Calculating the lighting performance gap in higher education classrooms

Article

Published Version

van Someren, K., Beaman, P. ORCID: https://orcid.org/0000-0001-5124-242X and Shao, L. ORCID: https://orcid.org/0000-0002-1544-7548 (2018) Calculating the lighting performance gap in higher education classrooms. International Journal of Low Carbon Technologies, 13 (1). pp. 15-22. ISSN 1748-1325 doi: https://doi.org/10.1093/ijlct/ctx015 Available at https://centaur.reading.ac.uk/73334/

Calculating the lighting performance gap in higher education classrooms

Katharine van Someren[1*], Phil Beaman[2] and Li Shao[3]

[1]*Technologies for Sustainable Built Environments Centre, University of Reading, JJ Thomson, PO Box 220, Reading RG6 6AF, UK;* [2]*School of Psychology and Clinical Language Sciences, University of Reading, Earley Gate, Whiteknights, Reading RG6 6AL, Reading, UK;* [3]*School of the Built Environment, University of Reading, Chancellor's Building, Chancellor's Way, Whiteknights, Reading RG6 6AW, UK*

Abstract

The background of performance gap measurement is outlined and field measurements are gathered and applied retrospectively to lighting upgrades in classrooms. The lighting upgrade projects in three university buildings and their assumptions are explained in relation to the operational hours proposed using the industry 'Energy assessment and reporting method'. We used relatively inexpensive environmental data loggers, which can be implemented prior to upgrade works or energy efficiency retrofits. Our results reveal different patterns of lights on use, occupancy and booking hours from those assumed by *a priori* estimates. In our study, the consequence of reporting energy savings using assumptions and estimates in calculations for classrooms resulted in limited overall differences in the savings achieved in practice. However, despite the industry metrics of power consumption and carbon being reported significant wasted lighting hours were prevalent across all classrooms studied.

Keywords: performance gap; lighting; classrooms; carbon emissions; power consumption

*Corresponding author: k.vansomeren@reading.ac.uk

Received 23 August 2017; revised 12 October 2017; editorial decision 17 October 2017; accepted 25 October 2017

1 INTRODUCTION

In 2014, lighting comprised 18% of all UK electricity use and consumed 58 000 TWh per year [1]. Having recognised the need for verification and evolving improvement of building systems the 'European Committee for Standardization Technical Body CEN/TC 169—Light and Lighting' is updating their documentation to include the 'Lighting Design Process' [2]. Of five stages within the 'Lighting Design Process', Stage 4 'Verification of the "Lighting Design Process"' is key to the credibility of any business case to support lighting upgrades [1]. As an example of the importance of lighting upgrades for overall energy consumption, in a school environment luminaires have a typical life expectancy of 11 years and a lighting capital expenditure (CAPEX) of £106 /m^2 over a 30-year life for the building, compared to £66 /m^2 for heating and £59 /m^2 for ventilation [3]. Importantly for Higher Education, the UK Government and Higher Education Funding Council for England (HEFCE) links English University funding to their Carbon Management Plan targets. In the first 6 years of our University's carbon management programme, lighting retrofit projects made up 12% of the total carbon energy efficiency projects and the nine lighting upgrades cost a total of £810 532 and achieved savings of £164 951 per annum (p.a.) and 800 tCO_2e (p.a.) [4]. This demonstrates the potential scale of energy, and financial, savings but predetermining when a lighting upgrade is necessary to make such savings, and what savings might be expected *a priori* remains an issue.

1.1 Performance gap

The performance gap is a measure of the difference between design assumptions and actual in field data. The performance gap, originally termed the 'credibility gap' by Bordass and Leaman [5], is well established in the built environment [6–12] and post occupancy evaluation is a means of addressing this

International Journal of Low-Carbon Technologies 2018, 13, 15–22

doi:10.1093/ijlct/ctx015 Advance Access Publication 13 November 2017

gap by providing designers with actual in-use data. Post occupancy evaluation is particularly valuable when there is any concern about the accuracy of the input to energy models. An evaluation of the accuracy of such models [13] recently investigated the internal 'mental models'—the psychological representation of a real or imagined system [14]—of 108 thermal modellers and found a wide variability in their approaches to model inputs and ranking input parameters. The findings included the observation that a quarter of modellers participating were making worse judgements than a random response—thus showing a lack of validity—and even the most experienced modellers, including external consultants, contributed great diversity (including some of the worst performance) to the overall results indicating a lack of reliability [13]. In terms of case studies within Higher Education, previous performance gap research has found that lighting in five higher education case study buildings can vary dramatically compared to regulatory calculations when measurements are taken: 2, 13, 14, 18, 286% higher than predicted, in absolute terms these are 0.3, 2, 4.1, 4.5, 22.3 kWh/m^2 above predicted [15]. In one case of non-domestic buildings, the performance gap was explored for lighting in office space where the calculations used 2600 total hours of operation per annum and 11 W/m^2 in their initial assumptions, however, the final model which most closely matched the actual energy use was 3640 h per annum and 13 W/m^2 [7]. In this study the absolute underestimation of 1040 h per annum and 2 W/m^2 is substantial; this is an additional 40 and 18%, respectively, relative to the initial model. This current study aims to contribute to this growing area of research by exploring consultants' predictions of energy savings used in financing and supporting these projects prior to installation. It does so by calculating and assessing how retrofit upgrades to luminaires and controls in classroom areas perform in practice. This study focuses on classroom areas and provides further empirical evidence to the already established field of classroom lighting [16–21] detailing the hours lighting in classrooms is switched on, compared to occupancy and room bookings. Calculating the lighting demand in existing buildings in the UK is a requirement of designers when retrofit works are undertaken to upgrade older systems [22] but in the absence of in field data the predicted consumption of lighting is often based on prediction and model simulation. The article compares in field measurements against design assumptions to measure the performance gap.

