SIMULATION OF PV-BATTERY-LED SYSTEMS IN OFFICE BUILDINGS

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ABSTRACT

We present a simulation model that can describe the coupled behaviour of PhotoVoltaics (PV), a storage battery, and solid-state Light-Emitting-Diode (LED) lighting, for a single office room in a generic multi-level building in the United Kingdom. The PV modules are integrated into an unobstructed south-facing façade possessing a window, and hourly data analysis for the whole year of the PV-generated electricity, daylighting, and artificial lighting levels is performed. The lighting load is split into background and task requirements, and for the background requirements a fairly modest PV area is required. The dependence of the payback period on the system parameters was investigated, and it was found that the efficiency of the photovoltaics, and their cost per unit area were most significant. The luminous efficacy and cost of the LEDs, and the battery cost, at best had a moderate effect. The use of daylighting to reduce the lighting loads had only a minimal effect on the payback period. These considerations must be made when designing PV-LED-battery systems for buildings.

INTRODUCTION AND BACKGROUND

Energy efficiency has been taken on an increasingly important role, given the threat of dwindling resources and climate change. Buildings are one of the largest users of energy in the Western world, and there is plenty of scope for reducing its use. Lighting contributes around 20% of the energy use, and the potential exists to half this figure. A technology that has matured during the last few years is semiconductor Light Emitting Diodes (LED), which use direct current (DC) electricity for their operation. Another technology that has also gained popularity in the Built Environment in recent years is semiconductor PhotoVoltaics (PV), which generate DC electricity directly from sunlight. The two technologies can be used in combination to potentially produce an efficient and sustainable interior lighting system.

Traditional lighting systems used incandescent (i.e. filament) light bulbs. Although cheap to purchase, and possessing a good light quality which mimics natural daylight, less than 5% of the electrical power is converted into light with the remainder being emitted as heat into the room. This means energy is wasted both in powering the bulb, and in the building cooling systems to extract the emitted heat from the room. A few decades ago, fluorescent lighting came on the market: It is more efficient than incandescent lighting (around 10%), but produces a rather artificial light output profile which can cause psychological discomfort to occupants, and also produces toxic substances (e.g. mercury) making their safe disposal quite problematic.

LEDs were first invented in the 1960s and were mainly used in lighting applications for electronic equipment, due to them emitting a particular colour, and due to emitting light in a quite narrow beam (less than 30 degrees). Compared to old light sources, they have a much longer lifetime, typically 25 years as opposed to 5 years (CFL) and 2 years (incandescent). The last decade has seen unprecedented improvements; LEDs can generate warm-white light with a spectrum that is almost as good as daylight, and even a single luminaire can have its spectral output programmed to be time-varying such that it can mimic the behaviour of daylight over a full day (Jou, Wu et al. 2009). Sophisticated optics allow light emission at both wide and narrow beam angles, and luminaire efficiencies are now at least as high as the corresponding CFL. The only major difference is the initial capital cost.

The big breakthrough came when (Humphreys 2008; Zhu, McAleese et al. 2012) shown that it was possible to take advantage of the processes in the manufacturing of computer chips to reduce the cost of producing LEDs by up to tenfold; the typical purchase price of an LED luminaire is now around three times as much as the CFL counterpart but the physical performance is at least as good as, if not better. According to (Shailesh and Raikar 2010), the operating costs over 25 years for an office room can be reduced by 80% if the constant use of fluorescent lamps is replaced by LED lighting combined with sensors for daylight and occupancy levels. The one outstanding issue that remains is thermal management: Although less heat is produced than in other light sources, if it is not extracted away from the device then the light output will degrade (Biber 2008), or even worse damage will occur. Both (Parry 2011) and (Dong and Narendran 2009) discuss how to address the issue using Computational Fluid Dynamics.

