Reducing hospital electricity use: an end-use perspective

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Abstract

Hospitals are an energy intensive building type for which high energy costs and sector carbon targets increasingly prompt attempts to reduce operational energy use. But evidence is sparse and generic one-fits all solutions are problematic due to the complexity and the differing specifications of hospitals. This study therefore focusses on departments as unit of analysis. Five department types (operating theatres, laboratories, day clinics, imaging departments and wards) with differing energy intensities, operating hours and at different stages within the patient pathway are investigated across three case study hospitals of different building age and size (11 departments in total). Detailed audits of installations and use are undertaken to attribute measured departmental electricity use to different end-uses. It is found that lighting loads are dominant in low energy intensity department types, while intensive department types have high loads for specialist ventilation and laboratory equipment. Resulting energy reduction strategies consequently need to take account of these differing challenges, for which an analysis of contributing factors as suggested for example by CIBSE TM22 proved useful. The use of floor area weighted operating hours is proposed as metric for hospitals and other complex buildings which may be beneficial in understanding end-use contributions to total energy use and in highlighting the after-hours switch off potential of building parts in otherwise continuously operating environments.

Context

Acute hospitals are complex buildings with unique energy requirements that exceed those of many other non-domestic building types [1]: They are occupied 24/7 by a large number of people, many of whom are vulnerable. Medical requirements necessitate strict control of the thermal environment and of indoor air parameters, especially in operating theatres and treatment rooms. Specialist medical equipment, sterilization, laundries and food preparation further increase energy use [2].

Given the crucial role of acute hospitals in providing health care to populations, the management of hospital energy demand has long been considered of little importance. Facilities management strategies tended to concentrate on the reliable running of building and building services (including in case of emergencies such as black outs) and the compliance with strict health and safety and other clinical requirements [3]. But high energy costs as well as climate change legislation, in some countries as specific as sector carbon targets, are increasingly prompting attempts to reduce hospital energy use [4]. It is also increasingly recognized that health and climate change are linked. The 2015 Lancet commission on health and climate change argues that tackling climate change could be 'the biggest global health opportunity of the 21st century' [5].

In the UK, hospitals are operated by the tax-funded National Health Service (NHS). The carbon footprint of the NHS and associated authorities amounts to about 32 million tons of CO2 equivalent per year and accounts for 40% of all public sector emissions in England [6]. In line with the UK Climate Change Act 2008, the NHS commits to reducing its total emissions, of which 15% are from energy use in buildings, by 28% by 2020 against the 2013 level and in the long term by 80% until 2050 (ibid). The NHS Sustainable Development Unit, a government agency with the mission to promote sustainable development in the NHS, proclaims that 'Our business is health and we have a moral duty to act on health threats and to manage future demand on the health service [7]'.

Strategies to reduce the energy use of existing hospital buildings are various. Primarily, they include technical measures such as the retrofitting of fabric insulation and updates to lighting installations as well as to pumps, motors, lifts and space conditioning equipment. Salix Finance, a government arm's length organization providing much of the funding for energy saving projects to NHS Trusts in England, Scotland and Wales, list combined heat and power, heat recovery and LED lighting as most commissioned technologies within the NHS between 2012 and 2014 [8]. Increasingly, wider organizational carbon management as well as building energy management strategies such as energy audit and post occupancy evaluation and behavior change are also being considered [9].

Apart from the access to funding, energy demand reduction efforts in hospitals are constrained by a lack of available evidence to benchmarks efficiencies at building or systems level and help identify reduction opportunities. Generic one-fits all solutions are further problematic due to the complexity and the differing set-ups of hospitals [10 - 12]. It is in this vein, that this study seeks to make its contribution: It focusses on departments as unit of analysis. Five department types (operating theatres, laboratories, day clinics, imaging departments and wards) with differing energy intensities, operating hours and at different stages within the patient pathway are investigated across three case study hospitals of different building age and size (11 departments in total). Detailed audits of installations and use are undertaken to attribute measured departmental electricity use to different end-uses. The contributing factors driving lighting energy use are analyzed in more detail based on CIBSE TM22 and implications for facilities management strategies aiming to improve building performance will be discussed.

Literature on energy end-uses in hospitals

Despite the availability of numerous high-level guidance documents on energy efficient hospitals (see EnCO2de 2015, p. 87 for an overview of UK documents [9]), the available evidence on actual energy use across a vastly heterogeneous building type remains sparse. Whole building energy consumption data as well as performance benchmarks are increasingly becoming available, in the UK for example through the Department of Health's 'Estates Return Information Collection (ERIC)' which annually publishes energy consumption figures and site characteristics for all of their premises. But information on the relevance of different energy end-uses, important for the identification of how building performance improvements could be achieved [13], remain very rare.

