Hybrid lighting systems: A feasibility study for Europe

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Abstract

Hybrid systems simultaneously deliver daylight and electric light into a building where they are combined and distributed via luminaires. Hybrid technology, both conceptual and realised, is discussed together with that of the more established of tubular daylight guidance lighting systems. Likely system performance in terms of daylight delivery and potential electricity savings is evaluated for different geographic locations throughout Europe. The results are discussed in relation to likely costs and potential impact on the building which they light.

Keywords: Daylight, guided daylight, hybrid lighting

1. Introduction

Until the start of the 20th century daylight was the only practical large scale light source for buildings. It had an overwhelming influence on the form and technology of contemporary buildings until the development of the electric lamp freed designers from this constraint. The end of the era of cheap energy has lead to a reappraisal of daylight in buildings. A large body of knowledge shows a general preference for daylight as a light source in buildings. This popularity is due to a number of factors related to its fulfilment of human needs, with consequent beneficial effects on human well-being and performance. Concerns about conserving energy and environmental protection have stimulated interest in the use of daylight as an electric lighting substitute. Conventional windows and atria have only a limited capacity to deliver daylight into the deep-plan buildings that have become the norm. The recent development of new highly efficient optical materials has made possible the ‘daylight guidance technology’ which redirects daylight into areas of buildings that cannot be lit using conventional glazing.

The most commercially successful type of daylight guidance – the passive Tubular Daylight Guidance System (TDGS) – has been sold in large numbers. Although available for the past decade or so, there is still a dearth of knowledge about integration of daylight guidance with electric lighting so as to achieve the full economic and user benefit. Attempts to better deliver daylight and electric light to the same space have led to the recent development of Hybrid Lighting Systems (HLS). These attempt to simultaneously deliver daylight and electric light via luminaire-like output devices.

This paper reviews developments leading towards the hybrid lighting concept. It describes the technology, both conceptual and realised, and sets out likely daylight delivery performance. The main section of the paper is devoted to a feasibility study of the use of TDGS and HLS in a range of locations across Europe. The results are expressed in terms of potential electricity savings.

2. Towards HLS

Vernacular architecture elements have evolved to control and enhance daylight. Over the last fifty years or so, highly efficient optical materials have been developed making possible ‘light guidance’. Hybrid lighting is the most recent development of this idea.

2.1. Daylight guidance

These transfer daylight into buildings using a large number of optical processes over a distance, typically, of some metres. TDGS are the most commercially developed and are passive devices, effective under both clear and overcast skies [1]. Their main application is in single storey buildings. Light transport is usually via a rigid tubular guide lined with a highly reflective material. A clear polycarbonate domed collector at the upper end may be horizontal or inclined at some angle to the guide axis. A diffuser at the lower end distributes light within the building (Figure 1). Façade mounted systems are another approach to guided daylight. The ‘anidolic ceiling’ consists of a light gathering device attached to a façade and oriented toward the equator, a horizontal guide system within a suspended ceiling, and output devices located deep in a building [2]. They are used in conjunction with conventional lower windows and electric lighting systems. The light collector is a curved mirror or

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Figure 1: TDGS collector (left) and output device (right).

other device which deflects daylight into a mirrored guide. This technology is intended for office buildings but only a few systems appear to have advanced beyond the prototype stage.

2.2. Hybrid Lighting Systems (HLS)

The systems described so far have used a variety of methods of delivering daylight into a room which is also equipped with conventional electric systems. Although control systems may regulate the flux output of each, light from the two sources are delivered using separate output components whose optical properties may differ substantially. In ‘hybrid lighting’ daylight is combined with electric light prior to delivery. Optical control is akin to that of an electric luminaire and the two sources may not appear as distinct.

