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Benchmarking acute hospitals: Composite electricity targets based on departmental consumption intensities?

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ABSTRACT

This study aims to explore how meaningful energy benchmarks—reflecting good energy management and design—can be constructed for hospital buildings, a category encompassing complex buildings with different set-ups and large variability between them. Current energy targets are sometimes considered of limited use by facility professionals in health care because they do not take account of differences in service delivery between acute hospitals which result in differing use of medical equipment and requirements for room conditioning. For this study, the electricity use of a number of department types has been quantified using on-site measurements. Findings confirm that different hospital departments have hugely varied electricity consumption characteristics. Wards, day clinics and some other departments have lower average consumption intensities which are reasonably well reflected by current hospital electricity benchmarks. Theatres, laboratories and also departments such as imaging and radiotherapy showed much higher consumption intensities exceeding available targets. A revision of current energy benchmarks for the latter category is therefore strongly recommended. It is further proposed to develop composite benchmarks for hospitals taking into account differing energy intensities at a departmental level for guidance and as basis for certification.

1. Introduction

Buildings use large amounts of energy, with significant short-term economic costs and long-term environmental implications [1]. Various policy measures aimed at improving their energy efficiency have consequently been implemented worldwide; many of them based on performance standards and codes for new buildings and alterations to existing buildings (such as 'Net Zero Energy' or 'Zero Emission Buildings') [ibid]. A growing number of studies, however, have uncovered a mismatch between the expectations around the performance of buildings and their actual energy use and resulting utility bills [2]. In the UK for example, the cross-sectorial online platform CarbonBuzz illustrates that new-built offices use 48% more energy on average than predicted at the design stage [3]. This difference between expected and realized energy performance of buildings has come to be known as the 'performance gap' [2].

Assessing and improving the operational performance of existing buildings has hence become increasingly important [4]. This involves comparing the in-use performance of a building to standards such as either the building's historical energy use or the levels of energy use achieved by a group of similar buildings or building systems [5]. The latter process is commonly known as benchmarking and allows building owners and operators to put their buildings' actual performance into a broader context [6]. Yet there is little transparency for comparisons across the property market while numerous rating tools and assessment programs exist in parallel and methodologies to measure and compare building efficiencies are not standardized [7].

There have been several attempts in both the academic literature and in guidelines for facility managers addressing some of the issues associated with the energy benchmarking of non-domestic buildings which are briefly reviewed subsequently [8–10]. Fundamentally, two major challenges have been identified: the availability of energy data from a sufficiently large number of buildings and the heterogeneity of non-domestic buildings resulting in

Abbreviations: SP & L, small power and lighting; AGS, anaesthetic gas scavenging; UCV, ultraclean ventilation.

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severe problems of classification. One building category for which both of these challenges are predominant due to size, functional requirements and metering infrastructure are hospitals.

Hospitals are complex buildings with unique energy requirements [11]: They are occupied 24/7 by a large number of people, many of which are unwell and therefore vulnerable to environmental conditions. Medical requirements necessitate strict control of the thermal environment and of indoor air parameters, especially in operating theatres and treatment rooms. The electricity consumption of hospitals also exceeds that of many other non-domestic building types due to the additional use of specialist medical equipment, sterilization, laundries and food preparation. Depending on hospital size and clinical needs of the served population the service provision can vary widely even between hospitals nominally classified as general (i.e. non-specialist) hospitals [12].

In consequence, nationally mandated energy performance targets seem to often be found of limited use by facility management professionals in health care. In the UK, an online survey by the NHS Sustainable Development Unit suggests that only 28% of the responding trusts thought that the government's energy performance targets had been very useful; one reason for this being that 'targets do not take account of inherent differences between trusts. (p.48)' [13]. The academic literature has also pointed out that hospital energy benchmarks need to be resolved for as specific an area as possible [14–16].

In response to these concerns, this study aims to explore how meaningful whole building energy benchmarks reflecting good energy management and design can be constructed for hospitals, a category encompassing complex buildings with differing service provision and large variability of facilities. Different departments and room suites within hospitals inevitably have different energy consumptions due to differing use of medical equipment and requirements for room conditioning; therewith affecting overall building energy use. For this study, the electrical use by a number of department types has been quantified using on-site measurements. The extent to which measured usage is reflected in current electricity performance targets for hospitals, and consequences for benchmarking methodologies are evaluated and discussed.

2. Energy benchmarking in the built environment

2.1. Theoretical considerations on statistical energy benchmarking

A number of reviews have previously summarized challenges for benchmarking methodologies [8–10] and their application in a real context [6,17–19]. Their findings are briefly summarized subsequently. Overall, two types of benchmarking methodologies can be distinguished: top-down approaches and bottom-up approaches. Burman et al. [18] conclude that while top-down methodologies can drive energy efficiency at a stock level and are therefore relevant to energy policy, bottom-up methods enable the performance diagnostic of buildings taking into account their specific context.

The aim of this study is to improve industry guidance and provide evidence as basis for the development of meaningful national energy performance targets for hospitals. Methodologies allowing for a stock level analysis are hence of foremost interest for this paper. Two approaches to developing top-down whole-building benchmarks can be distinguished:

- Descriptive statistics: when using descriptive statistics, the energy use intensity (EUI), most frequently in kWh/m^2 per year and if necessary weather corrected, of a sufficiently large number of buildings of a defined type is collected. Fifty [20] to hundred [21] buildings are commonly recommended to develop statistically robust benchmarks. Mean or more commonly median energy use intensities (minimizing the effect of outliers) of the sample are then computed. In a second step, performance targets (also referred to as benchmarks or limits of use) can be set based on the first quartile or some other defined percentile of a distribution of energy use intensities or through using performance bands [22].
- Multivariate approaches: multivariate approaches use a larger number of variables per building to predict the energy use intensity of a specific building, enabling the comparison with a typical building with the same features. Such variables may include information on building layout, operational activity or climatic location. Regression based approaches (as used for example in the US building performance certification programme Energy Star®) fall into this category, as well as artificial neural networks [23].