In the UK, the Energy Consumption Guide 72 on energy consumption in hospitals from 1996 [14] contains some typical and good practice values for different end-uses. The figures were, however, based on small samples and some engineering judgement and may also in parts be somehow dated now. A review of the academic as well as other literature relevant to energy management in health care further revealed 10 studies which identify the relevance of different energy end-uses in hospitals through audits (Figure 1, [15 – 24]). Scope, employed methodologies and quality of the reporting vary widely; presenting some challenges for systematic meta-analysis. Frequently, there are for example differences between the reported end-uses and what is encompassed within each term [25 -26].

Overall, it appears that except in tropical climates energy demand is dominated by space heating and hot water consumption, commonly from fossil fuels. This is line with an analysis of ERIC statistics showing that fossil fuel consumption accounts for two thirds of total energy consumption in UK hospitals (see also [27]). About two thirds of a hospital's electricity consumption occur locally through lighting, plug loads such as IT or medical equipment or through food preparation. The remaining third (more in tropical climates) is accounted for by the provision of building services, in particular cooling, ventilation, compressed gases and elevators.

This study focusses on departments as unit of analysis to account for the variety of processes on-going in hospitals. Perhaps with the exception of operating theatres, which have been researched some more due to their energy intensity (for example Balaras et al. [28]) few studies have attempted to link hospital energy demand specifically to the clinical processes and departments underlying them. In a study of two US hospitals, Rabanimotlagh et al. [29] identify the number of radiological imaging series performed to be a driver of electricity use. In a large UK consultancy project studying outpatient departments, Bacon [30] further argues that clinical activity decisively determines space use and therewith the design of healthcare facilities with important (albeit more indirect) implications for energy use. But no study is known to these authors which systematically compares the relevance of different energy end-uses for a number of prevalent department types in hospitals.

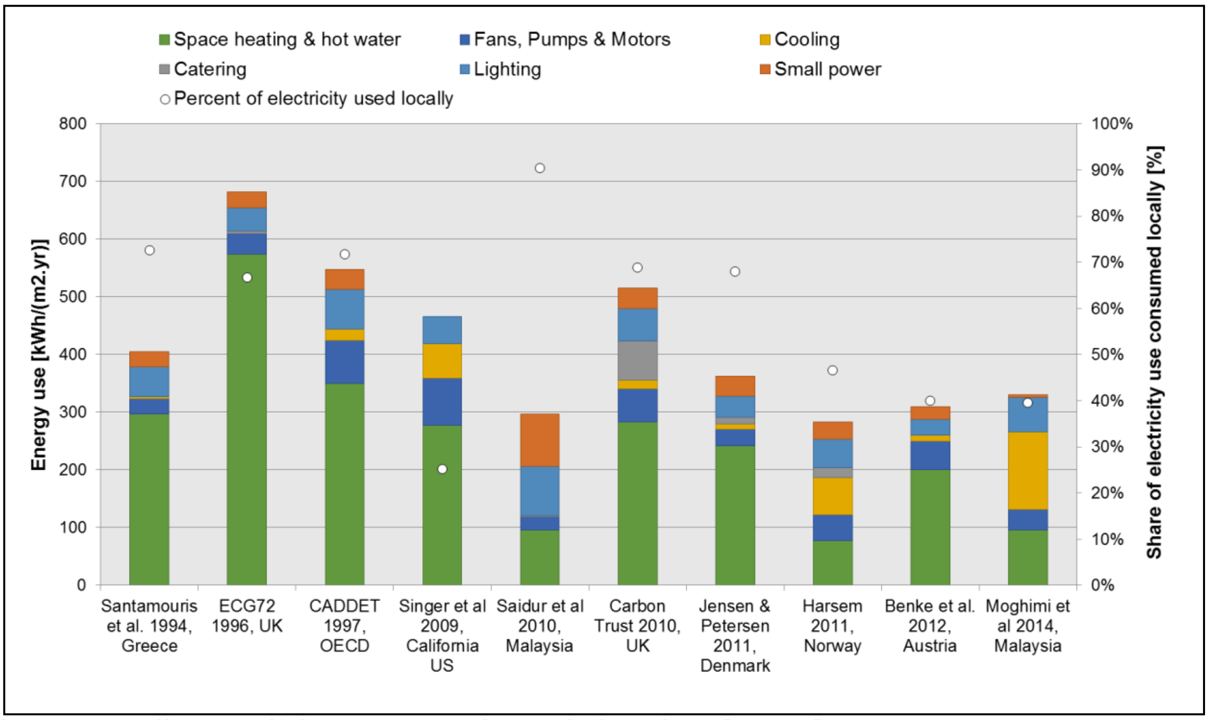

Figure 1: Studies specifying energy end-uses in hospitals [15 - 24]

Methodology of this study

Scope of the study

This study focusses on electricity due to its higher costs to the NHS compared to natural gas. It further restricts itself to the analysis of local electricity demands, i.e. lighting, catering and all types of small power consumption. Electricity use for ventilation, pumping and medical gas services, could not be assessed since it is often a central service, which can only with difficulty be attributed to separate spaces within a building. Finally, the study focusses on general acute hospitals as they occupy 60% of the total floor area within the NHS according to ERIC data.

