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The costs and benefits of using daylight guidance to light office buildings

M.S. Mayhoub [a], D.J. Carter [b,*]

[a] School of Architecture, University of Liverpool on leave from Al-Azhar University, Cairo, Egypt
[b] School of Architecture, University of Liverpool, Liverpool, L69 3BX, UK

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ABSTRACT

Daylight guidance systems are linear devices that channel daylight into the core of a building. This paper analyses costs and benefits of using the two main classes of daylight guidance to light offices as an alternative to conventional electric lighting. The work demonstrates that daylight guidance is generally not economical using conventionally accepted measures of both cost and benefit. It is shown that if intangible benefits associated with the delivery of daylight to offices are included in an analysis, a more favourable balance of cost and benefit is obtained. The implications of this for practical use of the systems are discussed.

1. Introduction

There is a large body of knowledge showing 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. Also the potential of daylight to conserve energy and hence protect the environment has stimulated interest in its use as an electric lighting substitute.

Conventional 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. Over the last fifty years or so the development of a number of highly efficient reflective and refractive materials has made the redirection of daylight into areas of buildings remote from the façade a practical possibility. There are two main approaches. The first, 'beam daylighting'—the redirection of sunlight by adding reflective or refracting elements to conventional façade—is essentially the enhancement of traditional devices such as louvers or light shelves using the new optical materials. The second method – known as 'light guidance' – captures daylight using collector devices and transports it into core areas of buildings using some form of linear guidance system. The latter method is the subject of this work.

The two main types of 'daylight guidance systems' (DGS) are the commercially successful tubular daylight guidance systems (TDGS) – used in combination with an electric lighting system (ELS) - and the newer hybrid daylight/electric systems (HLS). 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 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 ducts into the core of a building where it is combined with electric light within luminaires. These are equipped with controls that maximise use of available daylight. Fig. 1 illustrates examples of these systems.

The literature indicates that choice of DGS has differing impacts on light delivery and consequent energy usage for diverse geographic locations [1]. The energy savings quoted appear large and constitute a major argument for guidance systems. However other factors such as the wider relationship of the various systems to their host building, capital and running costs and benefits to user of the lighting system mean that savings must be viewed as part of a wider cost/benefit analysis rather than in isolation.

This work analyses costs and benefits of using DGS to light offices as an alternative to ELS. The study uses firstly, conventional quantifiable measures of cost and benefit and secondly, additional benefits including cooling loads savings, carbon emission savings, and user productivity improvements.

* Corresponding author. Tel.: +44 (0) 151 794 2622.
E-mail address: eb09@liverpool.ac.uk (D.J. Carter).

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Glossary of terms

DGS	daylight guidance system
ELS	electric lighting system
EU	European Union
HLS	hybrid lighting system
HRE	heat replacement effect
HSL	Hybrid Solar Lighting (commercially available product)
NPV	net present value
PB	payback period
PV	present value
SCIS	Solar Canopy Illuminance System (commercially available product)
TDGS	tubular daylight guidance system (generic name for a range of commercially available products)
WLCC	whole life cycle costing

2. Lighting economics

The most widely used method of assessing financial viability of lighting schemes, simple payback, is defined as the time taken for running cost savings to payback initial capital cost. Its main drawbacks are that it does not consider the 'time value' of money (the fact that the present capital is more valuable than a similar amount of money received in the future) and that savings that occur beyond the payback period are not taken into account. Also simple payback takes no account of the worth of the improved lighting – e.g. increased user productivity or rental value, or environmental benefits. The methodology used in this study to evaluate system costs and benefits is whole life cycle costing (WLCC) which permits diverse factors influencing a lighting scheme to be considered.

2.1. Costs and benefits

The main costs and benefits associated with lighting systems are summarised in Table 1. For each there are differences in both in the ease of which they may be quantified, and the magnitude of their effect on the outcome of any analysis. Cost and benefit analysis is conventionally undertaken for the more readily quantifiable Level 1 items identified in Table 1. These so-called 'tangible' aspects include initial capital and running costs, and direct savings due to the use of the systems.

Table 1
Costs and benefits associated with lighting systems.

	Costs	Benefits
Level 1 'Tangible items'	Initial capital cost Running cost	Electricity savings Electric lighting system capital and maintenance saving
Level 2 'Intangible items'	Opportunity cost of floor/roof space.	Building heating/cooling savings Carbon tax savings Effect of daylight on human well-being Enhanced corporate prestige Residual value

The Level 2 benefits are known as 'intangible' as they are by their nature more difficult to identify and/or quantify. Also their relative importance varies widely between different applications. Heating/cooling and carbon tax benefits for example will vary with geographic location. The benefits of using one particular luminaire rather than another, in terms of increased company prestige, is difficult to quantify but might be reflected in building rental values. The benefits of improvements in building occupant well-being due to the beneficial effects of enhanced daylight are also difficult to quantify. However since staff costs are the largest proportion of the total running cost of many types of building, notably offices, any benefits such as enhanced productivity are potentially large.

2.2. Whole life cycle costing (WLCC)

The WLCC method takes into account the costs of running and operating buildings or components over the entire lifespan or some specified period of time. The 'time value' of money is acknowledged by use of the present value method (PV) which compounds and discounts cash flows to reflect the increased value of money when invested [2]. PV is computed as follows:

$$PV = FV(1+r)^{-t} \tag{1}$$

$$FV = K(1+i)^{t} \tag{2}$$

where: PV = present value, FV = future value of capital, K = annual cost, r = discount rate, i = inflation rate, t = period of analysis.

The net present value (NPV) is an approach used in WLCC budgeting where the present value of cash flow is subtracted from that of cash outflows [2]. NPV is thus a metric for measuring the net value of an investment in building assets in today's money.

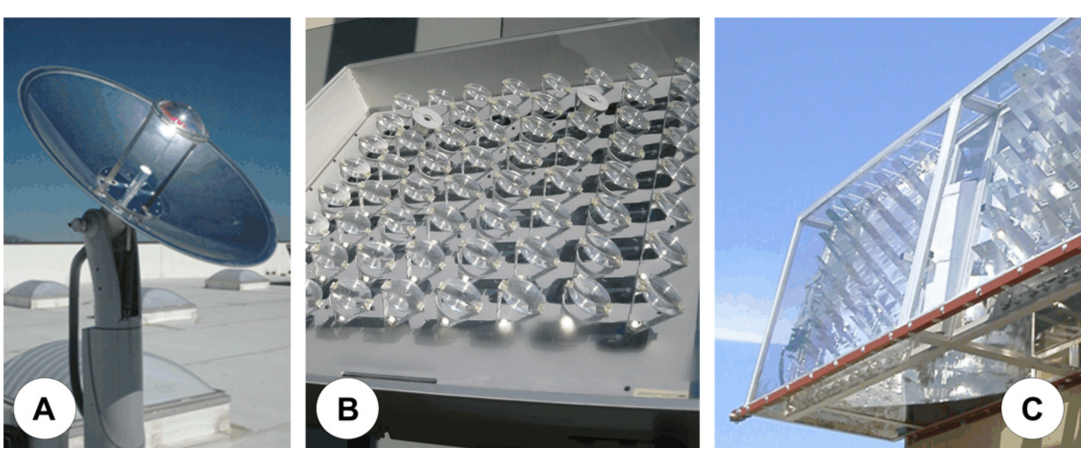

Fig. 1. Hybrid lighting systems: A Hybrid Solar Lighting (HSL); B Parans system; C Solar Canopy Illuminance System (SCIS).

Accordingly, when the difference between alternative lighting systems reaches zero, this is a turn point where a system pays back the investment and gains benefits.

NPV is calculated using the following formula:

$$NPV = \sum(PV_b - PV_c) \tag{3}$$

where: PV_b = discounted present value of benefits, PV_c = discounted present value of costs.