The core advantage of the use of descriptive statistics is the low data requirement per building, both in terms of numbers and in terms of types of variable per building: often only annual energy consumption and floor area are needed, both variables which are generally already being collected. The approach, however, proves insufficient in evaluating accurately how efficiently a building is being managed due to many confounding effects. It also requires large, well-distributed and up-to-date data sets in order to derive robust benchmarks. Additionally, the definition of category types has large influence on outcomes while approaches are not standardized.

Multivariate approaches, in contrast, offer a higher accuracy in evaluating operational efficiency while sector specific determinants of building energy use can be taken into account. The effort for data collection and analysis, however, is much higher and the data basis necessary to develop the predictive equations or algorithms remains large. This paper consequently focusses on descriptive statistics rather than multivariate approaches due to the smaller costs for data collection and analysis as well as the uncertainty about drivers of departmental electricity use in hospitals at this stage.

For building types with large heterogeneity between buildings as will be the case for hospitals or laboratories, two alternative approaches can be considered to customise whole-building benchmarks based on descriptive statistics [24]:

- Mixed use buildings: performance targets for individual buildings may be constructed as composite benchmarks based on the relative percentage of total usable floor area allocated to each use type (such as office or general retail). For hospitals, this approach currently seems to be uncommon due to a lack of available benchmarks for the different space types.
- Separable energy uses: consumption figures for individual buildings may be adjusted by excluding certain defined special uses such as server rooms in offices or bakery ovens in large stores from the metered energy use to obtain a fair assessment within the original building category. For instance the benchmarks to create Display Energy Certificates (DECs) in UK hospitals [24] allow high intensity furnaces and other heat treatment or forming processes to be excluded if they are sub-metered.

This paper sets out to further investigate how both of these approaches may contribute to constructing meaningful energy targets in the hospital context.

2.2. Benchmarking hospital energy use

In the UK, the majority of hospitals are operated by the tax-funded National Health Service (NHS). The carbon footprint of the NHS and associated authorities amount to about 32 million tonnes of carbon dioxide equivalent, this is 40% of all public sector emissions in England [25]. Energy use in buildings accounts for 15% of NHS carbon emissions, while 72% are from the procurement of pharmaceuticals, medical devices and gases and the remaining 13% from travel as well as the transport of patients and goods [25]. In line with the UK Climate Change Act, the NHS commits to reducing its total emissions by 28% by 2020 against the 2013 level [ibid]. It is acknowledged that while general practitioners (GPs) best contribute to this aim through preventing the need for resource intensive treatments through encouraging healthy lifestyles, acute hospitals additionally have significant potential to reduce building energy use.

An analysis of the energy consumption figures annually provided by english general acute hospitals through the Estates Return Information Collection (ERIC) shows that while fuel use intensity for heating has been decreasing over the last decade, electricity intensities are on the rise (Fig. 1). This is probably due to increased use of medical and computing/communication equipment as well as more ventilation and comfort cooling. A number of studies have investigated ventilation and cooling in hospitals, in particular with view of a warming climate [14,26,27]. While recognising the importance of HVAC systems in hospitals, this paper hence focuses on the end-use of electricity at a sub-building level to identify reduction opportunities in the light of this development.

There are at least three recent systems of benchmarking that cover NHS properties (Table 1) alongside a national energy target for NHS Trusts of 413–488 kWh/(m^2.yr) total energy use [26]. Overall, EnCO2de [12] most accurately represents current electricity use while the 1996 BRECSU figures [29] still used in CIBSE Guide F [20] now seem out of date. Figures published by CIBSE [24] forming the basis for display energy certificates (DEC) also seem low in comparison to reported consumption levels. Internationally, some published figures [30] and energy performance targets for hospitals are on the whole not dissimilar to those in the UK while in particular Germany [31,32] specifies more ambitious standards (Table 1).

Less evidence is available on hospital electricity use at a sub-building level. Some studies have focussed on energy intensive areas such as operating theatres [27] or imaging [33] but on the whole data on actual energy use remains sparse, likely due to access constraints and a prevalent lack of sub-metering. Notably, Beier [34] presents detailed end-use consumption measurements for heating, cooling, lifts and hot water use as well as for ventilation in operating theatres and intensive care units in 20 medium-sized German hospitals. An increasing number of studies is now also aiming to measure hospital electricity use at a sub-building or departmental level with view of providing input data for building simulation [35]. Additional electricity consumption data with a granularity exceeding entire buildings is becoming available through research on energy intensive equipment [36,37], primarily imaging and radiotherapy [33,37,38] (Table 2). As for electricity targets, CIBSE TM46 establishes a separate performance target for laboratories or operating theatres of 160 kWh/(m^2.yr), and up to 328 kWh/(m^2.yr), with a possible occupancy adjustment based on 8568 rather than 2040 h of annual occupancy [24].

3. Study design

3.1. Source of data

For this study, the electricity consumption of 28 departments was collected across 8 medium to large General Acute hospitals in England. The departments fall into 6 different categories which have been selected for analysis due to their prevalence in General Acute Hospitals (Wards), their high energy intensity (Theatres, Laboratories, Imaging and Radiotherapy) or their distinct operating hours (Day Clinics). Table 3 provides details on the data source for each department. Function and operational characteristics of the departments were confirmed through site audits, while floor area values were established from floor plans.

For some of the departments, automatic meter readings were available on the trust's energy management system. For all others, electrical measurements were carried out at the distribution boards serving the respective departments using various types of equipment (Table 4). With the devices that only measure current, it is assumed the voltage is 240 V and the power factor is 0.9 based on typical known on-site voltages in urban areas and hospital loads [12]. Loads were monitored for a minimum of seven days to capture day of week (particularly weekend) influence on electricity use. If possible, monitoring was continued for up to four weeks to increase the reliability of the measurement. It is focussed on local electricity use for power (including fan coil units if present) and lighting but excluding central services, i.e. ventilation and cooling.

3.2. Data analysis

Overall the data quality of the obtained measurements was good, with at most 2.4% (at NUH) of data points missing or corrupted likely due to metering equipment failure. Missing data points were replaced with the average current or energy consumption of the respective time period during all comparable weekdays.

Patterns of electricity usage in daily and weekly profiles, weekday and weekend day consumptions, base loads and peak loads were examined in order to provide characteristics of the hospital departments' energy use and potential energy saving measures. For this, base loads are defined as the mean of the minimum power readings as recorded in each 24 h period, and peak loads as the mean of the maximum readings as recorded in each 24 h period.