2.2.1 Enhanced tubular daylight guidance

The first developments in HLS lighting were enhancements to tubular daylight guidance systems to attempt to provide light during night hours. These use heliostats, and combine electric and natural light within the light guide rather than at point of use. Heliobus and Arthelio systems may be the most serious attempts in this direction. There are a number of examples of Heliobus system but one suffices to illustrate the principle. Figure 2-A. shows a school which is partially lit using a roof mounted static mirror heliostat which gathers and redirects daylight into a vertical prismatic light guide through three floors. Reflective diffusing extractor foil distributes daylight over the entire surface of the guide to allow each floor to receive similar quantities of light. At dusk or night, three metal halide lamps located at the top of the light pipe are turned on and the light distributed via the guide [3]. The Arthelio study developed systems combining daylight and electric light from sulphur lamps, one case was in a single storey warehouse in Milan [4]. This used a single axis light capture head based on a Fresnel lens. The sunlight is then reflected via an anidolic mirror into a 13m-long, 90cm-diameter circular guide lined with prismatic material. A diffuser unit is located at the end of the guide. Connected to the diffuser unit are two horizontal prismatic light guides powered by dimmable sulphur lamps.

2.2.2 Hybrid Solar Lighting (HSL)

This was developed for public buildings in areas of the USA where direct solar radiation is greater than 4 kWh/m^2/day and cooling is a major design concern. The sunlight collector is a primary 1.22m-diameter parabolic acrylic sun-tracking mirror with an elliptical secondary mirror (see Figure 2-B). The latter separates the visible and infrared portions of sunlight and focuses the visible sunlight into a bundle of 127No 3mm-diameter optical fibres used for transport. The optical fibre system delivers the sunlight to the end of a side emitting acrylic rod located inside a conventional 1.2m x 0.6m electric luminaire also equipped with dimmable fluorescent lamps (see Figure 2-C). A control system tracks the sun; light sensors monitor daylight levels; and electronic dimming ballasts regulate the electric light output to a pre-determined level [5]. A second type of luminaire uses end emission from the fibres and has a light distribution similar to a parabolic reflector lamp. A prototype luminaire incorporating LEDs has also been developed. System losses are of the order of 50% for single-story application with an additional 15-20% for a second storey [6].

2.2.3 Fibre Optic Solar Lighting System (Parans)

Figure 2-D. shows a detail of the roof or façade mounted 1m^2 modular solar panels containing 64No Fresnel lenses [7]. Each lens is able to track and concentrate sunlight into a 0.75mm-diameter optical fibre. Sixteen fibres are combined into a cable each of maximum length 20m. The tracking is controlled by a microprocessor which is continually fed information from a photo-sensor which scans

the sky to detect sun path. The system has five luminaire types, three of which are hybrid luminaires equipped with fluorescent lamps which dim automatically depending on sunlight conditions. Manufacturer's data for an installation with 10m optical cable and direct solar illuminance of 75klux quotes a luminaire flux output of 7500lm and 10000lm for a 4m cable. This corresponds to a system efficiency of around 60% and 80% respectively. The system has optimum collecting hours when the solar panel is within an angle of 120° of the sun.

2.2.4 Solar Canopy Illumination System (SCIS)

This facade mounted system collects sunlight using a grid of thin 16cm square mirrors located inside a weather-proof enclosure [8] (See figure 2-E). On the façade each unit is approximately 3m wide x 1.2m high. This is connected to a 0.25m high duct which extends some 10m into a building. The orientation of the mirrors changes with sun position; and by a series of lenses and mirrors the light is concentrated and redirected into the rectangular cross section guide. Electric light is from fluorescent T5 lamps located inside the guide. The guide inner surfaces are lined with multilayer optical film (MOF) which has high reflectance at all angles, and optical lighting film (OLF) which reflects light preferentially. Sunlight travels along the guide using total internal reflection within the MOF until hits an extractor material made of OLF. This diffusely reflects the light and the portion that no longer meets the angular conditions for total internal reflection exits the guide via the bottom surface (See figure 2-F). The control system uses DALI controlled ballasts, in addition to light sensors, to maintain the desired interior illumination level. A prototype shows that about 25% of flux incident on the mirror array arrives on the workplane extending 10m from the façade [9].