PV technology has traditionally been the domain of remote, off-grid systems, due to its efficiency losses when implemented in the form of centralized, large-scale power generating plants. Improvements in performance and cost have made PV panels increasingly popular in being integrated into the building architecture. As of 2012, the average efficiency of PV modules is around 15% with a cost of £500 per square metre, and this is set to improve even further. Solar electricity is DC, yet many of the appliances in a building are Alternating Current (AC), and an inverter is needed to make the required conversion; this will result in significant efficiency losses. Nevertheless, Liu has performed a system optimization for using PV and battery to power residential buildings in Queensland (Liu, Rasul et al. 2012; Liu, Rasul et al. 2012), and finds that 6kW roof-mounted panels with an angle of 20-25 degrees can provide nearly two-thirds of the AC electricity requirements.

Given that LED lighting is also DC, this makes it ideal to use PV panels to power LED luminaires for interior room lighting; there are efficiency savings on not involving the use of an inverter. However, sunlight is not constant, and the lighting energy is sometimes needed when the sun does not shine. Clearly, some sort of storage is required in the form of a suitable battery. During the winter months sunlight is minimal and electricity must be drawn from the grid, and correspondingly during the summer months more electricity will be produced than is needed for the building; the excess is sold to the grid at an externally determined rate. According to tests by (Sastry, Kamala Devi et al. 2010), the combined PV and battery energy sizing can be reduced by up to 50% if PV modules are used to power LED lamps rather than CFL lamps. Note that although an inverter is not needed when PV is used to directly power LEDs, it is needed when use is made of the grid. Having said that, (Boeke, Wendt et al. 2011) show that using PV to power LED lights still results in electricity savings of 15% compared to using AC mains alone. Moreover, by having an appropriate *local* DC electricity grid for rural businesses, the PV and Battery costs (and the overall economic costs of PV-powered systems) can be significantly reduced (Panguloori, Mishra et al. 2011). (Patel, et al. 2011) discusses a systematic procedure for estimating the overall efficiencies when various types of components are involved, and (Pode 2010) discusses strategies for encouraging uptake of PV-LED systems .

The benefits of wall-mounted PV are not only electrical: The structure can act as a Trombe Wall, where the heat generated from the incident sunlight can be used to warm the room using natural ventilation (Yun, McEvoy et al. 2007); typical heating efficiencies are round 45%. In addition, if a DC fan is used, cooling of the PV array can be assisted during the summer months (Jie, Hua et al. 2007). One consequence of changing to LED lighting is the reduced heat emitted into the room, and this has the potential for creating a 'rebound effect' where the occupants increase the heating in a cold climate. An ongoing investigation by the authors is to determine whether the heat generated by the PV Trombe wall can replace the heat lost by changing to LED lighting.

As the lighting load will vary during the year due to daylight, it is assumed that a suitable Maximum Power Point Tracking (MPPT) algorithm is in operation (see (Esram and Chapman 2007), and references contained therein). An innovative method of increasing battery charging capacity by nearly 80% has been suggested by (Huang, Wu et al. 2010), which states that instead of using MPPT for the PV in relation to the load, operate at *near* maximum power point while using pulse width modulation to control discharging of the battery. This also has the advantage of reducing the MPPT conversion loss when an undersized load is used.

It has been suggested that using solar-angle tracking for PV systems can increase power output by up to 50% (Kelly and Gibson 2009). Although this is not considered in the present work, it is nevertheless being considered by the authors in a separate investigation for residential buildings.

The analysis of non-uniform illuminance levels on the working plane normally requires detailed modelling (e.g. using Dialux), and it must be emphasized that the aim of this work is not to compete with such sophisticated methods. Rather, it is to give a first indication of the departures from uniform illuminance, such that key decisions on several 'what-if' scenarios can be made during early-stage design. Once the optimum building configuration has been chosen, then detailed analysis can proceed as usual; indeed, the resulting value of the lighting energy from this can be input into the spreadsheet used in this analysis to more accurately determine the PV area and battery capacity. It is hoped that this shall become a useful tool for architects, engineers, and building managers alike. Although this work focuses on the United Kingdom, the fundamental methodology can be applied anywhere in the world.

METHODOLOGY

The system under consideration consists of PhotoVoltaic (PV) panels, a battery, and the DC loads, in this case the LED lighting and computers (Figure 1). The PV and lighting energy performance of a single office room in a multi-level building that had PV panels attached to the south-facing façade (Figure 2) was evaluated for a wide variety of physical parameters.