Data from interval current and power readings and floor areas allowed for predictions of annual consumption intensities to be made. They are scaled up to a year based on mean daily weekday and daily weekend day consumptions during the measurement period, assuming bank holidays are as weekend days. This approach disregards seasonal differences in electricity consumption (mainly from fan coil units and occasionally lighting use) and further assumes the measurement period is representative for the year which for some department types such as imaging may underestimate an increase in clinical activity during winter.

3.3. Limitations of the study

The present study has a number of contextual and methodological limitations highlighting the need for further research on hospital energy benchmarking. Some central challenges are linked to the study design: firstly, it is a small, UK based study with very limited sample sizes for each department type. Annual electricity consumption means may hence be understood as indicative only. Secondly, measurements have been undertaken at one moment in time only for each hospital while the total data collection period for this project spanned more than five years (2009–early 2015). Given the increase in electricity use identified in General Acute Hospitals (see Fig. 1) this will somehow limit the comparability of the collected data, potentially underestimating current electricity use in the earlier project hospitals.

Further issues complicating departmental comparison arise from structural differences between departments. While core functions might be clearly defined for each department category, additional service and infrastructural arrangements may vary widely. In addition, the electrical layout determining which circuits and areas are served by different distribution boards and can therewith be monitored will often not correspond to the spaces constituting a clinical function or department. Especially in older

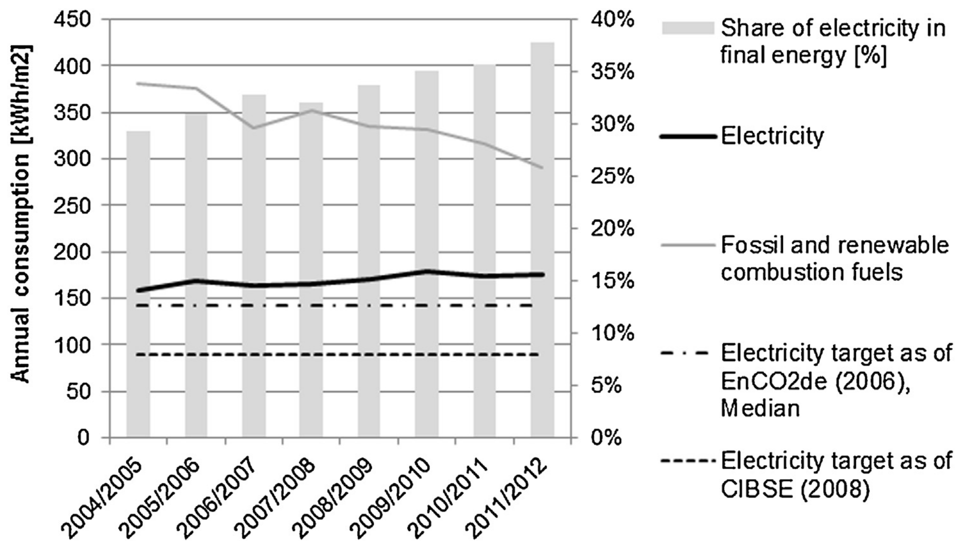

Fig. 1. Historical development of final energy use in English general acute hospitals.

Table 1
Overview of hospital energy performance figures and targets (final energy).

Source	Country	Year of data	Category	# data points	Current consumption kWh(m2.yr)		Target kWh(m2.yr)	
					Electricity	Heat	Electricity	Heat
Industry Guidance								
[29]	UK	Pre 1996	Acute Hospital	Unclear	108	510	74	422
[12]	UK	2006	General Acute Hospital	Unclear, likely about 150	143	373	122	317
[31]	Germany	1999	Hospital with up to 250 beds	102	53	289	32	170
			Hospital with 251 to 450 beds	76	67	243	45	172
			Hospital with 451-650 beds	46	77	314	48	204
			Hospitals with 651 - 1000 beds	27	78	308	36	230
			Hospital with more than 1000 beds	31	164	446	47	270
Mandatory Disclosure								
[24]	UK (DEC)	?	Hospital (Clinical and Research)	Unclear	90	420		
[32]	Germany (Energie-ausweis)	2007	Hospital with up to 250 beds	111	120	205	84	145
			Hospital with 251 to 1000 beds	104	115	250	80	175
			Hospital with more than 1000 beds	33	115	285	80	200

Table 2
Literature providing measured electricity consumption figures at departmental level.

Category	Description of monitored area	Included end-uses	Predicted (kWh/m^2.yr)	Measured by
Wards	General ward with 20 patient rooms	Small power and lighting (SP & L)	60	[35] (Germany)
Theatres	No details provided	SP & L (calculated as Total − AC)	383	[39] (Taiwan)
Imaging	CT room and control room	CT consumption measured, lighting and ancillary equipment estimated based on audit data	471	[33] (US)
	CT room and control room		402	[33] (US)
Laboratories	Several floors of a hospital laboratory building	Plug loads from clinical equipment	94–190	[40] (Germany)

Table 3
Summary of data sources.

