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Towards hybrid lighting systems: A review

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This paper reviews developments in hybrid light guidance systems. In these daylight and electric light are simultaneously delivered into a building where they are combined and distributed via luminaires. The technology used in hybrid systems, both conceptual and realised, is discussed. The review speculates as to their likely performance in terms of daylight delivery; capital and running costs; user reaction to the systems; potential impact of the systems on the building which they light; and suitable design methods. It is noted that a substantial amount of work remains before the potential of hybrid systems may be realised, notably on their long-term economics and feasibility in different geographic locations.

1. Introduction

Electric lighting is dominant in the majority of modern buildings. It offers the designer the opportunity to create an attractive and economic lit interior within any building configuration. Since electric lighting is a major energy consumer there is a case for the provision of daylight as a substitute. Also, research has confirmed user preference for daylight in working interiors, which has implications for user satisfaction and well-being. Taken together this makes the provision of daylight, or at least the perception of daylight, a powerful design aspiration for modern commercial buildings.

In vernacular architecture elements evolved to reflect, re-direct or control daylight. Conventional glazed windows can provide daylight some 5 m into a building. But since daylight levels decrease asymptotically with distance from the window, a disproportionate amount of daylight and associated heat gain must be introduced into the front of a room to provide small amounts of daylight at the rear. Attempts to direct daylight to areas remote from the building envelope using techniques such as atriums and skylights are limited in effectiveness by contemporary technology. Over the last 50 years or so, a number of highly efficient reflective and refractive materials have been developed making possible what has become known as 'light guidance'. Light from both daylight and electric sources may be guided. Both have a common characteristic that the light path from source to receiver may undergo a large number of optical processes over a distance, typically, of some metres. It is this feature that sets the systems described in this paper apart from conventional lighting techniques in which distance from source to point of use is kept to a minimum. There are two main categories of guided daylight. Beam daylighting – the redirection of sunlight by adding reflective or refracting elements to conventional windows – essentially enhances traditional devices such as louvres or light

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shelves using the new optical materials. The second, and most widely used, type is known as Tubular Daylight Guidance Systems (TDGS). This introduces daylight deep into electrically lit buildings, although current practice is to use the electric and daylight systems separately with minimal interaction (Table 1).

Attempts to better combine the delivery of daylight and electric light to the same space use two main approaches – ‘integrated lighting’ and ‘hybrid lighting’. Their main characteristics are summarised in Table 1. Integrated lighting uses separate daylight and electric lighting systems (the daylight being either conventional or guided) but with adjacent output devices and a linked control system. Hybrid Lighting Systems (HLS) attempt to simultaneously deliver daylight and electric lighting to an interior space. In these systems, daylight is channelled into the core of a building where it is combined with electric light within luminaires that are equipped with controls that maximise the use of available daylight. Optical control is thus similar to a luminaire rather than the simple diffusers used in the more basic daylight guidance systems. Unlike the mass market TDGS, integrated and hybrid systems are, with few exceptions, custom made for special applications.

This paper reviews developments leading towards the hybrid concept and describes a number of systems, realised or otherwise. It speculates about likely issues of system performance, costs, user response, building relationship and design methods. Gaps in existing knowledge are identified and suggestions for future work made.

2. System descriptions

Unless otherwise stated the performance and other data quoted in this section are from the sources cited.

2.1 Daylight guidance

Although TDGS are the only form of guidance having wide commercial application, a number of other types, notable because their technology has been adapted

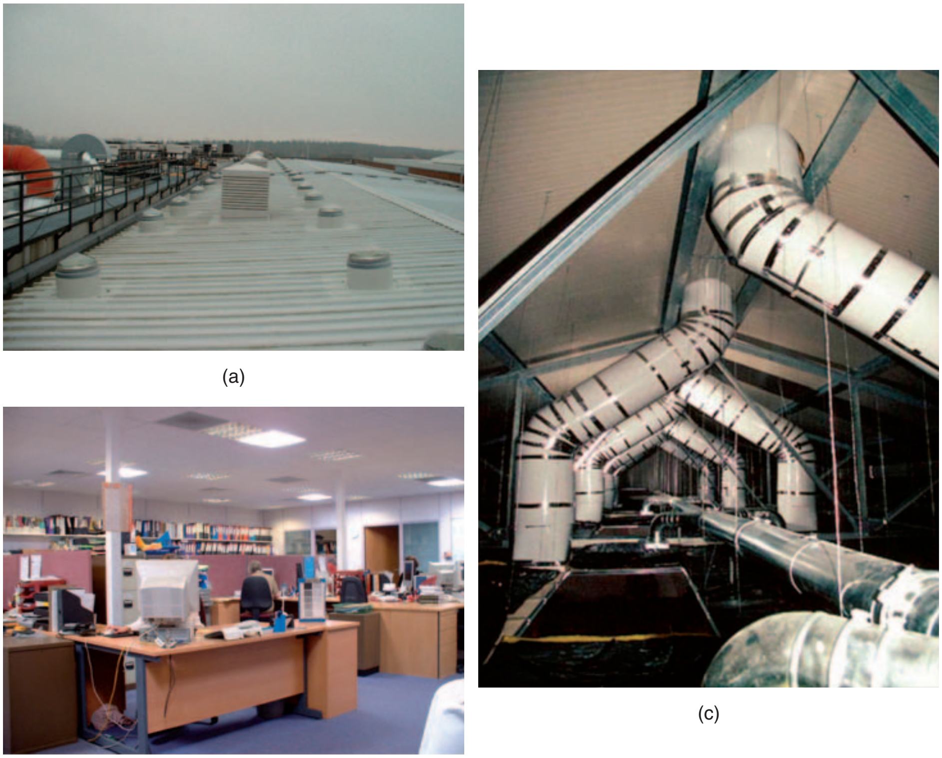
Table 1 System characteristics

	Tubular daylight guidance	Integrated lighting	Hybrid lighting
Daylight sources	Skylight and sunlight	Skylight and sunlight	Sunlight
Daylight delivery	Tubular daylight guidance	Conventional glazing, beam daylighting or tubular daylight guidance	Tubular daylight guidance
Electric lighting	Conventional luminaires at point of use	Electric light may be guided as supplement to daylight.	Electric light may be guided.
Method of use	Separate daylight and electric lighting	Uses daylight as main source automatically supplemented by electric light as required.	
Control system	Usually no daylight linking	Fully daylight linked	
Output device	Separate daylight output devices and electric luminaires	Separate output devices for daylight and electric light. Electric lighting may be ‘intelligent’.	One output device is used for both lighting sources.
Quality of delivered light	Optical control of daylight by diffuser and electric light by luminaire. Source colour differences apparent	Optical control of daylight depends on particular system. Electric light control by luminaire. Source colour differences apparent	Optical control of all light by luminaire. Single source colour.

