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A feasibility study for hybrid lighting systems

Mohammed Mayhoub [a,b], David Carter [a,*]

[a] University of Liverpool, School of Architecture, Liverpool L69 3BX, United Kingdom
[b] Al-Azhar University, Cairo, Egypt

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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 is described together and that of the more established of tubular daylight guidance lighting systems. Likely system performance in terms of daylight delivery and potential electricity savings are evaluated for representative geographic locations throughout the world. The results indicate a considerable variation in performance as a function of system type, geographic location, and building geometry, suggesting that choice of appropriate light guidance system may be strongly influenced by the solar resource at the building location.

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 forms that have become the norm for many types of commercial buildings. The recent development of new highly efficient optical materials has made possible the ‘daylight guidance technology’ which permits redirection of daylight into areas of buildings that cannot be lit using conventional glazing.

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. The most commercially successful type of daylight guidance – the passive Tubular Daylight Guidance System (TDGS) – has been sold in large numbers worldwide but is marketed mainly as devices to deliver solely daylight. Attempts to better deliver daylight and electric light to the same space have led to the recent development of Hybrid Lighting Systems (HLS). These systems attempt to simultaneously deliver daylight and electric light via luminaire-like output devices.

This study examines potential light delivery and energy savings in commercial buildings by the use of HLS and, for comparison purposes, TDGS. These technologies are briefly described. Results are expressed as likely usage patterns (the proportions of daylight, electric and hybrid lighting used) for combinations of building configuration, geographic location and types of daylight delivery system. The considerable variation in performance as a function of building geometry, geographic location and system type and suggests that choice of appropriate light guidance system may be strongly influenced by building location.

2. Study parameters

Previous work by the authors in 2009 indicated that daylight guidance systems potentially offered large energy savings when used in office buildings [1]. That work was based on the guidance technology, both conceptual and realised, that was current at that time, and on a limited range of geographic locations solely in Europe. Development of the technology has resulted in the demise of some of the systems promulgated in 2009 and the commercial development of others. This work investigates the potential performance of currently commercially available light guidance systems for a wide range of geographic locations and climatic types.

* Corresponding author. Tel.: +44 151 794 2622.
E-mail address: eb09@liverpool.ac.uk (D. Carter).

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2.1. Choice of locations

The investigation is based on locations which are broadly representative of conditions throughout Europe, Africa and the Middle East. The 26 selected locations include both maritime and continental cities and latitudes from the Equator to 60 °N at intervals of about 5°. They cover four main climatic regions according to Köppen-Geiger climate classification; tropical, arid, temperate, and cold climates [2]. Table 1 lists the selected cities, their locations and climatic regions.

2.2. Light guidance systems

HLS attempt to simultaneously deliver daylight and electric lighting to an interior space. In these systems, the light collector tracks the sun path, concentrates sunlight, and channels light via optical fibres or high reflective guides into the core of a building where it is combined with electric light within luminaires. TDGS comprise a clear polycarbonate domed light collector that accepts sunlight and skylight from the whole sky, a light transport tube lined with highly reflective silvered or prismatic material, and a diffuser to distribute light in an interior. HLS are equipped with controls that maximise use of available daylight. Similarly good practice for TDGS configures the associated electric lighting system control to supplement available daylight as necessary. Although TDGS have been available commercially for over a decade, only three HLS are on the market. These are: Hybrid Solar Lighting (HSL) (Fig. 1A), Parans system (Fig. 1B), and Solar Canopy Illuminance System (SCIS) (Fig. 1C) [3]. Generic TDGS are shown in Fig. 1D. The characteristic collector mounting positions, light transport routes and luminaire locations are illustrated in Fig. 1E.

2.3. Data sources

Two sources of data were used, both web-based. The *SoDa* solar radiation data website was used as the source of irradiation data, from which external illuminance data was produced using the concept of luminous efficacy [4]. This site covers an area from −66° to 66° both in latitude and longitude. The MIDC SOLPOS application was used for calculating solar position [5]. Global, diffused and direct data on horizontal surface and on surfaces tracking the sun at normal incidence were obtained from the two data sets.

Table 1
Location details and climatic regions.

Climatic region		Time zone (+UTC)	Location: City	Country	Lat. (N°)	Long. (E°)
Cold, fully humid	Df	1	Oslo	Norway	59.91	10.75
		3	Petersburg	Russia	59.89	30.26
		1	Copenhagen	Denmark	55.66	12.58
		3	Moscow	Russia	55.75	37.61
Temperate, fully humid	Cf	0	London	UK	51.50	−0.11
Cold, fully humid	Df	2	Kiev	Ukraine	50.43	30.51
Temperate, fully humid	Cf	1	Bordeaux	France	44.83	−0.56
Cold, fully humid	Df	2	Bucharest	Romania	44.43	26.10
Arid steppe	BS	1	Valencia	Spain	39.46	−0.36
Temperate, summer dry	Cs	2	Athens	Greece	37.98	23.73
Temperate, summer dry	Cs	1	Tarifa	Spain	36.01	−5.60
		2	Khania	Greece	35.51	24.01
Arid steppe	BS	0	Agadir	Morocco	30.40	−9.60
Arid desert	BW	2	Cairo	Egypt	30.05	31.25
		1	Reggane	Algeria	26.70	0.16
		3	Riyadh	KSA	24.64	46.77
		0	Atar	Mauritania	20.51	−13.05
		4	Hayma	Oman	19.93	56.31
Arid steppe	BS	0	Dakar	Senegal	14.67	−17.43
Arid desert	BW	2	Al Khartoum	Sudan	15.58	32.53
Tropical, winter dry	Aw	1	Koumra	Chad	9.25	18.20
Arid steppe	BS	3	Harare	Ethiopia	9.31	42.11
Tropical, fully humid	Af	0	Fishtown	Liberia	5.19	−7.87
Tropical, winter dry	Aw	2	Juba	Sudan	4.85	31.61
Tropical, monsoon	Am	1	Libreville	Gabon	0.38	9.75
Tropical, fully humid	Af	1	Kisangani	Congo, D.R.	0.85	29.36

2.4. Building configuration and system suitability

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 a case exists for the provision of daylight as a substitute. Throughout this study office working hours were assumed to extend from 08:00 to 18:00. Lighting needs in office work spaces are well defined with electric lighting usually delivered via regular arrays of ceiling mounted luminaires [6]. Daylight guidance output devices are also ceiling mounted usually in an array compatible with that of the electric luminaires. Contemporary interior design for offices is centred on the needs of individual workstations which are typically 3 m × 3 m. This work is based on modules of 72 m^2 (6 m × 12 m) each containing space for up to 8 individual workstations. The modules are oriented with short edge facing south. The rationale of this is that the modules can be used to represent a typical 12 m wide UK office building with glazing on both sides and, by combination of these modules, a variety of configuration of single- and multi-storey buildings as detailed below (see Fig. 2):

- One or multiple modules side-by-side to form a single-storey narrow-plan building of 12 m depth (the ‘basic case’).
- 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.

The basic case and the second case 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 light guidance means that all of the four configurations may be ‘day-lit’ in some measure.

Fig. 1E shows that 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. Lighting delivery and electricity saving calculation methodology

For each site external illuminance data was obtained and numerical processes subsequently used to predict the resulting internal illuminance delivered by the guidance system. Finally an estimation of electricity savings for each combination of system, building configuration and location was made.