Category	Unit	Description of monitored area	Included end-uses	# days	Data interval	Measured by
Wards	AH1 critical care unit	Intensive care ward	SP (including ventilators, patient monitoring, TVs, microwaves & kettles)	14	15 min	IESD
	AH1 Stroke ward	Intensive care ward	SP (including ventilators, patient monitoring, TVs, microwaves & kettles)	14	15 min	IESD
	GF children's ward	General paediatric ward	SP & L	14	10 min	IESD
	LRI children's ward	General paediatric ward	SP & L	7	10 min	IESD
	LRI emergency decision unit	Short stay ward, 16 beds	SP & L	7	10 min	IESD
	AH2 Trauma	General ward	SP & L	15	30 min	AH2
	AH2 23 h surgical ward	Intermediate care ward	SP & L	5	30 min	AH2
	NUH general surgical ward	General ward, 25 beds	SP & L	21	30 min	NUH
	KCH general surgical ward	General ward, 20 beds	SP & L	49	10 min	UCL
	RLH elderly care ward	General ward, 26 beds	SP & L	28	30 min	RLH
Theatres	GF cardio theatre	Emergency theatre suite	SP & L	19	10 min	IESD
	AH2 theatres	2 Non-emergency theatre suites	SP & L	4	30 min	AH2
	RLH Adult Theatres	2 emergency theatre suites and 3 non-emergency theatres suites	SP & L	28	30 min	RLH
	NUH main theatre	Non-emergency theatre suite	SP & L (AGS pumps, AHUs)	28	2 h	UCL
Imaging & radio-therapy	RLH inpatient X-ray	3 X-ray rooms, corridor, 3 offices	SP & L	28	2 h	UCL
	GF CT & MRI rooms	Rooms used for MRI and CT scanning only	SP & L	7	10 min	IESD
	BH X-RAY department	Entire department including X-ray rooms and offices	SP & L	62	30 min	BH
	AH2 radiotherapy	Department housed in its own building: bunker and associated rooms including offices	All electricity (main incomer for whole building)	28	30 min	AH2
	LRI linear accelerator bunker	Room itself and equipment servicing it from outside room	SP & L	7	10 min	IESD
Laboratories	NUH pathology	Entire pathology department including main lab, specimen reception, offices	SP & L	28	30 min	NUH
	KCH blood sciences lab	Main laboratory and two offices	SP & L	28	10 min	UCL
Day clinics	GF day clinics	Atomic medicine and physiology	SP & L	20	10 min	IESD
	RLH outpatient dialysis	Day clinic with up to 60 chronic dialysis units	SP & L	28	30 min	RLH
	KCH day clinics	Chemotherapy day unit	SP & L	28	2 h	UCL
Other	RLH day theatres	6 day theatres suites, recovery, 2 offices	SP & L	21	30 min	RLH
	LRI maternity	Maternity department consisting of two theatre suites, recovery rooms, changing rooms, kitchen, nursery, seminar room, store	SP & L	7	10 min	IESD
	NUH radiology	Entire radiology department for elective and emergency imaging incl. X-ray, CT, MRI, nuclear medicine	SP & L (excluding imaging equipment except ultrasound)	28	30 min	NUH
	BH offices	Oncology-offices, a kitchen and WC	SP & L	62	30 min	BH

Note: with AH1—Anonymous Hospital 1, GF—Glenfield Hospital, LRI—Leicester Royal Infirmary, AH2—Anonymous Hospital 2, NUH—Newham University Hospital, KCH—King's College Hospital, RLH—Royal London Hospital, BH—Birmingham Heartlands Hospital, IESD—Institute of Energy and Sustainable Development (De Montfort University), UCL—University College London.

Table 4
Specifications of measurement equipment.

Data logger	Current transformer	Overall accuracy (according to manufacturer specifications)	Used in hospitals
Current Cost EnviR Energy Monitor	Corresponding CurrentCost CTs (0.5–100A)	±3%	NUH, RLH, KCH
HOBO UX120-006Ms	CTV-C (10–100A)	±2.1%	RLH, KCH
Profile	CT attachments (no current range given)	unknown	GF
Dent Data Pro	Corresponding split-core Dent CTs (0–400A)	Unknown	LRI
Dent Elite Pro (0–6000 A, 80–600 V)		±0.2%	GF

buildings, spaces may have undergone various changes of use resulting in distribution boards with undocumented service provision or serving several departments. Distribution board layouts also present challenges for measurement practicalities, as they define which currents are measureable and therefore the extent to which different end-uses could be included into the study.

As to further challenges for measurement practicalities, the use of different equipment with varying accuracies also influences result comparability. More fundamentally, however, there is a systematic error from frequently only measuring currents instead of all power characteristics while the comprehensive use of energy analysers was not possible due to funding constraints. Similarly, it was not possible to monitor departments for a full year to fully understand the implications of seasonal variations in weather and clinical activity. And finally, electricity use for ventilation, pumping and medical gas services, could mostly not be measured since it is often a central service hardly attributable to separate spaces within a building. Central energy requirements for other HVAC components were not investigated due to study scope and resulting practical considerations.

Despite these limitations this study offers some valuable insights into an area where little data is currently publically available. Further research is recommended analysing larger sample sizes and extending measurement periods to increasing the statistical power of any conclusions. A close collaboration with trusts and other healthcare institutions was found useful for this purpose.

4. Findings

4.1. Wards

Wards, internationally sometimes also referred to as 'Inpatient Units', are composed of patient bedrooms and the spaces that support them, such as utility rooms, nurse bases, storage spaces and potentially food reheating facilities. Wards tend to account for substantial shares of overall hospital floor area and increasingly so following a trend to more single-patient accommodation [41]. On the whole, wards are characterised by their continued occupation regardless of time of day, week or year providing continuous medical observation or care for patients during and after treatment.

In this study, 11 ward spaces were monitored across seven hospitals (Table 5). Some difference in electricity intensity can be observed between general wards, intermediate care or so-called step-down units and intensive care wards such as stroke or critical care units (see Fig. 2a and b for exemplary profile comparison). In the latter, respiratory care services need to be available around the clock and monitoring and staffing levels are likewise higher, with one trained critical care nurse in charge of only one or two patients as opposed to typically eight patients on general wards. Intensive care wards also seem to have higher load factors than general wards, potentially due to more occasionally used emergency equipment.

Although all wards are occupied around the clock, activity hours and periods of afternoon downtime were found to vary between wards. Children wards (for example Fig. 2d) tend to have fewer activity hours than adult wards to account for higher needs for sleep of paediatric patients. The elderly care ward (Fig. 2b) in contrast showed a recurrent pattern of activity at odd times during the night, an effect ward staff explained as typical for elderly patients who often have trouble sleeping.

The energy use profile of different departments will, however, not only be due to clinical processes but also a result of other facilities present on the ward. Regeneration (regen) kitchens to reheat patient meals locally after they have been prepared in central catering facilities were identified as comparatively energy intensive pieces of equipment on wards, BRECSU for example estimate an annual electricity use of 328 kWh/bed [29]. The electricity use of the NUH General Surgical Ward (Fig. 2c) shows a pronounced peak at lunch and dinner time for this reason, while the other wards not including food preparation areas consequently display smoother profiles.