Research design

Subject to access constraints and the collaboration interest shown by NHS trusts, three case study hospitals are selected using a purposeful maximum variation sampling strategy [31] in line with the exploratory aim of the study (abbreviated in the following as RLH, NUH and KCH). The sampling criteria relevant for diversity were identified from literature review and scoping activities to be hospital age and resulting built form (expected to yield a variety in the implementation of building services) and hospital size (expected to influence extent and realization of service delivery).

The unit of analysis for this study is an individual department. Five department types prevalent in general acute hospitals were selected for analysis reflecting variety in electricity intensity and operating hours: imaging departments, laboratories, operating theatres, day clinics and wards. They selected pathways therewith represented different stages along the patient pathway within an acute hospital: from the diagnosis of an illness (through imaging or the analysis of blood or other body fluid samples in a hospital's pathology laboratory); via its treatment (exemplified here through surgery in an operating theatre and the day treatment for specific conditions such as cancer or kidney malfunctions); to the inpatient care on wards. More information on each department type can be found in the first author’s PhD thesis [32].

Given the abundance of possible clinical pathways, this approach excluded many relevant hospital department types while the selection nevertheless allowed for some understanding of hospitals from a healthcare perspective. Other hospital departments with relevant energy intensities such as sterile services or those where access constraints impeded data collection, for example in accident and emergency services, were also excluded from the study in accordance with the resources available to the project. At least two departments of each type were investigated to increase external validity, as well as at least three departments in each hospital to allow for a literal replication of building features.

Data collection

The study employs quantitative data collection methods to analyze the local electricity use in different hospital buildings and departments. Following a review of available methodologies, the understanding of local electricity use is primarily built from two components which are used to complement and validate each [26, 33]: a departmental level **electricity use profile** (top-down) and a **bottom-up end-use model** based on a detailed audit of lighting and appliances use. Further details on the measurement and analysis of the departmental electricity use profiles is published elsewhere [27], this paper will therefore focus on a description of the bottom-up end-use models.

Within the **bottom-up model**, the electricity use (W_i) of each item is determined as suggested by CIBSE TM54 [34] for small power equipment. For lights, parasitic consumption for controls and emergency lighting is taken into account based on departmental floor area [35]. Item electricity use (W_i) is calculated as the product of the item's average power consumption during operation (P_i) and the duration of its use (t_i), both of which are investigated. Additionally, average item power draw outside of operation (N_i) (often referred to a stand-by although terminologies are not clear) has to be accounted for in some items. The departmental electricity use is understood as sum of the electricity use of all individual items.

(1) $W_i = P_i * t_i + N_i * (8760 [h/yr] - t_i)$

Such an approach focuses on average electricity usage and disregards peak power consumption which (although of interest for load shifting strategies and for power system stability in hospital areas such as imaging) seems less relevant to an initial understanding of the comparative relevance of different energy end-uses across departments. More complex estimations for lighting or local heating and cooling electricity consumption were likewise disregarded because it was felt that the study's main challenge is from the collection and the uncertainty of the necessary data inputs (see also [36]), so keeping them to a minimum seemed preferable.

The data inputs into the bottom-up end-uses models are obtained through detailed lighting and appliances audits. Field et al. [26] and in more detail Mortimer et al. [33] have described methodologies to assess the end-use energy consumption of non-domestic buildings based on site-visits including the room-to-room inspection of the building, visual inspections of installed loads and consultations with staff as well as the analysis of secondary data on plant item and equipment listings, equipment ratings and time-schedule information. Accordingly, the collection of input data in this study takes place in two phases for each department: on site and as desk research.

On site, a room-by-room inspection of the area covered by the metered electricity data is carried out recording information on:

- type of use and reported duration of use of each room;
- lighting installations (identified based on lamp type and size, type of control gear and if in doubt light color and strike time) and lighting controls;
- HVAC installations and controls;
- windows and their operability;
- equipment items (including name plate ratings if available) and their use schedules
- spot-measurements of appliance wattage where possible; and
- the operational state of all items during the researcher's visit.

While information on the inventory is primarily observed or extracted from documentation, much of the duration of use information is reported by staff. In the literature, paper-based self-administered surveys are used to extract such information (e.g. [37]) but are found impractical in the dynamic hospital context where staff were rarely based in one space only. In addition, some of the more intense clinical areas such as labs and theatres are subject to strict health and safety regulations and introducing additional paper does not seem appropriate. A researcher-led approach asking a limited number of questions face to face to extract durations of room and equipment use is therefore preferred. Statements are validated against each other and followed up if inconsistent.

In a second step, the average power consumption of all items is determined in desk research based on information from literature for the specific piece of equipment or equipment type. If information on average consumption is unavailable, estimates are based on power ratings according to the respective plate rating or the equipment manual, taking into account that plate ratings provide measures of maximum as opposed to average consumptions. It is appreciated that the relation between average and peak power consumption can vary widely for different loads [38], but for want of better evidence it is relied on the following heuristics: For office equipment, CIBSE state that actual power consumption is about 10 - 25% of the nameplate rating [39]. For hospital equipment in particular, Hosni et al. [40] hold that for items with nameplate ratings up to 1000 W, the average consumption will be between 25% and 50% of the plate.