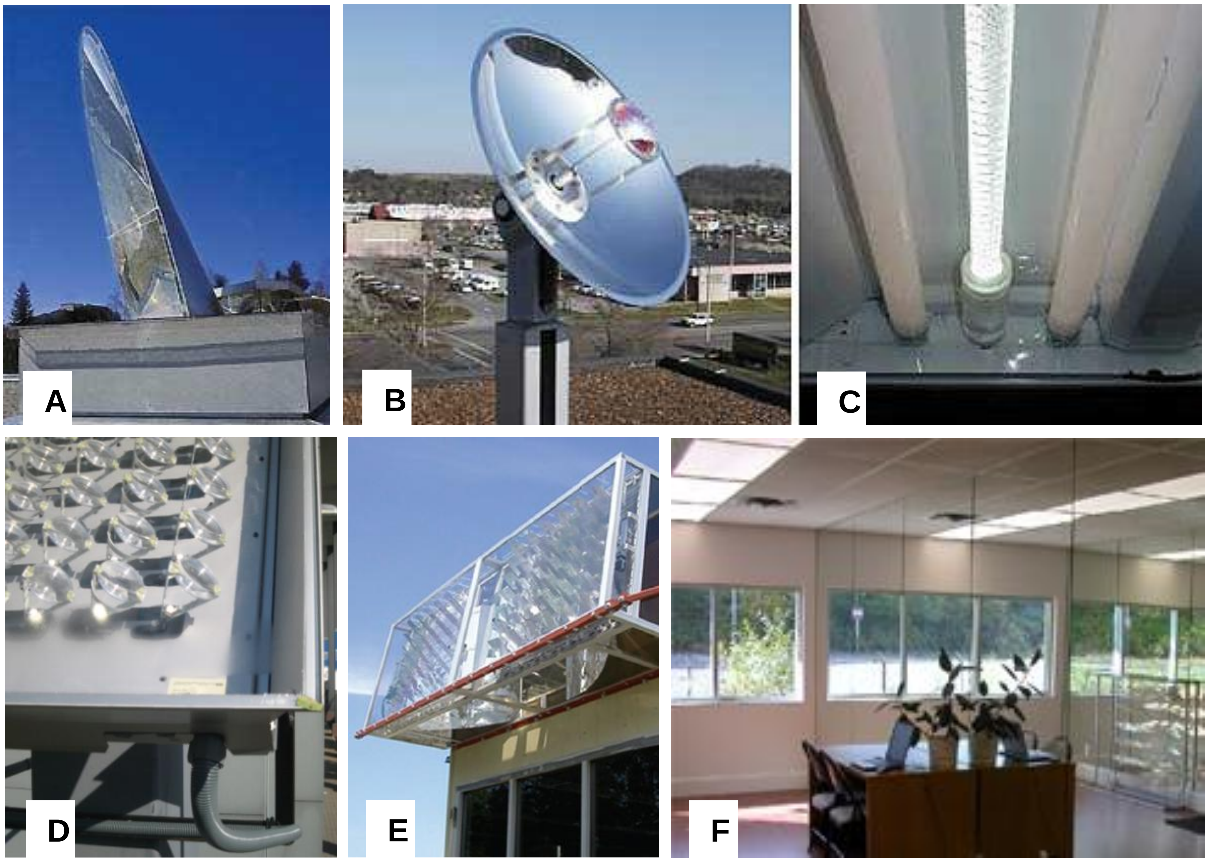

Figure 2: **A**. Heliobus static collecting mirror. **B**. HSL collecting heliostat. **C**. HSL conventional luminaire **D.** Parans collecting solar panel. **D**. SCIS façade mounted collecting canopy. **F.** SCIS output device.

3. Feasibility study

Offices are major employment locations and constitute a large sector of the total building stock. For almost all office buildings working hours coincide with daylight hours. Daylight guidance manufacturers have targeted offices as a potential market in an attempt to satisfy user preference for daylight on visual tasks in working interiors. Also since electric lighting is a major energy consumer in offices and there exists a case for the provision of daylight as a substitute.