for use in integrated and hybrid systems, are also reviewed in this section.

2.1.1 *Tubular daylight guidance systems*

TDGS are simple passive devices, cheap to manufacture, and effective under both clear and overcast skies. 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). TDGS have been the subject of considerable research, some of which is germane to this review. CIE Report 173 discusses system characteristics and selection and sets out standard photometry and design/analysis methods.[1] Using these it is possible to estimate likely flux outputs, system efficiencies and daylight distributions of TDGS under a variety of sky conditions. The CIE Report puts forward the Daylight Penetration Factor (DPF) to quantify daylight penetration via light guidance devices. This is analogous to the Daylight Factor (DF) used for conventional glazing. Whilst DF is the illuminance received at a point indoors expressed as a percentage of the exterior skylight illuminance, the DPF is the illuminance received at a point indoors via a light guide expressed as a percentage of the global exterior illuminance. Area weighted average values of each may be calculated (ADPF or ADF, respectively). Combination of the two quantities (ADPF + ADF) enables a quantitative assessment of the total daylight


(a)

(b)

(c)

Figure 1 (a) Tubular daylight guidance system collectors; (b) Output devices; (c) Light guides contribution from the various daylight providers.

Post-occupancy evaluation studies of TDGS in offices suggest that although TDGS devices are recognised as daylight providers, current design practice produces ADPF + ADF of the order of 1% on the working plane. This was not considered by users to produce a well day-lit interior, a result that led to the suggestion that a design criterion nearer 2% may be required.[2] A long-term cost study showed that TDGS provided poor economic return when viewed solely in cost terms but that this needs to be balanced by consideration of the value of the daylight delivered into a working area.[3]

2.1.2 Facade mounted systems

These consist of a façade mounted light gathering device oriented toward the equator, a horizontal guide system within a suspended ceiling, and output devices located deep in a building. They are used in conjunction with conventional lower windows and electric lighting systems. The light collector is a curved mirror or 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.

Courret et al. report the design, simulation and full scale testing of an 'anidolic ceiling' – a rectangular cross section horizontal duct using anidolic optics at each end to collect and distribute light (Figure 2).[4] The device is intended to use a predominantly overcast sky as a source. The design of the collector is based on the principle of matching the admission sector on the visible part of the sky. To avoid projections higher up the façade obstructing light rays the admittance angle varies along the entrance aperture. The collector is covered with insulating double glazing and the whole duct, which is almost 0.5 m high, is lined with polished aluminium. The emitting element is located between 3.5 and 4.5 m into the room and consists of a further anidolic mirror reflecting light onto a diffusing panel. Validation of the device by both simulation and measurement under overcast skies established that DF on the

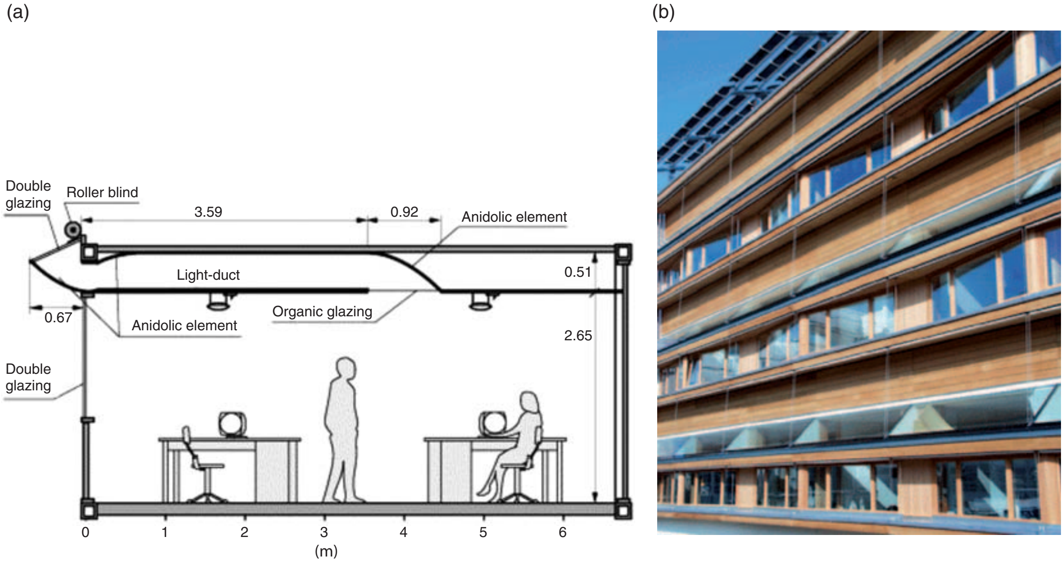


Figure 2 (a) The anodolic ceiling principle; (b) A façade incorporating an anodolic ceiling collector

working plane was enhanced at the rear of a room, some 4% at depths of between 3 m and 6 m into the room, or approximately 1.7 times the un-enhanced value. A value of 32% efficiency for the whole system is quoted.