4.2. Theatres

For many medical conditions surgery can be necessary to alleviate them and every acute hospital will therefore be equipped with a number of theatres suites (theatres, anaesthetic, scrub and preparation rooms) as well as recovery facilities where patients are supervised immediately after surgery. Additionally, most theatre departments include some administrative areas and facilities for staff changing and resting. In addition to the main theatres, some hospitals have dedicated day theatre departments for ambulant procedures as well as special paediatric theatre departments for surgery on children.

There are many different types of surgery broadly definable by their surgical speciality. The speciality decisively influences the use of medical equipment during surgery and the requirements for facilities such as ultra clean ventilation (UCV) canopies, but also operational characteristics such as the duration of surgery and time in recovery. To give but one example, orthopaedic surgeries may only be carried out in theatres equipped with UCV canopies because infections need to be avoided at all costs. They tend to be rather long with average case times of two hours while requiring frequent imaging (typically using mobile X-ray) to ensure correct implant positioning. On the other hand, minimal invasive surgeries using for example endoscopic ('keyhole') techniques are becoming increasingly popular in surgical specialities such as urology and otolaryngology. They are much quicker and up to 30 patients can be seen daily. Such interventions are often carried out as day-case procedures, in rooms more akin to regular treatment rooms than to fully equipped operating theatres. Ultra clean ventilation is not required and air change rates will be lower (15 AC/hr according to [42]) than prescribed for open theatre cases (25 AC/hr).

In this study, four theatres departments were monitored across four hospitals (Table 6). Additionally, operational data from the trusts accounting system was available for the NUH Theatre (see Fig. 3a for electricity use profile), providing details on actual theatre use and list specialities. It could be shown that periods of high energy use (with loads exceeding 60 W/m^2) reliably corresponded to trauma or fracture lists (typically on a Tuesday morning and Wednesday or Thursday afternoon) while general or ear, nose and throat surgery seemed to use less electricity intensive equipment.

In addition to elective (planned) surgery according to patient lists, emergency surgeries characterised by a need for swift action to avoid patient death or permanent disability are also carried out in all general acute hospitals at any time during day or night. During 2012–13 about a quarter of surgical hospital admissions were emergencies [43], this is also reflected at NUH were 30% of surgeries were emergency surgeries during September 2013 and 22% during October 2013 respectively. The electricity use of emergency theatres can be expected to exceed that of elective theatres due to higher operating hours (see for example Fig. 3b for the profile of an emergency theatre showing activity peaks during day and night). But while the CIBSE TM 46 benchmark for operating theatres allows for an occupancy adjustment with a maximum of 8568 h per year, actual operation did not seem to exceed 5700 h per year in any of the monitored theatres based on estimates from the electricity profile.

It may be noted that ventilation is not included in the monitored electricity consumption, which especially for theatres likely results in a significant underestimation of total departmental electricity

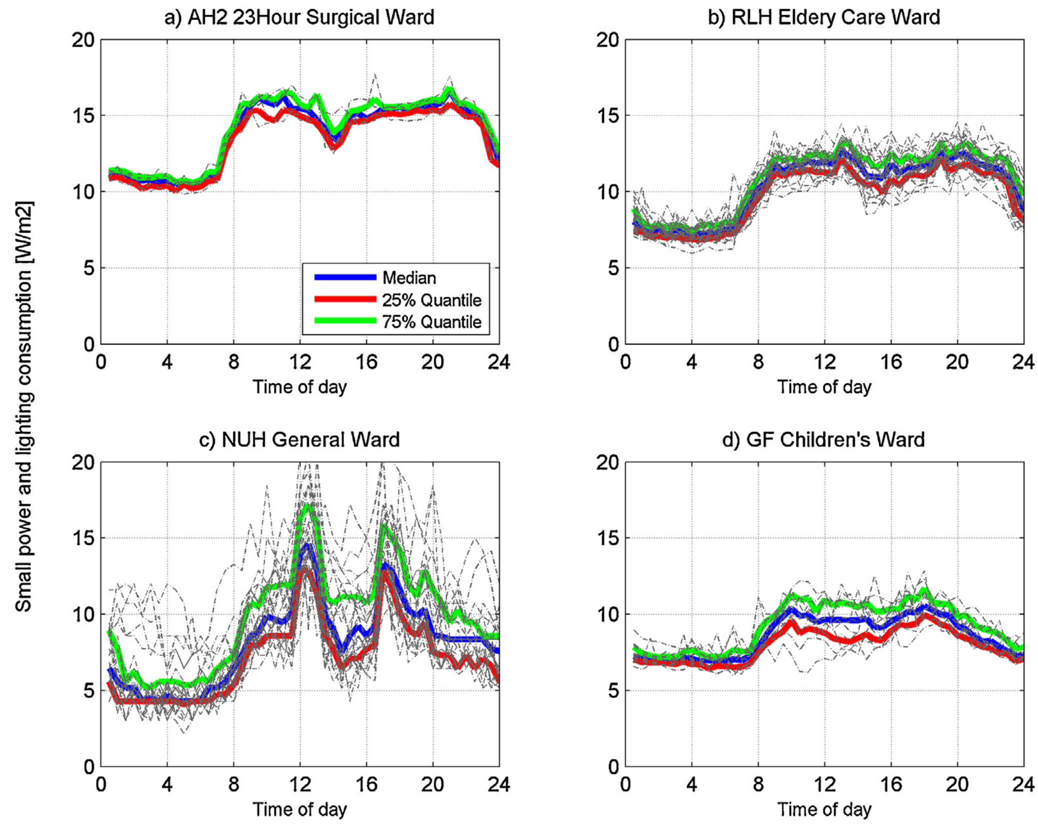

Fig. 2. Comparative electricity consumption profiles of hospital wards (data for all days represented by dashed lines, please note the smaller number of monitored days for a).

