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Key Factors Dictating Excessive Lighting Energy Consumption in Schools: a Post-Occupancy Analysis

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Key factors dictating excessive lighting energy consumption in schools: a post-occupancy analysis

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Abstract

Good practice in lighting energy consumption in schools is regarded to be around 13 kWh/m^2 per annum (CIBSE LG5, 2011). However, recent post-occupancy evaluations reveal lighting energy consumption in schools to be above 30kWh/m^2 p.a., despite the use of energy efficient lamps, switching based on infrared presence/absence detection, and digital controls for daylight-linked dimming. To identify causes of excess energy consumption for lighting, this study undertook detailed post-occupancy field measurements of the lighting consumption of two recently-completed K schools – a small primary and a large secondary – equipped with digitally-addressable lighting interface (DALI) systems.

Instrumentation of individual light fittings was carried out to obtain an accurate understanding of their switching and dimming characteristics. Results were compared with estimates of kilowatt hours per square metre per year (the Lighting Energy Numeric Indicator), calculated using the spreadsheet provided to support the European Standard that defines LENI, and against estimates of disaggregated whole-building energy consumption using the CIBSE energy assessment tool TM22. The post-occupancy evaluations uncovered excessive lighting consumption in classrooms and circulation area lighting, issues with DALI system installation and commissioning, and problems with the usability of lighting controls. Allied shortcomings included dysfunctional energy metering, lack of system fine-tuning after handover, and inaccuracies with as-built records. Methodological shortcomings were identified with the industry-standard methods of assessing lighting consumption. Recommendations are given on ways to mitigate excessive lighting energy consumption and to improve the predictive power of the current energy assessment methods.

Keywords

Schools, Energy Lighting, DALI, Soft Landings, CIBSE TM22, LENI.

Glossary

DALI:	*Digitally Addressable Lighting Interface*
LENI:	*Lighting Energy Numeric Indicator*
Lux:	*The unit of illuminance and luminous emittance,* *measuring luminous flux per unit area.*
PIR:	*Passive infrared*
PV:	*Photovoltaic*
Soft Landings:	*Post-handover professional aftercare and fine-tuning*
TM22:	*CIBSE Technical Memorandum 22: Energy Assessment and Reporting Methodology*

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1. Introduction

1.1 Introduction

Literature and POE review

Excessive energy consumption in UK schools is of national concern. In 2008 the schools sector was estimated to account for 10% of UK non-domestic electrical energy consumption[1], with the portion for electric lighting estimated at 8%[2]. Although fossil-fuel consumption has progressively fallen, electricity use in schools has risen. In 2009, a report by the former Department for Schools, Children and Families reported that the proportion of total national energy consumption attributable to schools had risen to 15%[3].

Recent trends in lighting guidance have focused on delivering levels of lighting conducive to visual function while maintaining energy efficiency[4]. However, problems with classroom daylighting persist, such as poor integration of glare control devices with window design, exacerbated on south elevations by the lack of external solar protection. The lack of external solar shading for classrooms on south-facing elevations leads to ad hoc glare control (Figure 1), while poor integration of glare control blinds is common, particularly with openable windows (Figure 2).

Figure 1: No external shading on south-facing classrooms.

Figure 2: Poorly executed glare control.

Digital control of lighting has become common, specifically to the Digital Addressable Lighting Interface (DALI) protocol. DALI facilitates individual control of luminaires using signals from daylight sensors and passive infrared (PIR) sensors. Research by Govén *et al* found that the use of such lighting controls can contribute to a significant improvement in the quality and quantity of electric lighting in schools[5].

Table 1: A database of Schools for which lighting energy consumption is known

School type	Opened	Treated floor area in m^2	Pupils	Display energy certificate (in 2016)	Lighting kWh/m^2 per annum (reported)
Primary	Sept 2010	685	N/A	C (64)	15.3
Primary	Nov 2010	809	82	B (45)	9.8
Primary	May 2010	1119	487	E (102)	9.2
School P (primary)	**Sept 2015**	**1130**	**367**	**N/A**	**12.2**
Primary	2005	1296	217	C (70)	9.0
Primary	Sept 2009	1660	210	C (73)	8.9
Primary	March 2010	1990	332	C (68) est.	7.4
Primary	Nov 2011	2639	283	E (115)	14 - 26
Sixth Form	Sept 2010	2799	300	N/A	15.6
Secondary	June 2009	5078	1600	C (74)	13.8
Secondary/ academy	Sept 2008	7715	900	N/A	52.5
Academy	June 2009	10,172	1100	E (108)	26.1 (from 32.5)
Academy	Sept 2008	10,490	900	N/A	29.0
Secondary/ academy	Sept 2003	10,627	1350	N/A	37.3 (total)
Secondary academy	Sept 2003	10,529	1300	N/A	70.3 (total)
Secondary/ academy	June 2006	13,000	1265	N/A	14.9 (auto) 23.8 – 25.8 (manual)
School S (secondary)	**2011**	**13,416**	**1976**	**N/A**	**25.5**
Secondary	April 2010	14,610	2030	N/A	15.7
Secondary	June 2009	16,185	1600	N/A	3.3 Est.
College	Aug 2012	16,900	1600	N/A	19.4