Other reasons further complicated data collection in the hospital context, among them the irregular nature of processes making it difficult for clinical staff to describe typical events and average durations of use, or the transient nature of the employment in some departments resulting in limited knowledge of local customs. To allow for some sensitivity analysis of the bottom-up model, the quality of each data input was coded (see [36] for details of the coding procedure) and the impact of the uncertainty in the most relevant items was explored.

Data analysis

To disaggregate the measured electricity use and understand the contribution of individual end-uses, representations of departmental electricity use were created based on the detailed audits of lighting and appliance use. A number of criteria were defined to establish the validity of these bottom-up electricity use model representations in the face of uncertain data inputs (see Table 1 for definitions):

1. Modelled annual electricity intensities per floor area were required to compare to measured values within the range of 20 to 30% as specified by Mortimer according to Liddiard [41].
2. Modelled and measured baseloads were expected to compare within a similar range.
3. The interpretation of load diversities needed to prove comprehensive with respect to the developed understanding of departmental processes: They were expected to be higher for departments with varied processes using much different equipment (in particular theatres) or equipment with a varied power output (hemodialysis) while departments with consistent equipment use such as laboratories or imaging departments (X-ray power use excluded) were expected to have diversity factors tending towards one.

In addition, lighting intensities were modelled based on the established lighting installations and compared to lux level measurements in some departments. Detailed model results were further interpreted in comparison to departments of the same type and in the context of available literature.

Failure to meet the above criteria was understood to require further investigation as to the source of the discrepancy, both at the desk and on the ground iteratively improving the model representation of the department. Table 2 provides an overview of the resulting validity characteristics for each department as well as a list of major uncertainties, which may be from either models or measurements.

Table 1: Definition of variables for model validity criteria

Variable	Definition
Base load (Modelled)	Base loads were modelled as stand-by loads plus active loads with annual operating hours exceeding 6570 h/yr.
Base load (Measured)	In measured data, base loads were defined as the mean of the minimum power readings recorded in each 24 hour period.
Total installed load (Modelled)	Sum of average power consumption of all recorded installed loads
Peak load (Measured)	Mean of the maximum power readings recorded in each 24 hour period
Load diversity	Total modelled installed load over measured peak load

Generally, the models complied well with the measured data according to the criteria listed above - with the exception of the KCH ward where some important base load components appeared to remain unaccounted for in the model (highlighted in grey in Table 2). The load diversity of the KCH ward also seemed with 1.4 rather low, providing further evidence that the model representation of this department should be used with caution only. A limited understanding of heating and cooling energy use by the installed split system was suspected to be the main reason for the modelling uncertainty. The load diversity of the NUH laboratory was also above expectations (1.7). Such issue may however be explained by the fact that the laboratory model covered the whole of the pathology department showing a much higher diversity of use than the investigated area at KCH.

Table 2: Validity of bottom-up representations of departmental electricity use

Department	**Modelled over measured**		**Load diversity**	**Key uncertainties (from modelling in normal font or measurement in italics)**
	Annual [kWh/(m²*yr)]	**Base load [W/m²]**		
NUH Imaging	101%	106%	1.9	• *Uncertainties around which areas & services were included in the sub-meter*[1] • Duration of use and power consumption of split units • Actual power consumption of analogue imaging processors
RLH Imaging	118%	71%	2.4	• Duration of use of reporting rooms which are shared with other departments
KCH Laboratory	99%	110%	1.0	• Power consumption of track system • (Stand-by) Consumption of automated analyzers • Duration of use and power consumption of split units
NUH Laboratory	88%	81%	1.7	• Power consumption of cold room • (Stand-by) Consumption of automated analyzers • Duration of use of IT equipment in specimen reception
RLH Main Theatres	103%	92%	1.7	• Actual operating hours at each theatre • Durations of use for medical equipment items generally • Actual loads from intensive medical equipment and those items hard to identify
NUH Main Theatres	103%	96%	1.4	• Actual loads of theatre panels and hard to identify medical equipment
RLH Day Theatres	122%	84%	1.5	• Actual loads from intensive medical equipment and those items hard to identify • Durations of use for medical equipment items generally
RLH Outpatients	117%	72%	1.3	• *Issues with metering suspected but could not be clarified despite collaboration with facilities management*
KCH Outpatients	99%	75%	1.9	• Duration of use and power consumption of split units

[1] The department had repeatedly been refurbished over the last decades resulting in changes to circuit and distribution board layouts. According to the responsible electrician, some loads within the X-ray area now ran through other distribution boards while the X-ray board included lighting loads in other areas. The exact determination of which circuits were served by which board resulted impossible due to a lack of documentation and the continuous operation of the department preventing experimental determinations of attributions through powering down boards sequentially out of hours.