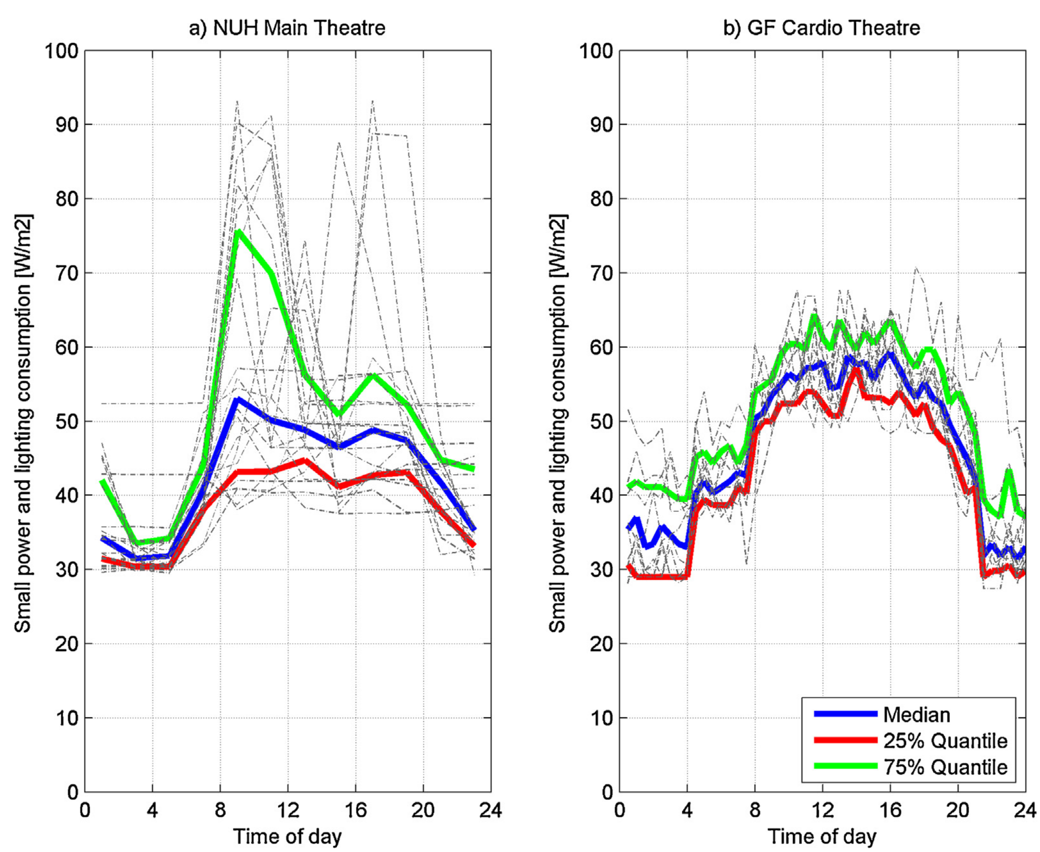

Fig. 3. Comparative electricity profile of two operating theatres.

use due to their elevated air change requirements. For the theatres in NUH, the air handling units (AHU) serving part of the theatre department (two theatre suites) as well as some ward spaces were monitored to get some understanding of ventilation energy use. Assuming ventilation requirements were equal across theatre and ward spaces and therewith again underestimating energy requirements for theatre ventilation, AHU electricity use amounts to 146 kWh(m^2.yr) (27% of total theatre electricity use including lighting, power, anaesthetic gas scavenging and ventilation). Beier [34] has previously measured a much higher mean electricity use for theatre ventilation of 364 kWh(m^2.yr), with extremes of up to 1275 kWh(m^2.yr) for continuously operated AHUs. The measured AHUs likewise operated continuously, suggesting that demand driven ventilation arrangements could enable energy savings here given that only parts of the ventilated spaces were required around the clock.

4.3. Imaging & radiotherapy

Departments in this category are characterised by the use of electricity intensive diagnostic equipment or linear accelerators for external beam radiotherapy. Modern medicine provides a number of means for imaging based diagnostics and treatment, those likely using significant amounts of energy due to intensity or high patient throughput are [44]:

- X-ray, in clinical terms also referred to as plain X-ray, is a frequently used tool for the diagnosis of fractures and issues related to bone abnormalities as well as pathologies of lung, bowels or other dense matter. Although the images do not show as much detail as those obtained using other modalities, plain X-ray is in wide spread use due to its comparatively low running and investment cost as well as its speed.
- Computerised tomography (CT) scans consist of an X-ray tube rotating around the patients' body allowing for more detailed images of internal organs, blood vessels, bones and tumours including tumours of the brain.
- Magnetic resonance imaging (MRI) uses a powerful magnetic field and radio waves to produce detailed pictures of internal body structures and organs in chest, abdomen, pelvic area as well as blood vessels and lymph nodes.
- Linear accelerators (LINACs) are used to generate high power beam radiation for the treatment of patients with cancer.

For this study, five imaging or radiotherapy departments across five hospitals have been analysed (Table 7). It was found that depending on the size of a hospital, separate imaging facilities can be available for different patient groups (inpatients, outpatients, GP patients referred for diagnosis as well as patients in theatres and the Accidents & Emergencies department) or all may be seen within the same area. At the RLH, one of the biggest hospitals in London, more than 700 patients undergo imaging or radiotherapy on a daily basis and six separate parts of the building, out of which some specialise in certain modalities only, are dedicated to this purpose. At NUH in contrast, all patients (except those undergoing surgery) are seen within the central radiology department. Such differences in set-up complicate the comparison of electricity consumption figures somehow more than for other department types.

On the whole, imaging and radiotherapy departments are characterised by high load factors, exceeding those of all other department types (Fig. 4). Theatres and laboratories may show higher peak loads over the monitored intervals due to more continuous loads, but beam generation can for short time periods reach peak power demands of up to 1.5–4 kW for X-ray [36,38], 60 kW for CT [33] and 50–80 kW for MRI [35,36] depending on equipment type, imaged body part and delivered exposure. To pick up on these peak loads, which are of interest for example when sizing substations and distribution boards in hospitals, shorter monitoring intervals would be required. Current figures show, however, that while base loads are moderate for this department type substantial peak loads are in line with the literature found especially for CT, MRI and radiotherapy rooms.

In terms of single electricity consumers, linear accelerators are also of major importance due to their more continuous power draw of 10–30 kW over 10 h per weekday. A comparison with the total electricity use of the entire department at AH2 shows however that loads from lighting and other plug loads may not be underestimated as they account for 71% of total departmental electricity use. There may be some savings potential here from reducing after-hour consumption.