Despite such evidence, high energy consumption is still occurring. Pegg et al found excessive consumption by systems designed to be low energy but poorly controlled in practice[6]. Other researchers have pinpointed systems complexity as a root cause of performance problems[7]. Dasgupta *et al* analysed 113 schools and found energy use to be on average two and half times the design estimates[8]. In 2010, an £8 million Building Performance Evaluation (BPE) research programme investigated the performance of UK domestic and non-

Table 2: Lighting specification for Schools S and P.

Room	Fittings	Fittings	Fitting load W	Floor area m^2	Context	Controls
School S						
A002	2x28 W Minirad 228 T5	9	62	59.8	Default to on 24/7. Lighting isolated by breaker switches	Tridonic DALI, PIR plus manual switches Neither operable during study
A006	2x28 W Minirad 235 T5	9	62	59.8	Absence detection with manual switches	Tridonic DALI, PIR plus manual switches. Whiteboard row on local switch
B202	2x28 W Minirad 228 T5	16	82	88.6	Absence detection with manual switches	PIR DALI. Wall switches Whiteboard row on local switch
School P						
Willow Room	2x28 W Minirad Orias T5	6	62	49.5	Absence detection with manually switched and auto daylight dimming	Whitecroft organic DALI. Switches for local dimming and pre-programmed scene selection
A006	1x35 W Minirad Orias T5	9	42	64.5	Absence detection with manually switched and auto daylight dimming	Whitecroft organic DALI. Switches for local dimming and pre-programmed scene selection

domestic buildings. Schools represented the largest percentage (14 schools or 29% of the sample). Bunn and Burman analysed academies studied under the programme and found actual carbon dioxide emissions to be three and five times greater than the design estimates[9]. Problems with automated lighting were found, such as infrared (PIR) detection control systems causing lights to default to 'on', both during the day and outside school hours[10], [11].

Accurate assessment of energy use and apportionment with end uses has been complicated by failings in electricity sub-metering. Post-occupancy evaluations regularly find problems with the quality of metering, interfaces with building management systems, poor commissioning, and energy metering calibration problems[12], [13], [14].

Table 1 lists recent UK schools studied for their energy performance and reported lighting energy consumption, ranked by floor area. Most schools in Table 1 are derived from the Innovate BPE programme, along with data from other schools studied between 2006 and 2015[7], [14]. The schools are characterised by widespread reliance on automated lighting control, with sometimes little or no local manual override. Technologies such as PIR detectors and daylight sensors were sometimes too sensitive in operation and therefore energy-wasteful. The zoning of lighting control was also sometimes inappropriate to space use.

2. Research hypotheses

The review of the research evidence led to the following research hypotheses:

- That lighting energy consumption in larger schools is a direct function of treated floor area. Larger schools will consume more energy with lighting per square metre than smaller schools due to the agglomeration of design and installation inefficiencies in lighting over a greater multiplicity of zones.
- While digital control of individual luminaires may improve the theoretical performance of lighting in classrooms, the quality of installation and system fine-tuning of the lighting controls is equally important in determining achievement of lighting and design performance targets.
- That current methodologies for assessing lighting energy consumption in controlled lighting, specifically CIBSE *TM22*[15] and the Lighting Energy Numeric Indicator (LENI)[16], are fundamentally sound.
- That current approaches to providing manual lighting override controls are contributing to sub-optimal operation of lighting and therefore increasing wasteful energy consumption.

3. Research design

3.1 Case study method

The research design involved the monitoring and detailed energy analysis of two recently-completed UK schools, one a large secondary (School S, completed in 2010) and the other a small primary (School P completed in 2015). Both schools used digitally-addressable lighting controls based on presence or absence detection with manual override, and with daylight dimming sensors. Details of the classroom lighting installations are shown in Table 2.

The secondary school (School S) replaced a 1950s school with a concrete-framed building of 13,416 m^2 over three storeys. The building comprises tapering classroom wings radiating from a central atrium. Suspended linear fluorescent luminaires were used in general teaching areas in accordance with CIBSE guidance[17]. The design proposed that the lighting fittings be manually switched in conjunction with microwave absence detection, such that the luminaires automatically switch off once movement fails to be sensed after a pre-set period. Lights in close proximity to interactive whiteboards were to be separately switched. Daylight linking aimed to ensure that the light output could be modulated with the availability of natural light.