KCH General Ward	98%	61%	1.4	• Duration of use and power consumption of split units • Operating hours for lighting in rooms where day light is available • Major unaccounted base load contribution and exaggerated installed load
NUH General Ward	110%	94%	2.0	• Operating hours for lighting in rooms where day light is available • Bedpan washer power consumption and duration of use

On the whole, the electricity models seemed to provide reasonable representations of departmental electricity usage. Some confidence could hence be had in end-use splits and saving potential estimates from operational changes on their basis. The next section will present a comparative analysis of electricity end-uses in different department types.

Findings

Local electricity use in different department types

Both annual electrical consumptions and the significance of different end-uses varied widely across different hospital department types (Figure 2). Intensive departments such as theatres and laboratory departments used on average roughly three times more electricity than wards, outpatient departments and imaging departments (excluding imaging equipment on three phase supply).

The former group i.e. operating theatre departments and laboratories used most of their electricity for ultraclean ventilation (UCV) and medical equipment or automated analyzers (also coded as medical equipment). Lower intensity department types were dominated by lighting loads. The RLH hemodialysis department (outpatients) was an exception here due to the extensive use of dialysis machines. Notably is also the higher local electricity use for cooling at KCH due to the provision of split systems, while cooling loads are met largely by central chillers otherwise.

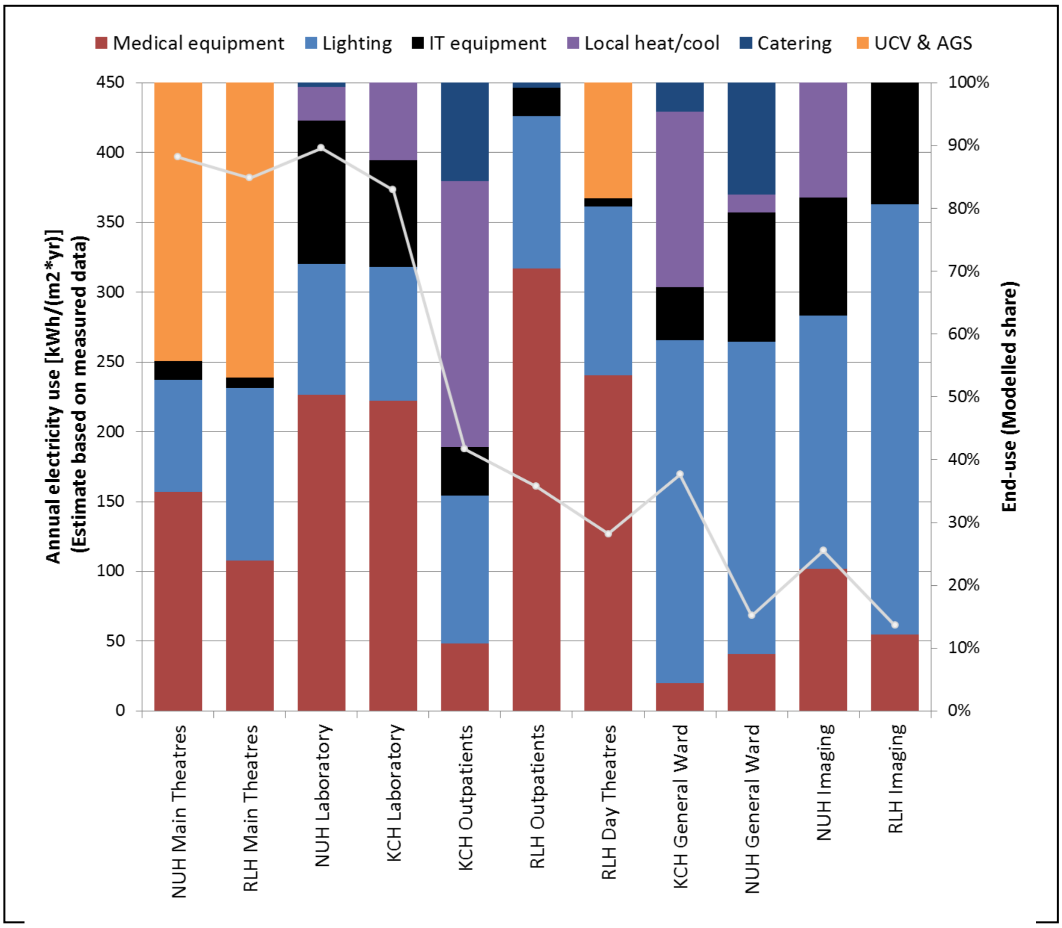

Figure 2: Local electricity use for all departments

The figure presents two information items for each case study department (x-axis): Firstly, a prediction of the annual electricity intensity based on four weeks of measured data, represented by the white line corresponding to the left y-axis. And secondly, the relevance of respective end-uses for each department type based on modelled data. The absolute consumption is scaled to represent 100% in each department so the relevance of different end-uses can be compared across departments. UCV stands for ultraclean ventilation, AGS stands for anesthetic gas scavenging; both are specialist ventilation services relevant in operating theatres.