1.2 Industry guidance

In the commercial sector the CIBSE 'Guidance TM22 Energy assessment and reporting method' is widely used in the UK to assess four (occupied) building types: offices, hotels, banks and agencies, and mixed use industrial, but there is no specific guidance for University buildings [23]. The International Performance Measuring and Verification Protocol (IPMVP) method is adopted predominately in the United States [24]. Other benchmarking tools exist and in the UK the 'Carbon Buzz' project is a collaborative and anonymous database of each sector's actual energy use in relation to initial design predictions [25]. As a sector the performance gap in university buildings was calculated to be 85% for electricity consumption (kWh/m^2/year) when comparing the predicted energy use against actual energy use in practice through the 'Carbon Buzz' project [26]. The Lighting Guide 5: Lighting for education acknowledges that there are two major factors for energy efficient lighting—the power consumption of the lighting and the hours it is used [27].

1.3 Objectives

(A) to explore the predictions and assumptions by inputting the actual values of hours of operation into the carbon and power consumption calculations;
(B) to measure the performance gap of lighting in classroom environments; and
(C) to identify interesting patterns of lighting use

2 METHODS AND BUILDINGS

The CIBSE TM22 method includes in Appendix A8 an Energy Tree Diagram, which is used as the basis for this study's assessment of lighting in thirteen classrooms in three university buildings. CO_2e saving predictions for calculating lighting installation energy over time, which includes parasitic load and controls, widely use the 'lighting energy numeric indicator' (LENI) measured in units kWh/m^2 per annum [22, 28]. The carbon savings predictions that form the basis of this performance gap assessment for classroom lighting, are calculated using Equation (1) LENI:

$$\text{Annual operating hours} \times \text{Load factor } x \text{ Predicted power consumption} = \text{Total predicted power consumption per annum } x\ CO_2 \text{ conversion factor} = CO_2 \text{ per annum}$$

where annual operating hours is the total hours of use (h), Load factor is a co-efficient based on industry assumptions (usually between 1 and 0.5), Predicted power consumption is the estimated power of luminaires, ballasts and parasitic load (kW), CO_2 conversion factor is the sum of generation (Scope 2) and transmission and distribution (Scope 3) factors, for example in 2016, respectively: 0.41205 + 0.03727 = 0.44932 kg CO_2e /kWh, and is extracted from published UK Government Greenhouse Gas Reporting Conversion Factors for the appropriate year of the project [29].

Equation (1) is extracted from the external consultants calculations used in these classroom lighting upgrade projects, they are based on the Carbon Trust formulae for calculating the business cases for retrofit projects [30]. The designs and calculations used in these projects were carried out in 2012 and 2013, since then the LENI calculation has been further refined, nonetheless the original calculation is used for comparison purposes. For lighting projects Equation (1) includes two predicted terms: operational hours and power consumption and one predicted co-efficient: load factor. As these predictions are multiplied any error in the terms and co-efficient will skew the estimate of predicted energy consumption overall.

2.1 Buildings and CO_2 project data

The classrooms were chosen as the three buildings were identified as core assets in the University's real estate strategy. The Urban building had data collected April–September (there are summer schools so the classrooms are occupied year round), Maths and Humanities data collection was December–June. Three areas of data collection will be identified as Humanities 1 (first floor), Urban 2 (second floor), and Maths 1 (first floor). Of the three buildings only Urban had the classrooms upgraded in 2013, the Humanities was costed and calculated but never carried out and Maths had upgrades completed by 2013 but excluded the classrooms. All 13 classrooms were chosen as they are centrally bookable by any school, department or society group and are accessible to all staff and students during the periods when the buildings are open. The classrooms have changing bookings which vary widely and are not solely occupied by one school or department but can be centrally booked by any group booking. The booking hours refers to the number of hours classes are scheduled for a particular classroom. The energy efficiency predictions for electricity consumption and reduction in CO_2 equivalent emissions for the three buildings are detailed in Table 1. These are the predictions as calculated from the individual projects.