Façade mounted systems have been used in tropical latitudes. A proposal for an office in Kuala Lumpur was evaluated using computer simulation and scale models.[5] In this example the collector was a fixed laser cut panel light that deflects predominantly high angle sunlight axially into a polished aluminium duct. Extractor laser cut panels inside the duct are used to redirect light 90° into the room. Studies using scale models indicated that daylight levels of between 200 and 300 lux would be achieved on the working plane some 6 m from the façade during the hours from noon to 1600. A computer simulation of use of similar technology in dwellings in Hong Kong suggested a working plane DF 1.5% at a distance 4 m into a room.[6]

2.1.3 Active guidance systems

The Himawari system, developed in Japan, collects and concentrates sunlight using tracking Fresnel lenses (Figure 3). Light may be transported up to 200 m by optical fibres, and distributed using a range of custom made luminaire-like devices. Each six 95 mm diameter lens cluster focuses sunlight with a concentration of 10 000 onto one cable, itself made up of a bundle of six 1 mm-diameter quartz glass fibres. The size of the application determines the number of lenses and cables. For example a 15 m long cable each of six fibres would deliver 1630 lumens from 98000 lux of direct sunlight on the collector.[7] The authors estimate that this would result in a workplane ADPF + ADF of ~1.2% if the output devices were at 1 : 1 spacing to height ratio. A major advantage of fibre optic transport is illustrated by the fact that some Himawari systems have been retrofitted to existing buildings. Notwithstanding the fact that the systems are self powered, they represent an extremely large capital cost which is unlikely to be justified for other than specialist applications.

Figure 3 A Himawari collector

2.2 Integrated lighting systems

'Integrated lighting' is a generic name for systems which deliver daylight and electric light separately but which are equipped with control that maximises the use of available daylight. There are two main approaches. The first uses custom made daylight devices with adjacent linked electric sources. The second is effectively an 'intelligent' electric lighting system with enhanced controls which seek the maximum benefit from any source of daylight.

2.2.1 Integrated skylight luminaire

The ISL combines in one unit a skylight with a sunlight control device, an electric lighting system, and a photosensor control system to automatically dim the electric output (Figure 4). The system uses passive daylight collection and was created for flat-roofed, high-bay buildings such as retail, warehouse, and light industrial buildings. It delivers daylight via 1.2 m × 1.2 m double-glazed clear

Figure 4 Integrated skylight luminaires (ISL) in a warehouse

roof-lights that capture both sunlight and skylight. This is supplemented by 12 T8 fluorescent lamps. The two light sources are linked by photosensor and luminaire controllers, which automatically reduce the electric light outputs when sufficient daylight is available. A 1.2 m-high daylight diffuser box is mounted below the roof-lights and distributes the sunlight via white acrylic diffusing panels. Diffuse skylight also enters the interior through the bottom of the diffusing box which is constructed of sandblasted clear acrylic. The electric lamps are housed in four industrial luminaire assemblies arranged in a square configuration 1.2 m outside the sunlight diffuser box. Four prototypes were tested showing a mean horizontal illuminance (taken on sunny afternoon between 1400 and 1500 in early September) of 240 lux over a working plane ~7 m below the skylight.[8,9] The authors estimate that this represents an ADPF + ADF of some 0.5%.

2.2.2 Intelligent lighting systems

In essence these are an electric lighting system with enhanced controls which seek the maximum benefit from any source of daylight – guided or otherwise. A number of manufacturers market systems of this nature, some of which are based on ‘open’ communication protocols such as digital addressable lighting interface (DALI). All are integrated into an appropriate building management system. In most cases luminaires are installed over individual workstations or defined visual task areas and equipped with, variously, integrated network controls, occupancy sensors, personal dimming or daylight dimming. The luminaires are usually designed to also provide ambient lighting[10,11]. Depending on the individual circumstances of use, the combination of features listed above can yield substantial energy savings. For example a field study of a deep plan office building having luminaires with occupancy sensors, daylight linking and individual dimming control saved 69% compared to a conventional lighting system. Electric lighting substitution by daylight accounted for 20% of this total.[12]

2.3 Hybrid lighting systems

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 more akin to that of an electric luminaire and the two sources may not appear as distinct. Table 2 summarises some features of HLS. It also includes the authors’ estimates of system efficiencies for one and two storey applications. These are based on cited information on size and efficiency of individual components. Approximate flux outputs for output devices are

Table 2 Summary of hybrid lighting systems

Name	Light collection method	Light transport method	Daylight output device	Electric sources	Electric lighting location	Daylight system efficiency at (i) 4 m – one storey (ii) 8 m – two storeys[a]	Approx. flux output per output device (*Simultaneous external illuminance*)[a]
(a) Heliobus (b) Arthelio	Mirror heliostat	Hollow light guide	Side emitting prismatic guide	(a) Metal halide lamp (b) Sulphur lamp	(a) Top of vertical light guide (b) End of horizontal light guide	(a) not measured (b) for 20 m long guide only: 8% under overcast sky 50% under direct sun	(a) not measured (b) 25000 lumens (15 000 lux)
HSL	Parabolic mirror heliostat	Optical fibres	Luminaire with: (a) Side emitting acrylic rod (b) End emitting rod	(a) T5 fluorescent tubes (b) Incandescent lamps	Within luminaire	(i) 50% (ii) 30%	6250 – 4170 lm (100 000 lux)
UFO	Fresnel lens heliostat	Liquid light guide and optical fibre	Luminaire with acrylic diffuser	Metal halide lamp and T5 fluorescent tubes	Metal halide lamp remote from luminaire. T5 fluorescent within luminaire	(i) not measured (ii) 3.4%	3000 lm (100 000 lux)
SCIS	Multiple mirrors and lenses system	Prismatic guidance	Prismatic guide with diffusing extractor	T5 Fluorescent tubes	Within guide	(i) 25% (ii) 25%	25 000 lm (Not stated)
Parans	Mini fresnel lenses heliostat	Optical fibres	Diffusing luminaire with end emitting optical fibres	T5 or compact fluorescent lamps	Within luminaire	(i) 80% (ii) 60%	7500 – 10000 lm (75 000 lux)

[a] Derived by the authors using cited data.

based on the estimated one storey system efficiency and cited values of external illuminance.