School P is an existing primary school to which has been added a two-storey 1130 m^2 teaching and administrative block. All classrooms face south. First floor rooms have high-level, north-facing clerestory windows. There is no roof overhang nor external brise soleil to control solar gain on the south-facing elevations (Figure 1). Manual internal roller blinds control glare. Rows of suspended T5 fluorescent luminaires are perpendicular to the windows – two rows of single 35 W fittings in some classrooms, and three rows of twin 28 W fittings in larger classrooms. The control switches have two pre-programmed scene options and manual dimming capability. Two manual control devices are provided in each classroom – one by the door to control room lighting and another to control the luminaires nearest the whiteboard. An internal daylight sensor in each classroom controls a DALI lighting system that can dim each row of fittings. Each classroom has a hard-wired DALI control module to which the daylight sensor and manual control switches are wirelessly linked.

The research process involved technical tours of each school and interviews with the caretakers about the technical specification of the schools and their operation (e.g. hours of use, maintenance regime, post-handover changes and upgrades, and outstanding defects). As-built drawings and operation and maintenance manuals were reviewed, and the lighting installation records were compared with the actual installation. Teachers were interviewed about their use of classrooms, the manual lighting controls, and use of glare control devices. Efforts were made to reconcile the school's electrical sub-meters with the energy supply (fiscal) meters, taking into account any renewables contribution.

The occupied hours for the monitored classrooms in the two schools were found to vary during the school week, but were largely comparable in the length of the teaching day. For the primary school, teachers tended to arrive early at around 07:30 and leave by 16:00. Some were found to be performing administrative tasks up to 16:45 (with some lighting on), although by that time the school was largely empty. For the secondary school, staff also tended to arrive around 07.30 and leave by 16.30, although a minority were found to be at their desks until 17:00 and sometimes slightly later. In both schools most classroom use was observed to have ceased by 16:00, and each school's cleaners were already active. The difference in classroom hours between the school classrooms was therefore found to be small.

Three separate approaches were taken to calculate and triangulate energy consumption: building energy analysis using the research version of the *CIBSE TM22 Energy Assessment Reporting Methodology*[15]; lighting energy consumption to the requirements of *BS EN 15193-1:2017*[18]; and instrumented readings of representative lighting fittings using on-site data loggers.

3.2 CIBSE TM22 analysis

In order to identify the portion of electricity consumed by the lighting systems, whole-building electrical energy models were constructed for each school using CIBSE TM22. This spreadsheet tool enables annual electrical loads in kWh/m^2 to be determined based on installed wattages multiplied by hours of operation. Operational hours are assigned via user-determined operational profiles for weekday, weekend and out-of-hours use. Usage and turn-down factors can be refined. Data was obtained from an inventory of loads gathered from site inspections, and those loads apportioned against electrical supply meter data.

For School S, it became apparent that the consumption of (known) sub-meters did not add up to the electrical supply (billing) meter, nor was the building management system (BMS) set up to record sub-meter data. Furthermore, the college's operation and maintenance manuals did not contain a clear electrical sub-metering schematic. This prevented identification of distributed sub-meters. The facilities manager subsequently found sub-meters in electrical services cupboards, some of which were not connected. A PV array was installed in late 2015. The lack of a PV export meter complicated the energy assessment.

It was decided to identify all regulated and unregulated electrical end-uses by manual inspection. The O&M manuals were data-mined to obtain installed wattages, and as-built lighting drawings checked against the lighting installation. This was supplemented by visits to count all fixed and equipment loads systematically, room by room. By this process it was found that many classrooms were fitted with twin 28 W fittings, whereas the as-built drawings erroneously recorded many classroom luminaires as having single 49 W fittings. All loads and their wattages were aggregated zone-by-zone for teaching blocks, offices, and external systems (e.g. lighting). The data were imported into a CIBSE TM22 model, and set against operational profiles as accurately as possible.

At School P, an attempt was made to reconcile sub-meters with manual readings of the billing meter and records held by school's BMS. However, the BMS was found to record lower values than the distribution board pulse sub-meters. Manual reconciliation for the two months to 13 May 2016 found that the sub-meters reported

31% more power consumption than the billing meter. As with School S, the disparity was complicated by the lack of a photovoltaic (PV) export meter. Apportionment of electrical energy by end-uses involved a manual inventory of all electrical loads, and estimation of run times from time clocks, personal observation, and insight from the caretaker. Installed wattages were checked against as-built drawings and schedules.

An annualised TM22 energy model for School P was created by extrapolating from nine months (253 days) of billing meter data and dividing by the measured treated floor area. The electrical end uses were tabulated room by room, and hours of operation assigned to each load. In this way the disaggregated energy end-uses summated to within 3% of the metered (extrapolated) annual consumption.