From Eq. (3) the NPV can be calculated as follows:

$$\begin{aligned} NPV &= I_{0\_EL} + \Sigma PV_{E\_EL} + \Sigma PV_{M\_EL} - \left[(I_{0\_EL} + \Sigma PV_{E\_EL} + \Sigma PV_{M\_EL}) + (I_{0\_DL} + \Sigma PV_{M\_DL}) + \Sigma PV_J - \Sigma\Delta PV_S - R_0\right] \\ &= -\left[(I_{0\_DL} + \Sigma PV_{M\_DL}) + \Sigma PV_J - \Sigma\Delta PV_S - R_0\right] \\ &= \Sigma\Delta PV_S + R_0 - \left[I_{0\_DL} + \Sigma PV_{M\_DL} + \Sigma PV_J\right] \end{aligned} \tag{4}$$

where: I_{0_EL} ELS initial investment [£], I_{0_DL} daylighting system initial investment [£], PV_{E_EL} PV of ELS annual energy cost [£], PV_{M_EL} PV of ELS annual maintenance cost [£], PV_{M_DL} PV of daylighting system annual maintenance cost [£], PV_J PV of future investment for replacement [£], ΔPV_S PV of total annual cost saving over use of ELS only [£], R_0 residual value of the lighting system [£]

This analysis considers NPV of costs and benefits of using daylight guidance to light offices as an alternative to conventional ELS. Assuming that the daylight guidance capital investment occurs at present and future costs are due to periodic maintenance, then these investments will result in annual energy and maintenance cost savings through the system lifetime. Using Eqs. (1) & (2) NPV can be expressed as follows:

$$NPV = \sum_{t=1}^{n} \frac{\Delta K_S (1+i)^t}{(1+r)^t} + R_0 - \left[I_{0\_DL} + \sum_{t=1}^{n} \frac{K_{M\_DL}(1+i_M)^t}{(1+r)^t} + \sum_{j=x,y,z} \frac{I_I(1+i)^j}{(1+r)^j} \right] \tag{5}$$

where: ΔK_S total annual cost saving over use of ELS only [£], K_{M_DL} daylighting system annual maintenance cost [£], I_{0_DL} daylighting system initial investment [£], R_0 residual value of the lighting system [£], I_j the investment for replacement j at time x, y or z [£], t considered time period for evaluation [year], r discount rate, i inflation rate, i_M maintenance inflation rate

Comparing Equations. (3) & (5) shows that the total annual cost savings and the residual values representing benefits. Costs for a DGS are made up of initial and replacement costs and annual maintenance cost. Thus a NPV of zero indicates that the sum of the savings and residual value equal the DGS initial, replacement and maintenance costs.

Typical inflation in countries with stable economies is under 5%. In the UK over the last decade, the consumer price index of annual inflation ranged between 0.8% and 3.8%, with mean of 2.3% [3]. Over the same period of time electricity inflation has been between −2.1% and 23.4%, with mean of 6.5%[1]. Labour costs inflation was between −6.7% and 13.8%, with mean of 2.8%[2]. The average annual UK official bank interest rate is between 0.5% and 6%, with mean of 4.3% [4]. In this work the mean values are used and thus 2.3%, 6.5%, 3.5% and 4.3% represent general inflation, electricity inflation, labour cost inflation and discount rates respectively.

In this work all systems are considered to have both a daylight and electric component and thus for hybrid systems the cost of a separate electric system is zero. TDGS costs comprise guidance system capital costs and maintenance, and a separate ELS is assumed. The benefits set out in Level 2 of Table 1 are discussed later and are included in the total annual cost savings (ΔK_S).

3. Evaluation process

Previous work studied the light delivery potential of light guidance at various locations throughout Europe [1]. This work studies the cost of their use in representative locations.

3.1. Variables in the study

Two European locations were selected: London (51N, 0°) and Valencia (39N, 0°) as representative of northern European and Mediterranean locations. The DGS used are the only currently available hybrid systems: Hybrid Solar Lighting (HSL), Parans, and Solar Canopy Illuminance (SCIS) systems, and the widely used passive TDGS.

The systems were assumed to light office spaces. 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. Electric lighting is the major energy consumer in offices and thus a case exists for the provision of daylight as a substitute. Daylight guidance manufacturers have targeted offices as a major market. This work is based on the lighting of a windowless modular space of 6 m × 12 m × 3 m high, with the short edge facing south, using each system in turn. The modules can be used to represent common office floor plan configurations; for example, side-by-side forming a multi-storey narrow-plan building or multiple modules in two directions forming a single-storey deep-plan building. Reflectance of ceiling, walls and floors are 70%, 50% and 20% respectively. Average illuminance level on work plane, 0.8 m from the floor, is assumed as 300 lx over annual working hours of 3650 h.

3.2. System costs

Calculations indicated that two HSL systems, two SCIS, or eight Parans systems were required to light each module to the design illuminance level assuming an external normal beam illuminance of 30 klx, equal to the European average. In actual conditions there would be considerable variation in external conditions and any consequent shortfall in daylight contribution would be made up by the linked electric systems. As the HLS market is still growing two capital costs are used; the first the current cost for low volume production, and the second that predicted for high volume. In the absence of one or the other the 'experience curve' approach was used in which costs fall by a constant and predictable percentage each time cumulative volume doubles. Studies suggest reduction of 10–30% [7,8], which was used to estimate Parans high volume and SCIS low volume. The low volume cost for HSL was its 2007 launch

[1] Electricity inflation percentages have been calculated using the electricity prices over the last decade [5].

[2] Labour costs inflation percentages have been derived from the UK hourly labour costs [6].

Table 2
Cost summary.

System	No	Low volume production capital cost (£)				High volume production capital cost (£)				Annual running cost (£)
		Initial	Installation	Total	Cost/m^2	Initial	Installation	Total	Cost/m^2	
Elec.[a]	–	–	–	–	–	–	–	3672	51.0	126
TDGS	10	–	–	–	–	4118	2359	6477	90.0	89
HSL	2	20000	3750	23750	329.9	3750	1250	5000	69.4	424
Parans	8	84964	1061	86025	1194.8	19984	1061	21045	292.3	289
SCIS	2	7470	2184	9654	134.1	1250	2184	3434	47.7	314

[a] Fit out cost only is included to be comparable with the other systems.

cost, and a predicted high volume cost was provided by the developer [9]. Since the Parans system is available on the market, the current list price was used. Installation costs were obtained using manufacturers instructions and standard labour costs [10]. The SCIS is still in the demonstration stage and actual costs are not available. The developers suggest a cost of £625[3] for the whole system based on 10000 units produced per year [11]. An estimate of low volume production cost; using the 'experience curve' suggests a unit cost of £3735. An estimate by the authors based on system components prices, and standard labour costs gives £3800. TDGS numbers, estimated using the CIE calculation method, suggested that 10 N^o 450 mm diameter were necessary to give 300 lux assuming an external illuminance of 35klx (hourly mean of global horizontal illuminance over Europe) [12,13].TDGS manufacturers' high volume prices were used [14,15].

3.3. Calculation results

Results of this study are expressed in terms of payback period (PB). The present work assumes the building life of 20 years used for UK health estate analysis [16]. For each system in every location PB curves are plotted using an electricity price range between 10 p/KWh (£0.10/kWh) and 50 p/KWh (£0.50/kWh). The electricity price median over EU-27 countries in 2009 is 14.01 p/kWh, which has risen some 46% in 5 years [5]. The 50 p/kWh figure represents the expected long term price. The PB curves show the variation in the PB by year against different system costs and electricity prices alternatives.

4. Tangible costs and benefits

4.1. Costs

Initial capital cost is the one-off cost of equipment at the beginning of a project. For purposes of this work the standard elements used in the calculations include equipment price and installation fees (excluding delivery charges, taxes, design fees, building adaptation cost, and overheads). The data are either obtained from manufacturers' price lists, if available, or are calculated from engineering price databases [10,17]. Running costs are incurred throughout the life of the project include maintenance, repair and replacement costs (hereafter, altogether called maintenance) and electric power cost. Lamps are assumed to be replaced at the end of their nominal life. Passive and active daylight elements are assumed to require regular cleaning, and active systems assumed to require also regular visits for repair and inspection by skilled labour. Labour rates and estimated cleaning time was obtained from maintenance price books [18]. Electricity rates have been obtained from the European Commission statistics [5]. Table 2 summarizes the initial and annual running costs for both high and low volume capital costs.

4.2. Benefits

Since hybrid lighting systems include lamps there is, unlike TDGS, no necessity for a separate ELS offering a capital cost saving. The main benefit of DGS however is that available daylight is used to supplement or replace ELS output, offsetting energy consumption and reducing maintenance costs. Energy load saving is estimated using software developed by the authors [1]. The percentage maintenance cost saving is assumed to be equal to the percentage of full daylight utilization during the assumed annual working hours.

5. Intangible costs and benefits

5.1. Saving in cooling/heating loads

ELS generates heat which although welcome in the heating season is undesirable in the cooling season. Luminaire design is a major influence. Recessed luminaires transfer some 50% of the heat into the ceiling cavity, whereas virtually all that from suspended luminaires enters the room [19]. All lamp types dissipate a large portion of input energy as radiant heat (Infra Red) and, to a lesser extent, by convection to the surrounding air (see Table 3). Only about 10% of the radiant heat is absorbed by the air, most being absorbed by high thermal capacity walls and room contents without any significant increase in temperature. In contrast, heat lost through convection direct affects the temperature of the surrounding air [20].

