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Cost/benefit analysis for building core sunlighting systems

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ABSTRACT

The economic efficiency of building core sunlighting systems (BCSS) that are used to deliver sunlight into building core is essential for their widespread use. This study analyses the costs and benefits of using the BCSS through a parametric evaluation process considering key parameters, such as installed and saved lighting power, electricity costs, BCSS initial costs and cleaning costs. The latest seems to be a very influential parameter. Values higher than $2/m^2 are not expected to result in a positive return of investment in the installation of the BCSS.

Economic performance matrices have been generated to provide parametric tools, by which the economic performance conditions can be easily estimated. They show a wide spectrum of scenarios includes best-case and worst-case scenarios. In the worst-case, the BCSS cannot payback the investment. Meanwhile, in the best-case, a payback period of about 4 years is achieved, which is equivalent to about 81% saving of the electric lighting system electricity costs throughout the BCSS lifespan. This can be translated into $0.56 savings for each kWh of installed electricity power throughout the BCSS lifespan.

1. Introduction

Building core sunlighting systems (BCSS) are used to deliver sunlight into building core spaces, i.e., spaces not adjacent to windows or skylights. BCSS have the potential to reduce energy requirements for electric lighting systems (ELS) and associated cooling loads, through electric lighting controls that dim electric lighting based on available daylight from BCSS.

The provision of daylight in buildings is not only aimed at reducing energy consumption and associated cost, but also improve the quality of the visual environment and contribute to occupant satisfaction and psycho-physiological well-being through connection to the outdoors and support for circadian rhythms [1,2]. This paper is focused on quantification of the tangible costs and benefits of BCSS. In spite of the intangible impacts of many of these aspects, since their monetary values are difficult to be quantified, all of them ultimately influence the economic performance of the BCSS [3].

1.1. Background

BCSS generally consist of three integrated components used to collect, transport, and distribute sunlight [4,5]. The sunlight collection component usually involves mirrors and/or lenses, which often concentrate sunlight. Sunlight collectors may also track the sun, as it appear to be moving on the sky, to maximize sunlight collection. The sunlight transportation component uses additional optical elements, such as fiber optics and light guides (ducts) to transfer the sunlight from the collector point, usually at the building envelope, to the daylight distribution point, at the building core. The sunlight distribution component uses additional optical elements to spread the transported daylight across the building core space being served [6–13]. In some cases, the light guide may be dual functioned to transport and distribute sunlight along its route [9,11,12]. Both sunlight and daylight can be transported by daylight guidance systems without concentration via light pipes or light shafts [14,15].

The literature about the BCSS economics is very limited. Most of the published cost/benefit studies either generally discuss the architectural lighting economics [16,17], electric lighting products and retrofits [18–20],or investigate a specific application [21,22]. The most related study to the current one is a study conducted by Mayhoub and Carter that investigated the economic performance of commercially available core sunlighting systems [3]. It concluded that the tubular daylight guidance systems (light pipes), which is considered the simplest BCSS, could payback the investment within

Abbreviations: BCSS, building core sunlighting system; ELS, Electric lighting system; PB, payback period; NPV, net present value; PV, present value; FV, future value; LCS, life cycle saving; kWh, kilo watt hour.

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the assumed 20 years lifespan. Meanwhile, the capital cost of more complicated BCSS than the light pipes, such as Parans [23] and SunCentral [11] systems, render them a very poor investment judged against the tangible benefits, mainly electric lighting savings and associated costs. The payback periods in these cases exceeds the assumed 20 years lifespan of the BCSS. Taking some intangible benefits into account, such as the effect on occupants' productivity and well-being, suggested that investment paybacks could be reduced by up to 75% of those calculated using only tangible assumptions [3]. The study assumed 1% increase in the productivity due to the utilization of the BCSS [3], based on study conducted by Carnegie Mellon University [24].

1.2. Study objectives

Meanwhile Mayhoub and Carter study is limited to particular systems under specified circumstances; this study is focused on a more abstract, and thus mode widely applicable, consideration of BCSS economic performance, through parametric performance evaluation considering key parameters, such as installed and saved lighting power and cost of electricity, including cleaning costs, which are generally ignored by developers and scholars. This study enables a general prediction of the economic performance of any BCSS under any circumstances. In addition, it provides economic indicators determine under which circumstances a BCSS can be used economically. Moreover, it identifies the most sensitive parameters that have the potentials to improve the BCSS economic performance. Furthermore, the study draws attention to the influence of the cleaning cost on the economic feasibility.