3.1. External illuminance prediction

The total annual sum of global horizontal illuminance gives a guide to the external illuminance available at a particular location. A more accurate estimation of hours of useful daylight, and hence potential burning hours of electric light, requires values of external illuminance over shorter time periods. A series of 10-min average external illuminance, throughout an entire year, for direct normal (DN) and global horizontal (GH) illuminance was used in this work. Of the 52,000 values a year available some 22,000 over the assumed annual working hours were used as the basis of the calculation. Using the 10-min average values daylight guidance system performance can be simulated numerically.

The *SoDa* website provides 10-min DN and GH irradiation averages for the 26 locations for the year 2005. These were converted into their photopic equivalents using the sun position values obtained from SOLPOS, and the universal luminous efficacy model developed by Mayhoub and Carter [7]. The 2005 annual irradiation values were compared with the 21-year irradiation averages (1985–2005) (see Table 2). It can be seen that in most locations the 2005 values were below the 21-year average, and the implications of this will be explored later.

It is also evident that peak irradiance values at around 10 °–15 °N latitude are up to 2.5 times those in the Northern latitudes. This is important since some of the systems collect, and concentrate, direct sunlight only, whilst others additionally collect small amounts of diffuse skylight. The high-concentrating systems, HSL and Parans, effectively distribute only direct sunlight. SCIS with concentration ratio of approximately 10 can distribute some diffused illuminance (providing internal illuminance of the order of 30 lux) in addition to the direct sunlight component [8]. TDGS collect and distribute daylight with no concentration.

3.2. Internal illuminance calculation (basic case)

This study assumes a design average illuminance of 300 lux on a horizontal working surface 0.8 m from the floor. Calculations were carried out to achieve this level in a windowless modular space of 6 m × 12 m × 3 m 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 there was one HSL system for 90–100 m^2; one Parans system for 20–30 m^2; one SCIS for 3 m × 12 m, and one ø300 mm TDGS for each ~10 m^2. The number of each system to light the 72 m^2 modular space was established as follows:

- One HSL collector supplying eight luminaires via approximately 7 m-long fibre optic cables.
- Four Parans solar panels supplying eight luminaires via approximately 3 m-long fibre optic cables.
- Two SCIS with 0.6 m-wide and 12 m-long dual function light duct.
- Eight 300mmø TDGS equipped with a 1.2 m guide and one elbow.

The internal planar illuminance delivered was calculated using the lumen method every 10 min for each location and lighting system.

3.3. Calculation of energy saving

Supplementary electric lighting system is not used if daylight provides more than the 300 lux design level. Below this average level, supplementary electric lighting controlled by light sensors and a continuous dimming system is assumed to top up the delivered daylight to 300 lux average. The electric lighting systems are designed to provide all of the 300 lux if daylight contributes less than 50 lux. The electric load is calculated every 10 min and the annual consumption summed. This is compared with the annual consumption for 100% electric lighting to estimate the saving in electric loads.

The electric lighting system is assumed to use 1200 mm T5/28 W fluorescent lamps (mean lumen output 2726 lm – the numerical average of three manufacturers quoted values). Luminaires having an assumed Utilisation Factor of 0.59 were used, chosen to replicate as closely as possible with those of the HSL system. The characteristic low UF is due to the conflicting demands of accommodating both daylight and electric lighting in the same output device, with the result that both systems are sib-optimal. The lamps described above were assumed to be used as integral parts of the HSL and SCIS hybrid systems and as the parallel system for TDGS. The Parans system used 600 mm T5/14 W fluorescent tubes (mean lumen output 1269 lm). In the absence of any data for hybrid systems in use a maintenance factor of unity was assumed in the calculation. The small parasitic power consumption for all of the hybrid systems was ignored in this work since it was very small in relation to total electrical load.

3.4. Usage pattern identification

A count of the 10-min average internal illuminance values that exceeded the design level allowed the determination of the percentage of time when daylight was the sole task lighting source. Similarly, a count of values less than 50 lux represented the percentage of working hours when electric light was the sole source. The hybrid devices were assumed to be used in the intermediate range with available daylight supplemented as required by the electric system.

3.5. Internal illuminance calculation for multi-storey case

The multi-storey cases assume a high-rise building. Calculations were made for one module only so that the total floor area considered was similar to the basic case. The second and fourth storeys from top of the building were investigated. The configuration of the various guidance systems differ with building configuration. The SCIS are assumed to be located on a south facing façade and thus will have a similar performance on all storeys in the absence of external obstruction. Parans collectors can be located on a southerly orientated façade, or be roof-mounted. In this work the shortest light transport routes are assumed and thus the second floor from top is supplied from both facade and roof collectors. The fourth floor from top is entirely supplied from façade-mounted Parans collectors. HSL and TDGS both use roof-mounted collectors. In both light transport losses will increase steeply with travel distance from roof to lower-storeys. TDGS would normally be not applicable for the fourth floor from the top because of the light loss over that distance and the practical and economic difficulties of accommodating the light guidance devices in the building.

3.6. Internal illuminance calculation for deep-plan case

The deep-plan case assumed a one storey building consisting of an array of 2 × 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 (>12 m depth). It is assumed that the second row of modules will be electrically lit.

4. Results

4.1. Relationship between external illuminance and latitude

Fig. 3 shows the relationship between latitude and DN and GH average external illuminance respectively over the assumed