5.1.1. Comfort zone

The desire to provide comfort temperatures in buildings determines the duration of heating and cooling seasons. Current design thinking is that occupants accept, and perhaps even like, variation of temperature over time, provided that it remains within overall limits [21]. This work uses weather data [22] and climate software [23] to determine thermal comfort zone using either heating or air conditioning. Fig. 2 shows an example of a psychometric chart for

Table 3
Power transformation forms for different lamp types.

Lamp type	Radiation power %			Heat %	Total heating power %
	Visible Light	Infra Red	Ultraviolet	Conducted/ Convict	
Filament lamp GLS	9	84	<0.1	7	14.5
Tungsten Halogen	13	79	0.1	8	16.0
Fluorescent tube	25	35	0.4	40	43.5
Compact F L	24	45	1	30	34.5
Daylight (6500 K)	53	42	5	0	4.0

[3] Currency exchange rate of £1 = US $1.6 is used throughout the paper.

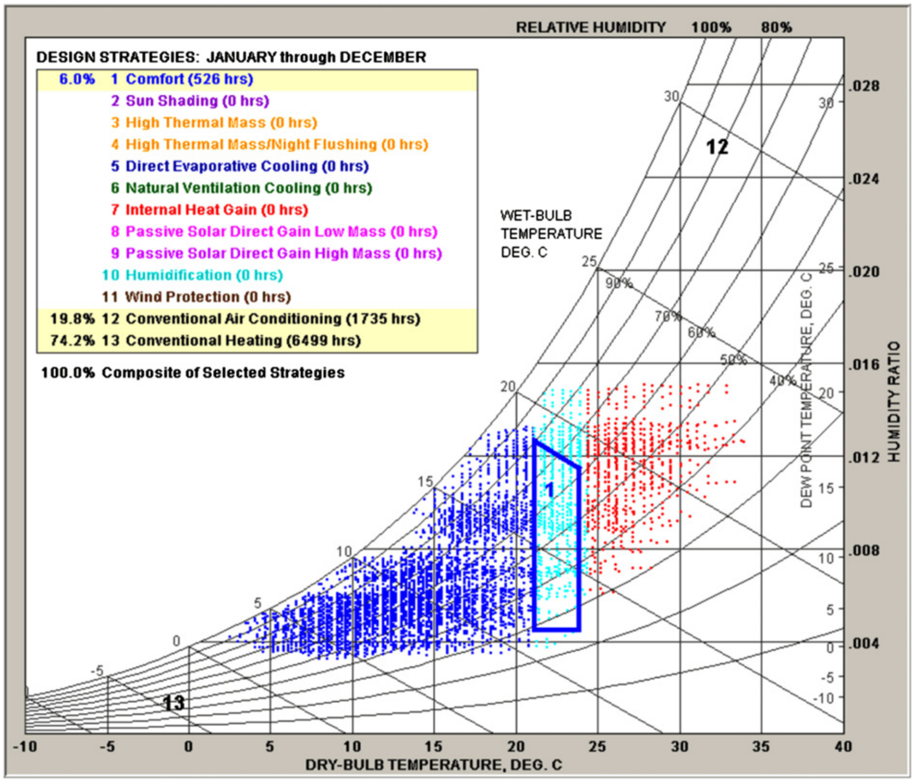

Fig. 2. Psychometric chart for Valencia.

Valencia, showing comfort, air conditioning, and heating zones. The percentage of different temperature zones during assumed working hours is estimated using the two-hourly means of monthly temperatures zones charts and is shown in Fig. 3.

5.1.2. Heat replacement effect

Heat replacement effect (HRE) is the process where energy savings achieved by reducing electric lighting consumption is offset by adjustment in the energy required from the heating/cooling

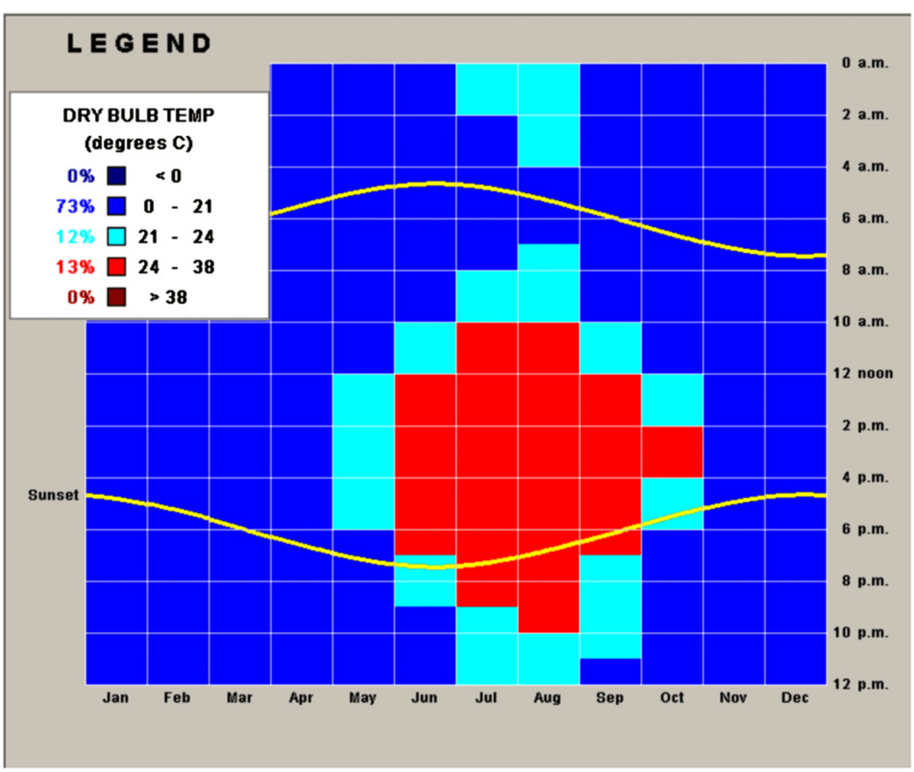

Fig. 3. Two-hourly means of monthly average temperature zones.

system. The adjustment to heating or cooling loads in their respective seasons can be estimated as set out below. This assumes UK practice of heating/cooling system is controlled by a thermostat, the heating system is a gas-fired wet central heating, and the cooling system is a chilled water fan coil units [24]. Efficiency values for other heating and cooling systems can be obtained from reference 24. Solar heat transmission via DGS is assumed to be negligible [9,12,25,26].

The following parameters are used:

h_a annual operating hours [hour]
S_H percentage of heating season [% of h_a]
S_C percentage of cooling season [% of h_a]
W_O power of original lighting system [kW]
W_N power of new lighting system [kW]
HER_O heating efficiency ratio of old lighting system, (from Table 3, column 6) [%]
HER_N heating efficiency ratio of new lighting system, (from Table 3, column 6) [%]
HGE heat generator efficiency for heating system [84% according to Ref. 24]
EER energy efficiency ratio of cooling system [340% according to Ref. 24]
T_e electricity tariff [£/kWh]
T_g gas tariff, (T_g can be assumed = 0.21 T_e) [£/kWh]

$$\text{Emitted heat of original lighting system(kWh)} = (h_a \cdot W_O)HER_O \quad (6)$$

$$\text{Emitted heat of new lighting system(kWh)} = (h_a \cdot W_N)HER_N \quad (7)$$

From Eqs. (6) & (7):

$$\begin{aligned}\text{Reduction in heat emission(kWh)} &= [(h_a \cdot W_O)HER_O] - [(h_a \cdot W_N)HER_N] \\ &= h_a[(W_O \cdot HER_O) - (W_N \cdot HER_N)] \quad (8)\end{aligned}$$

$$\text{HRE during heating season, } HRE_H\text{, (extra loads on the heating system)} = S_H \cdot h_a[(W_O \cdot HER_O) - (W_N \cdot HER_N)]/HGE \quad (9)$$

$$\text{HRE during cooling season, } HRE_C\text{, (extra saving in the cooling loads)} = SC \cdot h_a[(W_O \cdot EER_O) - (W_N \cdot EER_N)]/EER \quad (10)$$

$$\text{Net HRE} = HRE_H - HRE_C \quad (11)$$

From Equation (11), if there is no cooling system in operation, using more efficient lighting system results in extra loads on the heating system. Meanwhile, if there is no operating heating system, using more efficient lighting system means extra saving in cooling loads.

The HRE during moderate seasons, between 21° and 24° as indicated in Fig. 3, is neglected despite the fact that it will slightly offset the air temperature towards heating/cooling zone. The room air temperature is assumed to be remained changing within the thermal comfort zone.