2.3.1 Enhanced tubular daylight guidance

The first developments in HLS lighting were enhancements to TDGS 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.

a) *Heliobus*

There are a number of examples of this type of system but one suffices to illustrate the principle. Figure 5 shows a school which is partially lit using a roof mounted static mirror heliostat whose shape is optimized to gather and redirect the largest possible amount of daylight. Light is directed 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 400 W metal halide lamps located at the top of the light pipe are turned on and the light distributed via the guide[13,14]. Measurements quoted in Reference 1 for an overcast sky providing 10 000 lux horizontal indicated an internal illuminance ranging from 420 lux adjacent to the output device to 30 lux at 3 m from the device. The authors estimated that this would give an approximate working plane ADPF + ADF of the order of 0.8%.

b) *Arthelio*

The Arthelio study developed systems combining daylight and electric light from sulphur lamps, and culminated in the construction of two large installations – one of which was in a single storey warehouse in Milan (Figure 6).[15] This uses a single axis light capture head based on a Fresnel lens. The sunlight is then reflected via an anidolic mirror into a 13 m-long, 90 cm diameter circular guide lined with prismatic material.

Figure 5 A Heliobus collector and the output device

A diffuser unit, shaped like a truncated cone is located at the end of the guide. This delivers a working plane daylight illuminance varying between 100 and 400 lux depending on time of year.[1] Connected to the diffuser unit are two horizontal prismatic light guides powered by dimmable sulphur lamps. These provide an additional uniform illuminance of 250 lux over the working area by a control system that tops up or replaces the daylight as necessary.

2.3.2 Hybrid solar lighting

This was developed by Oak Ridge National Laboratory 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 1.22 m-diameter parabolic acrylic sun-tracking mirror with an elliptical secondary mirror (Figure 7). The latter separates the visible and infrared portions of sunlight and focuses the visible sunlight into a bundle of 127 3 mm 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 1.2 m × 0.6 m electric luminaire also equipped with dimmable fluorescent lamps. 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[16,17]. 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 light-emitting diodes has also been developed. Further work suggested that system losses of the order of 50% for single-story application with an additional 15–20% for a second storey[18]. It is claimed that one collector can power 8–12 fluorescent, or 30–40 reflector luminaires, so lighting an area of ~100 m^2. This displaces about 1 kW of electrical lighting load. On a sunny day one Hybrid Solar Lighting (HSL) system is reported to deliver 50 klm per group of luminaires. The authors estimate that this would give an approximate daylight illuminance in a typical office of the order of 700–1000 lux or a ADPF + ADF 3 of ~1%.

Figure 6 The Arthelio used to light a warehouse

2.3.3 Universal Fibre Optics

This project was the result of a multinational development under the European Commission Energy Programme, but does not appear to have been commercially exploited.[19] Sunlight is collected by a roof mounted heliostat with a 1 m-diameter Fresnel lens and delivered to luminaires via 10 m-long 20 mm-diameter liquid light guides. In addition light from two 150 W metal halide lamps, located adjacent to the heliostat, may be delivered to the luminaire via plastic fibre optic cables. The luminaires contain a coupling system linking both liquid and optical fibre guides to the edge of a 20 mm thick sheet of 'Prismex', an acrylic material with a dotted surface developed for illuminated advertising signs (Figure 8). Light passes through the panel and exits such that it delivers an even brightness across its emitting surface. The luminaire also has two T5 fluorescent lamps located along the edge of the emitter. The system is photocell controlled such that when daylight fails the luminaire switches to light from the metal halide lamps. Because of the limited dimming capability of metal halide lamps, variation in output was achieved by switching but at a speed which could not compensate in real time for quick variations in the external illuminance. The output of the fluorescent lamps compensates for this.[20] A prototype, installed in Athens, had a flux

Figure 7 The hybrid solar lighting (HSL) collector and the hybrid luminaire

Figure 8 A universal fibre optics (UFO) collector and luminaire

output of 3060 lm for a normal illuminance on the collector of 90 029 lux and using a 10 m-long guide. The overall efficiency of the daylight system was ~3.4%, a low value presumably caused by the large number of components and optical couplings, and the inefficiency of the side emitting diffuser.

2.3.4 Solar canopy illumination system

This facade mounted system collects sunlight using an Adaptive Battery Array (ABA) – a grid of thin 16 cm square mirrors located inside a weather-proof enclosure with a transparent front window.[21] Figure 9 illustrates this. On the façade each unit is ~3 m wide × 1.2 m high. This is connected to a 0.25 m high duct which extends some 10 m into a building. The orientation of the mirrors changes with sun position by means of pulleys and linear actuators and the light is concentrated and redirected by a series of lenses and mirrors into the rectangular cross section 'dual function prism light guide' (Figure 10). 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 it 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. The control system uses DALI controlled ballasts, in addition to light sensors, to maintain the desired interior illumination level. A prototype at the British Columbia Institute of Technology shows that ~25% of flux incident on the mirror array arrives on the workplane extending 10 m from the façade.[22] System efficiency is significantly reduced in the early morning and late afternoon since the mirror array configuration and orientation only redirects incident sunlight 3 h either side of solar noon for most of the year.