3.1. Study parameters

This study examines potential performance of HLS for office applications in terms of both delivered illuminance and energy saving for combinations of building configuration, geographic locations and types of hybrid system.

3.1.1. Choice of locations

The investigation is based on locations which are broadly representative of conditions throughout Europe. The twelve locations include both maritime and continental cities; and latitudes from 60°N to 35°N at intervals of about 5°. Table 1 lists the selected cities, their locations and altitudes, and the frequencies of occurrence of the characteristic sky conditions of the location. Throughout this study working hours were assumed to extend from 08:00 to 18:00.

Table 1: Location details and frequencies of sky conditions.

		Location Conditions			Sky Conditions (%) from 0800 to 1800			
CITY	Country	Lat (°N)	Lon (°E)	Alt (m)	Sun	Intermediate	Overcast	Night
Oslo	Norway	60	11	19	30	36	24	10
S Petersburg	Russia	60	30	5	29	39	22	10
Copenhagen	Denmark	56	13	0	31	35	27	7
Moscow	Russia	56	38	155	29	40	24	7
London	UK	51	0	15	28	39	27	6
Kiev	Ukraine	50	31	169	33	34	27	6
Bordeaux	France	45	1	9	45	34	19	2
Bucharest	Romania	44	26	84	46	30	20	4
Valencia	Spain	39	0	11	70	19	10	1
Athens	Greece	38	24	110	64	22	12	2
Tarifa	Spain	36	6W	0	67	21	9	3
Khania	Greece	36	24	1	66	19	13	2

Source of data in the table: the European database of daylight and solar radiation website [10].

3.1.2. System selection

The review in Section 2 discussed the characteristics of daylight guidance and HLS. The HSL and Parans systems used in this work are developed commercial products that are available on the market. The SCIS has been successfully tested in a prototype facility and the first demonstration system on a real building is being constructed. The various hybrid systems are compared with passive TDGS. The present study has not used enhanced TDGS***;*** each of which is custom-built for an individual application at great capital cost.

3.1.3. Building configuration and system suitability

Lighting needs in office work spaces are well defined [11]. Conventional lighting is by regular arrays of ceiling mounted devices, usually electric luminaires. Contemporary interior design for offices is typically based on modules each containing a number of workstations. This work is based on the lighting of modular spaces of 72m^2 (6mX12m) with the short edge facing south. Interiors of common office layouts can be configured using this module thus (see Figure 3):

- One or multiple modules side-by-side to form a single-storey narrow-plan building of 12m depth.
- One or multiple modules side-by-side forming a multi-storey narrow-plan building.
- Multiple modules in two directions forming a single-storey deep-plan building.
- Multiple modules in two directions forming a multi-storey deep-plan building.

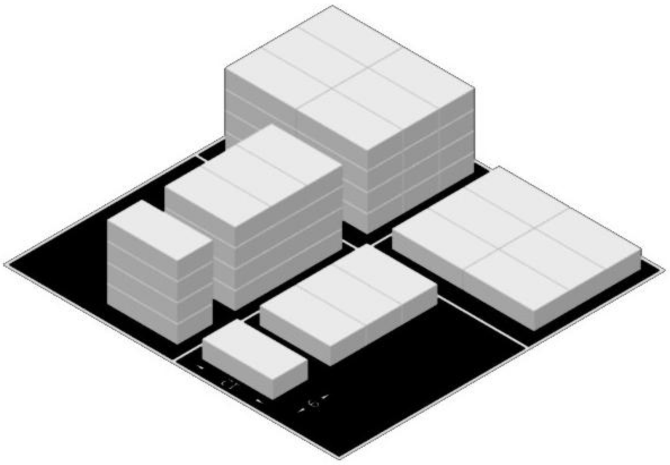

Figure 3: Building form possibilities.

The first two cases are usually lit using combinations of daylight and electric light. The latter two are usually considered to be electric light only due to horizontal and/or vertical distance of the core areas from the building envelope. However the long distances over which light may be transported using HLS means that all of the four configurations may be ‘day-lit’ in some measure.