The HRE annual cost and saving calculated using the following formulas:

$$\begin{aligned}\text{Annual cost of } HRE_H &= S_H \cdot h_a[(W_O \cdot HER_O) - (W_N \cdot HER_N)]T_g/HGE \\ &= HRE_H \cdot T_g \quad (12)\end{aligned}$$

$$\begin{aligned}\text{Annual saving in } HRE_C &= S_C \cdot h_a[(W_O \cdot HER_O) - (W_N \cdot HER_N)]T_e/EER \\ &= HRE_H \cdot T_e \quad (13)\end{aligned}$$

5.2. Carbon tax savings

ELS account for up to 30% of electricity consumption across the office sector, and substitution by daylight offers a potential for reducing this. Electricity generation is one of the largest sources of carbon dioxide (CO_2) emissions, which comprises a significant amount of greenhouse gas emissions. The amount of CO_2 released into the atmosphere depends on the fuel mix used in generation in different countries. Table 4, derived from published data, shows the influence of the fossil/non-fossil fuel mix on ‘carbon intensity’ – the CO_2 emission per unit of generated electricity [27,28]. It is clear that wide variations exist.

A number of systems have been promulgated to ascribe a monetary value to carbon emission pollution. Global carbon trading aims, as set out in Article 17 of the Kyoto Protocol, allows countries and organisations that have emission units to spare – emissions which are permitted but not “used” – to sell this excess capacity via a carbon trading market [29]. The Kyoto Protocol established a legally binding commitment on national governments to reduce greenhouse gas emissions. A number of countries have applied the principle of carbon trading – ‘the polluter pays’ – by use of a carbon tax. These first enacted in 1990 by Finland, are effectively a tax on the use of fossil fuels, and vary in method of application between countries. The U.K. version, known as Climate Change Levy,was introduced in 2001 and is currently £0.0043/kWh added to electricity bills [30].

5.3. Effect of daylight on human well-being

5.3.1. Preference for daylight

The popularity of daylight as a light source in buildings is due to a number of factors related to its enhancement of human well-being. Daylight can deliver light of high illuminance together with a spectral composition that ensures favorable perception of color. It can also provide meaningful spatial and temporal variation in illuminance providing interior conditions that are bright, visually interesting and dynamic. Daylight providers such as windows also provide contact with the exterior and can, by influencing physiological responses such as the regulation of diurnal cycle of body activity, improve health conditions in working environments.

Office lighting installations equipped with ELS and conventional glazing systems provide interior conditions that satisfy part or all of the above. A recent study of quantity and quality of daylight delivered by TDGS in large open plan offices in the UK suggests that the light delivered by the guides was recognized by users as daylight [31]. The daylight contribution was of the order of 25% of total workstation illuminance but the guides provided minimal contact with the exterior. Although user views suggested that TDGS were inferior to windows in delivery of both quantity and quality of daylight, there was evidence that user satisfaction improved with increased daylight penetration. Thus it appears that DGS can, if correctly configured, deliver some elements of ‘daylight’ to areas of office buildings remote from, or devoid of, windows [12]. Under

Table 4
CO_2 emissions per kWh from electricity generation for year 2007.

Country	Energy mix (%)				Carbon intensity g CO_2/kWh
	Fossil	Hydro	Nuclear	Other renewable	
United Kingdom	71.4	1.3	20.3	5.3	500
Sweden	2.0	46.9	44.7	4.4	40
Spain	58.1	6.9	19.3	9.4	390
Europe	47.0	13.3	25.0	10.2	310
United State	68.8	6.6	18.4	4.4	549
World	60.6	23.1	9.1	4.3	507

these circumstances the benefits of the delivered daylight could constitute an argument in favour of DGS in any cost/benefit analysis.

It is clear that DGS can introduce some elements of daylight into areas remote from windows. Under these circumstances the benefits of daylight might be less than that delivered via windows but the evidence is that this could still influence user well-being and, possibly, productivity. Since most DGS are sold on the premise of delivering daylight to interiors, and its consequent benefits, it is worth speculating what the magnitude of these benefits might be as part of the cost/benefit process.

5.3.2. Daylight and productivity

Since the majority of office costs are staff salaries (up to 85%) and in comparison energy costs are tiny, small increases in staff productivity are equivalent to large savings in energy. Recent work has demonstrated for the first time the link between lighting conditions and feelings of health and well-being [32]. It showed that people who perceived their office lighting as being of higher quality rated the space as more attractive, reported more pleasant mood, and showed greater well-being at the end of a working day. Also lighting conditions that improved visibility also improved task performance. This is a large step in the process of demonstrating that better quality lighting can enhance productivity.

In industrial or retail settings, productivity may be measurement of output per worker or sales per worker. In knowledge-based work typical of offices productivity encompasses a much wider range of variables some of which are measurable; such as speed and accurately of task completion in rule-based jobs such as call centres. Generally any assessment is confounded by factors contributing to employee productivity – motivation, health, and corporate culture for example – making it difficult to determine how much to assign to the lighting system improvement. Despite the difficulties of quantification it is clear that any small improvement in worker performance would reap huge benefits. Data from the Centre for Building Performance and Diagnostics at Carnegie Mellon University (CMU) estimates building costs/m^2 for offices. Physically housing employees and their activities is typically around £437.5/m^2 (for lease/mortgage, utilities and facilities management costs) while their salaries cost up to £2000/m^2. Thus costs of employees is some 160 times that of energy. The CMU work went on to demonstrate that daylight in the offices studied yielded an annual energy cost savings of £76 per employee (£7/m^2) and annual productivity gains of £1547 per employee (£142/m^2). It also identified in five case studies individual productivity benefits from daylighting ranging from 0.45% to 15%, with an average improvement of 5.5% annually [33]. The CMU case studies were conventional offices equipped with windows. Since DGS do not deliver all elements of 'daylight' it would be anticipated that any improvements in offices partially or wholly lit in this manner would be lower. For purposes of this study a 1% productivity gain is assumed amounting to £28/m^2 based on the CMU figures.

6. Using WLCC method to estimate payback periods

The calculation was performed, firstly, for the costs and benefits set out in Level 1 of Table 1 (the 'base case'), and subsequently including the effects of the heat replacement, carbon tax and productivity Level 2 benefits. Finally the effect of all of the identified costs and benefits were examined. NPV has been calculated for each of 20 years in order to determine the payback point.

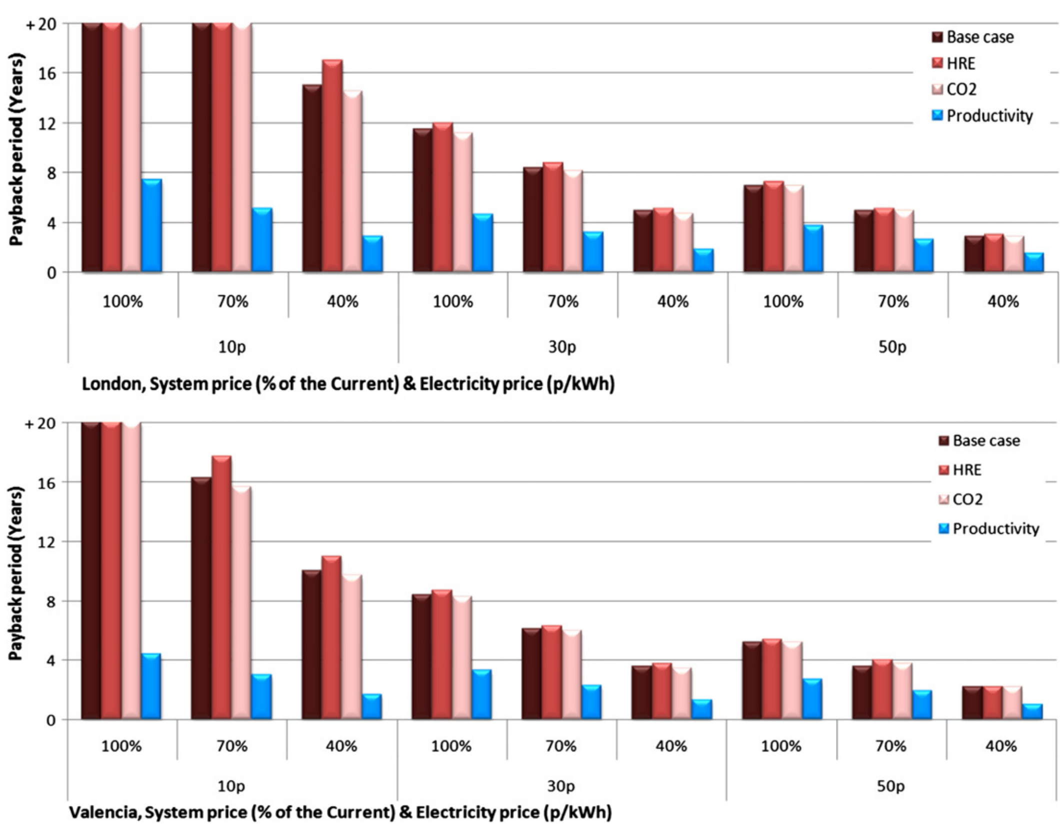

Fig. 4. TDGS – payback period for base case, and base case including the effect of individual intangible cost/benefits.

