may contain lenses or other devices to redirect the light. Light is distributed in an interior by emitters which differ little from conventional luminaires.

Light transport is the feature that sets tubular guidance systems apart from other daylight redirection methods. The principal function of transport elements is to deliver light from the collector to the point of exit, but some may additionally act as emitters. Recently considerable research effort has been directed at transport systems, a major factor being the availability of new low-cost light redirection materials. Usually there are four different transport methods, namely, beam/lens systems, hollow mirrored pipes, hollow prismatic pipes, and solid core systems.

The light pipe, lined with highly reflective material, is used to guide sunlight and daylight into occupied spaces (*figure 2*). Highly reflective materials include anodised aluminium and coated plastic film such as Silverlux, which have reflectance greater than 95%. Commercial light pipes are available from a number of manufacturers, in straight and bend sections for on-site assembly and installation. They allow the light pipe to go through complex roof spaces to reach rooms that are not easily accessible to skylights. A light pipe is normally fitted with a clear top dome which removes harmful UV radiation and prevents the ingression of rainwater and dust. A diffuser fitted to the bottom of the light pipe ensures that light is distributed around the room it illuminates. Compared to skylight or windows, the light pipe transmits less solar heat on to the illuminated surfaces. This is particularly valuable in summer for preventing inhabitable hot spots in a building. In winter, a light collector (e.g., a sun-scoop) could be mounted above the top opening to allow significantly more sunlight from low angles to be collected.

A passive TDGS was evaluated – under real conditions. The device was installed in a residential house from Cluj-Napoca, Romania. A light pipe produced by the Velux Company was mounted inside a 4 x 4 m room on the first floor of the building, as shown in *fig. 3*.