3 DATA COLLECTION

In each of the thirteen classroom monitoring areas a single environmental logger was installed at 1.5 metres from finished floor level to avoid being accidentally removed by student's baggage, cleaner's vacuum cleaner and avoid tampering. The orientation of each classroom is shown in the results graphs for each building, where north is indicated the windows are on the north side of the building, the classrooms are numbered to distinguish similar orientations. The HOBO^{TM} UX90-005 occupancy/lights on (Passive Infra-Red (PIR) detector 5 m), or UX90-006 occupancy/lights on logger (PIR detector 6 m) was installed and this logger also recorded lights on/off with a photocell. The occupancy/lights on logger was placed within five metres of the lecturer's IT desk to pick up lecturer and other occupants. The occupancy/lights on logger was configured to log occupancy events and return the light state every 1 min as on or off. The photocell in the UX90-005/006 occupancy/lights on logger is triggered by the illuminance levels and can be calibrated on set up and at each data download with the lights on. The occupancy/lights on loggers cannot differentiate between daylight and artificial light, so data can be recorded as lights on when daylight reaches this threshold of toggling it on/off. To prevent this from happening the logger was placed in an area away from direct sunlight, for example on a wall opposite the single wall with the windows. The data were collected for 6 months and the data extrapolated for the full year as the university buildings are in constant use even in the summer months when several summer schools take place.

4 RESULTS

4.1 Urban building—measured lights on less than predicted

Six classrooms in the Urban building were studied on the second floor and are shown in Figure 1. Median measured lights on hours was 1809 per annum (p.a.), median measured occupancy hours 746.9 (p.a.), median booking hours 1365 (p.a.). The predictions used 2100 operational hours (p.a.), based on these findings this represents a performance gap of −14%, when the measured lights on hours are used, the lighting is used for less time than predicted.

The predicted annual CO_2e and power consumption is compared to the measured values using the before and after process in Table 1. The measured savings are 3% more than predicted, these findings are conflicting with CarbonBuzz data for other University buildings where increased power consumption is the norm [31]. These data indicate that the Urban building CO_2e and power consumption was calculated using overestimates of operating hours after the upgrade. Inputting the measured lights on hours into the original calculation for the after scenario, this

Table 1. *Power consumption predictions for each building.*

	Location	Year	Annual operating hours(h)	Load factor (multiplier)	Total predicted power—luminaires(kW)	Total predicted power consumption per annum(kWh)	CO_2e conversion factor(multiplier)	CO_2e per annum(tonnes)
Urban second floor–upgrade carried out 2013								
Estimate before	Current (2012)	2012	2394	1	27.93	66 867	0.0005246	35.1
Estimate after	T5 and absence and daylight sensors	2013	2100	0.7	8.7626	12 881	0.0005246	6.8
Predicted savings			294		19.17	53 986		28.3
Humanities first floor—upgrade costed in 2012 but not carried out								
Estimate before	Current (2012)	2012	1680	1	14.66	24 629	0.0005246	12.9
Estimate after	T5 and daylight sensors	2013	1680	0.7	6.08	7150	0.0005246	3.8
Predicted savings			No change		8.58	17 479		9.2

Maths first floor—upgrade completed in 2013 but excluded classrooms.