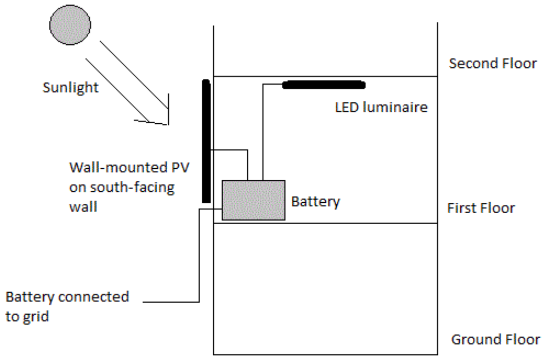

Figure 1. Cross section of the office room in the multi-level building, with PV mounted on the south-facing wall.

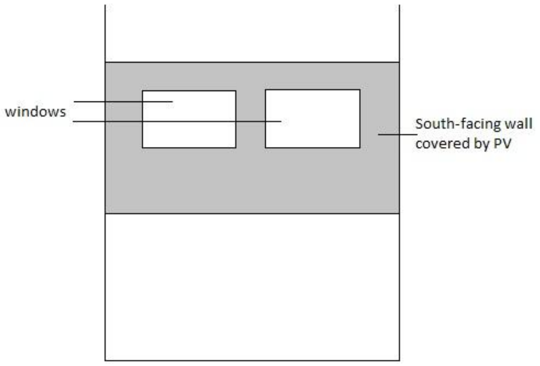

Figure 2. The office building as viewed from the front, i.e. towards the south-facing wall.

Both commercial software and Excel spreadsheet-based analyses were used. Annual hourly solar radiation data for Bristol was obtained from ECOTECT, and converted into Watt-hours (Wh) for the PV panels. Hourly daylight simulations for a cloudy sky were also carried out for each month, and this illuminance was subtracted from the background lighting illuminance requirement to create an effective hourly background lighting load. In order to ensure MPPT, the required PV area would be determined by the annual load requirement.

The battery capacity was sized in relation to the daily excess of the load requirements versus the PV input averaged over the year, and this was termed the daily **deficit**. In sizing the battery, a margin of 50% spare capacity was allowed to account for various losses. Its state of charge was determined by the difference between energy input from the PV, and energy extracted by the loads, including a battery self-discharge of approximately 2% per month. As the hourly self-discharge is relatively small, of the order of a fraction of a Wh, this behaviour can be assumed as linear.

The **state of charge** on the battery is determined by the difference between the PV energy input and its use by the loads. If this difference is greater than the maximum capacity of the battery, then any **excess** is fed to the grid. Conversely, if the PV input is insufficient to power the loads, then the (hourly) deficit will be taken from the grid. Separate hourly profiles for both the background and task lighting were specified, and annual hourly values for the state of charge, deficit, and excess were calculated. From these quantities, the monthly values over the year of highest and lowest excess/deficit are obtained, and whether or not there is an annual net use of the grid. The price for using the grid is 12p per kWh.

Excess energy fed to the grid will result in a price being paid by the government to the building owner, called a *feed-in tariff* (FIT). The FIT gradually decreases every year, and as of early 2013 it is 16 pence per kWh for generation (irrespective of whether or not it is used locally) plus an *additional* export tariff of 4.5p per kWh (UK Govt. DECC, 2012). This payment, in addition to the savings on the electricity bill prior to installation, can be used to offset the initial cost. The time it takes for this to happen is called the **payback** period, and it can depend on a number of factors, which this research attempts to quantify. The following factors were chosen: PV area, FIT, PV cost, LED efficiency/cost, Battery size/cost, and efficiency/cost of the lighting system used prior to installing LEDs. When describing the efficiency of a luminaire, one must only consider the wavelengths (and corresponding light energies) that are sensitive to human vision, and not anything outside this range. One therefore talks of lighting power in **lumens**, which, approximately speaking could be regarded as 'optical watts', and the number of lumens reaching a square metre of the working plane is termed **lux**. The ratio of lighting power to electrical power is termed **luminous efficacy**, or just 'efficacy'.