Overall, the findings were in reasonable agreement with the limited available evidence on end-use relevance for hospitals as a whole. An analysis of Figure 1 showed that lighting loads were dominant over equipment loads in entire hospitals on average. This suggested that non-energy intensive department types played a major role within the make-up of a building's total energy performance, an interpretation that was substantiated by the fact that wards accounted for a significant proportion of space in general acute hospitals [42].

Lighting energy use and service provision

In order to identify opportunities for reducing energy consumption from selected end-uses, specifically ventilation and lighting, it is recommended to break down the respective energy use into contributing factors [13]. The following section will do so for the lighting electricity use in two of the above departments, while drawing on relevant benchmarks available for energy end-use components in hospitals. Lighting was selected for discussion here because it was found to be comparatively independent of building design and system age. Only window design was important in areas with daylight and replacement cycles influenced installed lighting technologies.

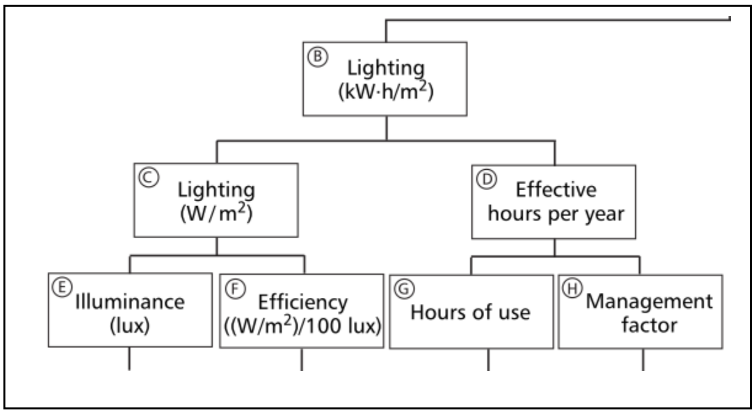

Figure 3: Analysis of lighting energy consumption and service provision according to CIBSE TM22 (from Appendix 2, [25])

According to CIBSE, illuminance levels, the efficiency of the lighting system as well as hours of use and a management factor summarizing issues of lighting control have hence been identified as main drivers for lighting energy use[2] (Figure 3). Ideally, benchmarks for all contributing factors (each box in Figure 3) are available to help the analysis of building and system level performance. For acute hospitals, the following values (discussed from the bottom upwards) may be indicative:

> E) Illuminance levels for health care premises are prescribed in BS EN 12464-1:2011 [43]. Notably, the differentiation of illuminance requirements for different room types and activities is very detailed and outperforms any comparable evidence for energy metrics in availability. Typical illuminance levels range between 100lux as general lighting on wards and 1000lux for treatment in examination rooms and operating theatres.

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2 According to an updated version of the TM22 tree diagram published by the Technology Strategy Board, load control from dimmable lights is also increasingly relevant, but will not be discussed here.

F) If no further details are known, the National Calculation Methodology (NCM, [44]) for buildings other than dwellings in England and Wales recommends lighting efficiencies of 6.2 W/(m2*100 lux) in spaces other than offices, storage or industrial spaces. 3 W/(m2*100 lux) could be used for efficient installations also in health care, as suggested for offices in CIBSE Guide F [39] and ECG19 [45].

G) In a first instance, the hours of use of a hospital department may be concluded from its opening hours. Especially for areas with continuous operation such as laboratories or wards, this assumption may overestimate actual use significantly, as the case discussed below will exemplify.

H) The management factor for lighting relates primarily to the installed means of lighting control. A value of 1 is typically assumed for manual light switching, while photoelectric day light sensors or occupant sensors may reduce this value to 0.9 each or 0.85 in combination (CIBSE Guide F [39] Table 9.4).

At a more aggregate level, lighting load (C) and effective usage hours per year (D) become relevant. Here, this study may contribute the in-situ metrics collected for the 11 investigated departments as basis for the further development of these box benchmarks (Figure 4). The average lighting efficiency was 16 W/m2, with little coherent differentiation between high intensity and low intensity department types. As expected, operating theatres did however stand out with higher power densities. These findings compared well but overall on the lower side with the default benchmark values for hospitals presented in BS EN 15193:2007 [35], which range between 15W/m2 and 35W/m2 depending amongst others on the color rendering properties of the installation and the level of special attention to health issues.