4.4. Laboratories

For this study, two pathology laboratories have been analysed (Table 8). Both provide in-house analytical services around the clock and the year as well as receiving outpatient blood and urine samples from general practitioners (GP) outside of the hospital. According to the respective departmental managers, GP samples account for 40–70% of all analysed samples depending on the size of the hospital, resulting in a higher sample volume during GP opening hours (commonly 9am to 5pm from Monday to Friday with some GP practices not opening on Thursdays). The electricity use of both analysed labs is hence somehow lower on weekends and during the night.

On the whole, laboratory electricity use seems to be dominated by very high base loads exceeding those of all other department types (see Fig. 4). It should however be noted that only two laboratories have been monitored, this being the smallest sample size for all department types. All results may hence be understood as indicative only while the consumption profiles compare well for both laboratories (Fig. 5). There were minor issues with the data quality at NUH where 2.4% of all data points had not been logged due to equipment issues.

An investigation into the nature of the high base loads showed that large parts were associated with laboratory equipment in constant use complemented by around the clock IT and lighting use. For much equipment it remained unclear whether they could be switched off when not in use due to concerns about calibration needs and availability in case of emergency. Jensen [36] have made similar observations in a Danish hospital laboratory concluding that equipment corresponding to a base load of 10–20 kW (in a much bigger lab with 3900 m^2) could most likely be switched off at night while staff were often uncertain about recalibration times and whether the equipment was affected by frequent on/off operations.

Similar to operating theatres, hospital laboratories also require extensive ventilation to protect staff from pathogens and toxic substances and remove heat generated by equipment. In the UK, the Healthcare Technical Memorandum HTM 03–01 on specialised ventilation for healthcare premises prescribes air changes rates of 20 AC/hr or above as opposed to 6 AC/hr on general wards [41]. In addition, the high cooling loads will also be responsible for large shares of central electricity use from chillers. The total electricity use attributable to laboratory spaces can hence be expected to greatly exceed the local consumption estimates presented above.

4.5. Day clinics

Day clinics, also known as outpatient departments, are spaces dedicated to diagnosis and treatment of patients who do not need to be admit to the hospital overnight. They are generally staffed by the same consultants attending to inpatients and may be held daily or on a weekly or even two-weekly basis depending on clinic

Table 5
Power characteristics, wards.

Category	Unit	Area (m²)	Predicted (kWh/m².yr)	Base load (W/m²)	Peak load (W/m²)	Load factor	All days (kWh/d.m²)	Weekdays (kWh/d.m²)	Weekend days (kWh/d.m²)	Weekday/ weekend
Wards	AH1Critical care unit	475	136	9.0	28.9	3.2	0.37	0.37	0.37	1.0
	AH1 Stroke ward	572	143	10.0	28.6	2.9	0.39	0.40	0.37	1.1
	GF Children's ward	701	76	6.2	13.6	2.3	0.21	0.21	0.20	1.1
	LRI Children's ward	653	98	8.8	14.6	1.7	0.27	0.28	0.25	1.1
	LRI Emergency decision unit	417	116	9.5	24.2	2.6	0.32	0.32	0.31	1.0
	AH2 Trauma	573	99	9.1	14.3	1.6	0.27	0.28	0.26	1.1
	AH2 23 h surgical ward	573	112	10.1	17.0	1.7	0.33	0.33	0.33	1.0
	NUH General surgical ward	466	68	3.6	14.5	4.1	0.19	0.19	0.18	1.0
	KCH General surgical ward	567	169	11.7	29.8	2.5	0.46	0.47	0.45	1.1
	RLH Elderly care ward	751	91	7.6	12.8	3.4	0.25	0.25	0.25	1.0
Average (wards)		575	111	8.6	19.8	2.6	0.3	0.3	0.3	1.0

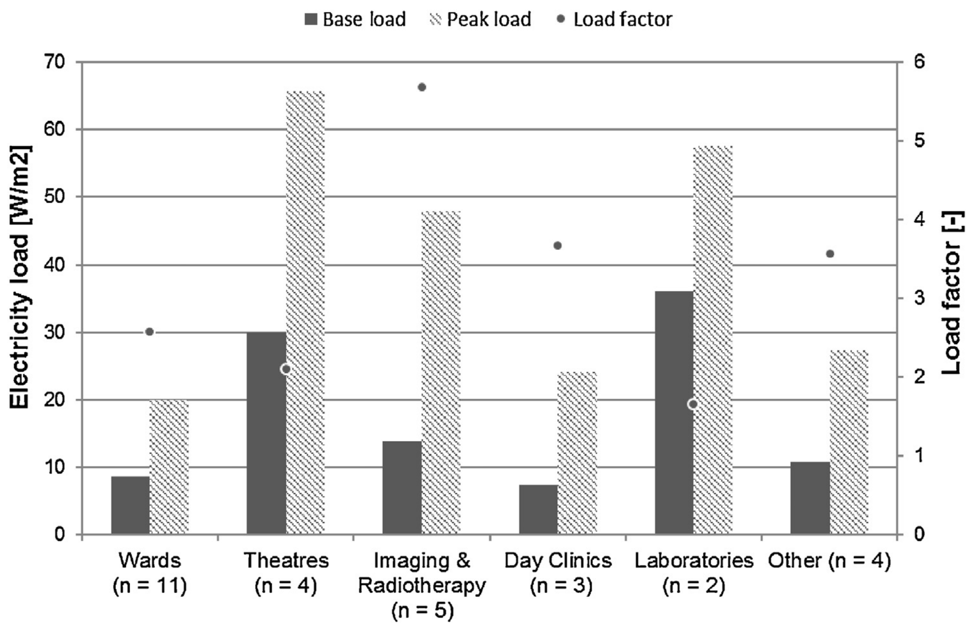

Fig. 4. Load characteristics per department type.

Table 6
Power characteristics, theatres.

Category	Unit	Area m²	Predicted (kWh/m².yr)	Base load (W/m²)	Peak load (W/m²)	Load factor	All days (kWh/d.m²)	Weekdays (kWh/d.m²)	Weekend days (kWh/d.m²)	Weekday/ weekend
Theatres	GF Cardio theatre	248	379	27.6	68.7	2.7	1.04	1.13	0.83	1.4
	AH2 theatres	198	419	21.82	77.2	2.3	1.05	1.23	0.95	1.3
	RLH Adult theatres	970	382	37.8	48.3	1.3	1.05	1.06	1.02	1.0
	NUH Main theatre	66	397	32.5	68.9	2.1	1.09	1.07	1.16	0.9
Average (theatres)										

Table 7
Power characteristics, imaging and radiotherapy.