The **Lumen Method** regards the light from a luminaire as corresponding to a mathematically equivalent source that is uniformly distributed over a certain area of the ceiling, and emitting vertically downwards over that same area of the working plane. If the luminaire has power P and luminous efficacy η, then the total number of luminaires N that are required to produce a given lux level E at the working plane of area A is

$$N = \frac{EA}{\eta PMU}$$

M is the maintenance factor, and U is the utilization factor. M accounts for the degradation of the luminaire over time (e.g. due to dirt), and U describes the fraction of light from the luminaire that actually reaches the working plane. For a given capital cost of the PV-battery-LED system (C), annual FIT (G), and annual costs of the old lighting system (L), the payback period (T) in years is given by

$$T = \frac{C}{(G+L)}$$

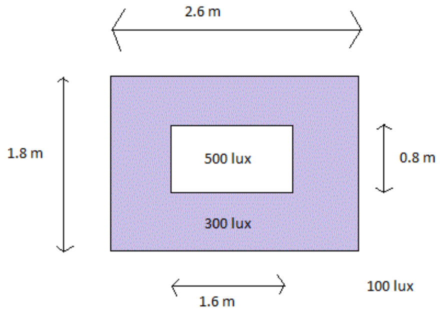

Figure 3. The modern requirement for illuminance in offices – 500 lux at the desk, 300 lux in the immediate neighbourhood, and 100 lux in the background.

Traditionally, the illuminance requirement for an office was a uniform level of 300 lux on the working plane; this originated from having to use a typewriter for detailed tasks. Now that computers are used, the requirements have changed (Raynham 2006), where increased illuminance is required on the desk, and a lower illuminance away from the desk (Figure 3). The **background** lighting level of 100 lux is the minimum required to safely move around the space, and the lighting level of 500 lux at the desk is what is required to do a detailed **task** (and minimize the risk of glare). The area immediately surrounding the desk, the **neighbourhood**, has a lighting level of 300 lux. Given that the occupants of the office will not always be at their desks, the lighting load was split into two parts: The background load, and the task load.

The loads will depend on the type of luminaire we use, but a typical luminous efficacy for warm white LEDs (as of 2012) is 60 lm/W, and this can only improve even further. For a room with 7m x 7m floor area and 3m height (implying K-factor and Utilization factor of 1.17 and 0.9 respectively), one can use the lumen method to show that if the desk level requirement of 100 lux is to be satisfied using 7W ceiling-mounted luminaires, sixteen of these luminaires are required resulting in a total power requirement of 112 W.

For the task lighting, it was assumed that a single luminaire was 10W with an efficacy of 60 lm/W, and the lumen method was separately applied to both the neighbourhood and task areas.

The old lighting system that is being replaced is a CFL based system of efficacy 60 lm/W producing a uniform distribution of 300 lux over the *entire* working plane of the office.

The exterior wall area was 21 m^2, and the total window area was 4 m^2, leaving a maximum area of 17 m^2 for mounting PV panels; it was assumed that there were no exterior obstructions to create shadowing. The PV efficiency is assumed to be 15% with a cost of £500 per m^2, and the battery cost is 40p per kWh; this is expected to drop below 30 p/kWh in a few years, making lithium-ion batteries competitive (Braun, Büdenbender et al. 2009).

RESULTS AND DISCUSSION

To begin with, only the background lighting is operating. At a later stage, we shall bring in task lighting.

Assuming an overcast sky, the daylight levels at a height of 1 metre varied between 24 lux (winter), and 76 lux (summer) (Figure 4). During the summer months, daylight can provide more than half the required illuminance.

Naturally we would expect the use of daylight to reduce the electric lighting load. Mathematically speaking, this is equivalent to reducing the electric lighting requirement, and the illuminance was varied between 100 lux and 20 lux. This resulted in a slight decrease in the payback period of just less than 2 years (Figure 5).