Figure 9 The solar canopy illumination system (SCIS) collector

2.3.5 Fibre optic solar lighting system (Parans)

The system developed commercially by Parans Solar Light shares some features of the Himawari system.[23] Figure 11 shows the roof or façade mounted 1 m^2 modular solar

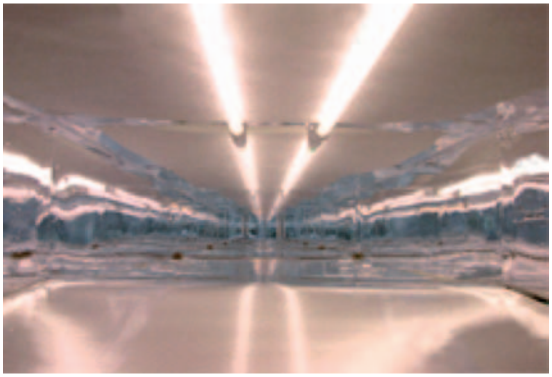


Figure 10 The dual function light guide for the solar canopy illumination system

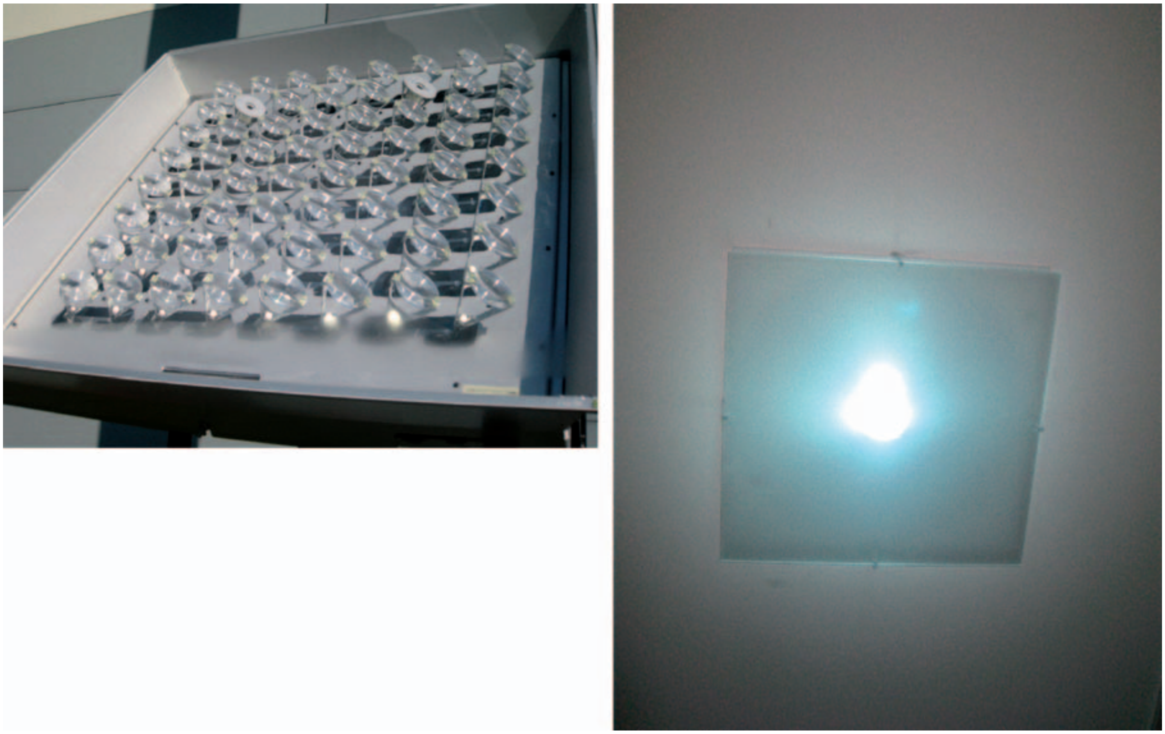


Figure 11 The fibre optic solar lighting system (Parans) collector and luminaire

panels containing 64 Fresnel lenses. Each lens is able to track and concentrate sunlight into a 0.75 mm diameter optical fibre. Sixteen fibres are combined into a cable each of maximum length 20 m. 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 learns and remembers the sun path at any location and thus can be moved without pre-programming. 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 10 m optical cable and direct solar illuminance of 75k lux quotes a luminaire flux output of 7500 lm and 10 000 lm for a 4 m cable. This corresponds to a system efficiency of ~60 and 80%, respectively. The system has optimum collecting hours when the solar panel is within an angle of 120° of the sun.

3. Evaluation and discussion

The above suggests that the success or otherwise of systems is related to both the nature of the technology and to the interaction of the lighting with the building. This section addresses these issues.

3.1 Light delivery

Table 2 summarises some aspects of HLS performance. Quantity of daylight delivered depends on system type, its method of use and the solar resource. Overall system efficiency is a function of the individual optical elements used and the optical processes linking them.

The Universal Fibre Optics (UFO) system, which has a notably low overall efficiency, consists of two separate guidance systems for daylight and electric light, each with two optical couplings. The diffusing output device alone accounts for 25% of total losses. By comparison the HSL, which is some 20 times more efficient, has only one light guide and light output devices for both sources contained within a mirrored luminaire. Thus simplicity appears to be a virtue in system configuration. As in any lighting system the location of the hybrid output devices has a major bearing on light delivery. For working areas where good distribution of light is important, those systems having a number of discrete output devices (e.g. HSL) or large area sources (e.g. SCIS) are likely to perform better than those having large linear sources such as Heliobus and Arthelio. HSL, UFO and Parans systems use luminaires as output devices. In the case of the first two, these are modified off-the-shelf luminaires but the Parans version is a specially constructed hybrid luminaire. All have light outputs of the order of 3000–6000 lumens – comparable to that of electric luminaires used in offices – given optimal sunlight conditions. The output of SCIS is much larger and must be compared with that of a luminous ceiling rather than a conventional luminaire. The hybrid device outputs are all greater than those of measured discrete TDGS output devices set out in Al-Marwaee and Carter.[2] There are two reasons for this. Firstly TDGS are usually smaller (typically 300 mm diameter or 600 mm square) and, secondly, the TDGS outputs quoted were largely for overcast conditions.