3.3 Lighting Energy Numeric Indicator (LENI) analysis

Lighting energy consumption was calculated in accordance with *BS EN 15193-1:2017*[18]. This Standard describes the methods for calculation of the amount of energy used for internal lighting and provides indicators for lighting energy requirements for the purposes of regulatory certification to meet the requirements of the EU *Energy Performance of Buildings Directive*. *BS EN 15193-1:2017* defines a method of assessing the efficiency of a lighting installation, including controls, called the Lighting Energy Numeric Indicator (LENI). A LENI Excel spreadsheet, originally developed to validate the Standard, was used to calculate the efficiency of the classroom lighting. Separate LENI spreadsheets were created for each classroom. The LENI spreadsheet requires the user to define floor area, light sources, target illuminance values, daylight contribution, hours of use, daylight factor, maintenance factors, and lighting control characteristics using data entry and options from drop-down menus. Three calculation options are available for the calculation of LENI:

1. A rough calculation;
2. A more detailed calculation based on specific light sources;
3. A thorough measurement for an actual installation.

Option 2 was used in this study.

3.4 On-site data logging

Battery-operated, calibrated data loggers with light-sensing capability were chosen for capturing the light output from the fittings in each classroom. Relative light levels, recorded in units of Lux, were derived from placing the loggers on top of suspended luminaires, thereby using the uplit portion of light to determine switching and dimming characteristics. Although the daylight contribution could not be disaggregated from electric light, the close proximity of the data logger sensor to energised lamps (less than 20 mm) led to luminance levels of between 4000 - 10,000 lux, effectively masking any daylight contribution. The daylight contribution picked up by the data loggers when lights were off was between 50 - 120 lux, not high enough to be confused with the operation of the lights. It was also found that electric light readings would begin at around 1300 lux. The energy calculations therefore ignored all measured values below 900 lux, as all lights would be dimmed to zero, or be off, at that level of detection.

In order to balance data resolution with manageable datasets, monitoring intervals were set at five minutes. For School S, three representative classrooms were selected for study – two in Wing A (rooms A002 and A006) known to have different electric lighting characteristics, and a science room B202. The refectory and sports hall were also monitored, primarily to refine the operational profiles in the TM22 model. For School P, two south-facing classrooms on the first floor – Willow Room and Birch Room – were selected for field monitoring.

An initial monitoring period bridged a half-term holiday and thereby provided evidence for any non-occupied daytime operation of the lighting. Planned out-of-hours operation was only found at School S. Initial monitoring enabled plotting of results and analysis of interim findings, and evidence for the schools' facilities teams to improve the operation of the lighting system settings.

The monitoring process was refined following assessment of the initial data. In each school, daily operation was plotted for the occupied period of the schools (and for weekends where lighting was operating) for 20 weekdays (a school month). Likely maximum hours of classroom occupation were based upon maximum lighting utilisation per day. The monitoring and operational evidence was used to backfill and/or refine the load profiles and operating hours in the TM22 energy spread sheets. This helped improve the strength of calculation comparisons.

3.5 Field data analysis

The illuminance data were imported into an Excel spreadsheet. The daily maximum illuminance measured by each data logger in lux was treated as each lamp's maximum output, and a formula devised to convert the detected lux levels for each row of lights to a power consumption value as a proportion of the maximum load as defined by the maximum lux value, with a 30% offset assumption for dimming levels as embedded in *BS EN 15193-1:2017*. The equation was also devised to take into account control gear losses. In the absence of guidance in the manufacturers' lamp data sheets, a generic value of 0.3 W/m^2 for losses (i.e. while the luminaire was nominally off) was added to the consumption calculations.

Power consumed for every five-minute period of measurement, with manual or daylight-dimming calculated as a fractional value, was summated for each school day. Power consumption was then divided by the (measured) treated floor area to generate an average kWh/m^2 value for the monitored period. This was then factored up to a standard 40-week annual occupancy for both schools to arrive at an estimated kWh/m^2 p.a. for each classroom.

4. Results

4.1 TM22 assessment

Results are shown in Table 3. For School S, it was possible to apportion all (known) loads to within 3736 kWh (1%) of the value reported by the main supply meter. This led to an estimated total internal lighting energy consumption of 341,767 kWh per annum (p.a.), equating

Table 3: Results of all energy modeling and monitoring for School S and School P. Some data contain approximations.