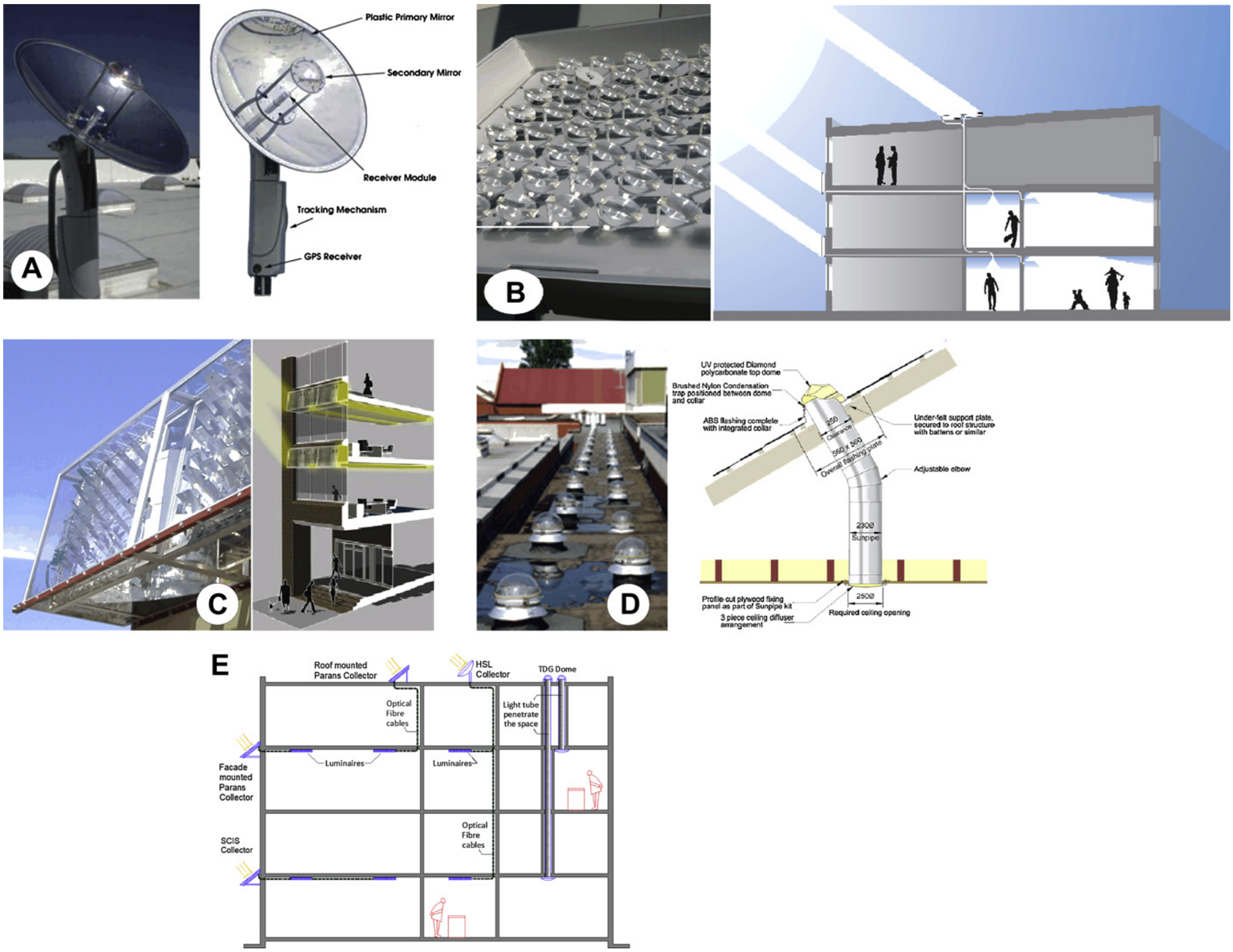

Fig. 1. A: HSL collector, B: Parans collector, C: SCIS collector, D: TDG domes, E: Hybrid systems summary.

working hours. Third degree polynomial curves define the relationships that show the external illuminance peak occurring between 10 °N and 15 °N. The coefficient of determination (R^2) indicator for DN and GH illuminance is 0.84 and 0.96 respectively.

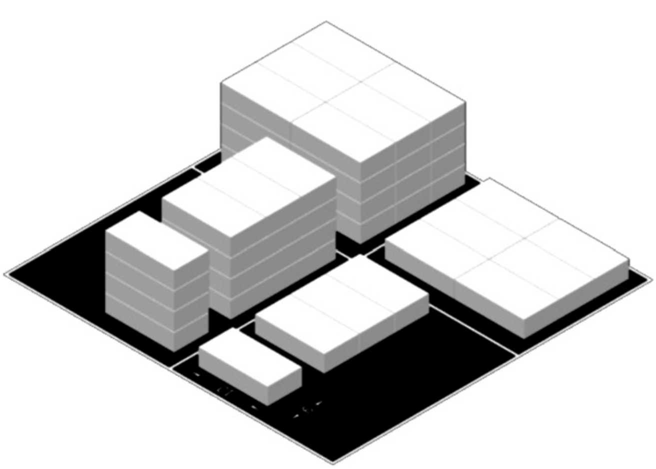

Fig. 2. Building form possibilities.

The outliers in Fig. 3A occur mainly in tropical regions (e.g. Fish-Town), where there is a combination of high values of solar radiation and a high probability of clouds. Similarly London (51.50 °N) and Tarifa (36 °N) are other outliers. In these cases these locations are very cloudy, and very sunny, respectively in comparison with other cities at similar latitudes.

4.2. Relationship between external illuminance and climatic region

Fig. 4 illustrates both DN and GH external illuminance, over the assumed working hours, for the different climatic regions. In terms of GH illuminance tropical and arid regions, not surprisingly, have the highest values with an average of 61 klux, followed by the temperate region with an average of 44 klux and the cold region at 32 klux.However in terms of DN illuminance, the arid region comes first with an average of 54 klux, with tropical, temperate and the cold regions having averages of 48, 37 and 26 klux respectively. A big variation in both illuminance components can be seen in the temperate region where, for example, the GH and DN values in London are 46% and 29% of the comparable values in Tarifa.

The DN illuminance, expressed as a proportion of the global normal (GN) illuminance over the assumed working hours, is shown in Fig. 5. The highest values, as expected, are in the arid

Table 2
Annual and 2005 averages of DN. and GH. Irradiance, and the differences from the averages.

Location	DN. (W/m^2)		Difference from Ave. (%)			GH. (W/m^2)		Difference from Ave. (%)		
City	Annual Ave.	2005 Ave.	Actual Diff.	Min Diff.	Max Diff.	Annual Ave.	2005 Ave.	Actual Diff.	Min Diff.	Max Diff.
Oslo	109	97	−11	−23	32	115	109	−6	−13	20
Petersburg	96	107	11	−22	19	115	119	3	−9	10
Copenhagen	114	116	2	−22	18	131	130	−1	−13	11
Moscow	121	101	−17	−22	43	129	121	−6	−12	21
London	84	76	−9	−27	48	121	112	−7	−14	29
Kiev	135	130	−3	−16	24	149	147	−1	−7	10
Bordeaux	138	138	0	−20	30	163	163	0	−9	13
Bucharest	175	163	−7	−15	10	185	174	−6	−6	6
Valencia	187	180	−4	−10	12	197	194	−1	−5	5
Athens	155	148	−5	−11	14	185	181	−2	−6	8
Tarifa	238	243	2	−6	10	226	229	1	−3	4
Khania	175	175	0	−9	11	198	199	1	−4	5
Agadir	216	212	−2	−8	16	228	226	−1	−4	6
Cairo	196	195	−1	−16	19	222	222	0	−6	6
Reggane	225	220	−2	−8	11	242	242	0	−3	4
Riyadh	212	207	−2	−24	24	237	234	−1	−9	8
Atar	237	231	−3	−22	14	258	253	−2	−7	5
Hayma	214	210	−2	−27	29	243	242	0	−9	9
Dakar	226	210	−7	−7	9	257	246	−4	−4	4
Al Khartoum	264	262	−1	−5	6	274	272	−1	−2	2
Komura	241	233	−3	−7	8	263	260	−1	−3	4
Harare	283	273	−4	−8	7	288	285	−1	−3	3
Fishtown	178	161	−10	−12	29	237	226	−5	−5	11
Juba	232	225	−3	−11	9	262	259	−1	−4	4
Libreville	177	165	−7	−13	24	238	228	−4	−4	9
Kisangani	213	215	1	−14	15	257	255	−1	−4	6

region with average of 72%. The tropical, temperate and cold regions have averages of 68%, 65% and 64% respectively. The tropical and temperate regions show big variations among the different locations. The explanation for this is that both arid and cold regions have relatively dominant and stable sky conditions over the whole geographic area in contrast to those in the tropical and temperate regions. Systems based on sun-tracking collectors would be expected to perform better in locations where this proportion is the highest.

4.3. *Electric saving in the basic case*

The relative importance of DN and GN depends on nature of the particular guidance system. The HSL system has a capability to track the sun and thus collects DN illuminance for the whole sun path. The most common configuration for passive TDGS collects GH illuminance from both sky and sun on a horizontal roof. In a minority of TDGS installations the collectors may be tilted, usually towards the Equator, so as to maximize the benefits of low elevation sunlight. Both Parans and SICS collectors, even when oriented towards the equator, are unable to cover the whole diurnal sun-path since their arrays of sun tracking elements are located in fixed enclosures and may be mutually shading. For both systems the tracking limit % (T), the percentage of total diurnal sun-path actually tracked was calculated.