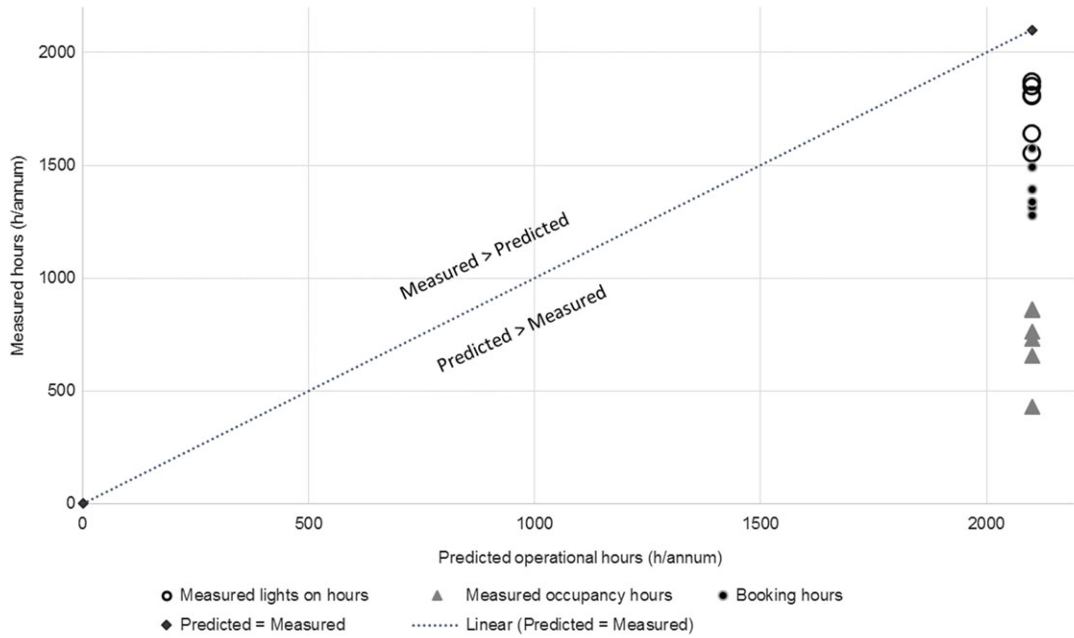

Figure 1 *Predicted (2100 h pa) and measured (h pa) in the Urban building.*

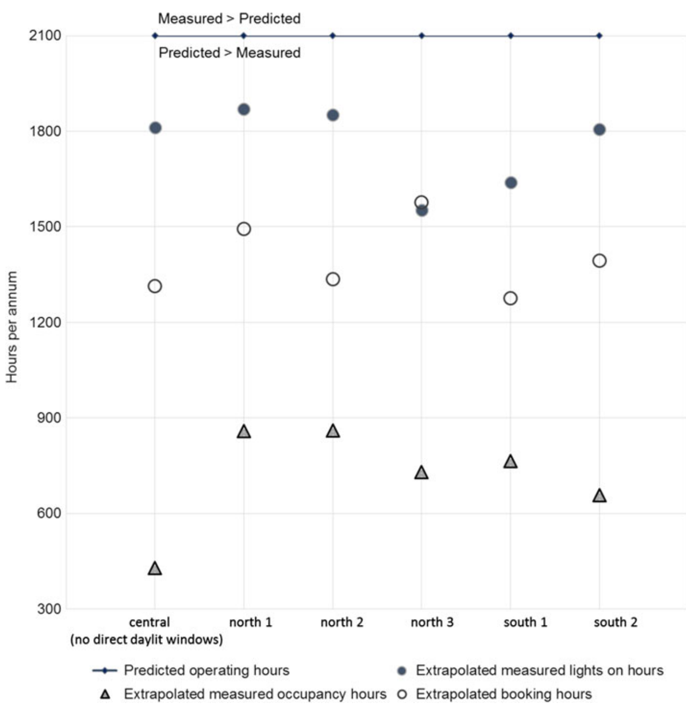

Figure 2 *Patterns of lights on, occupancy and booking use hours (per annum) in the Urban building.*

project has saved more annual power, 1785 kWh (p.a.), and annual CO_2e emissions, 1tCO_2e (p.a.), than originally predicted.

The patterns of lighting use as shown in Figure 2 indicate the lights being left on when the classroom is not in use and unoccupied, this pattern of behaviour is well established and acknowledged in industry literature [27] and the results here corroborate that position. There was a single classroom (north 3) where the measured lights on hours and booking hours were almost identical, although nobody was 'using' the room for the many hours it remained unoccupied with the lights on.

4.2 Humanities building—measured lights on more than predicted

Four classrooms in the Humanities building were studied on the 1st floor and are shown in Figure 3. Median measured lights on hours was 2133 per annum (p.a.), median measured occupancy hours 1394 (p.a.), median booking hours 1629 (p.a.). The predictions used 1680 operational hours (p.a.), based on these findings this represents a performance gap of 27%, when the measured lights on hours are used, the lighting is used for more time than predicted.

The predicted annual CO_2e and power consumption was compared to the measured values using the before and after process in Table 1. The potential savings this measured are 11% less than originally predicted for this lighting upgrade that was appraised but not carried out. In the original assessment of the Humanities building, CO_2e and power consumption were calculated using underestimates of operating hours both before and after in the upgrade calculations. Inputting the measured lights on hours into the original calculation for the after scenario, this project—if it had been carried out, would have consumed more annual power, this would have reduced the savings by 1928 kWh (p.a.), and annual CO_2e emissions, by 1tCO_2e (p.a.), than originally predicted.

The patterns of lighting use as shown in Figure 3 indicate the lights being left on when the classroom is not in use and unoccupied, a common finding. The two north facing classrooms both had measured lights on and booking hours (p.a.) that were closely

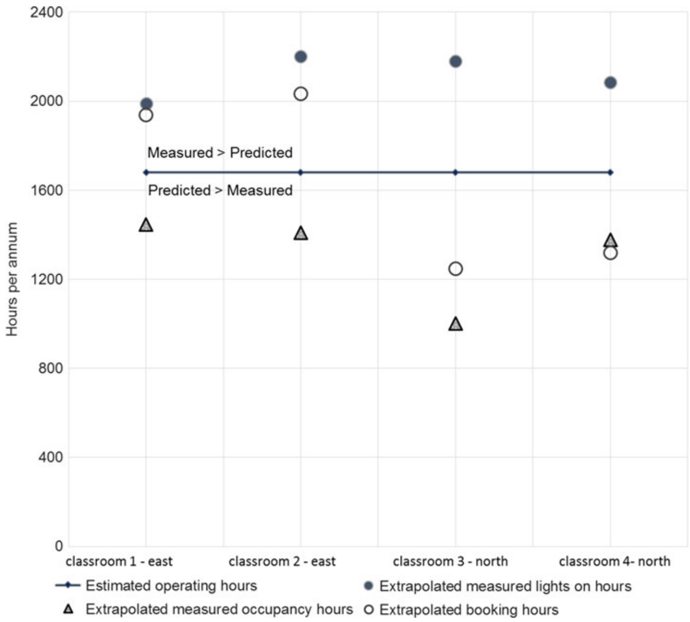

Figure 3 *Patterns of lights on, occupancy and booking use hours (per annum) in the humanities building.*