There are a number of concerns relating to the delivery of electric light via hybrid systems. The first is the sub-optimal optical processes within the luminaires – the optics necessary for electric sources need modification to accommodate the daylight emitters and vice versa. For example the mutual obstruction of light from the lamps and the emitting rods is apparent in Figure 7. The dual function light guide (Figure 10) largely avoids this but relies on the duct walls to redirect light from the lamps. A more general point is that most of the hybrid luminaires use diffusers to deliver light to the building interior. Luminaires using this method have the merits of low glare and even light distribution, but their light output ratios are generally inferior to, say, contemporary mirrored luminaires. A second concern relates to electric lighting control. In Western Europe for example, where cloudy skies predominate, daylight illuminance may fluctuate throughout the day, placing unusual demands on the control system and potentially affecting lamp life. Finally the additional complexity may mean that the maintenance costs of hybrid systems are greater than those or comparable conventional equipment.

It can be argued that the quality of light from hybrid devices is likely to be an improvement on that from a typical TDGS. Some hybrid devices, notably HSL and Parans, offer luminaire optical control that is superior to that of the basic diffusers used in TDGS. Also the proximity of electric and daylight sources within the luminaire may mask gross differences in colour appearance. To extend this idea there is potential for the use of colour changing electric sources in hybrid devices to mimic changes in daylight colour, although this has not yet been realised.

Whilst TDGS have been demonstrated to work in both sunny and cloudy latitudes, it is by no means evident that systems based on sun tracking will consistently deliver adequate amounts of light in, say, Northern Europe. The authors measured approximate luminaire flux output on a Parans system in Southern England having a south facing collector mounted at 30° to vertical, and with a 20 m cable. The luminaire output was 15 000 lumens for direct sun giving 98 000 lux normal to the collector, but only 50 lumens for a cloudy sky giving 10 000 lux normal to the collector. This suggests that work to identify the optimum methods of guiding daylight into buildings for regions with different characteristic sky conditions is urgently necessary before large investments are made in the technology.

Any comparison between the systems must be made with care because the various published information differs in both format and completeness. Some idea of the utility of the various systems may be gained by attempting to use each in turn for a nominally similar arbitrary task – to provide 2% ADPF + ADF across the workplane of a 12 × 12 × 3 m windowless space. Clear sky and sun were assumed and to ensure uniform illuminance discrete output devices were at 1 : 1 spacing to height ratio. The system configurations would be as follows:

Using daylight guidance technology:

- Sixteen 250 mm-diameter TDGS each comprising collector, guide and output device.
- One Himawari collector comprising 198 lens, with 16 luminaires.

Using HLS:

- One HSL system comprising one collector and 16 luminaires.
- Sixteen UFO systems each comprising a collector and a luminaire.
- Three Solar Canopies are enough to provide an ADPF + ADF of 3%, but four systems are required to provide a reasonably uniform illuminance level.
- Fibre optic solar lighting system (Parans) comprising four solar panels and 16 luminaires.
- One Arthelio system comprising one collector and two guides will provide an ADPF + ADF of 2.8% but with poor illuminance uniformity.

Using electric lighting only:

16 triple F14W/T5 fluorescent luminaires would give an equivalent illuminance.

It is clear that although the numbers of discrete luminaires/output devices are similar for many of the specifications, the number of collectors and guides differ markedly. Thus a wide range of equipment may be used to give a nominally similar result. Subsequent sections examine the implications of this on cost, integration of the systems into a building and likely user response.

3.2 Cost and value

Whole life cost calculations for a lighting system include both initial and running costs. Capital cost comprises system component and installation costs, and that of modifications required to the building structure and fabric. Running costs include energy consumed, maintenance, and the ‘opportunity cost’ of floor area required for devices. Costs may be offset by savings including reductions in electricity consumption by daylight substitution, reduction in cooling loads, and reduction in electric lighting maintenance costs. An indirect financial benefit may be improvement in well-being and productivity of occupants due to daylight, although this is difficult to quantify.

There is some published information on capital cost of HLS systems but there is little accumulated experience of running costs. This section attempts to compare system cost using published information. The results need to be treated with caution because of wide differences in system performance and intended application. A future comprehensive study comparing like for like using standardised data and including all aspects of offset costs and value is necessary for full understanding.

For comparison purposes the various systems were used to light the 12 × 12 m two-storey windowless building used in the previous section. An external illuminance of 60 000 lux and 2% ADF + ADPF was assumed. Table 3 shows estimated capital costs based on published information. It is worth bearing in mind that the electric

Table 3 Estimated hybrid lighting system capital costs

Name	Estimated cost/m^2 based on published information	Estimated cost of hybrid system for the example building
(a) Heliobus	No data available	Not applicable
(b) Arthelio	No data available	Not applicable
TDGS	£40 – £50 (single storey) £80 – £100 (two storey)[3]	£24 000
HSL	£80[16] (Possibly reduced by volume manufacturing to £20[17])	£23 000
UFO	No data available	Not applicable
SCIS	£125 with volume manufacturing[24]	£38 000 plus installation and modification to building
Parans	£300[23]	£100 000
Electric lighting	£40 – £50[25]	£14 400

systems, TDGS and Parans systems are on the market, and thus the figures quoted are full commercial costs. Those for HSL and SCIS are estimates made by the system developers in anticipation of the likely effects of volume production. None of the figures include installation or building modification costs, which are likely to be substantial in the case of SCIS and multi-storey TDGS. Installation costs for the systems based on optical fibre light transport are likely to be of the same magnitudes to those of electric systems. None of the published sources give quantitative estimates of running costs.

It is evident that capital costs of HLS systems are generally more expensive than electric lighting, but comparable to TDGS for two storeys or above. Before conclusions can be drawn about long-term costs, the issue of running costs must be addressed. Electric lighting is dominant both visually and economically in the majority of buildings that have been equipped with daylight guidance to date, given that electricity is the major running cost. TDGS long-term costs compare with an electric-only alternative only if a series of favourable assumptions about future energy costs and system configurations are made.[3] The suspicion must be that hybrid systems also will provide a poor economic return when viewed solely in cost terms. Cost needs to be balanced by value – principally the benefits of delivered daylight. This suggests that the configuration of a HLS system, notably its ability to provide a 'day-lit space', will have a marked impact on long-term cost and benefit.