4.3.1. *The relationship between electric saving and external illuminance*

The relationship between electric saving due to the utilization of a HSL system and the DN external illuminance is the positive linear relationship as illustrated in Fig. 6A. A similar relationship exists for TDGS savings and the GH illuminance (see Fig. 6B). In both cases the more illuminance available, the more the savings. The relationship between Parans and SCIS electric saving and DN illuminance cannot be as simply explained (see Fig. 6C & D). For both, the illuminance gathered, and hence energy saving, is influenced by the tracking limits, which are themselves latitude dependant. Fig. 7 shows the near linear relationship between the tracking limit and latitude.

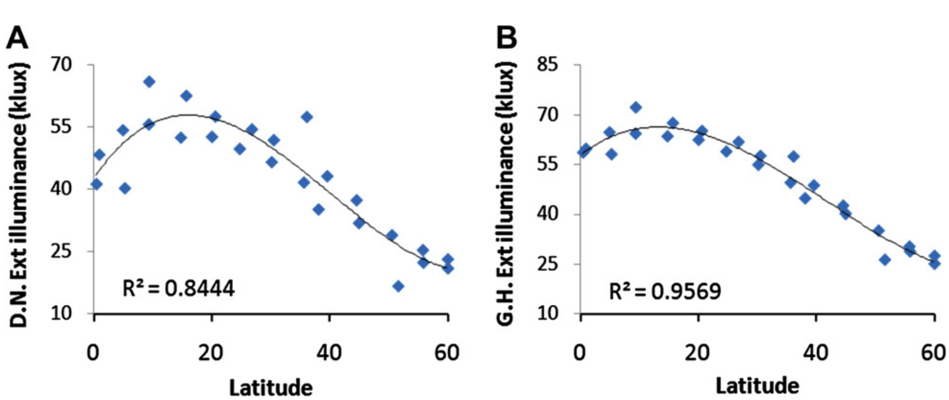

Fig. 3. A (*Left*): Relationship between direct normal (D.N.) external illuminance and latitude over the assumed working hours, B (*Right*): Relationship between global horizontal (G.H.) external illuminance and latitude over the assumed working hours.

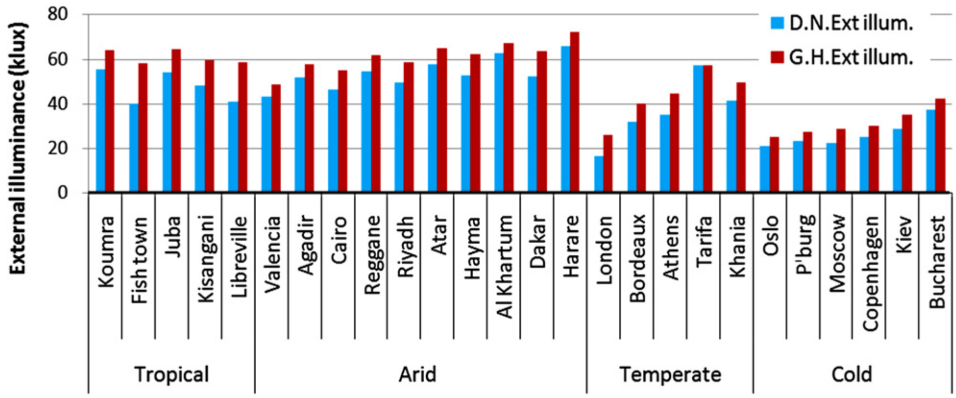

Fig. 4. DN and GH external illuminance over the assumed working hours for the different climatic regions.

Fig. 8A & B suggest that for both Parans and SCIS the energy savings are functions of the product of the DN illuminance value and the tracking limit percentage, *T* factor. This relationship in both cases is near linear.

4.3.2. Electric saving amounts

Fig. 9 plots the percentage electric saving for the basic case system configuration. It is clear that TDGS achieved the biggest savings over almost all locations (average 55%), followed by SCIS (39%), HSL (33%) and Parans (31%). SCIS and TDGS have similar savings in the Northern locations. However TDGS was far superior in Southern locations because of the limited coverage of the SCIS tracking systems of between one- and two-thirds the working hours in latitudes lower than 30 °N. The two high-concentrating systems, HSL and Parans had similar saving magnitudes but with Parans being slightly superior in the Northern locations and vice versa.

4.3.3. Electric saving trends

The third degree polynomial relationship between the DN illuminance and the latitude (Fig. 3A), and the linear relationship between the DN illuminance and the HSL electric saving (Fig. 6A) suggests that a third degree polynomial relationship also exists between HSL electric saving and latitude. The same logic applies to the relationship between the TDGS and the latitude and this is plotted in Fig. 10A. It is apparent that some locations, notably London, Tarifa and Fishtown are outliers for reasons stated earlier. The maximum savings for both systems are achieved between 10 °N and 15 °N, and the minimum in the extreme Northern locations.

Fig. 8 revealed that the electric savings for both Parans and SCIS were influenced by the tracking factor. Fig. 10B plots the load savings for the two systems against tracking factor and latitude. It is apparent that the largest savings occur between 15 °N and 40 °N. In this region the DN illuminance is more than 40 klux and tracking covers between 47 and 77% of the working hours. Lower savings are achieved in the very high and very low latitudes. At high latitudes the tracking limits are as high as 88%, but DN illuminance may be as low as 22 klux. At lower latitudes DN illuminance may be up to 50 klux but the tracking is limited to less than 40% of working hours.

4.4. Usage pattern in the basic case

Large variations in usage patterns are apparent between the different systems, and at the various locations using the same system. These are related to the variations in external illuminance amounts and type. Fig. 11 shows that HSL failed to deliver a fully day-lit interior for any location, but achieved the highest hybrid lighting usage mean of 61%. The SCIS with mean of 33% achieved the best wholly daylight delivery, although this did not lead to the largest electric saving. This was achieved by the TDGS which had the lowest full electric lighting usage at 22%.

Fig. 12 shows usage patterns and electric savings for the four systems. Fig. 12A suggests that HSL electric savings track the proportion of full electric lighting. Fig. 12B shows that although Parans electric saving also are strongly influenced by electric lighting usage, there are big variations in both full daylight and hybrid lighting usage. This is caused by the characteristics of the tracking system described earlier. For example, although Koumra

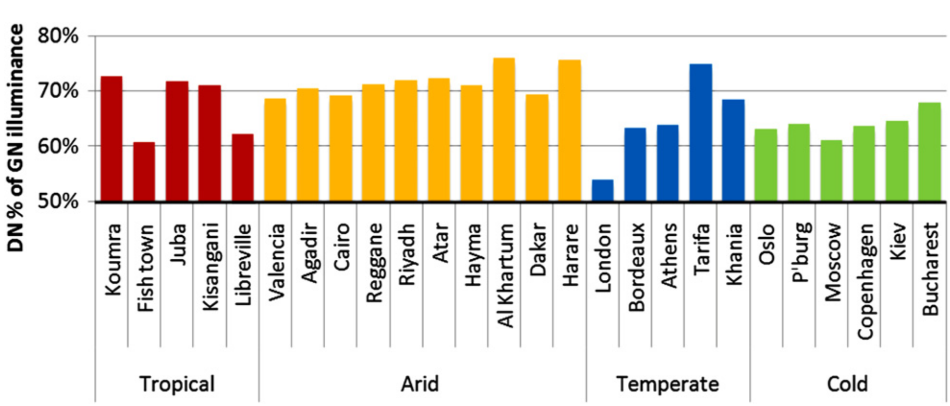

Fig. 5. DN illuminance expressed as a proportion of GN illuminance over the assumed working hours.