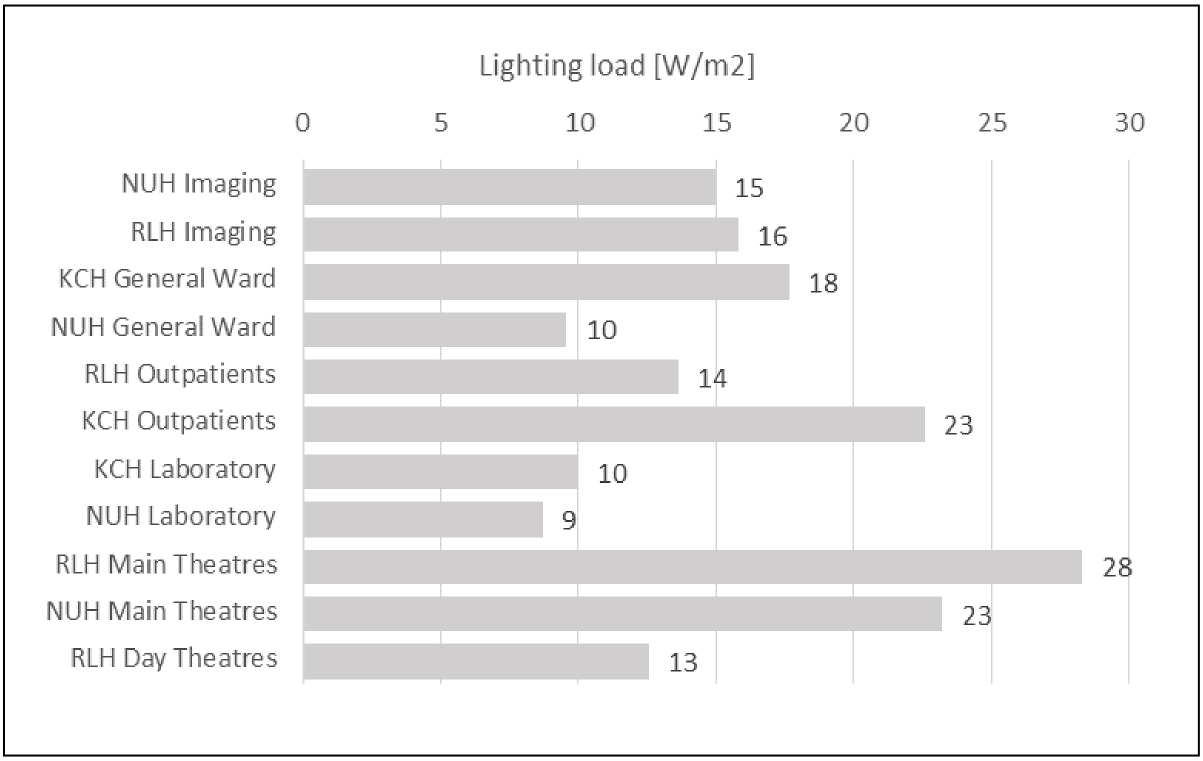

Figure 4: Departmental lighting loads

As for effective usage hours per year, the case investigation revealed that both the over- and the underestimation of actual usage hours may result in a biased evaluation of departmental lighting performance as demonstrated in the following for two quite different department types. For the KCH Outpatient department it could be shown that longer effective operating hours due to preparations and after hour cleaning activities resulted in a 10% higher lighting energy use than originally expected based on standard assumptions (Figure 5).

In complex departments and those with continuous operating hours, such as laboratories, however the analysis was less straightforward. The expected lighting load (Table 3) based on standard service provision benchmarks as discussed above vastly exceeded the actual load expected according to the audit results which were reconciled with available measurement data. The structure of the analyzed pathology department could be identified as driver of this discrepancy: apart from a continuously operating main laboratory, the department also contained a number of office spaces with shorter operating hours (and differing illuminance requirements). Understanding such variations in space use proved crucial for modelling and energy management and will be further discussed in the next section below.

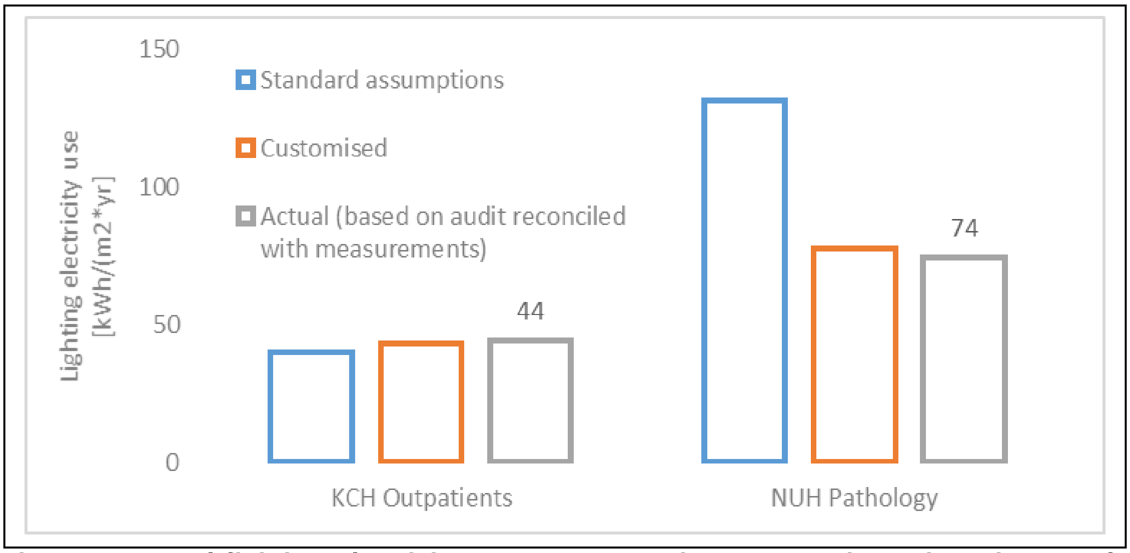

Figure 5: Actual lighting electricity use as opposed to expected use based on analysis of drivers for two case departments