3.3 Relationship with building

HLS systems may affect interior and exterior architecture and have implications for structural and services systems.

3.3.1 Architectural implications

The main external architectural concerns relate to collecting devices. Mirror and lens arrays located on roofs may be visually intrusive and limit other roof uses. They may be large items – for example the Arthelio mirror is 2.5 m diameter – and require protection by additional constructions above roof level. Also the necessity to track the sun over as large an area of the sky as possible dictates an exposed location. Façade mounted systems may occupy considerable areas of the building envelope and present problems of appearance and integration with other façade elements. Furthermore systems such as SCIS require at least extra storey height and, potentially, almost dictate that the whole building be designed around them.

Internally HLS affect space layout, ceiling design and luminaire selection. All systems require vertical and/or horizontal paths for guides. Those that deliver daylight via flexible optical fibre cables would require little more space provision than electrical or communications cables. They also have few implications for interior spatial layout, and merely require coordination with other luminaires and building services. At the other extreme, enhanced daylight guidance and SCIS require dedicated ducts, through or over several storeys. These are of widths measured in metres and lengths in tens of metres and may occupy rentable floor area. Although these might be seen as a visual feature they will dominate the interior design and restrict internal spatial flexibility.

3.3.2 Structure and services implications

There were few structural implications for HLS. Roof mounted heliostats may require additional structural work to account for wind and dead loads but these are likely to be of the same orders of magnitude as equipment such as cooling towers. Façade mounted collectors are structurally similar to cladding. Light transport and distribution elements present no more structural problems than, respectively, ventilation ductwork or luminaires. They are of negligible dead load, must be routed so as not to conflict with structural elements such as beams, and may require provision for openings in slabs.

HLS components present few coordination problems that are not overcome in ventilation and electrical services. The main unique concern is fire resistance and to the prevention of passage of smoke in both vertical and horizontal transport components. Regulations on fire protection include restrictions on fire and smoke spread within buildings, which is addressed by provision of fire compartments. HLS based on light guides may pass through compartment enclosures and a range of measures including fire-protected ducts, fire dampers and fire-resisting cladding may be required.[26] Façade mounted systems will generally be within one compartment.

3.4 Human response

The literature contains no work specifically on human reaction to HLS. Work on human response to TDGS, however, gives some clues about user attitudes to daylight delivered via guides or via devices similar to conventional luminaires. The Arthelio installation (Section 2.3.1) was evaluated by Ejhed.[27] A user questionnaire indicated a general preference for daylight; that detection of changes in exterior conditions was possible; and that it provided bright, glare free, diffuse, evenly distributed light in which the daylight contribution could be discerned by its colour properties. Courret et al.[4] assessed visual comfort conditions in a full sized prototype ‘anidolic ceiling’, similar to SCIS, which increased illuminance and room brightness in areas remote from the window. Users perceived the improved quantity of lighting and appreciated the enhanced room brightness and colour due to the device.

Carter and Al-Marwaee[28] studied user reaction in offices equipped with TDGS and a separate electric system, and some also with windows. In these the electric lighting was dominant with the guide output making only a modest contribution to task illuminance (the equivalent of 1% ADPF + ADF). Users recognised that the TDGS provided daylight but were dissatisfied with the amounts provided. Also TDGS were considered inferior to windows in delivery of most aspects of daylight quality (notably light distribution and external communication) although satisfaction improved with increased ADPF + ADF. It was found that daylight output devices that resembled luminaires were perceived as delivering electric light.

With the aid of the above it is possible to speculate in general terms about likely human response to HLS systems and some desirable design features. The quantity of daylight delivered needs to be high enough to convince users that it is indeed daylight; the evidence suggesting that an ADPF + ADF in excess of 2% is required for TDGS. The TDGS studies were in buildings in temperate latitudes. It may be however that a different criterion applies to HLS located in sunny latitudes and delivering large light outputs. Work is required to establish if this is the case. Spatial and diurnal illuminance variation is one of the unique properties of daylight and must be accommodated. If the designer is trying to create the appearance of a 'day-lit space' then clearly façade-based systems such as SICS have an advantage. There is a danger that automatic illuminance 'top-up' will create a uniformly lit space that users will perceive as dominated by electric lighting no matter how much daylight is being delivered. Similarly the perception of diurnal variation apparently requires a user view of a daylight device which is capable of mimicking external illuminance. It is at least arguable that control of 'top up' light on a working plane should include some diurnal variation where spaces are intended to be 'day-lit'.

The nature of the output devices is important. It is clear that colour is important in user recognition of daylight and thus care should be taken in the design of devices that mix electric and daylight. The proportions should be such that daylight is not swamped by the electric component although when devices are supplied with sunlight this is unlikely to be a problem. There is a danger that daylight from 'luminaire-like' devices will be considered as electric light so there is a case for making hybrid luminaires distinct from wholly electric luminaires. In this respect there may also be a case for the use of diffusers as light control since these have directional properties similar to that of windows. Although there is some evidence that users can detect time and weather variations via guides, they do not provide a satisfactory external view. This can only be provided by clear glazed windows, even of minimal size.

3.5 Design methods

Standardised methods of design calculation, data production and exchange are universal in the lighting industry. Electric and daylight codes set out recommendations for, variously, equipment, illuminance levels and surface properties. Recent work extends this guidance to TDGS[1]. Currently, no independent design information exists for HLS and manufacturers' websites are the main source, usually offering little more than output device spacing and installation advice. They appear to be based on optimal conditions of the most favourable possible system configuration and assumed daylight resource. Also different methods are used to describe system performance meaning that evaluation of alternatives is difficult. Although most HLS have their origins in academic research, a generic research effort based on accumulated experience of their use has not had time to materialise. A similar exercise for TDGS produced design guidance and norms, and it is to be hoped that this process will be repeated for HLS.