Room	**Assessment period**	**Floor area**	**Estimated utilised annual hours**	**LENI results kWh/m^2 p.a.**	**TM22 results kWh/m^2 p.a.**	**Monitoring kWh/m^2 p.a.**
School S						
A002	18 Dec – 19 Jan	59.8	6720	52.1	24.3 - 26.7	61.76 (80.51)*
A006	18 Dec – 4 Feb	59.8	1205	16.72	24.3 - 26.7	7.52
B202	18 Dec – 19 Jan	88.6	1900	21.70	24.3 - 26.7	17.45
School P						
Willow Room	11 April – 13 May	49.5	786	11.86	7.25	7.33
Birch Room	11 April – 13 May	64.5	578	10.29	4.32	5.15

* Based on 280 days per year operation. Figure in brackets assumes 365-day operation.

to somewhere between 24.3 - 26.7 kWh/m^2 p.a. The school's size (13,416 m^2), complexity, and difficulties with calculating loads and apportioning hours of operation, led to a wide range of assumptions, particularly hours-run at full and part-load and overall utilisation. For example, it was found that the absence detection control worked for 10% of the circulation fittings in some areas and 85% in others. Furthermore, owing to the many forms of teaching spaces in School S and its wide range of light sources, it was not possible to strictly define classroom lighting. For the purposes of the study classroom lighting was defined as that in any bounded room where formal teaching took place. This included conventional seated tuition as well as science rooms and craft skills workshops. The estimated lighting consumption of 25.5 kWh/m^2 p.a. is therefore an overall figure. As such it is comparable to the lighting data reported in Table 1.

For the primary school (School P), the TM22 calculations returned an annual energy consumption for internal lighting as 12.2 kWh/m^2 per annum, approximately half that of School S. The annual hours of operation (40 school weeks) were 578.3 h p.a. for Birch Room and 785.8 h p.a. for Willow Room. This was used to backfill the usage factors in both the TM22 and LENI spreadsheets so that hours of operation matched within a few hours.

5 On-site monitoring

A wide range of lighting energy consumption profiles at School S emerged from the monitoring of the three classrooms. Room A006 performed close to good practice, with annual consumption extrapolated from a typical month's operation of the middle row of luminaires equating to 11.28 kWh/m^2 p.a. The data from Room A006 also revealed that the front row of lights were off during the monitoring period. If this operation is typical, then only six fittings out of nine would be used regularly, bringing consumption down to 7.52 kWh/m^2 p.a. The data also shows no night or weekend operation. There is therefore confidence that the lights are off during vacations, except during maintenance.

The monitoring at School S highlighted differences in classroom utilisation. Data for Room A006 demonstrates the problems inherent in assuming consistent classroom lighting hours when digital lighting controls are used. Lighting operation after 16:30 will be caused by the cleaners. During a typical mid-January week, daily hours of lighting operation in A006 varied from 4.83 hours to 7.33 hours (Figure 4). This shows that the DALI lighting system in that particular classroom was responsive to need. The responsiveness is thought more likely a function of the classroom's occupation profile rather than daylight availability or local switching, as there is no evidence of the light fittings exhibiting dimming characteristics.

Severe control problems were found in classroom A002, with permanent default to "on'" (Figure 5). The light fittings in the classroom – and other rooms adjacent – were found to be on 24 h/day, and therefore the load could occur for up to 8760 hours p.a. depending on how often power to the lighting circuit was isolated manually at the distribution board by the caretaker (the only way they could be turned off). Inspection of the lighting control system found that the DALI control wiring for the bank of classrooms (including A006) was wired back to DALI control gear located in the local electrical cupboard, rather than each classroom possessing local DALI controllers (as at School P). Without as-built records of the wiring installation, or clearly-labelled wiring, it was not possible to determine how the installers had wired the DALI system.

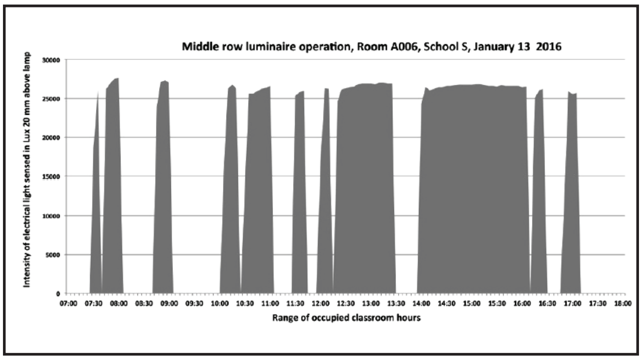

Figure 4: Data for Room A006 in School S.

Figure 5: The north-facing Classroom A002 in School S.

Figure 6: South-facing Birch classroom in School P.

Monitoring of the front row of lights in Room B202, a science classroom, showed consistently less than half the consumption of the middle row fittings. The exact reason is unknown. It may be a consequence of a pre-set scheme in the DALI installation or the teachers using the manual dimming facility for the front row lights. The 58% increase in utilisation of lighting in B202 compared with Room A006 is reflected in the room's estimated annual consumption of 17.45 kWh/m^2 p.a.