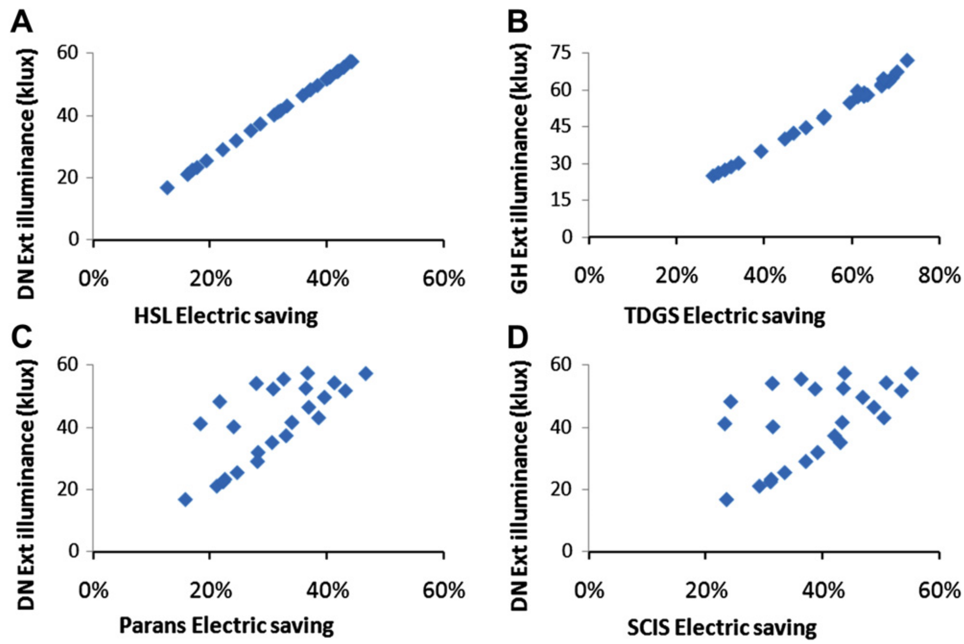

Fig. 6. A (*top left*): HSL saving, B (*top right*): TDGS saving, C (*bottom left*): Parans saving, D (*bottom right*): SCIS saving.

and Dakar have similar savings, they have 19% and 2% full daylight usage respectively. The most notable feature of the SCIS usage patterns shown in Fig. 12C is the small proportion of hybrid usage. This is as low as 4% in some locations. In Fig. 12D the influence of all of the usage pattern components on TDGS electric savings is evident. The high overall levels of electric saving are strongly influenced by the remarkably low full electric lighting usage, with values as low as 10% in many locations.

4.5. Multi-storey influence

The configuration of the assumed multi-storey building was described in Section 3.5. SCIS is a facade mounted system and thus has the same performance as the basic case in multi-storey application. The performance of the other systems is influenced, to a greater or lesser extent, by the building configuration. The HSL system has increased losses due to the additional lengths of guide necessary to transport daylight; resulting in a significant increase in energy usage. The mean electric savings over all geographic locations for the second and fourth storeys were 20% and 13% respectively, compared with 33% for the basic case. However the savings trends were almost identical to that of the basic case illustrated in Fig. 10A. The actual saving amounts over the most locations are around 60% and 40% of the basic case for the second and fourth storeys respectively. For TDGS, the mean electric saving in the second storey dropped to 42% compared with 55% in the basic case. The savings trend is similar to that of the basic case, and the saving amounts range between 72% and 81% of the basic case.

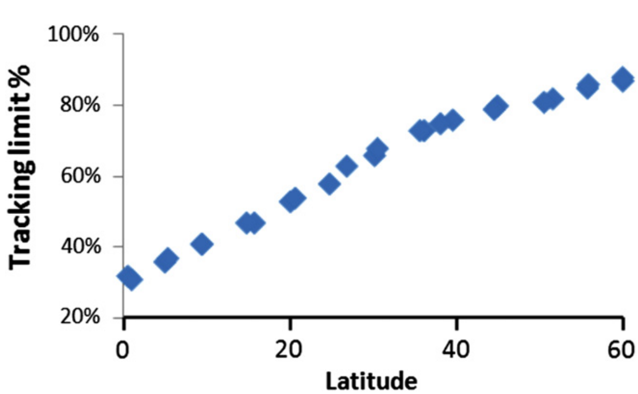

Fig. 7. The relationship between the tracking limits and the latitude.

The use of the Parans system in multi-storey configurations is a special case because of the location of its collectors. The second storey was supplied with daylight from both facade and roof with two facade mounted solar collectors linked to the four luminaires next to the external wall, and another two roof mounted collectors linked to the other four luminaires. On the fourth storey, only facade attached collectors are used necessitating four different cable lengths for each row of four luminaires. These arrangements minimised light transport distances and hence light losses. This resulted in mean electric savings of 28% and 27% in the second and fourth storeys respectively compared with 31% for the basic case. Saving trends are very similar to that of the basic case, and the saving amounts are around 90% and 86% for the second and fourth storeys respectively (see Fig. 13).

4.6. Deep-plan influence

Since HSL, Parans and TDGS are roof mounted systems no changes would occur in their electric savings or usage patterns when used in deep plan. The SCIS saving is half that of the basic case since the building depth is doubled and the current arrangement of the SCIS allows for only 12 m of efficient daylight transport. However for this system an increase in the height of the light guide would allow longer daylight travel distance and/or decreased light losses.

5. Discussion

5.1. Deviation from the electric savings trend

There are a number of locations where the electric saving amount is at variance with the general trend. There are three possible explanations for this:

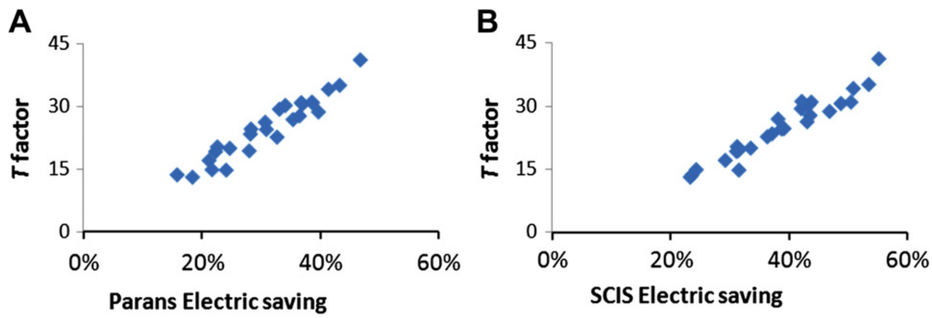

Fig. 8. The relationship between electric saving and the DN illuminance X the tracking limit (*T* factor), A (*left*): Parans saving, B (*right*): SCIS saving.

The first is local daylight conditions. London, for example, has more clouds than the other temperate location studied, and indeed has the lowest proportion of DN illuminance among all locations studied (54% over the working hours). The next lowest location had 61% and the average over all locations is 68%. Table 3 compares the electric saving for all the systems for London and Kiev. Note that the latter has similar latitude but its GN illuminance is 65% of average. The Table shows that the predicted daylight internal illuminance, and the enhanced GN values for Kiev have a clear influence on load saving. A further influence on light collection amounts is the local occurrence of atmospheric dust. This has not been included in this study but this could under some circumstances be a major influence, particularly in arid latitudes.