Both HSL and TDGS require roof mounted collectors. SCIS is an integral part of a building façade having a suitable orientation. The Parans system collectors may be mounted on either roofs or facades. Thus HSL or TDGS are more suitable for first and third cases and SCIS is more suitable for the second cases, Parans is suitable for all cases.

3.2. Lighting delivery and electricity saving calculation methodology

External illuminance for each site has been estimated using the ‘satel-light’ European database of daylight and solar radiation website [10]. Numerical processes have been used to predict the resulting internal illuminance. Finally an estimation of calculation of electricity saving for each system at the various sites has been made.

3.2.1. External illuminance prediction

The total annual sum of global horizontal illuminance gives a useful guide to the external illuminance available. To estimate hours of useful daylight, and hence hours of electric light, the Monthly Mean of Hourly Values (MMHV) for direct and diffused daylight on collectors is required. This is usually a surface orientated and tilted such that the input is maximised. MMHV gives individual monthly average values for each hour throughout the year and more accurately represents daylight hours than using total annual illuminance as the basis of the calculation. The maximum incident illuminance in Europe is usually at an orientation of around due south and at a tilt from the horizontal equal to the latitude of the site minus 20° [12]. Some of the systems collect, and concentrate, direct sunlight but others collect diffuse skylight in addition. HSL and Parans systems with a concentration ratio as high as 1000 effectively distribute only direct sunlight. SCIS with concentration ratio of approximately 10 can distribute considerable amount of diffused illuminance (approximately 10-20%) as well as the direct sunlight component. The various TDGS collect and distribute daylight with no concentration.

3.2.2. Internal illuminance calculation (basic case)

This study assumes a design illuminance of 300 lux on a horizontal working surface 0.8m from the floor. Calculations have been carried out to achieve this level in a windowless modular space of 6m x 12m x 3m high using HSL, Parans, SCIS, TDG or electric lighting systems in turn. Each specification was in accordance with the recommendations of the system developer or manufacturer. In summary these were one HSL system for 90-100m^2; one Parans system for 20-30m^2; one SCIS for 3m x 10m, and one ø350mm TDGS for each ~14m^2. The number of each system to light the 72m^2 modular space was established and then used to calculate the minimum required external illuminance that is essential to provide 300 lux internally. This then allowed a count of the hours (monthly mean of hourly values over the year) which exceed the minimum values to be made, hence determining the percentage of time when daylight will be the sole source of task lighting. This was repeated for each location and lighting system. The same procedure was used to determine the external illuminance values necessary to provide an internal illuminance of less than 25 lux which was considered the threshold for full electrical lighting to be used. In the intermediate range it was assumed that the hybrid devices delivered the available daylight which was supplemented as required to provide the design illuminance. The electric lighting system assumed 1200mm T5/28W fluorescent tubes (mean lumen output 2726 lm). The same tubes were assumed to be used with HSL, SCSI and TDG. The Parans system used 600mm T5/14W fluorescent tubes (mean lumen output 1269 lm).

3.2.3. Calculation of energy saving

To calculate the energy saving for the different lighting systems linked with daylight-sensor/dimmer control, software has been developed which treats the dimming control as a multi-step switch control. The choice of a large number of steps permits a close approximation to the continuous dimming. For present purposes 13 steps are assumed from 300 lux to 0 lux using even 25 lux intervals. For example, if 225 lux will be provided by HLS then automatically 75 lux will be topped up by the electric system. For the 225 lux case, the external illuminance that could provide internal illuminance ≥225 and <250 was calculated. The hours count will then determine the percentage of the assumed total annual working hours where this will be the case. The electrical consumption to provide 75 lux for this period was then determined. This is repeated for the 13 steps. Summing the electricity consumed in each of the thirteen steps and dividing by the electricity consumption to provide 300 lux illuminance gives the annual percentage electricity saving assuming the daylight linked system had been used.