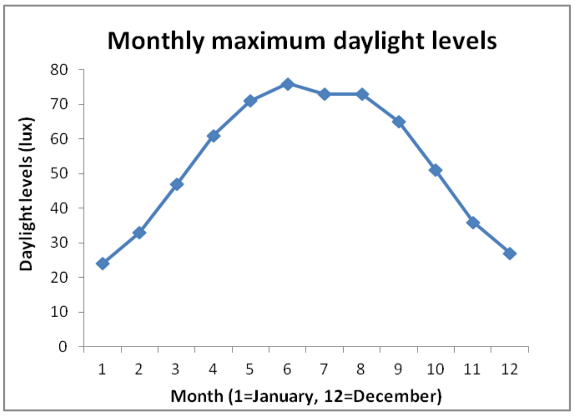

Figure 4. Monthly peak daylight levels on the working plane for an overcast sky

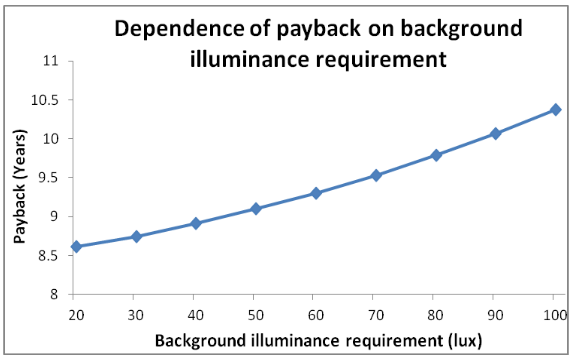

Figure 5. The effect of background illuminance requirement on payback

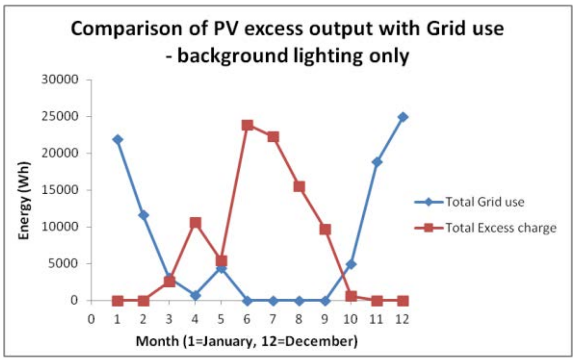

Figure 6. Comparison of PV output with grid use over the year

Figure 6 shows that the for background lighting, excess PV capacity is generated for six months, and most of the grid use is during the other six months. The PV area corresponding to this requirement that the annual net sum is zero was found to be 4.4 m^2, which is a fairly modest size. This also resulted in a battery size of 127 Ah, which is well within the range of typical devices on the market, including the emerging Lithium-Ion technologies.

The exterior wall has an area of 21 m^2, and the windows occupy an area of 4 m^2, both of which are fixed. The amount of the wall covered by PV was gradually increased, until the available wall space of 17 m^2 was completely filled. The payback period appears to increase quite rapidly at small PV areas, and increases less rapidly at larger PV areas (Figure 7). This is due to the increased cost of PV at larger areas in comparison to the money gained from selling electricity to the grid. It is better to choose smaller PV areas than larger ones.

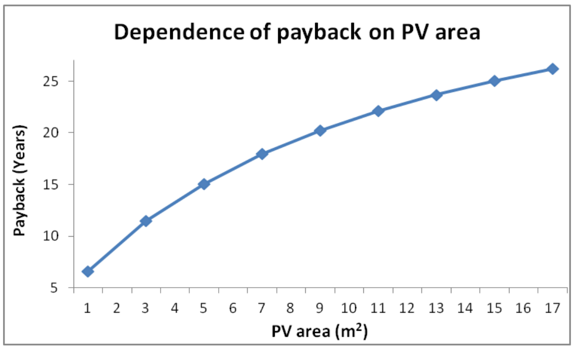

Figure 7. Dependence of payback on PV area

For a battery cost density of 40p per Wh, the capacity of the battery was varied from 200 to 1000 Wh (Figure 8). It was expected that as the capacity of the battery increases, then so does the proportionate cost (and payback period). Indeed, this is what is observed. So there is little point in oversizing a battery beyond that required to provide for the daily deficit for most months of the year.