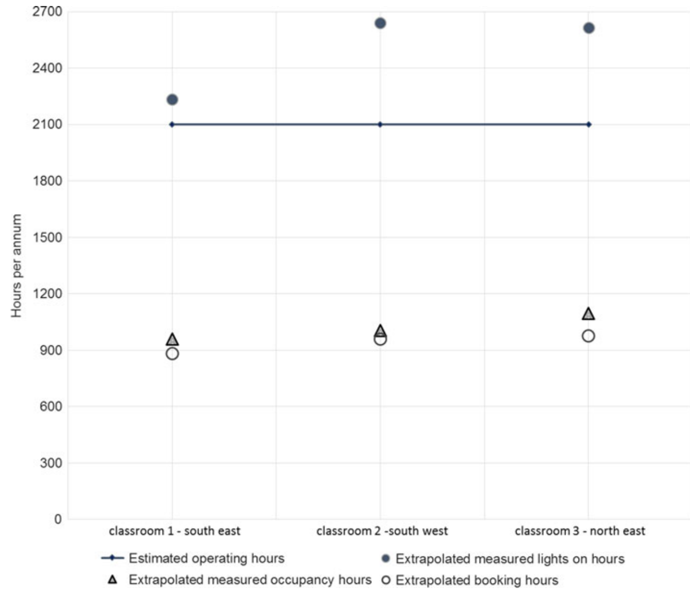

Figure 4 *Patterns of lights on, occupancy and booking use hours (per annum) in the Maths building.*

related, and this finding is similar to the pattern of use in the north 3 classroom in the Urban building. Interestingly classroom 4 has more occupancy than bookings in Figure 3.

4.3 Maths building—occupancy and booking

Despite the Maths building undergoing refurbishment and retrofit upgrades to corridor, office and communal area lighting in 2013 the classroom lighting was excluded from this upgrade project. The impact of piecemeal upgrades on users' experiences at the university has been highlighted elsewhere through qualitative case studies [32]. Three classrooms in the Maths building were studied on the 1st floor and are shown in Figure 4. Median measured lights on hours was 2614 per annum (p.a.), median measured occupancy hours 1003 (p.a.), median booking hours 958 (p.a.). If the Urban building's prediction for 2100 operational hours (p.a.) is used—in the absence of designer's assumptions—as a baseline for comparison, based on these measurements this represents a potential performance gap of 24%, when measured lights on hours are used, the lighting is used for more time than anticipated.

As no CO_2e calculations were drafted for the Maths classrooms for upgrade it is not appropriate to theorise about consequences, however the Maths building does provide interesting patterns of use not found in the other two study buildings. The most surprising aspect of the data in Figure 4 is in the overlap of booking hours and occupancy hours. The patterns of lighting use as shown in Figure 4 indicate the lights being left on when the classroom is not in use and unoccupied, again this is a common finding. This mismatch between occupancy and lights on hours is seen across all three classrooms in this building, there is a clear indication that power savings could potentially be

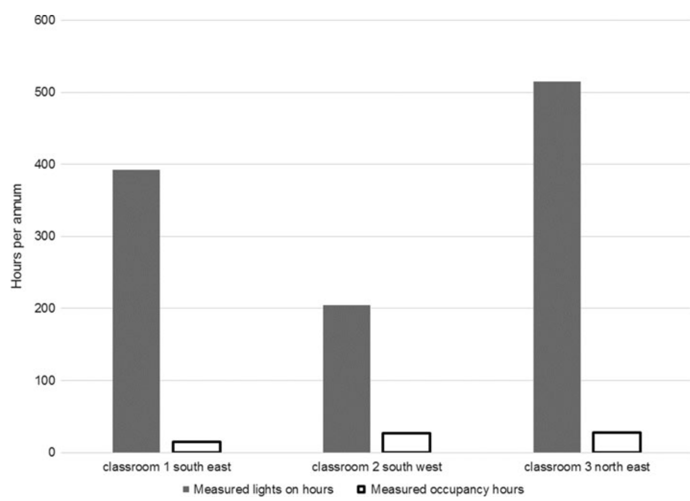

Figure 5 *Out of hours (19:00–06:59) Maths building lights on and occupancy hours per annum.*

made. However as previously mentioned in Section 3. Data Collection, the environment loggers used in this study were triggered by illuminance levels. Despite every effort to not record daylight by placing the loggers where predominantly artificial light triggered a measurement, we cannot be certain that the lights on hours necessarily always reflect energy waste.

The patterns in the three Maths classrooms were further investigated and a potential area for minimising waste was considered to be overnight when analysing the data, as this was a distinct time when daylight would not be influencing the measurements. The out of hours lighting use between 19:00 and 06:59 is shown in Figure 5. All three classrooms have wasted lights on hours and this is compared to the measured occupancy during those same periods and linearly extrapolated for the year.