The calculation was repeated for all DGS at each location using the following:

- Capital and annual running costs summarised in Table 2.
- PB calculations initially assumed a capital cost for low volume production (indicated as 100%). The calculations were repeated assuming capital cost reductions in the initial cost.
- Likely savings as discussed in Section 4.2.
- Inflation and discount constant rates as set out in Section 2.2
- Range of electricity prices as detailed in Section 3.1.

Payback periods for all systems at each location were calculated using Equation (5). The results are expressed in two ways. The histograms in Figs. 4–7 show the payback period for the base case (Level 1 cost/benefits), and the base case including the effect of each individual Level 2 cost/benefit. Note that in some cases the payback period is in excess of 20 years. The graphs in Figs. 8–11 illustrate the effect on payback period for both locations of the Level 1 costs and benefits, and Levels 1 and 2 combined. The dotted line on the graph identifies the local electricity price for 2009 for each location.

6.1. Base case

It is clear from Figs. 4–7 that the two main factors influencing PB are electricity price and system cost. Investment in TDGS at current market prices result in a PB of 5–6 years assuming electricity prices of 50 p. Whilst this price might be reached in the long term, electricity prices nearer to the EU median give PB of between 12 and16 years. In general it can be observed that the HLS systems have longer PB than TDGS even using favourable assumptions.

The HSL system has a PB period above 20 years except when assuming a low capital cost (20% of current) and electricity prices in access of 40 p for Valencia. The Parans system has PB of over 20 years for all locations even under the most favourable circumstances of a Southern location, electricity at 50 p and a mean external illuminance greater than 60 klx. The lower estimated capital cost of SCIS gives PB of 5 years in Southern locations using 50 p electricity. Ten year PB are achieved even using current capital costs assuming 30 p electricity prices in the South and 40 p in the North. In general it is can be observed that the more complicated HLS systems (HSL and Parans) have a long PB; the simplest system, TDGS, has a short PB; while SCIS may have a short PB in sunny locations.

6.2. Heating/cooling savings

The heating periods in London and Valencia are 96.7% and 60% respectively of annual working hours from 0800 to 1800 (see Table 5). From inspection of Figs. 4–7 it is apparent that the heating replacement effect raises the PB due to the extra loads on the heating system. Although 25% of the working hours in Valencia fall in the cooling zone, this is not enough to balance the effect of the heating hours since more energy is required to increase air temperature one degree than to decrease it.

Figs. 4–7 show that the HRE slightly raised the PB for all systems in both locations, though that in Valencia is generally about half that of London. In Valencia the PB of TDGS rose by 0.2–0.5 years, that of HSL system by 0.1–0.9 years, Parans system by 0.3 year and that of SCIS 0.0–1.2 year, all assuming either current market price or estimated high volume production price.

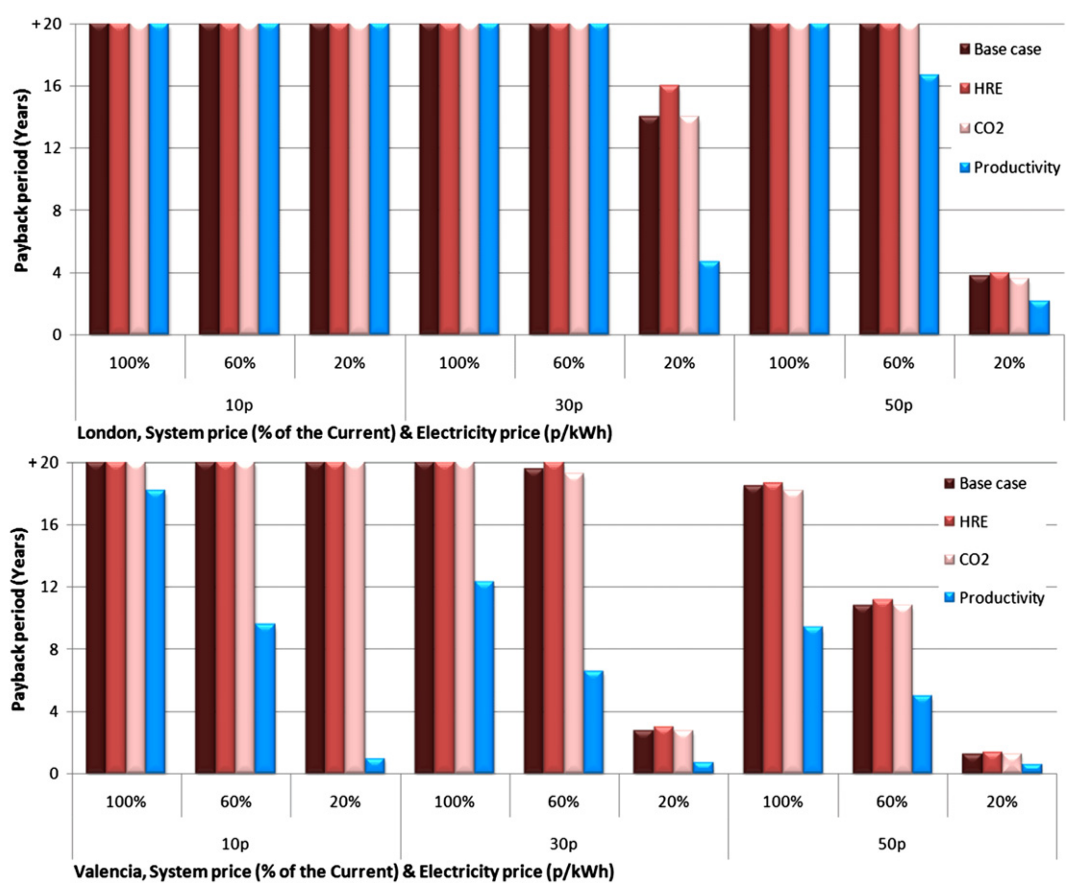

Fig. 5. HSL – payback period for base case, and base case including the effect of individual intangible cost/benefits.

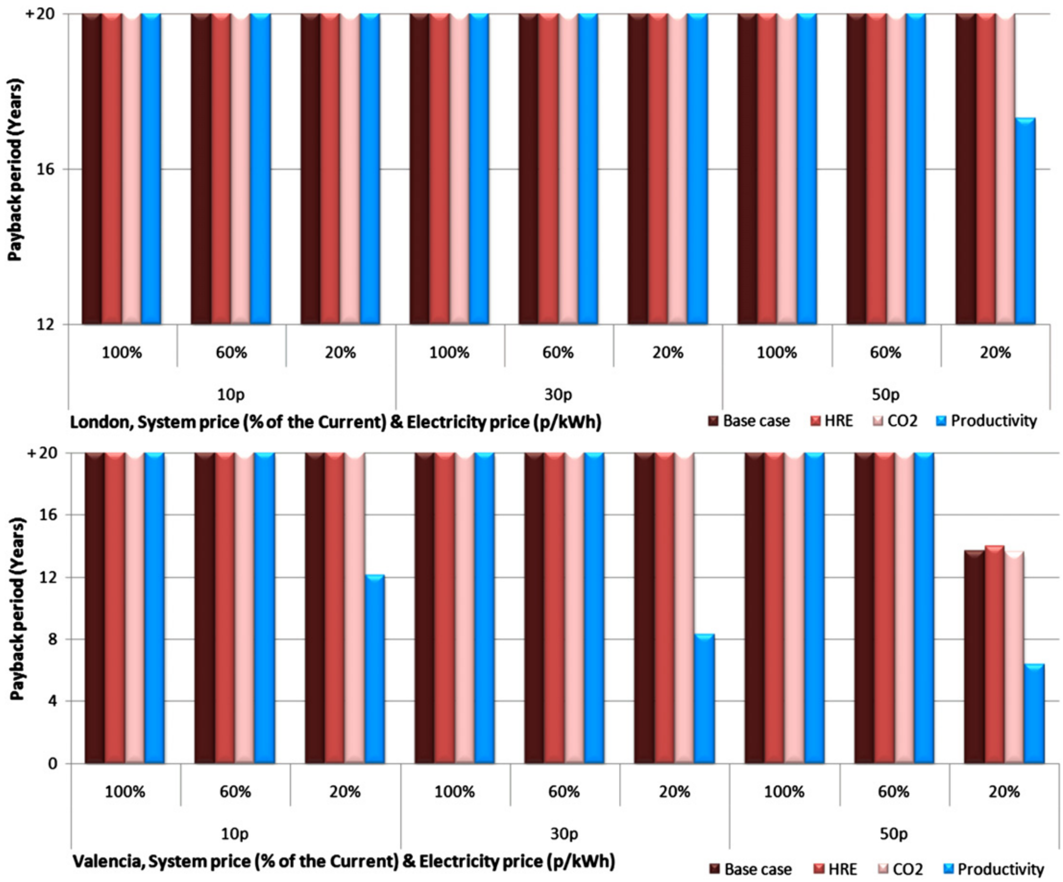

Fig. 6. Parans– payback period for base case, and base case including the effect of individual intangible cost/benefits.