A month's monitoring results at School P indicated, by extrapolation to annual consumption, that lighting in Willow Room consumed 7.33 kWh/m^2 p.a., while Birch Room consumed 5.15 kWh/m^2 p.a. Some of the gap is due to the installed lighting load of Willow Room, which was 38.9% higher. However, annual consumption in Willow Room was estimated at 42.3% higher. The difference may be slightly greater utilisation, or it may be disinclination of the teacher to control the lighting, a clue being much less frequent dimming of the whiteboard row of luminaires. Figure 6 shows the south-facing Birch classroom in School P, in a "blinds-down, lights on" operating condition, and classwork stuck on glazing behind the blinds.

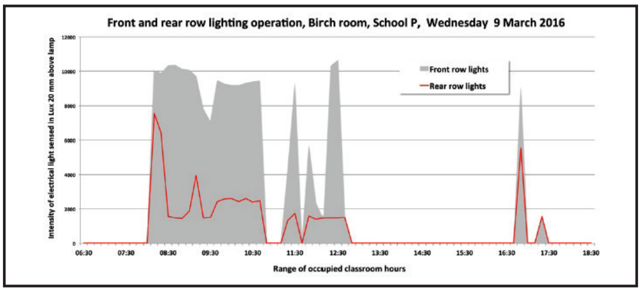

Figure 7: South-facing Birch classroom in School P.

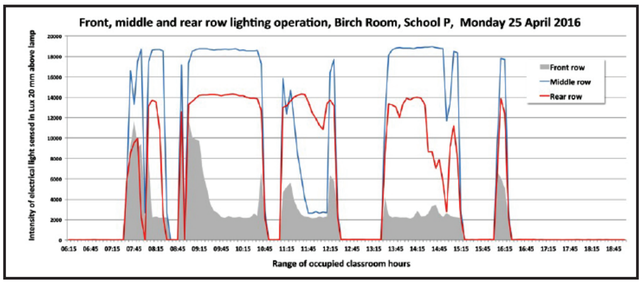

Figure 8: Monitored data Birch Room in School P.

During the initial monitoring period it was found that the rear row of lights in Birch classroom dimmed down more than the row nearest the whiteboard (Figure 7). It was initially considered that the rear of the classroom may be better daylit, and therefore that the row is more likely to dim. Nevertheless, the local authority was informed of the counter-intuitive dimming characteristic and the lighting sub-contractor was called in to check and re-commission the classroom lighting. Although no records were available of the adjustments (which involved the entire school block), the results of the second period of monitoring seemed to reverse the initial findings: i.e. the front row of lights in Birch Room now dimmed more than the rear row (Figure 8).

In Figure 7 the switching of the rear row of lights on 9 March is superimposed on the operation of the front (whiteboard) row of lights (shown shaded). The front row consumed more energy prior to the DALI fine-tuning. Lighting operation after 16:30 h is usually cleaning or caretaker maintenance.

Figure 8 shows monitored data from all three rows of lights in Birch Room in School P on a relatively heavily-utilised day, and after the re-programming of the DALI settings to enable the front row of luminaires to dim.

5.1 LENI calculations

Details of the classroom lighting at both schools were entered into the quick version of LENI. For School S, the LENI energy calculation for classroom A002 was 15.6% lower than the closest estimate from monitored data, even using the hours of operation from the monitoring as an input to the LENI spreadsheet. The default-to-on condition of the A002 lighting, and the failure of the DALI system to exercise control, could not be reflected by any of the control options in LENI, which presumes at least some degree of effective control. The LENI prediction for Room A006 was therefore 122.3% higher than the lowest value derived from monitoring data (48.2% if all lighting rows operated identically). The LENI value for B202 was 24.3% higher than the monitored estimate, but may be only 11.3% higher if the front row lights are not dimmed manually as presumed.

The LENI calculations for School P's classrooms returned values of 11.86 kWh/m^2 p.a. for Willow Room and 10.29 kWh/m^2 p.a. for Birch Room. Although there is higher incidence of dimming in Birch

Room and more frequent switching of the whiteboard luminaires, Birch Room has four emergency fittings compared with two in Willow Room. While a 6 W emergency charging load would be present for 8760 h/p.a., the year-round consumption could not be added within LENI as the hours of use were based on the monitored data as a single, fixed, input value. The reported LENI values could therefore be 3.05 kWh/m^2 p.a. higher for Birch Room, and 1.93 kWh/m^2 p.a. for Willow Room. The LENI analysis indicates that the DALI-controlled classroom lighting at School P is performing close to the CIBSE LG5 "excellent" level of 12.8 kWh/m^2 p.a.