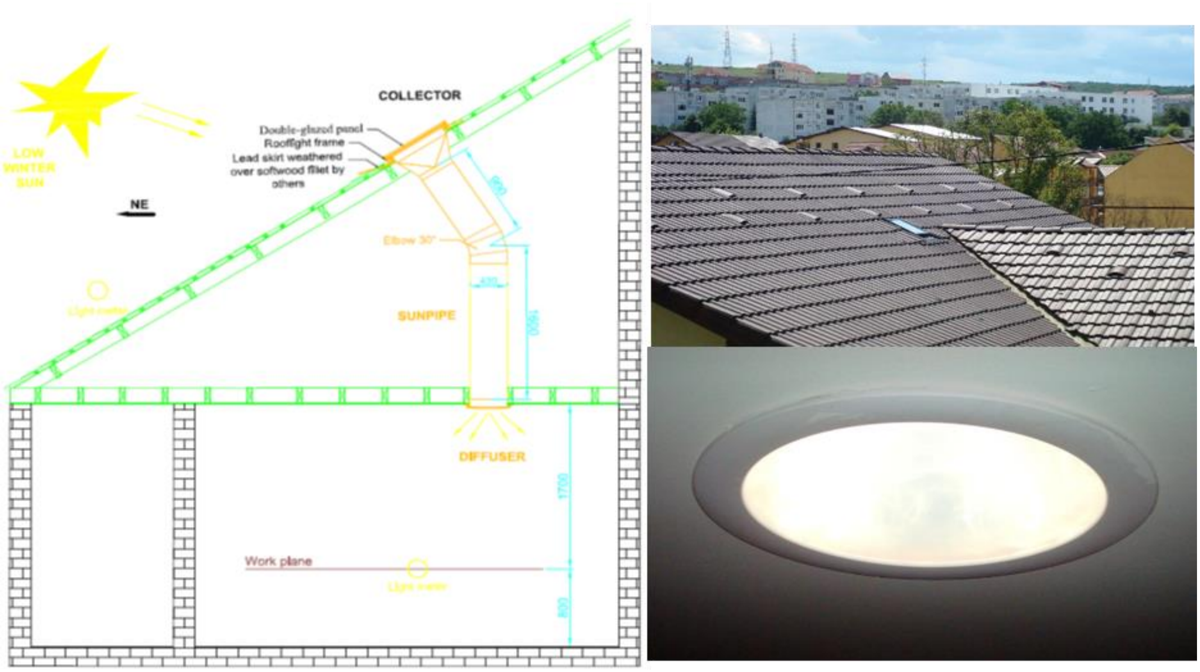


Fig. 3. The experimental set up - Velux TWR14 installed in Cluj-Napoca, Romania

The house is part of a duplex situated in Cluj-Napoca. The cylindrical light pipe has a length of 2.5 m and a diameter of 350 mm. A highly reflective film is laminated, using adhesives, to the interior surface which has a minimum reflectivity of 95%. The top of the pipe was sealed with a clear anti-yellowing acrylic plate. A pearl white diffuser was fitted to the lower opening of the light pipe for even light distribution within the room.

Illuminance measurement was carried out using a standard light meter which had a range of 0.05- 100,000 lx. The meter was based on a photovoltaic cell which has a spectral response similar to that of a standard human eye thus avoids the need for correction for various types of light sources.

Illuminance of the sun on the open field, and that within the working plane inside the room, were obtained using two separate photocells. The readings were recorded manually and care was paied to ensure that there were no passing clouds or other significant changes of lighting condition between reading the two cells. The photocell within the room was normally placed right under the diffuser, at a 0.8 m distance above the floor where the working plane is assumed to be. The data was measured in 30 different days, all around the year 2009. The collector is unfortunately facing the NE direction. Moreover, there are some shading problems when the sun is low. That is why most of the presented results are around noon, in order to eliminate these errors.

Analysing the measured data there can be calculated the maximum, minimum and average values of the indoor and outdoor illuminance. The results are presented in Table 1. For some winter days the results were not conclusive because the collector was covered with a layer of ice and snow. This should ask for second thoughts regarding the shape, geometry and orientation of the flat-type collectors, at least for northern areas with heavy winters.

Table 1. Measurements average results

Value	**Internal illuminance (work plane)**	**External illuminance**	**Average internal illuminance /day**
	lx	lx	lx
Max	238	88000	206
Min	34	3200	65
Average	151	41926	145

The maximum illumination achieved for the work plan was 238 lx, for the day 31.07.2009, at 13.45, corresponding to a value of external illumination of 80000 lx. This value does not coincide with the maximum recorded external illumination, about 88000 lx (21.07.2009, time 13.55), probably due to measurement errors. The lowest illumination value on the work plan was 34 lx registered on 04.02.2009, 14.15, overcast conditions and coincides with the minimum outdoor illumination of 3200 lx. In general, the system has provided an average illumination of about 145-150 lx.

3. HYBRID TUBULAR DAYLIGHT GUIDANCE SYSTEMS

The Technical University of Cluj-Napoca - Lighting Engineering Laboratory – LEL developed a new hybrid TDGS system that is presently under survey. The new system was developed based on the previous survey studies for a TDGS installed in Cluj-Napoca, [5].

Presently a new Hybrid TDGS is under survey. The new system is using a passive TDGS and a small photovoltaic 40W system powering LED light sources, placed next to the diffuser. The tubular daylight guidance system installed is a Velux TWF, 350 mm diameter, flexible light pipe. The photovoltaic system is geared with a 40 W photovoltaic panel 12V Poly 670×475×25mm, a Blue Solar charge controller PWM 12/24V-5A and a 12V/22Ah AGM Deep Cycle Battery providing a 10-hour autonomy for the 28 W LED. A dimming control system is used to maintain a certain lighting level on the work area – Fig. 4.