A second consideration is the effect of differences between the 2005 irradiance values and the 21-year average. In Fishtown, for example, the minimum difference over 21 years between the DN irradiance values and the average is −12%, and that for GH irradiance is −5%. The actual differences for 2005 are −10% and −5% respectively (see Table 2). If the 10-min irradiance values for 2005 were normalized to the average, the savings were increased by 3.3%, 1.8%, 0.5% and 2.1% for HSL, Parans, SCIS and TDGS respectively. Although there was not a perfect match with the trend curve for Fishtown the points were much closer to that curve. Other influences were sky conditions. Fishtown's GH irradiance in 2005 is 87% of that for Juba which has similar latitude. A similar normalisation exercise for DN irradiance shows that for Fishtown has only 72% that of Juba. This explains the large difference between the HSL saving and the trend curve, and the small difference in the TDGS case (see Fig. 10).

The third possible explanation for these deviations relates to inconsistencies between the local time zone of the location's country and the supposed time zone for the location's latitude. For example, although St Petersburg, Kiev, Cairo, Al Khartum, Juba and Kisangani are all approximately at longitude 30 °E, the local time zones vary; for St Petersburg is UTC+3; Kisangani is UTC+1, and the rest are UTC+2. This made more difference in some locations than others. In St Petersburg the original estimated savings for HSL, Parans, SCIS and TDGS were a maximum of 0.6% more than the revised values. However the original values in Kisangani were respectively 3.2, 1.6, 2.1 and 5.3% less than the revised figures, which explain some of the variation. Many locations on the other hand may have the same local time despite a big difference in the longitudes (e.g. Tarifa (6 °W) and Kisangani (29 °E)) and this would also result in unrealistic comparisons if not accounted for.

5.2. Variation in usage patterns

Variation in usage patterns is apparent in installations which have similar electric savings, or geographical locations. This is most apparent in the proportions of full daylight and hybrid lighting with the Parans system, but is also the case for the others to a lesser extent. Using a Parans system, Koumra and Dakar achieved similar savings although the full daylighting proportions are 19% and 2% respectively. Table 4 shows predicted internal illuminance distributions for both locations. The main difference is that Koumra has some 20% of values greater than 300 lux whereas Dakar has 12% more values in the 250–300 lux range, where minimal electric lighting contribution is required. London and Kiev have similar latitudes but using HSL hybrid lighting was 27% and 42% respectively. Similarly for Juba and Fishtown, 35% and 20% full daylighting was delivered when the TDGS was used. It is thus clear that the internal lit environment created may be very different for systems designed if the sole criteria are minimising energy.

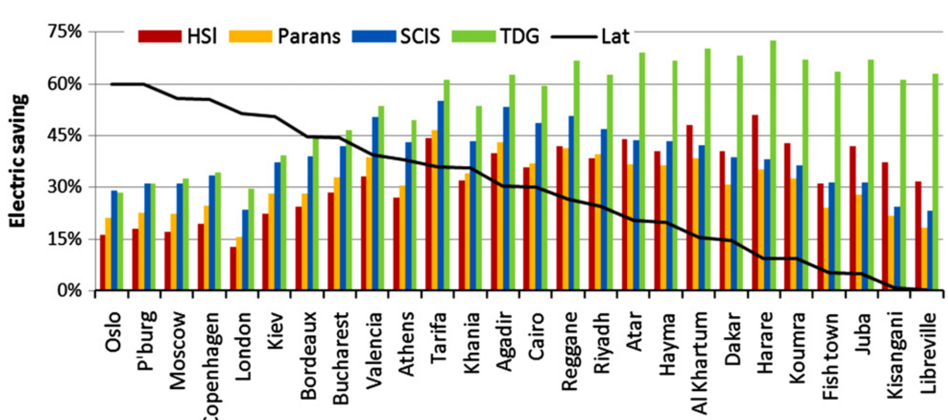

Fig. 9. The percentage electric saving for the basic case system configurations.

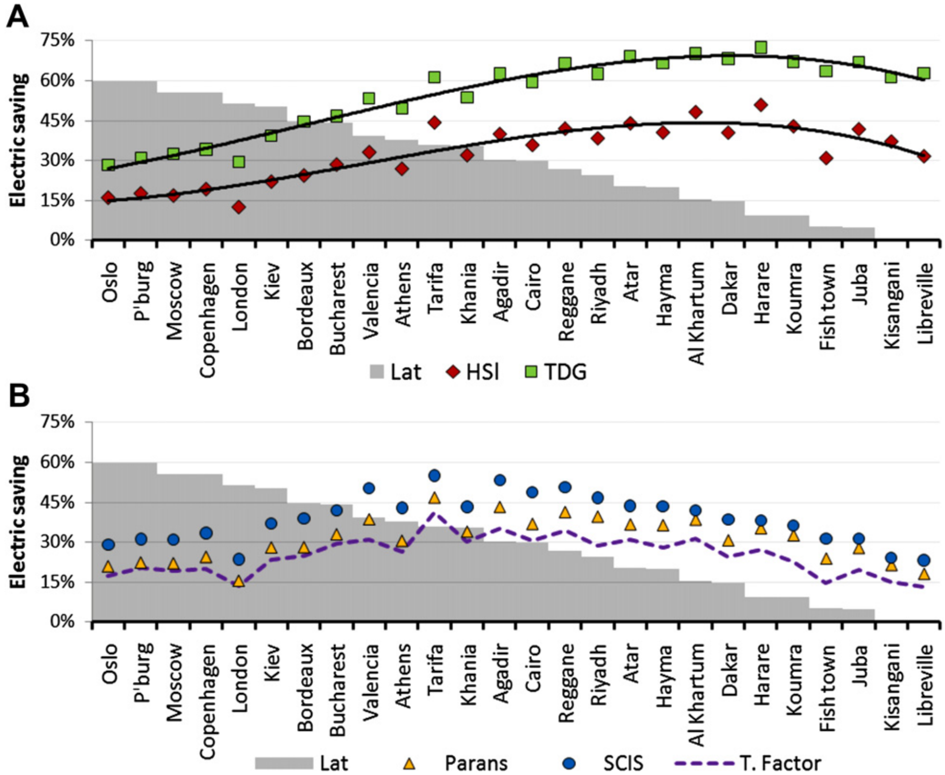

Fig. 10. Relationship between electric saving and latitude, A (*Top*): for HSL and TDGS, B (*Bottom*): for Parans and SCIS.

5.3. The influence of tracking limits

The light collection process using both Parans and SCIS is governed by the limitations of their tracking coverage, and this result in the loss of some potential daylight. Fig. 14A compares electric savings using Parans acknowledging both the limitations of its existing tracking system and those of possible savings assuming a sun tracking system for the whole duration of working hours. The mean saving in the first case is 31% rising to 48% in the second. The modified tracking has a small influence in northern latitudes. Further south there is a much bigger effect, for example in Libreville the existing tracking arrangements produce savings of 39% of the revised system. Although full daylight proportions using the two methods were identical in 10 locations, in the rest the modified system was superior in this respect. Overall the mean full daylight proportion rose from 10% in the first case to 14% in the second.

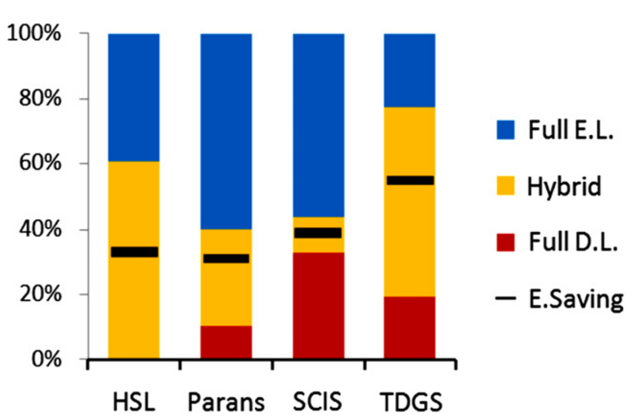

Fig. 11. Mean usage pattern and electric savings.