3.2.4. Calculation of illuminance received by an active HLS

Active daylight systems track the sun to maximise input. Simulation of this process is complicated by the fact that daylight data is normally only available as discrete values for particular orientations. Four methods of simulating the daylight collected by the tracking process were tested using software and data for Bordeaux. In the first method the collector system was assumed to be passive and oriented near the optimum angle (25° from horizontal, 180° from North). The monthly mean value was 250.8 klux. Secondly the system was assumed to rotate horizontally to collect sun at angles 135°, 180° and 225° from North, corresponding to early morning, noon and late afternoon. The monthly mean value was 282.3 klux. In the third attempt, the system ‘rotated’ horizontally 13 times from angle 90° to 270° from North with interval angle 15°. Using the most favourable annual mean of hourly values summed gave monthly mean values of 287.9klux. Finally, for the same thirteen angles, using the most favourable monthly mean of hourly values collected over a year the result gave a monthly mean value of 288.8klux. The differences between the last three cases and the first one are consequently 12.6%, 14.8% and 15.2%. This study used the second method because it yielded satisfactory results without the considerable amounts of manual data manipulation necessary in the third and fourth methods. It should be noted that all methods assumed tracking with only one axis.

3.2.5. Internal illuminance calculation for deep-plan case

The deep-plan case assumed a one storey building consisting of an array of 2 x 2 modules. Since HSL, Parans and TDG are roof-mounted systems the calculation process will be the same as the basic case. The SCIS system, being façade-mounted, will have a limited use since it will not be able to efficiently redirect daylight beyond the first row of modules (>12m depth). It is assumed that the second row of modules will be electrically lit.

3.2.6. Internal illuminance calculation for multi-storey case

The multi-storey cases assume a four storey building. Each consists of only one module so that the total area of these cases will be similar to that previously. The SCIS is part of a façade but the Parans collectors can be located on a suitably orientated façade, or roof-mounted. In this work it is assumed that the top storey is supplied from the roof and the rest from façade-mounted collectors. The HSL and TDGS may be roof-mounted only and thus light transport losses will notably increase from the upper- to lower-storeys.

4. Results

Table 1 suggests that around one third of working hours have direct sun in Northern (N) latitudes and about two thirds in the Southern (S) locations. Similarly the proportion of night plus overcast skies is around one third in the N and one eighth in the S. The upshot of this is that the annual mean daylight illuminance doubles between N to S extremes. The effects of longitude on daylight conditions are by comparison small with the exception of some maritime locations.

Table 2 illustrates that for all systems the calculated potential energy savings roughly double from N to S although there are large differences between the systems. As would be expected the proportion of time that systems operate with daylight providing all workplane illuminance increases from N to S. In the S the daylight replaces the majority of the lighting electrical load (see Figure 4). In N latitudes TDGS, the most optically simple system, produces savings of comparable magnitude to that of the heliostat systems – the former by collecting light from both sky and sun, and the latter by efficiently

Table 2: Potential energy savings and percentage of time with full daylight and full electric lighting.

	Type of system											
	TGDS			HSL			Parans			SCIS		
	Save%	%DL	%EL	Save%	%DL	%EL	Save%	%DL	%EL	Save%	%DL	%EL
Oslo	28	0	25	40	0	20	31	0	22	50	36	25
S P’sburg	31	0	25	50	22	21	42	12	21	53	41	26
C’hagen	32	0	17	49	7	12	38	0	15	59	40	17
Moscow	33	0	18	47	7	14	37	0	15	56	38	18
London	31	0	13	36	0	12	26	0	13	54	27	13
Kiev	39	1	13	55	20	8	46	13	10	66	47	13
Bordeaux	45	0	8	61	22	7	51	6	7	72	58	8
Bucharest	49	12	8	68	42	7	61	31	8	77	61	8
Valencia	56	16	6	73	45	5	66	37	5	80	70	6
Athens	55	15	4	69	36	4	61	28	4	80	65	4
Tarifa	60	26	5	76	54	4	70	45	5	81	73	5
Khania	61	16	4	76	48	2	70	44	3	85	75	4

making use of available low elevation sunlight. In the S high angle sunlight is collected by TDGS to compensate for reduced skylight but there is a marked fall-off in energy saving performance relative to the heliostat systems. The SCIS has the best performance of the systems investigated. It should be noted that SCIS has the largest collector and diffuser areas of all the systems. HSL performs best of the two heliostat based systems. This may be due to differences in light losses between the mirror based HSL and the lenses that form the Parans collector.