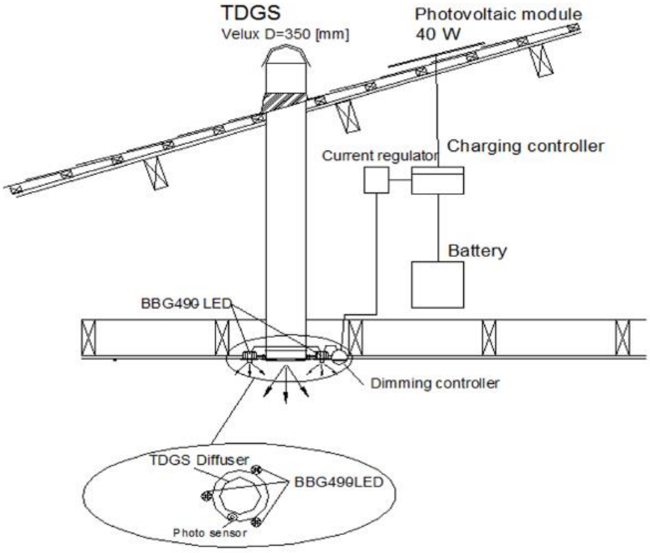


Fig. 4. Hybrid Passive Tubular Daylight Guidance System

The Hybrid Passive TDGS was installed in an outside experimental booth (3 m length, 3 m width, 2.5 m height) outside the building. The booth can provide different cardinal orientations and different roof pitches to provide various setups for the installed Hybrid Passive TDGS.

The designed hybrid system does not need the support of the electric network system, being suitable / adaptable for isolated areas where there is no electricity or for refurbishment solutions where new electrical wiring is not desired.

4. TDGS ENERGY SAVING POTENTIAL FOR THE RESIDENTIAL SECTOR

One major disadvantage of the TDGS is that it can provide natural light only during the day. Relevant for the energy saving potential of the TDGS in the residential sector there is the non-working population, the end users that need light during the day – *fig. 5*.

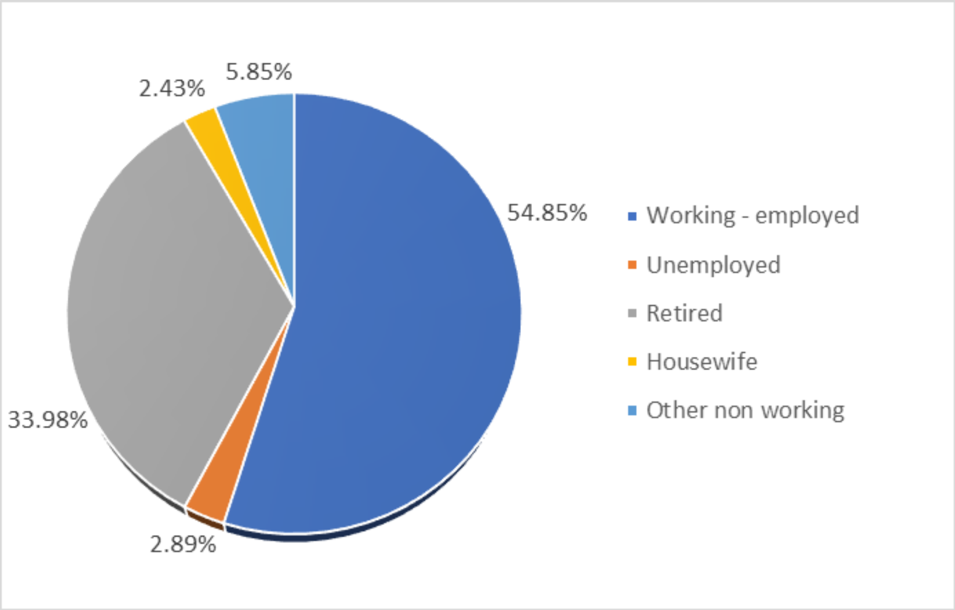


Fig. 5. Dwellings distribution by occupation of family head, Romania [10]

The last official numbers provided by the Romanian National Institute of Statistics for the year 2011, shows a total number of over 7.4 million dwellings for the Romanian residential sector. The values presented in Table 2 denote the large number of households owned by non-working family heads (approximately 3.3 million). Dividing this number with the national average of dwellings per building we can assume a total of 2.40 million buildings with dwellings having non-working family head.