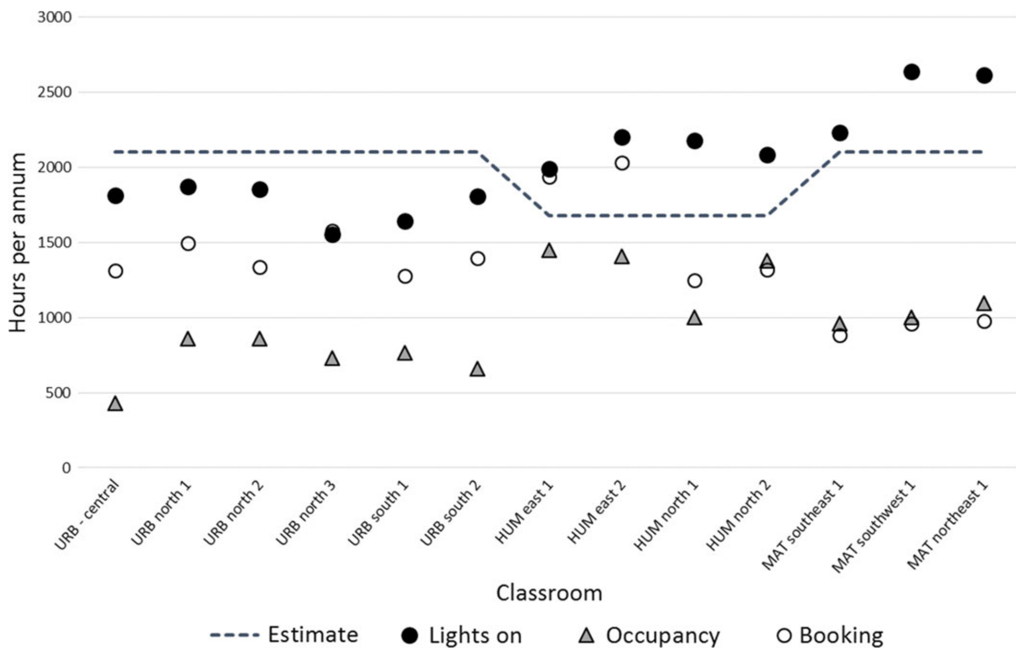

Figure 6 *Patterns of lighting, booking and occupancy hours of use per annum.*

4.4 Wasted lighting in all classrooms

The final objective was to explore interesting patterns of lighting use. Across all thirteen classrooms studied the trend of wasted lighting use was prevalent, as shown in Figure 6. The dark solid circles indicate lights on, the grey triangles occupancy and waste is identified as being the difference in those two variables. The wasted hours of lighting when the classroom is not occupied but the lights are on totals 13 885 h for the thirteen classrooms, the equivalent of 1.5 years in hours. Two further interesting patterns occur, the first where lights on (dark solid circle) and booking hours (outlined circle) are similar in three classrooms: Urban north 3, Humanities east 1 and Humanities east 2. The proposed reasoning for this is based on observing the porters in these buildings monitoring the communal areas regularly. The second pattern is where occupancy (grey triangle) and booking hours (outlined circle) are similar in four classrooms: Humanities north 2 and all three Maths classrooms southeast 1, southwest 1 and northeast 1. This second pattern provides the opportunity to consider other methods of lighting control. It is recommended that classroom lighting controls be based on using campus access cards, much like a hotel room to activate the ability to switch on and off, thereby avoiding waste and maintaining user control.

5 DISCUSSION

Despite the classrooms in the upgraded Urban building being fitted with photocells and absence detection from the measured data it would indicate that these were not performing to their full potential. The LightingEurope (2017) paper which details commissioning, verification and operation and maintenance if carried out in practice has the potential to narrow the gap between lights on hours and occupancy hours. The inputs used in the LENI calculations, Table 1, by the external consultants in these feasibility studies were based on assumptions and best guess estimates, and the unreliability of these methods is congruent with other performance gap research showing that consultant's thermal modelling input assumptions were highly variable [13]. As we have demonstrated, the estimated operational hours can easily be replaced by actual data collected in practice. The use of widely available environmental loggers provided insightful and practical inputs to calculations that would otherwise be based on assumptions about unknown variables.

Integrating these environmental loggers into common use enables Energy Managers and Project Managers in all sectors to collect field measurements rather than relying on assumptions. Using environmental loggers can provide an additional tool to support decision making in energy efficiency projects. The use of the HOBO™ loggers in lighting applications enables commissioning engineers to reduce the performance gap between the lights on hours of use and occupancy patterns. It is proposed that the closer the lights on hours are to the occupancy hours in these buildings, the greater the savings in annual electricity consumption and carbon dioxide emissions.

5.1 Management factor and load factor

It is worth noting that a significant element of the CIBSE TM22, Energy assessment and reporting method, calculation comes from the management factor which is not explored in depth here and yet which also affects the accuracy of predicted energy savings. This term is understandably ambiguous as each mechanical and electrical service will have different requirements in a building. In lighting terms this encapsulates the additional complexity of commissioning, dimming, daylight, hold on time, contextual elements involving school schedule, types of occupant and operation, times of year and overarching policies on energy management. The load factor in the LENI calculation is not benchmarked or validated by evidence and remains another ambiguous estimation for external consultants and designers, this is often used as a crucial co-efficient for promoting the justification for automated controls over manual lighting controls.