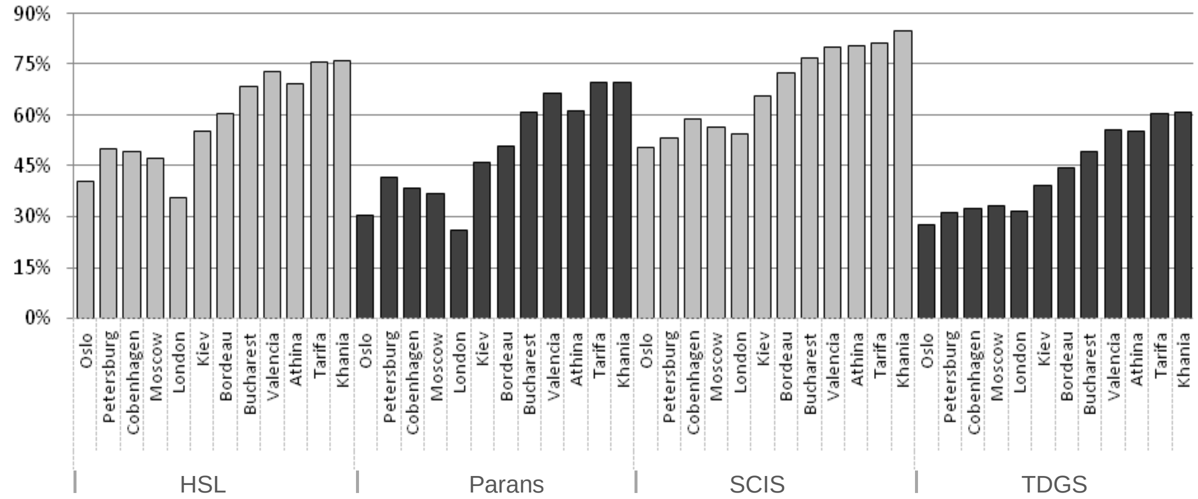

Figure 4: Electric lighting load saving.

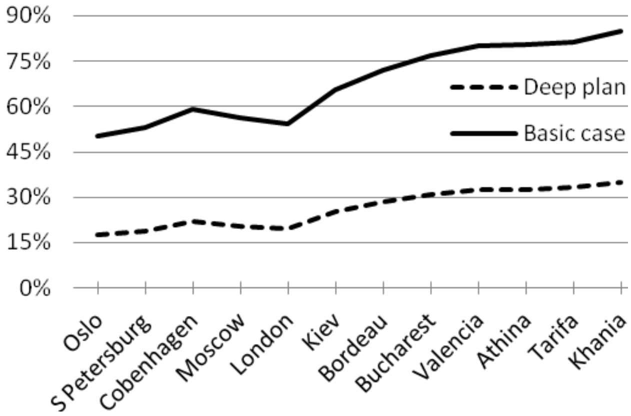

Figure 5: The difference between SCIS electricity saving in the basic case and deep-plan one-storey case.