Table 2. Number of dwellings distributed after the family head occupation, Romania [10].

DWELINGS BY OCCUPATION OF FAMILY HEAD	
Total Residential Buildings	**5326972**
Total Dwelings	**7470429**
Average number of dwelings per building	1.40
Working - employed	*4097641*
Non working	*3372788*
Unemployed	215972
Retired	2538226

DWELINGS BY OCCUPATION OF FAMILY HEAD	
Housewife	181860
Other non working	436730
Buildings with dwelings having working family head	**2921923**
Buildings with dwelings having non-working family head	**2405049**

Scientists estimates electric lighting savings for the residential sector taking into consideration a non-working residential couple who spend a considerable amount of time at home with a 300 mm diameter passive TDGS installed (usually in the kitchen/hallway/bathroom). The system typically replaces the burning of 200 to 500 Watts of electric lights for 3 to 7 hours per day. We can assume a 300-Watt savings for 5 hrs. per day, only 5 working days per week. This leads to electric consumption savings for a TDGS 300 mm diameter of about 390 kWh per year.

If we consider that in each 2.40 million buildings with dwellings having non-working family head, at least one TDGS 300 mm diameter is suitable to be installed and considering the previous electrical savings example, we can assume total energy savings for residential lighting in Romania of about 936000 MWh per year. Additionally, savings can be assumed for the total number of residential buildings during the weekends (total number of residential buildings – 5.32 million * 300-Watt savings for 5 hrs. per day, only 2 days in the weekend leads to additional total electricity savings of 829000 MWh per year). The previous predictions examples show electricity savings for the residential sector in Romania by installing in each building a TDGS 300 mm diameter of about 1.76 million MWh per year. Even a greater saving potential should be available for the commercial sector where usually the main activity take place during the day.

For the non-working family head, the payback of installing one TDGS can be estimated. If we consider a total electricity price of 0.15 euro/kWh and electric consumption savings for a TDGS 300 mm diameter of about 547 kWh per year (300W x 5h x 365days), a total annually running cost reduction of 82 euro can be achieved. If a 300 mm passive TDGS costs around 400 euro, the system payback time for a nonworking family head should be around 4.9 years.

Calculating the payback time for working family head if we consider a total electricity price of 0.15 euro/kWh and electric consumption savings for a TDGS 300 mm diameter of about 165 kWh per year (300W*5h*110 holydays and weekends), a total annually running cost reduction of 25 euro can be achieved. The system payback time for a working family head should be around 16 years.

5. CONCLUSIONS

A typical passive TDGS costs 300 to 500 euro installed and will prevent over 3 tons of CO_2 from entering our air over the next 10 years. All this, while providing healthy, natural interior illumination, far superior to any electric light in both colour and intensity. It just makes good common sense to implement such technology [9].

Daylighting systems require a specific conception, very close related to the geographic context where they are built, to environment (natural and artificial obstructions), to imposed levels of visual comfort and to climate.

If we think only about the annually cost reductions and make a strict economic evaluation – the passive TDGS is economic viable only for non-working family heads or places where there is limited daylight and are used during the day.

Combining a passive TDGS with an artificial LED light source powered by a photovoltaic module and a battery can extend much more the system autonomy and running hours [8].

The development of new materials with better performance in light reflection and transmission has led to various solutions of energy efficient lighting systems able to grow potential for future applications.

Any technical and economic analysis of these systems must take into account both energy efficiency, and visual comfort conditions for the lighted spaces. For example, these solutions present outstanding possibilities to improve visual comfort in underground spaces, which are energy efficient due to low thermal losses.

Perspectives offered by these solutions of integrated lighting systems lead to a higher visual comfort and to new possibilities of space utilization.

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