6.3. Carbon tax savings

The effect of Carbon tax savings on the PB is very small using the current UK Climate Change Levy tariff. This is slightly below the average of such taxes enacted in different countries but it is clear that the effect on PB is negligible in comparison with other variables. Figs. 4–7 suggest that the PB reduction, in both locations and with any system, ranges from zero to a maximum of 0.5 year.

6.4. Productivity improvement effect

The productivity improvement of 1%, which assumes the maximum possible delivery of daylight by the DGS over the working hours, is reduced by the percentage of daylight actually delivered due to diurnal and seasonal variation.

It is apparent that the productivity effect gives the most favourable payback of any of the Level 2 benefits. For TDGS and SIC systems the PB is generally below 5 years for all combinations of other variables. For HSL and Parans the high capital costs mean that PB are of the order of 20 years even taking into account any productivity effects. The productivity gains do vary with location due to the greater delivered quantities of delivered daylight in southern locations. Although this result needs to be treated with caution because of the assumptions made, it does suggest that the argument that small increases in staff productivity are equivalent to large savings in energy has some substance.

7. Discussion

Daylight guidance technology has only been commercially exploited over the past fifteen years or so and consequently the accumulated technical and economic experience of its use is limited. Of the two main guidance types tubular daylight guidance systems, although commercially successful, have been used to light only a limited number of working buildings, mainly offices, worldwide. The newer hybrid daylight/electric systems, although on the market, have to date been used for only a handful of actual installations.

This work concerns whole life cycle economic analysis of daylight guidance. Current practice for application of this method to lighting systems is to include only capital cost items, and running costs such as electricity and maintenance. The associated ‘Level 1’ benefits are mainly savings in electricity by daylight substitution, and maintenance. This work uses whole life cycle methods for interiors lit using daylight guidance and electric systems but extends the analysis to include a range of ‘Level 2′ costs and benefits. The latter may include the cost of accommodating guidance systems in a building, and the range of possible benefits include reductions in heating/cooling loads, reduction in carbon taxes and improvement in well-being and productivity of occupants due to daylight.

This work is based on a number of assumptions about the systems and their mode of use and, to aid the interpretation of the results, it is perhaps worth restating these. Assumptions are necessary because DGS is a new technology for which full information is not available. The Level 1 capital costs are those appropriate to high volume production. For some systems market price is used. For some hybrid systems which are not at that stage, high volume costs have been estimated using the ‘experience curve’ based on published costs of prototypes in the expectation that costs will reduce as the technology matures. History suggests that this has been the case for TDGS. Also there is little published

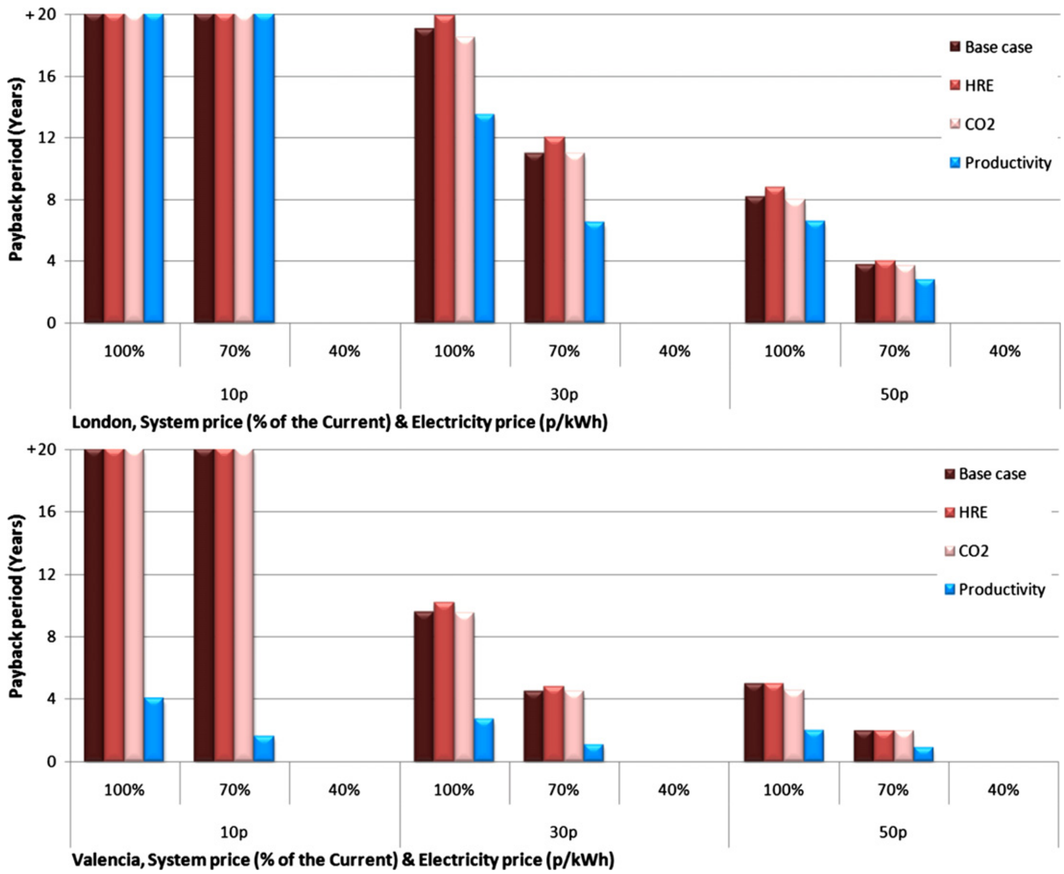

Fig. 7. SCIS– payback period for base case, and base case including the effect of individual intangible cost/benefits.

information on DGS running costs and therefore realistic assumptions have been made on the range of present and future electricity prices and system maintenance. Throughout the work costs of building modification necessary to accommodate guidance systems, particularly in multi-storey buildings, have been excluded since these are specific to a particular building. These may be substantial for some system types, particularly in relation to light transport components, and might include capital costs of ducts and associated opportunity cost of lost floor area. For systems that use optical fibre light transport they will be minimal. TDGS guides require substantial duct accommodation whilst the SCIS requires at least extra storey height and, potentially, almost dictates that the whole building be designed around it. There are a number of assumptions relating to the Level 2 costs/benefits. The heating and cooling systems used, and the carbon taxes, were those typically used in UK practice. Although other assumptions might apply in other countries and geographic locations it has been demonstrated that the effects of both on overall cost/benefit are small.

One of the major marketing arguments used for guidance systems is that it leads to improvement in human well-being in working areas due to the delivery of daylight. In order to investigate the magnitude of the possible productivity effect due to guided daylight a complex set of assumptions, each of which might be challenged, is necessary. The most important assumption relating to productivity is that it may be used as part of a lighting cost/benefit exercise. A link has recently been reported between lighting conditions and feelings of health and well-being, and that lighting conditions which improved visibility also improved task performance. This is a large, but far from conclusive, step in the process of demonstrating that better quality lighting can enhance productivity. Assuming that such a link exists the current work has used data on user productivity enhancements based on conventional offices with windows with the benefits reduced in proportion to the quantity of diurnal and seasonal daylight shown to be delivered by DGS. It should be noted that the remaining two Level 2 benefits listed in Table 1 have not been included in this work. Enhanced corporate prestige is impossible to quantify in this context, and the residual value of DGS are unlikely to be more than a minimal scrap value.

The results of the Level 1 costs/benefits analysis suggest that capital cost is the major factor in determining payback periods. The two systems with the shortest payback (see Figs. 8 and 10), TDGS and SCIS, have low capital costs due to their reliance on simple and relatively cheap optical systems employing low concentrations of sunlight. A caveat here is that the costs of modification of the host building, particularly in the case of SCIS, may significantly increase capital cost for low concentration systems which, by their nature, use large light transport components. The best performing of the low concentration systems-TDGS – although a mature technology, is still unable to payback investments within five years at the current European price of electricity. Indeed the use of electric lighting delivering the same task illuminance on its own would arguably represent a better investment. To approach a five year payback for TDGS, average electricity prices would need to at least double and system price be reduced to 40% of current. Whilst the former condition might, sadly, occur in Europe in the near future, further reductions in price in this technology are unlikely.