A similar pattern using for SCIS is evident (Fig. 14B). The mean full daylight proportion rose from 33% in the first case to 52% in the second, giving mean electric saving of 39% and 62% respectively.

5.4. The influence of building geometry

In multi-storey buildings roof mounted hybrid systems are able to deliver significant amounts of daylight for the topmost storeys. The limiting factor in the use of daylight guidance is the distance over which useful quantities of light can be transported from collector to output device. This is up to 20 m for most of the currently available systems. Facade mounted hybrid systems may be used for lower floors of multi-storey buildings as long as the collector can be suitably oriented. The large diameter of the guide components for roof mounted TDGS required limit their application in multi-storey building. Current practice is for two storeys to be the limit.

For low-rise deep-plan buildings, the performance of roof mounted hybrid systems is similar to that of the basic case, since collectors may be installed close to the luminaires so as to minimize daylight travel distance. Facade mounted systems are presently only able to deliver significant amounts of daylight to areas adjacent to the facade. This is 12 m currently for SCIS, and deeper into the building electric lighting systems will be dominant. Bigger SCIS light guides would enable more daylight to be delivered but at the expense of increased floor height and/or the necessity to re-route other services networks.

5.5. Limitations of the work

Any work of this nature has a number of limitations. The lighting design calculation method used in this work is a version of the familiar lumen method. More sophisticated methods, such a EN

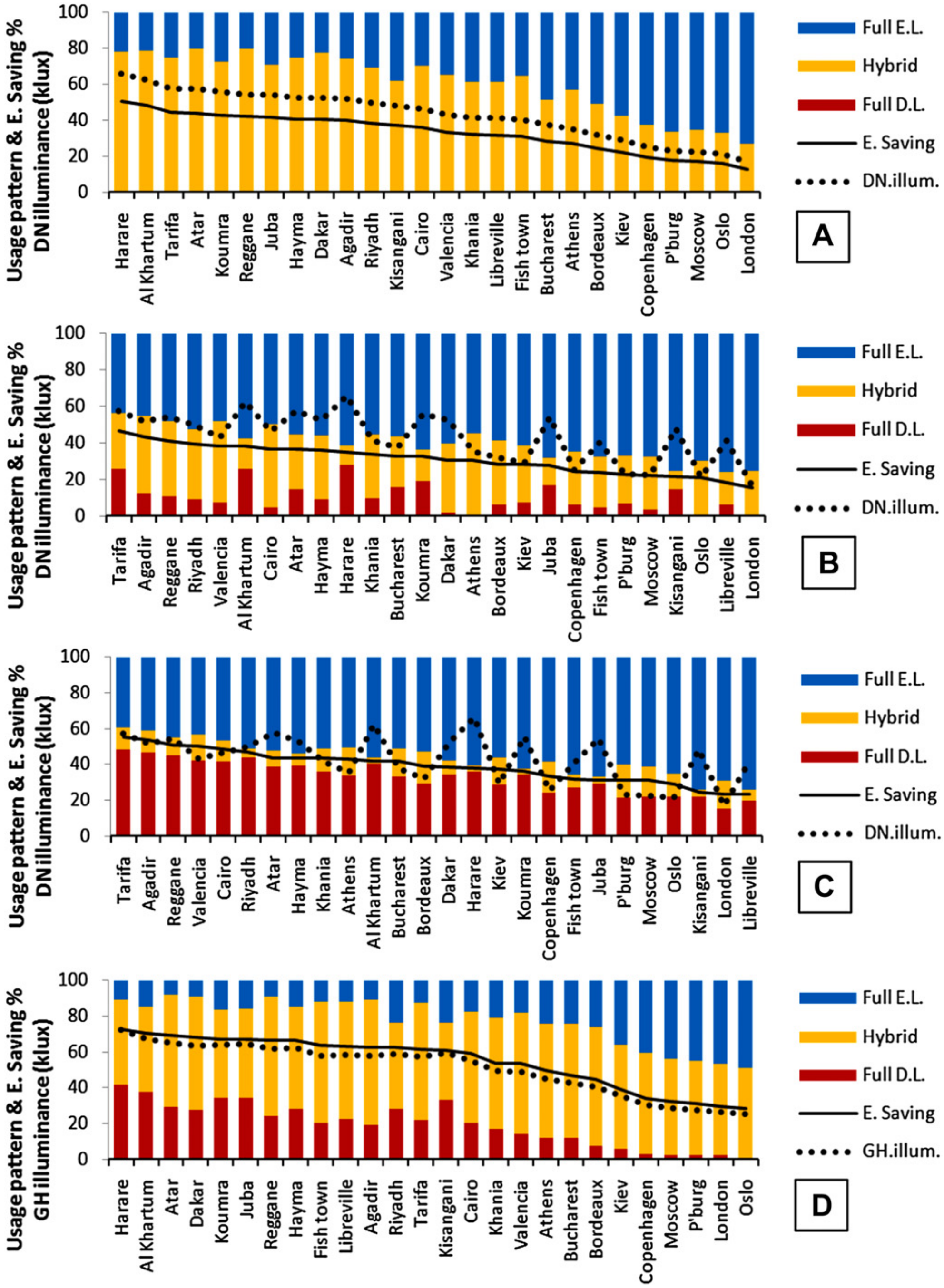

Fig. 12. Usage pattern and electric saving of… A: the HSL, B: Parans system, C: the SCIS, D: the TDGS.

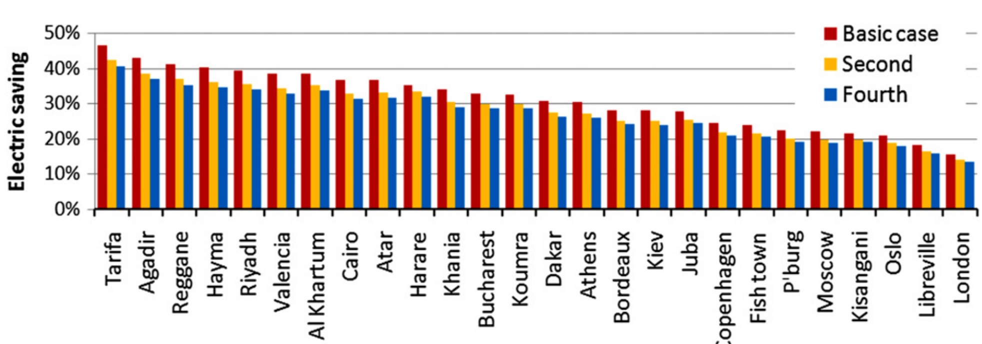

Fig. 13. Comparison between Parans electric saving in the basic case and in the multi-storey cases.

Table 3
Electric saving and illuminance distribution for London and Kiev.

Internal illuminance (X) ranges	Ranges percentages of working hours (%)															
	HSL				Parans				SCIS				TDGS			
	London		Kiev		London		Kiev		London		Kiev		London		Kiev	
X ≤ 50		73		58		75		61		69		56		46		36
50 < X ≤ 100	9	27	10	42	6	24	6	31	5	15	5	15	18	51	16	59
100 < X ≤ 150	8		10		4		5		3		3		11		12	
150 < X ≤ 200	9		15		4		5		2		3		10		10	
200 < X ≤ 250	1		8		4		6		2		2		8		11	
250 < X ≤ 300	0		0		6		10		2		2		5		9	
300 < X		0		0		1		7		15		29		2		6
Electric saving	12.7%		22.2%		15.7%		28.1%		23.6%		37.1%		29.6%		39.3%	

Table 4
Parans electric saving and illuminance distribution for Koumra and Dakar.