Table 3: CIBSE TM22 analysis of lighting energy use

Case	**Scenario**	**Illuminance [lux]**	**Efficiency [W/(m2*100lux]**	**Hours of use**	**Management factor**
KCH Outpatients					
	Standard assumptions	300	6.2	2080	1
	Customised	307	6.2	2270	1
NUH Pathology	Standard assumptions	500	3	8760	1
	Customised	372	3	6957	1

The customized hours of use are based on floor area weighted operating hours for the department, taking into account the likely operation of each room as following:

$$\frac{\sum \text{Room annual operating hours } (h/yr) \cdot \text{Room floor area } (m^2)}{\text{Department floor area } (m^2)}$$

As for total lighting energy use, all departments were found to exceed the good practice lighting benchmarks presented in ECG72 of 20 kWh/(m2*yr) for acute hospitals [14]. It will however seem that, given a design lighting load of at least 15 W/m2 according to BS EN 15193:2007 [35], this benchmark may be little realistic. The average lighting energy use across all departments in this study was 63 kWh/(m2*yr), while a indicative good practice typical benchmark based on the 25percentile may range around 45 kWh/(m2*yr). This figure is however severely limited by the small sample size of this study, while the above analysis suggested that a more detailed analysis of local service provision will likely result in a more meaningful benchmark anyway, given the heterogeneous nature of clinical processes across a hospital.

Discussion and conclusions

The presented study has highlighted a number of issues relevant to the building performance evaluation in existing hospitals and other complex building types. Firstly, it was argued that due to the differing energy intensities of clinical processes and building service requirements, the analysis of hospital energy performance needs to look beyond entire buildings and consider departments or other sub-spaces as unit of analysis in order to understand building use and develop meaningful strategies to reduce energy consumption.

Secondly, in measuring electricity use at a sub-building level, it is paramount to correctly identify the areas and circuits served by distinct distribution boards or the services included in sub-meter data available on building or energy management systems. Hospitals, however, are dynamic environments which continuously evolve to meet the changing requirements of health service provision. This may result in changes to circuit and distribution board layouts, which in combination with a lack of documentation and the continuous operation of many departments (preventing experimental determinations of attributions through powering down boards sequentially out of hours) may limit the usefulness of sub-metering results. Previously also reported by Janda et al. [46], this finding highlights the importance of careful primary data collection efforts to make sure it is understood what is being measured and reported in building performance studies.

It was further suggested that in complex buildings, such as hospitals but surely also industrial facilities with continuous production processes or research laboratories, the estimation of effective usage hours across the entire building can be problematic. Guidance documents on energy management generally stress the need to break buildings down, for example into areas with different uses, operating hours and tenancy arrangements [39]. In complex buildings, floor area weighted operating hours may be one alternative metric which could be beneficial in highlighting the diversity of use across a building. The level of detail may not need to go down to room level in practice, for facilities management purposes a more indicative understanding of the use of space across a complex building may be sufficient. It could in any case point towards untapped energy efficiency potentials not only with respect to lighting use, but more importantly also for HVAC systems.

Timer settings for lighting, mechanical ventilation and heating set-points in spaces that are likely to be unoccupied for a significant number of operating hours, such as outpatient departments or day theatres, could benefit from such an improved understanding of space use and operating hours in hospitals. Given the sensitive and demand driven nature of health care, the options for and the effectiveness of manual override should also be explored in the context of timers and other centralized controls to building services in hospitals.

At a methodological level, the study also highlighted some of the difficulties for built environment research in hospitals. In particular, more data on the actual energy consumption of and the heat loads from both major and small medical equipment will be useful in the optimization of existing hospital buildings and the design of new facilities. The current study was somehow limited by the small number of investigated buildings and departments as well by restrictions to the monitoring of sensitive medical or laboratory equipment and access difficulties resulting in opportunistic auditing, i.e. the lighting and appliance audits were arranged when convenient for the respective department in an attempt to minimize disruption and increase research participation. Consequently, data collection took place at different times during weekdays or weekends, mornings or afternoons, somehow restricting the replicability of audit results.

For future projects in health care, increased collaboration between interested clinicians and technical personal is recommended to reduce access difficulties and identify viable options to reduce the energy use of existing hospitals while improving their overall performance in the service of staff and patients, in particularly also with respect to overheating issues. Methodologies to attribute central energy requirements to disparate spaces within complex buildings will also help to improve building performance models and therewith reduce the performance gap. Despite the above limitations this study offers some valuable insights into an area where little data is currently publically available.

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