In general the hybrid systems have long payback periods based solely on Level 1 cost/benefit considerations rendering them an unattractive investment proposition. Three influences would have to work together to shrink payback periods: electricity price, system capital cost, and available external local illuminance. The trend for electricity

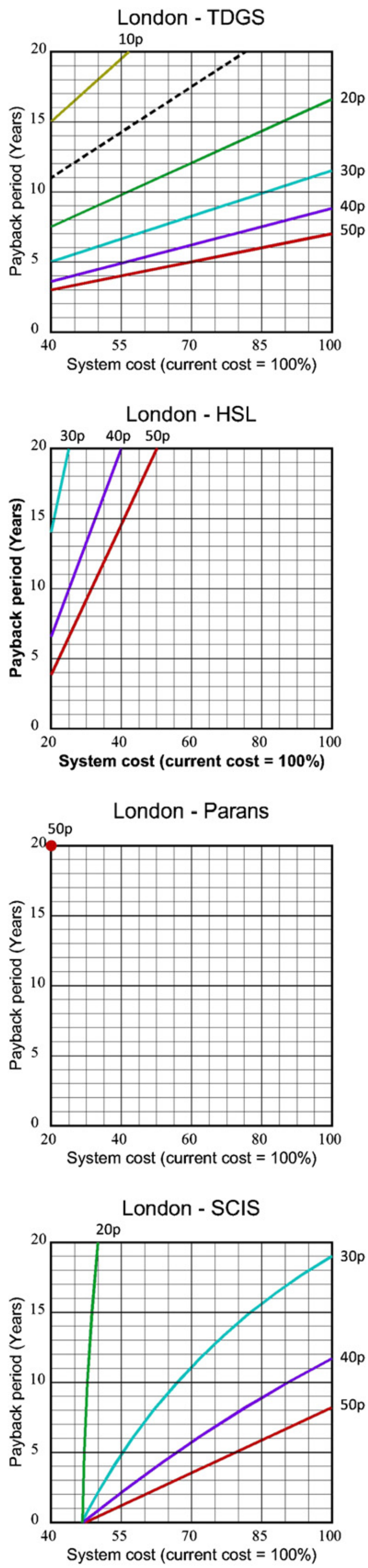

Fig. 8. Payback period for base case – London.

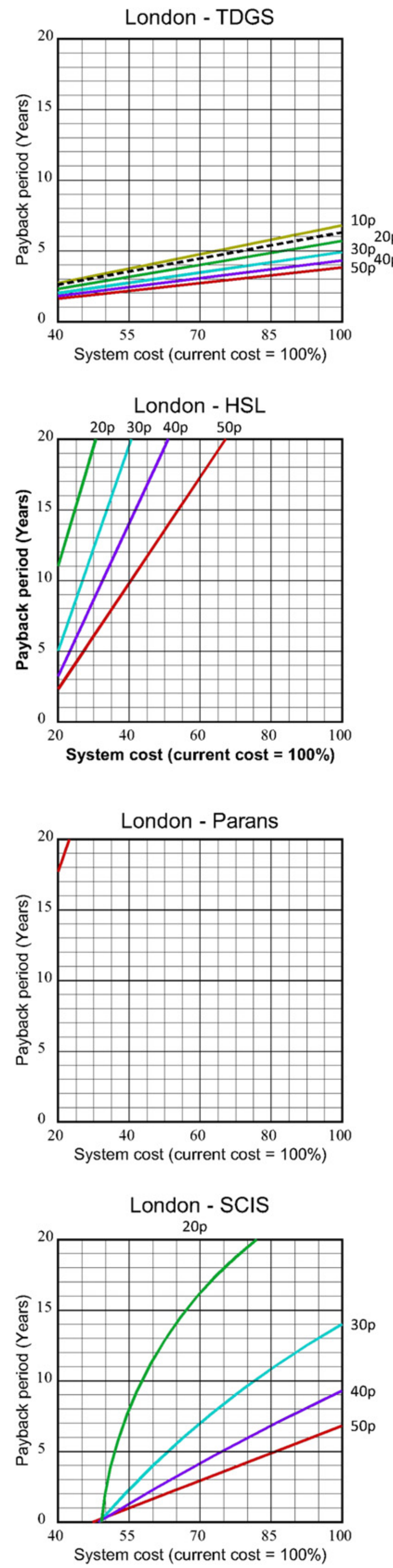

Fig. 9. Payback period including all intangible cost/benefits – London.

price is universally upwards – over five years about 46% across the EU-27 countries [5]. That suggests that in ten years the electricity price in the EU-27 is likely to exceed 30 p/kWh, making the technologies more economic. The current hybrid capital costs are a significant barrier to their use, but reductions in costs due, for example, to volume production are not occurring at the time of writing. The capital cost reductions required to make the systems economic are large. The best performer, HSL requires a reduction equal to one fifth the current price to approach

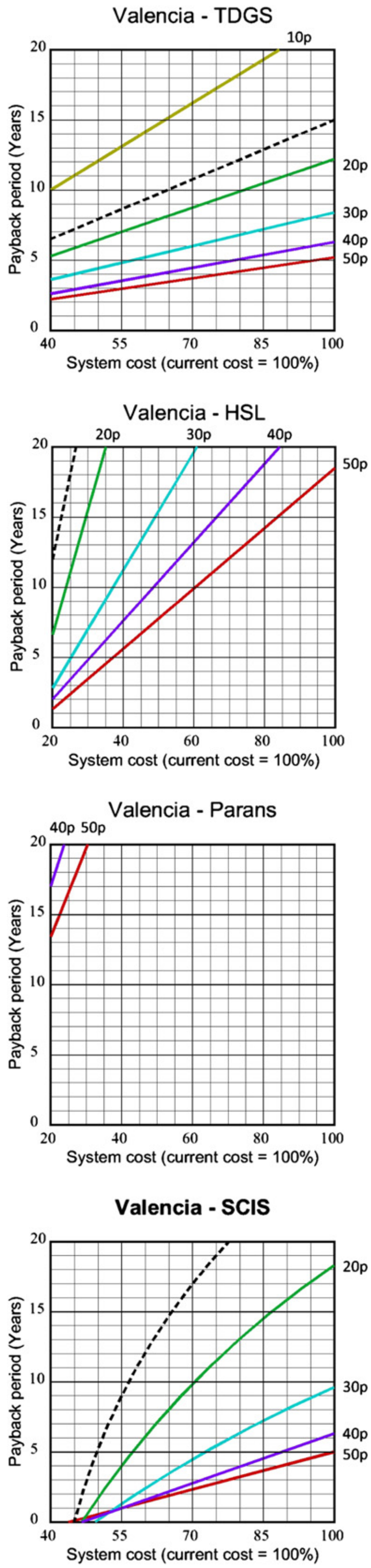

Fig. 10. Payback period for base case – Valencia.

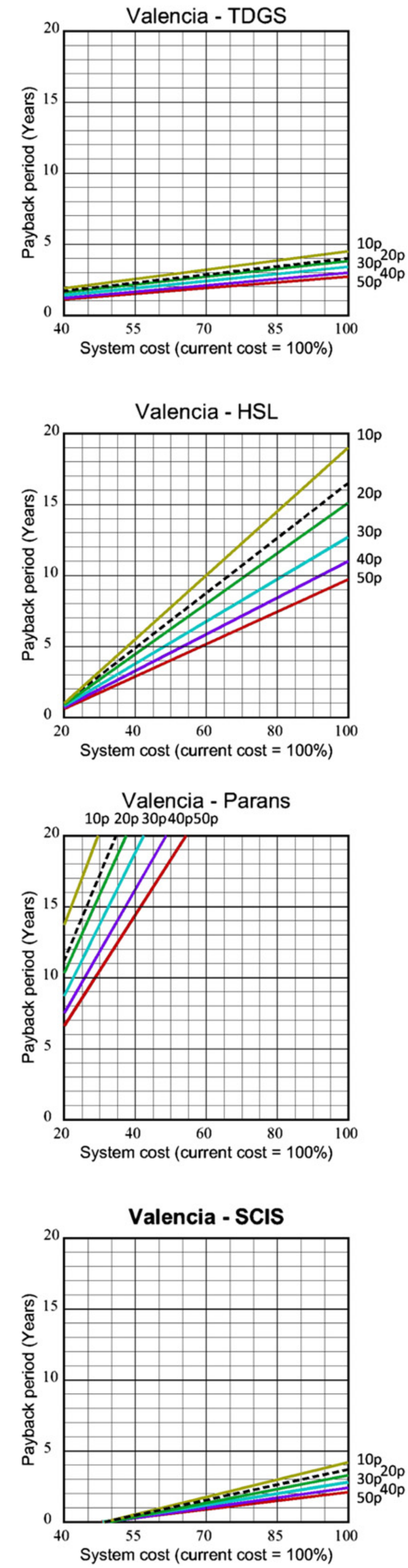

Fig. 11. Payback period including all intangible cost/benefits – Valencia.

a five year payback period in both locations assuming a 30 p electricity price. On the other hand the Parans system capital cost would need to be 10% of current, combined with 50 p electricity price to give the same payback. High external illuminance levels help to reduce the number of hybrid units, and hence capital cost, required to deliver a given luminous flux. A comparison of Figs. 8 and 10 shows the influence of local illuminance conditions in the marked improvement in the performance of the sunlight concentrating HSL and Parans systems between London and Valencia. The low optical concentration TDGS and SCIS units also improve their performance through increased daylight

Table 5
Temperature zones.