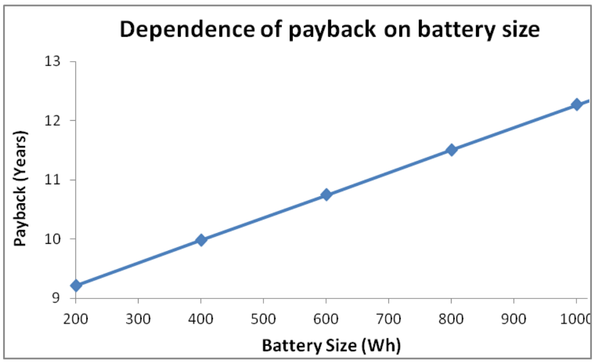

Figure 8. Dependence of payback on battery size

One of the major factors affecting the payback is the savings on the cost of electricity before the PV-LED system is installed. For this reason, we would expect to recoup the investment a lot quicker if we were replacing an incandescent lighting system compared to one that is based on CFLs. (Figure 9) confirms this, however the results are totally dominated by the luminous efficacy (and therefore the electricity costs), as opposed to the capital costs.

The effectiveness of solar power is well-known for being highly dependent on FITs. In recent years, governments have have been rapidly reducing them, claiming that this is countered by the increase in PV efficiency. An analysis of this was made for a variety of FITs and PV efficiencies (Figure **10**), and it appears that the reduction in FITs are far more significant than improvement in PV efficiency. This is contrary to claims made by advocates of the FIT reduction, and FITs should not be reduced any further than the current rate of 16p per kWh.

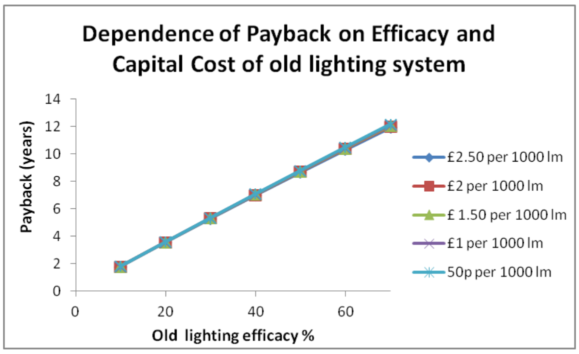

Figure 9. Dependence of efficacy on properties of old lighting system

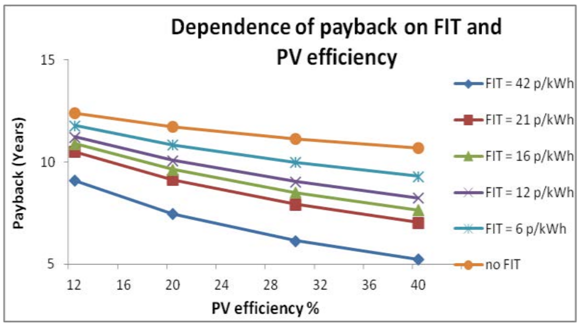

Figure 10. Dependence of payback on FIT and PV efficiency.

Figure 11 and Figure 12 show that as PV modules cost more than LED and batteries respectively, variations in the costs of the latter components hardly affect the payback. Such variations change the payback at most by around one or two years.

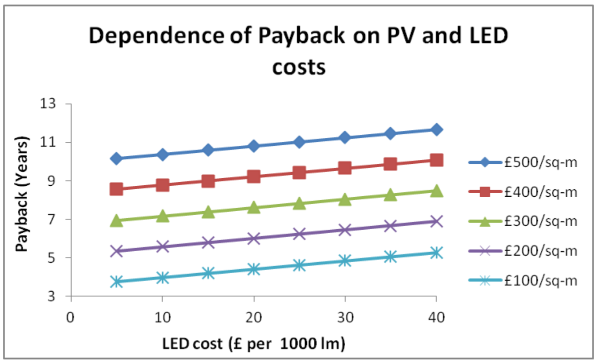

Figure 11. Dependence of payback on PV and LED costs.