4. Conclusion

Daylight guidance has been one of the major areas of innovation in interior lighting in recent years and HLS is the latest expression of the technology. The desire to create low energy buildings with good daylight penetration means that daylight guidance has become attractive to designers. The innovative nature of HLS means that there are currently only two commercially available systems. As a result there is little accumulated experience of their use. It is likely that the lessons learned from feedback from TDGS installations in respect of design criteria, integration with other lighting systems and the building fabric and economics may be relevant to HLS.

The advocates of daylight guidance advance two main arguments for its use – firstly that they deliver daylight deep into interiors and, secondly, that in doing so energy may be saved by electric light substitution. The evidence to date is that some HLS can under favourable circumstances deliver large quantities of daylight, possibly sufficient to create a 'well day-lit space' as defined by ADF criteria. The light is delivered via luminaires. The evidence from studies of TDGS suggests that under some circumstances light coming out of a guide via a luminaire-like device will not be perceived as 'daylight', particularly in the absence of the other components of daylight notably contact with the exterior. In other respects HLS can potentially deliver better quality lighting than TDGS since the luminaires used have better light control and the possibility exists of colour matching of the dual sources.

HLS represents an advance over TDGS on a number of fronts. They offer the opportunity to transport light deeper into buildings and pose less practical problems, notably in terms of fire precautions. The use of a single output device offers seamless integration of electric and daylight. However this process requires sub-optimal solutions. For example the optics necessary for electric sources may need modification to accommodate the daylight emitters and vice versa. It is arguable that an integrated lighting system with separate output devices may perform better. Most of the HLS 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, have yet to be appreciated.

The economics of HLS have yet to be explored. On the limited published evidence they represent substantially greater capital cost than TDGS. The latter have been shown to be economic over the long term only if favourable assumptions are made regarding energy costs and the same must apply to HLS. To offset this, a case must be made for enhanced value of HLS because of delivery of daylight with its associated benefits.

A review of this nature inevitably poses more questions than it provides answers. HLS offers an exciting possibility for lighting practitioners but much work is required to realise this. This includes – study of human response to HLS and development of suitable design criteria; development of design methods; feasibility of use of the various types of daylight guidance in different geographic areas; and the long-term economics of such systems.

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Discussion

Comment 1:

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In many cases, the daylight delivery performance of tubular daylight guidance systems (TDGS), integrated lighting systems (ILS) and hybrid lighting systems (HLS) is given in terms of the sum of the average daylight penetration factor (ADPF) and the average daylight factor (ADF), even for a windowless space.

What is the physical meaning of ADPF + ADF? In Section 2.1, it is stated that the combination of the two quantities (ADPF + ADF) enables a quantitative assessment of the total daylight contribution from various daylight providers. Would this imply that (ADPF + ADF) is the sum of ADPF of the daylight guidance system and ADF of the window system? However, the quoted or estimated working plane (ADPF + ADF) values mentioned when discussing active guidance systems, integrated skylight luminaires and the Heliobus are apparently for indicating the daylighting performance of the daylight guidance systems only without considering windows. In any case, the daylighting performance indicated by (ADPF + ADF) can have a large range even under the same sun and sky condition. For example, when the unobstructed sky illuminance is 25 klx and the global exterior horizontal illuminance is 100 klx, a value of 1% (ADPF + ADF) can give an estimated average working plane illuminance of 250 lx (ADPF = 0, ADF = 1%) to 1000 lx (ADPF = 1%, ADF = 0). Therefore, the 'quantitative assessment of the total daylight contribution' by (ADPF + ADF) may be too vague.

From Table 1 it seems that the major difference between ILS and HLS is that ILS uses separate light output devices for daylight and electric light while HLS uses one single output device for both light sources. When separate output devices are used for daylight and electric light, each device can be optimally designed to give maximum output of either daylight or electric light. Would it be difficult to optimise the output device of the HLS to achieve maximum efficiencies for both daylight and electric light? In a HLS, how is the performance of the electric lighting part evaluated? It would be useful if a method can be developed for evaluating the total performance of HLS for both daylight and electric light.

Reply to comments

MS Mayhoub and DJ Carter

We thank Professor Chung for his thoughtful comments. Hybrid lighting systems (HLS) are the most recent developments of the guided daylight concept. A large number of tubular daylight guidance systems (TDGS) are now in use in working buildings and thus there is a body of knowledge about design criteria and methods, daylight delivery, costs and benefits, user reaction and the implications for buildings in which they are housed. The purpose of this paper is to try to draw together such published information as exists to attempt to gauge the potential use of hybrid systems for mainstream lighting applications.

Most guided daylight systems to date are configured to deliver daylight either to areas of buildings remote from windows or to windowless spaces (c.f. TDGS described in Reference 2). The published information suggests that the same mode of use is intended for HLS. Thus in most cases it is likely that particular areas are either supplied by daylight via windows or via HLS, with the result that one or another of average daylight penetration factor (ADPF) or average daylight factor (ADF) is zero. We have used ADPF and ADF as general indicators of the quantity of delivered daylight. Whilst the accuracy of our estimates of these quantities is limited by the dearth of detail in some of the published information, both criteria have been shown to be indicators of user perception of a 'well daylit space'. A more general question is whether the ADPF (which was developed for TDGS) is applicable in assessing the daylight delivered by essentially electric lighting equipment. The answer to this question can only be obtained by user reaction surveys of HLS which, we suspect, will not be possible for some years.

We agree with Professor Chung that the compromises within a single luminaire to accommodate both electric sources and daylight will lead to sub-optimal solutions for both. It may be that development of HLS in future will lead to improvements in efficiency of delivery of both. What must be remembered, however, is that any reduced efficiency of HLS output devices compared with conventional equipment must be balanced by potential savings in capital cost, in providing one device in place of two and by the maximum use of the available daylight as an electric lighting substitute. We understand that to date the HLS output devices have been modified electric luminaires for which standard photometric information is applicable. We agree that new methods for evaluating the performance of hybrid devices may be necessary.