		Comfort zone		Cooling zone		Heating zone	
		Hours	%	Hours	%	Hours	%
London	24 h	250	2.9	135	1.5	8375	95.6
	Working h.	122	3.3	0	0.0	3528	96.7
Valencia	24 h	526	6.0	1735	19.8	6599	74.2
	Working h.	548	15.0	912	25.0	2190	60.0

delivery in these circumstances having paybacks of less than ten years using electricity at 30 p. Alas even in southern European below 40N latitude where hourly mean of normal beam illuminance exceeds 50klx, HSL will have a twenty year payback assuming 60% of capital cost and 30 p electricity level. The payback for Parans, even in southern conditions, is considerably in excess of 20 years.

Figs. 4–7 show that the results of the addition of Level 2 cost/benefits to the analysis. It is clear that the benefits of HRE and carbon taxes pale into insignificance in comparison with those of productivity improvements. The HRE generally increases payback by a few months but the effect of the carbon tax is largely neutral. Inspection of Figs. 4–7 shows that productivity gains reduce payback by up to 75%. However it is clear that daylight guidance which is fundamentally uneconomic using Level 1 cost/benefits cannot achieve satisfactory payback even taking productivity into account. Taking all intangible costs and benefits into account TDGS has a payback of between 4 and 6 years (compared with 17–25 years assuming Level 1 costs/benefits) using current electricity prices. A similar pattern of results is apparent for SCIS. Using the same electricity price HSL in the southern location have one year payback instead of 12 years, and in London the payback becomes five years instead of 14 for an electricity price of 30 p. The present high capital of the Parans system,on the other hand, means that even in southern locations the system struggles to achieve payback of approaching fifteen years assuming electricity at 50 p level and capital costs at some 20% of current. Taken together the above suggests that the major influences on the costs and benefits of daylight guidance are capital cost, electricity price and the effects on productivity of daylight. The HRE and carbon taxes appear to have a minor effect.

8. Conclusions

It is clear that DGS require a substantially greater capital investment than ELS. Some such as TDGS have been shown to be economic over the long term if they are solely regarded as devices to enable daylight to be substituted for electric lighting – the 'tangible benefits'. The capital costs of hybrid systems are such that even favourable assumptions about economies of scale render them a very poor investment judged against Level 1 benefits. This work has attempted to quantify the 'intangible' benefits of the delivery of guided daylight to an interior. These are by their nature more difficult to quantify and a number of assumptions, each of which may be questioned, are necessary to make this possible. The results suggest that the benefits of HRE and carbon taxes pale into insignificance in comparison with those of productivity improvements. The latter suggests that investment paybacks could be reduced by up to 75% of those calculated using only Level 1 assumptions. However it is evident that DGS which are fundamentally uneconomic using Level 1 cost/benefits struggle to achieve satisfactory paybacks even taking productivity into account. However in the case of those systems that are only marginally uneconomic the inclusion of productivity does give a more favourable balance of cost and benefit.

This work has established that the economical performance of daylight guidance systems has several dimensions. System payback periods are mainly determined by levels of capital cost, energy costs, external illuminance level (which in turn is influenced by geographical location) and, potentially, considerations of the influence of productivity gains due to daylight in working areas. This study, although based on current technology and costs and a limited number geographic locations, has set out the principles of economic analysis of guidance systems. Work of this nature is essential to enable lighting practitioners to realise the exciting possibilities of daylight guidance.

References

[1] Mayhoub M & Carter D. Hybrid lighting systems: a feasibility study for Europe. In proceeding of the 11th LuxEuropa, vol. 1. Istanbul, Turkey; 2009. p. 265–72.
[2] Boussabaine H, Kirkham R. Whole life-cycle costing, risk and risk responses. Blackwell; 2004.
[3] Office for National Statistics. Prices and inflation. Available at, http://www.statistics.gov.uk/instantfigures.asp; 2010.
[4] Bank of England. Statistical interactive database – interest & exchange rates data. Available at, http://www.bankofengland.co.uk/mfsd/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx; 2010.
[5] European Commission Statistics. Statistics on focus. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/publications/collections/sif_dif/sif; 2010.
[6] European Commission Statistics. Hourly labour costs. Available at, http://epp.eurostat.ec.europa.eu/portal/page/portal/labour_market/labour_costs/main_tables; 2010.
[7] Day G, Montgomery D. Diagnosing the experience curve. Journal of Marketing 1983;47(spring):44–58.
[8] McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy Policy 2001;29:255–61.
[9] FEMP – Federal Energy Management Program. Hybrid Solar lighting illuminates energy savings for government facilities, technology focus, a new technology demonstration publication, DOE/EE-0315; 2007.
[10] Langdon Davis, Wall Mott Green, editors. Spon's mechanical and electrical services price book. 40th ed. Oxon, UK: Taylor & Francis Group; 2009.
[11] SunCentral Inc.. Private communication; 2010.
[12] Commission Internationale de L'Eclairage. Tubular daylight guidance systems; 2006. Vienna, Austria,Technical Report No. 173:2006.
[13] The European database of daylight and solar radiation. Available at, http://www.satel-light.com/core.htm; 2010.
[14] Monodraught Ltd. Available at, http://www.monodraught.com/downloads/index.php; 2010.
[15] Monodraught Ltd. Private communication; 2010.
[16] Department of Health, www.dh.gov.uk/ProcurementAndProposals/PublicPrivatePartnership/PrivateFinanceInitiative/fs/; 2006.
[17] Longdon D, editor. Spon's architects' and builders' price book. 134th ed. Oxon, UK: Taylor & Francis Group; 2009.
[18] BCIS. BCIS building maintenance price book; 2009.
[19] Center of Construction Ecology. Environmentally friendly lighting products, Technical memorandum TM 18/98, produced as part of BSRIA research project 78270. Bracknell, UK; 1998.
[20] The Lighting Industry Federation. LIF technical statement No. 33; 2004. London, UK.
[21] Clements-Croome D, editor. Creating the productive workplace. London, UK: E & FN Spon; 2000.
[22] EnergyPlus. Energy simulation software. Weather data, (Available at, http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm; 2010.
[23] Building energy software tools dictionary. Climate consultant 3.0. Available at, http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=123/pagename=alpha_list; 2010.
[24] Department for Communities and Local Government. The building regulations 2000, as amended 2006. London, UK: Non-domestic heating, cooling and ventilation compliance guide; 2006.
[25] Parans Solar Lighting. Available at, http://www.parans.com/Default.aspx; 2010.
[26] Rosemann A, Mossman M, Whitehead L. Development of a cost-effective solar illumination system to bring natural light into the building core. Solar Energy 2008;82:302–10.
[27] International Energy Agency. CO_2 emissions from fuel combustion. Paris: IEA; 2009 Edition.
[28] Carbon Monitoring for Action, CARMA. Available at, http://carma.org/region; 2010.
[29] Unfccc, Kyoto Protocol. Available in 2010 at, http://unfccc.int/kyoto_protocol/items/2830.php; 1997.
[30] HM Revenue & Customs. Climate change levy. Available in 2010 at, http://www.hmrc.gov.uk/index.htm.
[31] Carter DJ, Al Marwaee M. User attitudes toward tubular daylight guidance systems. Lighting Research and Technology 2009;41(1):71–88.
[32] Veitch JA, Newsham GR. PR Boyce and CC Jones Lighting appraisal, well-being and performance in open-plan offices: a linked mechanisms approach. Lighting Research and Technology 2008;40:133–51.
[33] Cargegie Mellon University. Building investment decision support [BIDS]; 2004.