The effect of the dust accumulation on the solar panels industry has been addressed since 1940s [25,26]. Most of these studies investigated the dust accumulation effect on the photo voltaic panels, however, a few studies have investigated the dirt accumulation effect on the flat and parabolic mirrors [27,28]. A recent study by California Lighting Technology Center (CLTC) has found that dirt accumulation on BCSS collector surfaces significantly reduces its performance. The dirt was allowed to accumulate on the solar collector for 89 days. The average peak output of the system luminaire by the end of this period was about 160 lux. After cleaning the solar collector, the average peak output increased to about 630 lux [29]. Accordingly, a periodic cleaning scheme needs to be applied. Such a scheme restores the performance of the BCSS, which increases their economic performance; conversely, it raises running costs, which reduce the economic performance.

2. Methodology

Many financial metrics can be used for comparing different possible courses of investments. Among them, the Payback period (PB) is one of the simplest investment appraisal techniques. It indicates how quickly the cost of an investment is recovered, but does not measure its profitability [30]. The two main deficiencies of the PB method are that it does not take into account cash flows after the project's payback period and that it ignores the time value of money [31]. Accordingly, more advanced calculation methods based on discounted cash flows were suggested, since the investment in the commercially available BCSS tends to lead to a PB period that exceeds the accepted limit [3], which is usually less than 5–7 years [32].

Since this work is intended to be widely applicable, the calculations are not based on the data of a particular BCSS, but values ranges are used to suit most of the BCSSs as explained in Section 2.2.

2.1. Calculation method

The economic analysis was carried out using the net present value (NPV), which is the difference between the present value (PV) of cash inflows and the PV of cash outflows over time [33]. The NPV is calculated using the following formula.

$$\begin{aligned}\text{NPV} &= \text{PV of cash inflows} - \text{PV of cash outflows}\\ &= \text{PV of electricity saving} - (\text{Initial cost} + \text{PV of cleaning cost})\end{aligned} \tag{1}$$

In Eq. (1), the cleaning costs are considered the dominant part of the maintenance costs. Although other maintenance costs may be exist, the cleaning costs have been determined to be the most important and applicable to most BCSSs.

Since the electricity savings and cleaning costs are calculated using today's money, the time value of money is acknowledged by use of the PV method, which compounds and discounts cash flows using Eqs. (2) and (3). The today's values of the electricity savings and cleaning costs are estimated, then compounded using Eq. (2) to calculate a series of future values (FV) of the electricity savings and cleaning costs over the BCSS lifespan. All FVs are discounted using Eq. (3) to calculate the PV of the electricity savings and cleaning costs in order to calculate the NPV.

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

$$\text{PV} = \text{FV}(1+r)^{-t} \tag{3}$$

where:

K = Annual cost or savings ($)
r = Annual discount rate (%)
i = Annual inflation rate (%)
t = Considered time period for evaluation (Year)

Using Eqs. (2) and (3), the NPV (Eq. (1)) can be expressed as follows:

$$\text{NPV} = \sum_{t=1}^{n} \frac{\Delta E_t (1+i)^t}{(1+r)^t} - \left(I_0 + \sum_{t=1}^{n} \frac{C_t (1+i)^t}{(1+r)^t} \right) \tag{4}$$

where:

I_0 = Core sunlighting system Initial cost ($)
ΔE = Annual electricity cost saving ($)
C = Core sunlighting system annual cleaning cost ($)The point in time when the difference between the cash inflows and cash outflows reaches zero is the PB period, where the investment in the BCSS is returned and the net benefits start.

2.2. The parametric approach

Since a large number of parameters influence the economic performance of BCSSs, a parametric approach was used focusing on the most influential parameters (Table 1). In this work, they are considered the least number of key parameters that are required to accomplish a cost/benefit analysis.

In Table 1, we show the fixed values (Group A) and value ranges (Group B) that were assigned the key parameters that affect economic performance. The justification of the values ranges in Group B is listed in Table 2. By this way, the cost/benefit analysis is not dependence on the data of a particular BCSS, but can be widely applied on any BCSS, regardless its initial cost, cleaning cost, or efficiency (electricity savings).

The influence of each parameter in group B on the economic performance was investigated. Therefore, the default values (Bold values in Table 1) were used in every case with exclusive change in the values of the investigated parameter. The default values of the electricity savings and cleaning cost were assumed at 100% and 0.0 $/m^2, respectively, to eliminate as many parameters as possible for each variable considered. Examination of the PB trend curves