Internal illuminance (X) ranges	Ranges (%) of working hours			
	Koumra		Dakar	
X ≤ 50		63		60
50 < X ≤ 100	1	17	3	38
100 < X ≤ 150	1		3	
150 < X ≤ 200	2		5	
200 < X ≤ 250	4		7	
250 < X ≤ 300	8		20	
300 < X		19		2
Electric saving	32.6%		30.8%	

15193, could have been used for calculations relating to the electric and conventional daylight systems in this work. The absence of reliable and comprehensive photometric data for hybrid systems however preclude their use in this work. It is to be hoped that as hybrid systems mature the use of more sophisticated calculation method becomes possible.

A restricted number of internal configurations of buildings have been used, all of which are assumed to be offices. The light guidance equipment used is the best that is currently available and the collection, transport and internal light distribution efficiencies are those that apply now. TDGS is a mature technology and little further major development is likely. Some technical progress might increase the performance of hybrid systems but the laws of physics will inevitably limit this to incremental advances. Development to increase limits of the amount of sky tracked by the non-heliostat based systems such as Parans and SCIS may be the most promising area. In this regard work is required not simply to increase the range of movement of the tracking mirrors but also to address the problems of the mirrors mutually blocking sunlight and, in the case of those with overall glass protective covers, the reflection of sunlight at glancing angles.

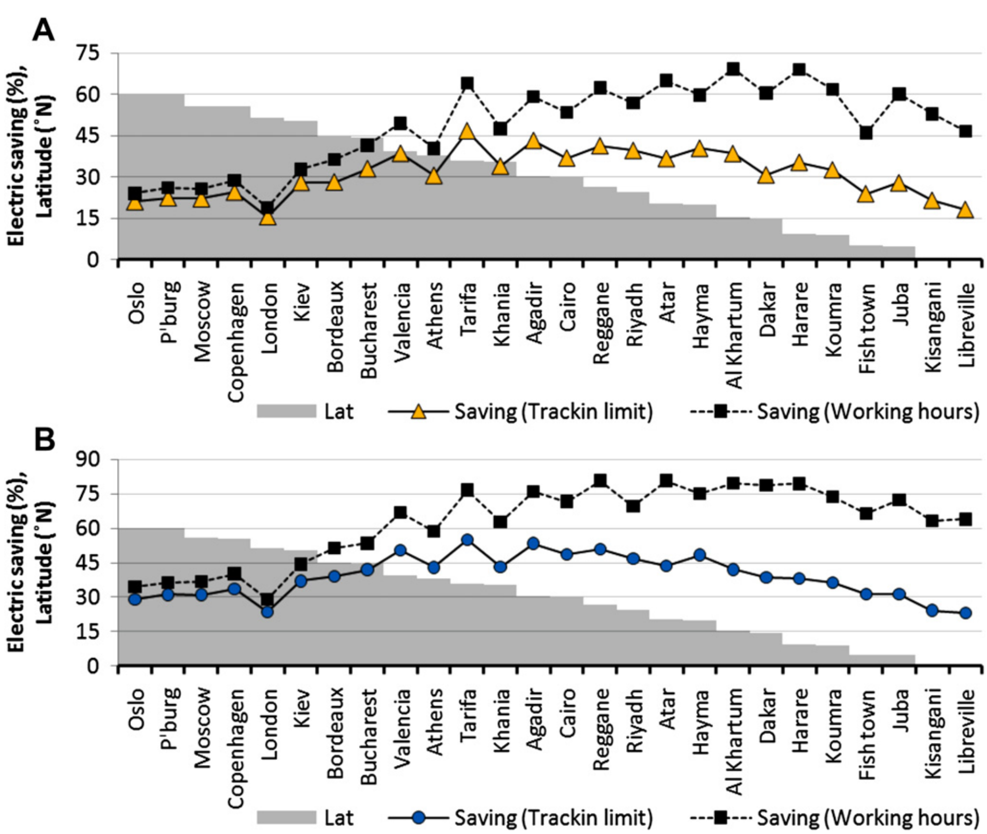

Fig. 14. Comparison between saving over the tracking limit, and over the entire working hours, A: Parans system, B: the SCIS.

There are other aspects of the wide geographic spread of the assumed locations in this study that have not been included in this work. The most important of these are the thermal properties of the guidance devices. Good optical design, and the use of dichotic materials, ensures that the majority of infra-red radiation is rejected by sun-tracking systems before entering the building. However work published by CIE suggests that TDGS could act as conduits of both heat loss and solar gain [9].

The results of this work are in terms of electric savings relative to the electric lighting only case. The savings in absolute terms would be higher with increases in cost of electricity and the more attractive the systems would become economically. The wider question of the long term economics of the various systems has been addressed in other paper in this Journal [10].

6. Conclusion

It is clear that building geometry has a major influence on the choice of light guidance system. Some systems, notably SCIS, have limitations on the distance from a facade over which daylight can be transported. A similar limitation applies for vertical distances with TDGS. It also clear that the reverse is true – that some systems make demands on form and layout of the building as a prerequisite to their successful use. SCIS imposes at least a minimum floor to ceiling and a worst almost dictates that the building be built around the system. The use of TDGS in multi-storey application requires duct space which occupies potentially useful floor area. The optical fibre transport based systems make far less demands on internal building space but do, of course, require a suitable roof to mount the collection system. They also lend themselves better to changes necessary to cope with change of building use and thus could be seen to contribute to flexibility of building use.

The relationship of external illuminance and latitude was examined and the results offer information to enable an informed choice of guidance system for location. The magnitude of GH illuminance is of importance for devices like TDGS that collect from the whole sky. On the other hand the DN illuminance modified for tracking factor is of major importance to sun-tracking systems. This value peaks between 15 °N and 40 °N and for this reason these types of system are less effective in producing electric savings in both equatorial areas and northern latitudes.

Generally, TDGS gives the best electric savings throughout and is far superior for locations near the equator. All of the systems except HSL are to be capable of providing all of the necessary internal illuminance by daylight. Since the specification for HLS used in this work is that recommended by the manufacturer if might be that this advice requires revisiting. The usage patterns are a major factor in the magnitude of electric savings but also have another significance. The marketing for guidance systems all emphasise the beneficial effects of the delivered daylight. However for these benefits to be real the ‘daylight’ element must be recognised by building’s users. Work on TDGS suggests that perception of ‘daylight’ depends on both the amount and the nature of the output devices inside the building [11], but no similar work has yet been done on hybrid systems. It would be useful for designers to know at which point in the usage pattern a particular system is perceived to deliver ‘daylight’.

It is apparent that there is a considerable variation in performance as a function of system type, geographic location, and building geometry. This means that choice of appropriate light guidance system may have differing impacts on light delivery and consequent electric saving and usage pattern in diverse locations.

In this study an overall rank order of systems by achieved electric savings over all locations would have TDGS at the top followed by SCIS, HSL and Parans. The latter two were markedly inferior in terms of electric saving but HSL performed relatively better than Parans in the Southern locations and vice versa. This is an important conclusion because it suggests that the mature but relatively unsophisticated TDGS technology performs generally better than the hybrid systems. The latter are complicated pieces of optical engineering and for many applications have the capital and running costs greater than TDGS [10]. The assumed system configurations in this work were in accordance with manufacturers’ recommendations and current practice. It is clear that there is scope for the ranking to be changed by future development in light collection or guidance technology, both of which would have a major impact on the amount of useful daylight delivered.

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