6. Discussion

The research project aimed to test four hypotheses as outlined in Section 3.1. The combination of physical monitoring with energy modelling (i.e. TM22 and LENI) was found to generate new and useful insights into DALI-controlled lighting in schools. The methodology provided deeper knowledge of performance of the lighting installations, and to a greater resolution than that achieved in the Innovate UK BPE studies (Table 1).

As neither School S nor School P possessed functional sub-metering systems, lighting energy consumption could not be apportioned accurately. Due to School P's small size and simplicity of lighting installation, it was possible to construct a TM22 energy model by counting loads and their run times to get within 4000 kWh (3%) of a nine-month extrapolation of the main meter total. Closer reconciliation was not possible due to the absence of a PV export meter. For the large secondary School S (over eight times the floor area of School P), the TM22 energy model could only be constructed from laboriously counting loads. Normalised to floor area, School S had approximately double the estimated lighting energy consumption of School P.

The research found that the TM22 models for both schools had inherent weaknesses in determining lighting energy consumption at the level of individual spaces. While the operational profile function in TM22 worked reasonably well for estimating switched constant-power loads, it could not model the variable operational characteristics of an addressable lighting system unless monitored data was used as input data. TM22's operational profiles were therefore massaged until the running hours in the model broadly matched the measurements.

Shortcomings were also found with the LENI spreadsheet used for the study. While the LENI spreadsheet follows the requirements of *BS EN 15193-1:2017*, its drop-down menus did not enable enough refinement of the key operational variables, such as the daylighting conditions and the control factors of the actual lighting installations.

As a result, the actual operating hours for the lighting at School P were lower than the values output from the LENI spreadsheet. Also, for School P, the LENI spreadsheet over-predicted the monitored energy performance of the lighting. The monitored data reflected School P's comparatively low classroom utilisation.

No *Standard* (nor any spreadsheet based on its requirements) can be expected to cater for the extreme shortcomings in installation and commissioning of the DALI installation seen at School S. Performance-critical failings were found in virtually every aspect of the lighting installation, including inaccurate as-built lighting installation records, dysfunctional energy sub-metering, non-compliant DALI programming of corridor lighting, and – in the extreme case of Room A002 in A wing – a total breakdown of the automatic switching. A failure to account for such deficiencies is not a flaw of a measurement tool, whether LENI or TM22; the failure to account for such potential performance risks lies with the user of the energy model.

The results from the classrooms monitored at School S show that the DALI-controlled lighting rarely dims. Nevertheless, in classrooms B202 and A006, lights nearest the whiteboards could be off most of the occupied time, providing evidence that some DALI functionality was delivered in practice. This good performance was compromised elsewhere by lighting found to default to "on" 24 h/day, without any means by which the school could turn it off, short of manually isolating the lighting power supply. It was concluded that nothing short of a complete re-wire of the system would solve the problems affecting classroom A002, and others like it (but not monitored).

At School P, absence detection ensured that all lights remained off out-of-hours and during school holidays. Both classrooms demonstrated what could be achieved from a well-installed and fine-tuned daylight-linked lighting system. Monitored data from Birch classroom demonstrated that lighting energy consumption could be driven down to 5.15 kWh/m^2 p.a. for a 40-week school year, while estimated consumption of Willow Room was close at 7.33 kWh/m^2 p.a. It is thought that School P's results could have been even lower with better passive solar detailing, and less use of glare control blinds and classroom furniture as *ad hoc* shading devices.

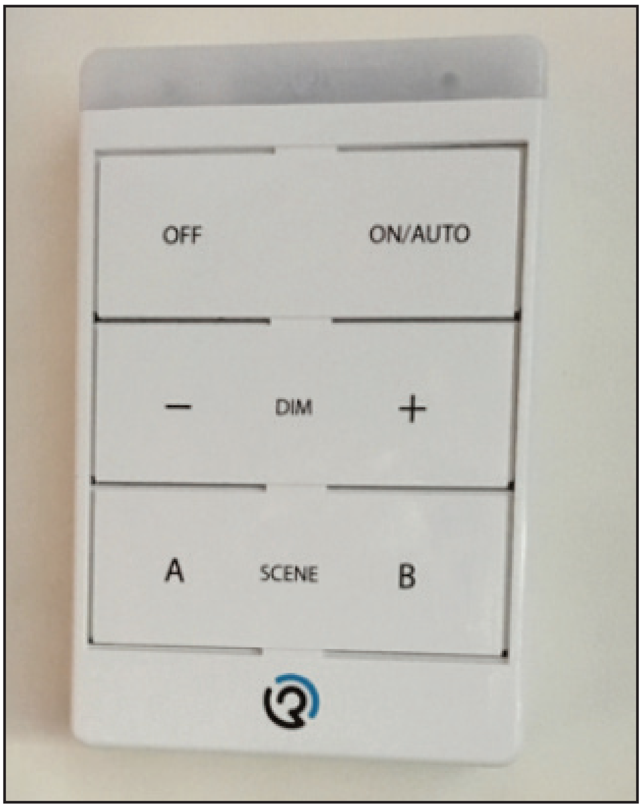

Figure 8: The manual light switch installed in classrooms at School P.