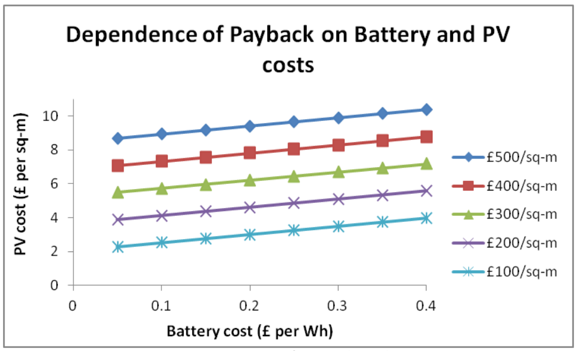

Figure 12. Dependence of payback on Battery and PV costs

So far, we have been varying parameters while only the background lighting is operating. Now we shall consider the ability of PV to provide for Task Lighting (in addition to background lighting). The number of desk-based occupants shall increase until the maximum space available on the exterior wall for PV panels has been filled. This happens when 7 occupants require task lighting, and the relationship is found to be linear (Figure 13). As is the corresponding battery capacity requirement, (Figure 14), and there is quite a wide range, with the low occupancy numbers being within reach of batteries currently available on the market, and the higher occupancy numbers requiring utility scale batteries. However, the payback time variation is slightly non-linear (Figure 15), the rate of increase slows at higher occupancy numbers, probably due to the financial gains of feeding into the grid.

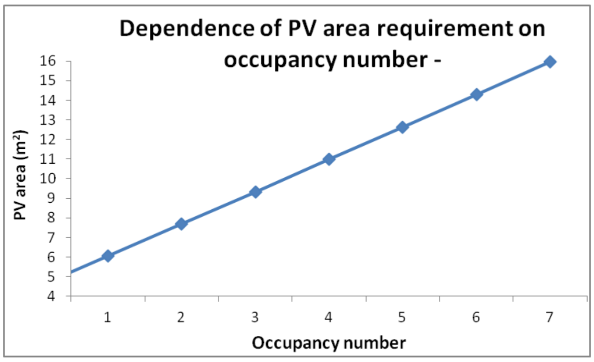

Figure 13. Dependence of PV area requirement on occupancy number

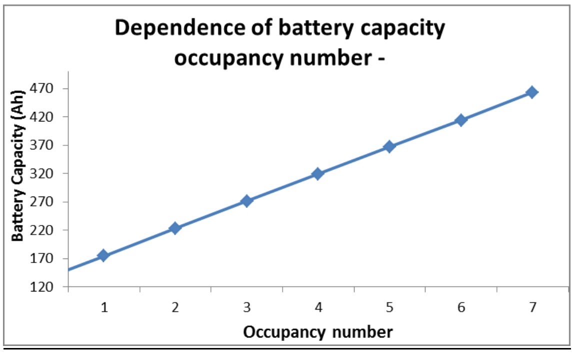

Figure 14. The dependence of battery capacity requirements on occupancy number

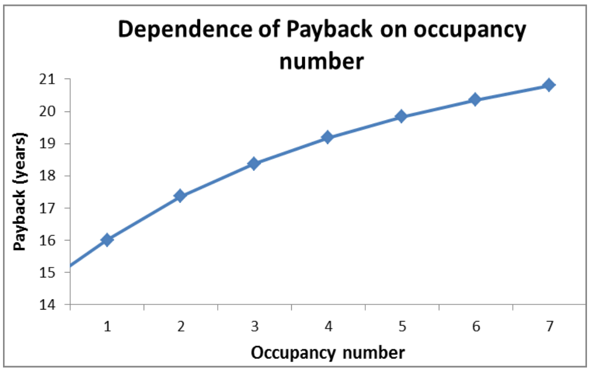

Figure 15. Dependence of payback on occupancy number

SUMMARY

The economic viability of PV-LED systems for office interior lighting have been investigated over several parameter types, and it was found that clearly the PV cost and efficiency, occupancy number, Feed-In tariffs, and cost of the old lighting system being replaced were the most dominant. The decomposition of the lighting load into background requirement and task requirement means that a relatively small PV area is needed for the former, which operates continuously. Any unused PV energy can then be used for part of the latter, which is of a more transient (and therefore less predictable) nature. Moreover, it appears that even a slight oversizing of the system results in a substantial increase in cost (and payback time). This is all due to the high cost and relatively low efficiencies of PV, and it is anticipated in future years this will considerably improve with new breakthrough technologies.

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