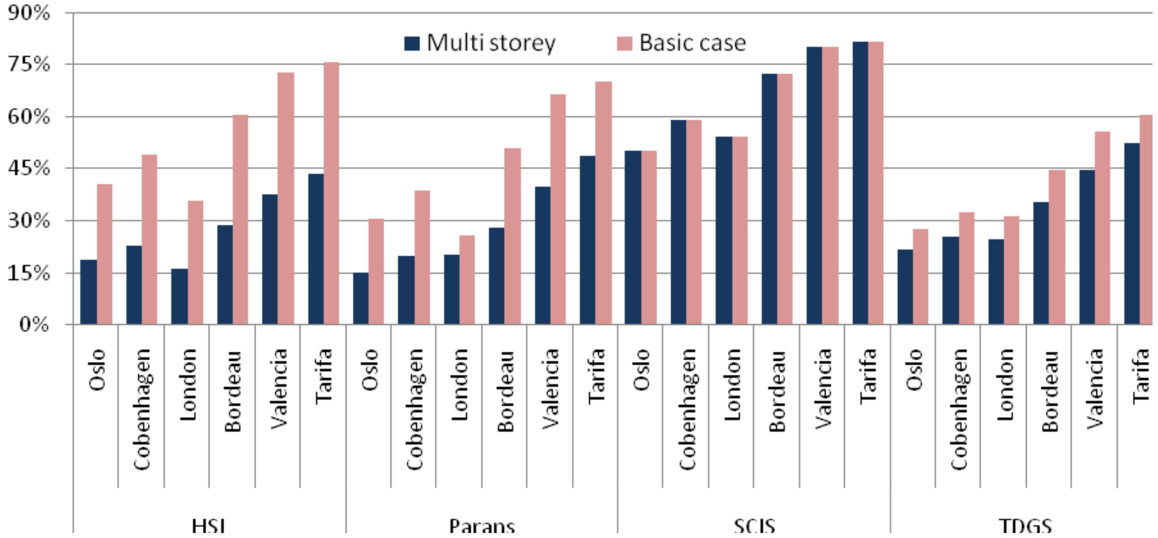

Figure 6: Comparison between the basic case and the second case.

A comparison of results between London and the Russian and Ukrainian cities offer some insight into the relative performance of systems in maritime and continental climates. London has the lowest sun hours and the highest cloud hours. By comparison Kiev – at similar latitude – has a similar number of cloud hours but more sun, with the effect that all systems, but particularly the hybrids, show marked increases in energy savings. St Petersburg, which is at higher latitude has similar hours of sun but less cloud. Despite this the heliostat based systems perform much better in the more northern city. The hybrids also perform better in St Petersburg in comparison with Oslo which is at similar latitude. However there is less difference in the performance between TDGS and SCIS both of which collect skylight and sunlight. There is some evidence of the influence of longitude on performance in more southerly latitudes (cf Bordeaux and Bucharest) but generally any differences are of a smaller magnitude than in the north.

Comparison of results between the basic case and the deep-plan one-storey case show no differences when HSL, Parans or TDGS are used since all are roof mounted systems. Being façade mounted the ability of SCIS to send daylight deep into a building is limited. Figure 5 illustrates that the efficiency – expressed in electricity saving - falls by almost two thirds of its value.

On the other hand, when multi-storey narrow plan is compared with the basic case, SCIS is the only system to remain unaltered. The efficiency of HSL and Parans was reduced by around half, while that of TDGS by around one fifth (see Figure 6).

5. Discussion

It is apparent that there is a considerable variation in performance as a function of both system type and geographic location. This means that choice of appropriate light guidance system may have differing impacts on light delivery and consequent energy usage in diverse locations. The energy savings quoted in this work at first sight appear large and constitute a major argument for hybrid system use. However other factors such as, for example, the relationship of the various systems to the buildings in which they are housed, capital and running costs, user expectations of lighting, and the effects of legislation, mean that savings must be viewed as part of a wider cost/benefit analysis rather than in isolation. Since hybrid lighting is new technology there are a several unknowns. The capital costs include not only of the systems but also the cost of adapting a building to take them. Thus those systems that use optical fibre transport will generally be cheaper in this respect than TDGS and SCIS which require large dedicated ducts which may also have implications for the fire performance of the building. Some of the systems provide light via 'luminaires' and user reaction to these – specifically whether they provide 'daylight', and hence the benefits of daylight – is not known. Most hybrid systems have been developed for sunlight sources but are now being marketed in locations where other sky types predominate. The same sequence of events occurred with TDGS and the full implications, in terms of requirements in other locations, are only just being appreciated. This work represents a first step in this process.

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