Although the manual lighting override controls at School P were simple in concept, the teachers were unsure of their function and found their annotation confusing (Figure 8). The teacher in Birch Room used the dimming and switching controls to control the row of lights by the whiteboard, but not the scene-setting functions, as the teacher didn't understand them. The teacher in Willow Room claimed to use the lighting controls at least five times per day. As the monitored data did not show regular dimming of the whiteboard row of luminaires, the teacher may only be switching lights on and off.

7 Conclusions

Intensive site monitoring of lighting systems in two schools has revealed how inadequacies, with their root in poor installation, have led to operational performance shortcomings. Based on the CIBSE TM22 calculation, whereby all loads were counted and their operational hours factored, the secondary school was estimated to consume double the power for lighting compared with the primary school, taking into account hours of operation (40 weeks at quoted school occupied hours), treated floor area, the various different lighting loads, and the control problems encountered in both classroom and circulation lighting. While some of this consumption at School S will be due to extended hours of operation for facilities such as the sports hall lighting, measured lighting energy consumption of the classrooms ranged from two times to 19 times higher per square metre of electrically-lit classroom space compared with the lowest estimated consumption of 5.15 kWh/m^2 p.a. in School P.

Despite high overall lighting energy consumption in School S, Room A006 in School S performed close to good practice, with annual consumption of 11.28 kWh/m^2 p.a. This demonstrates that the lighting specification was fundamentally viable. Unfortunately, failings in installation, commissioning, and control of both classroom and circulation lighting elsewhere in the school contributed to its poor overall performance. These issues are consistent with data from other studies shown in Table 1 [6] [10] [11].

While it has not been demonstrated that lighting energy consumption rises in direct proportion to treated floor area, it is suggested that size may matter when it comes to a construction team's ability to maintain the quality of an installation, ensuring the adequate commissioning and setting-up of the extensive use of complex systems. Risks may grow disproportionally to the construction team's ability to deal with them. The problem may even be greater where "plug and play" systems like DALI are thought to be low risk when, in reality, they can be prone to error in installation and setting up that leads to energy penalties. These failings were found in both schools.

While scale is not an excuse for poor installation and commissioning, it may be a reason why it happens. On a large school, conventional construction management practices and resources may be unable to control the increased volume of operational performance risks that on a smaller school may be managed more successfully (and incipient problems identified and resolved earlier, and more quickly). While the major lighting problems at Schools S escaped the defects period without being resolved, at School P the research monitoring during the defects period gave an opportunity to spot performance shortcomings with the DALI systems. These were occurring under the radar not only of the teaching staff but also the school caretaker. Once the problems were spotted, the contractor quickly returned to reset the lighting controls. This was, in effect, a fine-tuning intervention of the kind recommended by Soft Landings[19].

TM22 proved a worthy modelling tool for whole-school energy estimation, particularly in the absence of sub-metered data. The research suggests that estimates that do not take account of dimming and switching characteristics may lead to inaccuracies in a TM22 assessment. The results certainly bring into question the accuracy of TM22 lighting consumption assessments reported in Table 1, as older schools with simpler lighting systems may be relatively easier to model accurately than newer schools with digitally-controlled lighting where the control regime could be highly variable.

The study also shows that while LENI is robust for describing lighting energy consumption, problems emerge when there are differences between a design intention and the as-installed installation. As with all energy-consuming systems, out-turn performance of a DALI lighting installation is dependent upon the professionalism of the project team in making sure that the anticipated quality is achieved in installation and commissioning, and that system fine-tuning takes place after handover. Designers need to be mindful of construction deficiencies when calculating LENI in design, and perform sensitivity analysis so that potential performance deficiencies are transparent in their energy calculations and predictions.

The final hypothesis, that manual lighting controls are not aiding efficient operation, is partly supported. Problems at School S were deeper and more fundamental than problems created by local controls. Monitoring indicated that some teachers were able (and motivated) to turn off lights nearest the whiteboards. At School P, while one teacher was able to control the lights effectively, the teacher in the adjacent classroom was less successful. It is suggested that optimisation of electric lighting via local controls can only be significant when all other parameters have been fully satisfied: i.e. a good installation, thoroughly commissioned, with diligent customer support and system fine-tuning during initial occupation. However, if the control devices are complex and confusing, end-users may be alienated and reluctant to optimise their lighting.

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