5.2 Limitations

The HOBO^{TM} loggers used in this study were agreed for installation with the Building Managers and Energy Manager as they could then be subsequently utilised for other applications. They were relatively low in cost and this justified using them in classroom areas where they were liable to tampering and even theft. However, the loggers are limited in their operation such that the occupancy hours are likely to be more accurate at recording occupancy when occupants are in the direct spatial vicinity of the logger, hence, the recorded occupancy hours may underestimate the amount of time the classrooms were occupied. It is for this reason that the actual lights on hours were used as part of the calculations for assessing the performance gap in classroom lighting. The occupancy does however give another separate opportunity to analyse the data for time of day analysis, this would provide insights for other mechanical and electrical systems, such as heating to determine the profiles in term time and out of term periods. The calculations for CO_2e and power consumption estimates relied on the assumption that the sensors would be more efficient at switching off the lights than a manual switch and routine operation by say the security staff member walking around at the end of the day. Since the study was limited to 6 months of data (the loggers were redeployed to other locations) it was not possible to give a full year of data. The extrapolation of 6 months of data to a full year is also another aggregation that limits the contribution of this study.

6 CONCLUSIONS

This study aimed to explore the predictions and assumptions by inputting the actual values of hours of operation into the carbon and power consumption calculations. Firstly the input parameter for predicted operational hours ≠ occupancy hours ≠ lighting on hours: the terms are not analogous for measured lighting use across the three buildings studied. The impact the hours of use had on carbon and power consumption calculations was not substantial in the two classroom upgrades studied in the Urban and Humanities buildings. Another objective was to measure the performance gap of lighting in classroom environments, for the two buildings with consultant's calculations these were −14 and 27% for the Urban and Humanities buildings, the potential performance gap for Maths classrooms was estimated to be 24% higher. These findings are comparable to CarbonBuzz data in higher education buildings [31]. The final objective of this study was to identify interesting patterns of lighting use. The out of hours lighting use in the Maths building from this retrospective study demonstrated that savings could be found by revisiting the lighting upgrade in the Maths building and potentially using absence controls.

This study provided original empirical evidence on lights on hours, occupancy hours and booking hours in classrooms which was previously unknown and found that neither of these are synonymous with operational hours. These results suggest that there is a valuable distinction between lighting on hours and occupancy hours, a parameter not captured in the current 'Energy assessment and reporting method'. The performance gaps calculated between the original estimates and predictions based on actual measured data are different however this did not materially affect the CO_2e and power consumption savings. As the research into performance gaps has previously found the difference between design estimates and actual performance data can be up to 85% in University buildings [26]. There are still many unanswered questions about the management factor, used in the LENI calculation, and load factor, used in TM22, both can lead to conceivable variance in measured annual power consumption and would be suited to further in field studies with empirical evidence. Taken together, these findings support the use of environmental loggers and recommendations to use empirical evidence from field data in energy efficiency upgrade projects. There is abundant room for further progress in utilising small unobtrusive and relatively inexpensive environmental loggers across all building services which can be implemented prior to upgrade works or energy efficiency retrofits.

CONFLICTS OF INTEREST STATEMENT

None declared.

FUNDING

Funded through EPSRC grant EP/G037787/1 and sponsored by the Sustainability Team in the Estates & Facilities Department at the University of Reading.

REFERENCES

[1] Lighting Industry Association. *UK Lighting Sector Strategy [Internet]*. Telford, Shropshire; 2014. http://luxreview.com/uploads/uklightingsectorstrategy.pdf

[2] LightingEurope. *Position Paper on the review of Directive 2010/31/EU on the Energy Performance of Buildings [Internet]*. Brussels; 2017. http://www.lightingeurope.org/images/publications/position-papers/LightingEurope-Position_on_the_review_of_EPBD.pdf

[3] Karbasi HM, Marsh D, Pitman A. *Life Cycle Cost of Mechanical and Electrical Services Case Study of a New Build School. CIBSE Technical Symposium 2016—'Integration for whole life building performance' [Internet]*. CIBSE, Edinburgh, 2016. http://www.cibse.org/getmedia/aaaaa938-e57d-4de7-b86d-53df09f25133/Mohammadpourkarbasi-slides2.pdf.aspx

[4] Fernbank D. University of Reading Carbon & Water Management 2013 Update. Reading; 2013.
[5] Bordass B, Leaman A. Making feedback and post-occupancy evaluation routine 3: case studies of the use of techniques in the feedback portfolio. *Build Res Inf [Internet]* 2005;**33**:361–75. http://www.tandfonline.com/doi/abs/10.1080/09613210500162032
[6] Way M, Bordass B. Making feedback and post-occupancy evaluation routine 2: soft landings—involving design and building teams in improving performance. *Build Res Inf [Internet]* 2005;**33**:353–60. http://www.tandfonline.com/doi/abs/10.1080/09613210500162008
[7] Menezes AC, Cripps A, Bouchlaghem D *et al*. Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap. *Appl Energy [Internet]* 2012;**97**:355–64. http://dx.doi.org/10.1016/j.apenergy.2011.11.075.
[8] Min Z, Morgenstern P, Marjanovic-Halburd L. Facilities management added value in closing the energy performance gap. *Int J Sustain Built Environ [Internet]. The Gulf Organisation for Research and Development* 2016;**5**:197–209. http://dx.doi.org/10.1016/j.ijsbe.2016.06.004.
[9] Lawrence R, Keime C. Bridging the gap between energy and comfort: post-occupancy evaluation of two higher-education buildings in Sheffield. *Energy Build [Internet]* 2016;**130**:651–66. http://dx.doi.org/10.1016/j.enbuild.2016.09.001.
[10] Bordass B, Leaman A. Making feedback and post-occupancy evaluation routine 1: a portfolio of feedback techniques. *Build Res Inf* 2005;**33**:347–52.
[11] Bordass B, Cohen R, Standeven M *et al*. Assessing building performance in use 3: energy performance of the Probe buildings. *Build Res Inf [Internet]* 2001;**29**:114–28. http://www.tandfonline.com/doi/abs/10.1080/09613210010008036. [cited 2014 Dec 5].
[12] Bordass B, Associates WB. *Energy Performance of Non-Domestic*. Closing the Credibility Gap, Buildings, 1994.
[13] Imam S, Coley DA, Walker I. The building performance gap: are modellers literate? *Build Serv Eng Res Technol* 2017;**38**:351–75.
[14] Craik K. *The Nature of Explanation*. Cambridge University Press, Cambridge, 1943:136.
[15] Burman E. Assessing the operational performance of educational buildings against design expectations-a case study approach. *EngD Thesis* [Internet]. University College London 2015. http://discovery.ucl.ac.uk/1482161/
[16] Gentile N, Goven T, Laike T. A field study of fluorescent and LED classroom lighting. *Light Res Technol [Internet]* 2016:1–20. http://lrt.sagepub.com/cgi/doi/10.1177/1477153516675911
[17] Ramasoot T, Fotios S. The model of DSE user acceptability and performance: derivation of new lighting recommendation for the classroom of the future. In: *Plea2009* 2009:22–4.
[18] Ramasoot T, Fotios S. Acceptability of screen reflections: lighting strategies for improving quality of the visual environment in the Classrooms of the Future. *Passiv Low Energy Archit Dublin, Irel [Internet]* 2008. http://architecture.ucd.ie/Paul/PLEA2008/content/papers/oral/PLEA_FinalPaper_ref_224.pdf
[19] Drosou N, Mardaljevic J, Haines V. Uncharted territory: daylight performance and occupant behaviour in a live classroom environment. In: *6th VELUX Daylight Symp* 2015:4–7.
[20] Drosou N, Haines V, Mardaljevic J *et al*. Let There Be Daylight? Assessing Actual Daylighting Performance of a Classroom in Use. *4th Eur Conf Behav Energy Effic* (Behave 2016). 2016:8–9.
[21] Goven T, Laide T, Raynham P *et al*. The influence of ambient lighting on pupils in classrooms. 2010;1–8.
[22] HM Government. *The Building Regulations 2010 Conservation of Fuel and Power, Approved Document L2B [Internet]*. Part L2B 2010. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/540329/BR_PDF_AD_L2B_2013_with_2016_amendments.pdf
[23] CIBSE. *Energy Assessment and Reporting Method TM22*. CIBSE, London, 2006.
[24] Borgstein EH, Lamberts R, Hensen JLM. Evaluating energy performance in non-domestic buildings: a review. *Energy Build [Internet]* 2016;**128**:734–55. http://dx.doi.org/10.1016/j.enbuild.2016.07.018.
[25] CIBSE, RIBA, BRE. *Carbon Buzz [Internet]*. 2017 [cited 2017 Apr 10]. http://www.carbonbuzz.org/index.jsp
[26] Menezes AC, Cripps A, Bouchlaghem D *et al*. Analysis of electricity consumption for lighting and small power in office buildings. *CIBSE Technical Symposium*, DeMontfort University, Leicester, UK, 6–7 September 2011 [Internet]. Leicester; 2011. https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/9433/6/110905-Anna Menezes-Analysis of Electricity Consumption for Lighting and Small Power.pdf
[27] Ken Butcher CIBSE, Society of Light and Lighting (SLL). *Lighting Guide 5: Lighting for Education*. Chartered Institution of Building Services Engineers, Wakefield, West Yorkshire, London, 2011.
[28] The Society of Light and Lighting. *Lighting Guide 14: Control of electric lighting*. CIBSE, Suffolk, UK, 2016.
[29] Department of Energy and Climate Change. *Greenhouse Gas Reporting—conversion Factors 2011 [Internet]*. London; 2011. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2011
[30] Carbon Trust. How to use retrofit kits to convert fluorescent light fittings to T5 fluorescent or LED lamps. London; 2012.
[31] van Dronkelaar C, Dowson M, Spataru C *et al*. A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. *Front Mech Eng [Internet]* 2016;**1**:1–14. http://journal.frontiersin.org/Article/10.3389/fmech.2015.00017/abstract
[32] van Someren KL, Beaman CP, Shao L. Users' experiences of lighting controls: a case-study. *Light Res Technol [Internet]* 2017;**0**:1–16. http://journals.sagepub.com/doi/pdf/10.1177/1477153517709063