Category	Unit	Area (m²)	Predicted (kWh/m².yr)	Base load (W/m²)	Peak load (W/m²)	Load factor	All days (kWh/d.m²)	Weekdays (kWh/d.m²)	Weekend days (kWh/d.m²)	Weekday/ weekend
Imaging & radio-therapy	RLH inpatient X-ray	249	163	10.9	23.6	2.2	0.44	0.46	0.42	1.1
	GF CT & MRI rooms	587	389	30.4	66.8	2.2	1.06	1.10	0.97	1.1
	BH X-RAY department	1770	181	7.9	16.2	2.1	0.27	0.29	0.22	1.3
	AH2 radiotherapy	2135	211	15.4	43.9	2.9	0.58	0.64	0.41	1.6
	LRI linear accelerator bunker	133	232	4.6	88.9	19.2	0.65	0.87	0.11	7.9
Average			235	13.8	47.9	5.7	0.65	0.73	0.47	2.6

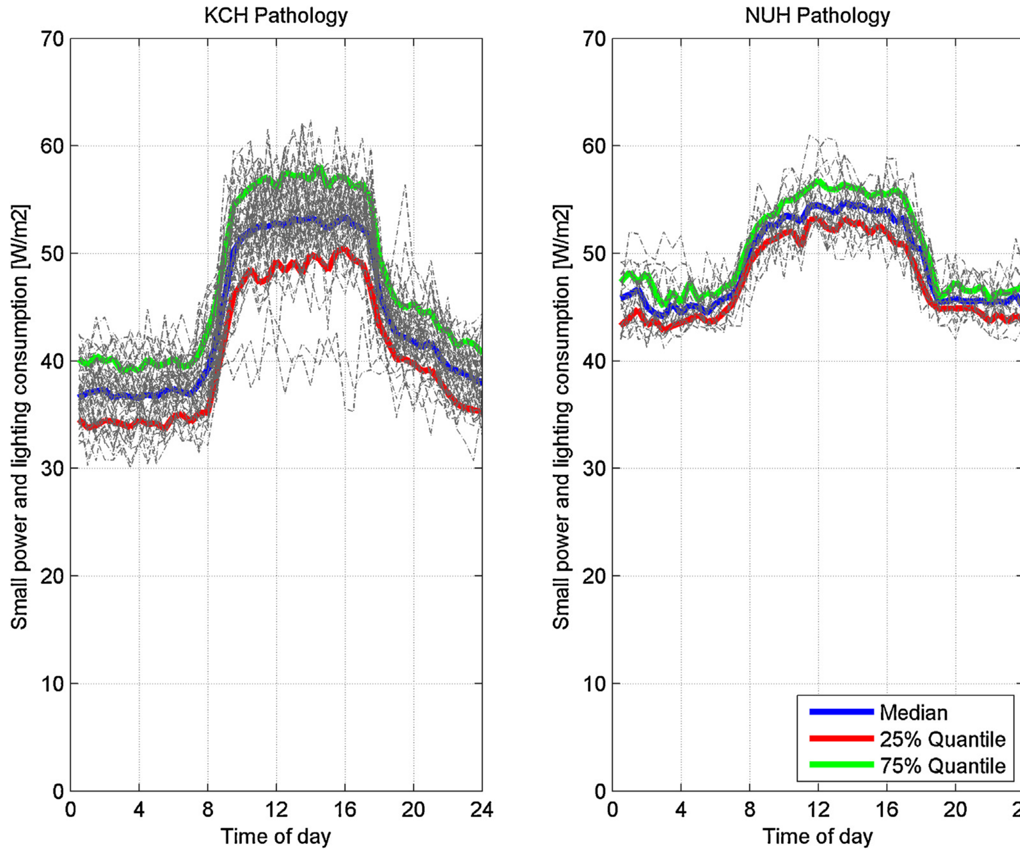

Fig. 5. Electricity consumption of hospital laboratories.

Table 8
Power characteristics, laboratories.

Category	Unit	Area (m^2)	Predicted ($kWh/m^2.yr$)	Base load (W/m^2)	Peak load (W/m^2)	Load factor	All days ($kWh/d.m^2$)	Weekdays ($kWh/d.m^2$)	Weekend days ($kWh/d.m^2$)	Weekday/ weekend
Laboratories	NUH pathology	486	420	42.4	55.6	1.3	1.15	1.17	1.09	1.1
	KCH blood sciences lab	258	373	29.7	59.5	2.0	1.02	1.05	0.94	1.1
Average		372	396	36	58	1.7	1.09	1.11	1.02	1.1

Table 9
Power characteristics, day clinics.

Category	Unit	Area m^2	Predicted ($kWh/m^2.yr$)	Base load W/m^2	Peak load W/m^2	Load factor	All days ($kWh/d.m^2$)	Weekdays ($kWh/d.m^2$)	Weekend days ($kWh/d.m^2$)	Weekday/ weekend
Day clinics	GF day clinics	881	112	8.3	20.6	2.5	0.30	0.35	0.21	1.7
	RLH outpatient dialysis	910	119	4.4	25.0	5.7	0.33	0.37	0.22	1.6
	KCH day clinics	184	151	9.4	26.5	2.8	0.41	0.45	0.22	2.0
Average		895	115	6.4	22.8	4.1	0.31	0.36	0.22	1.7

Table 10
Power characteristics, other departments.

Category	Unit	Area (m^2)	Predicted ($kWh/m^2.yr$)	Base load (W/m^2)	Peak load (W/m^2)	Load factor	All days ($kWh/d.m^2$)	Weekdays ($kWh/d.m^2$)	Weekend days ($kWh/d.m^2$)	Weekday/ weekend
Other	RLH Day theatres	1998	127	10.4	18.7	1.8	0.35	0.35	0.33	1.1
	LRI Maternity	809	186	18.8	24.3	1.3	0.51	0.51	0.51	1.0
	NUH radiology	1314	115	8.3	20.0	2.4	0.31	0.33	0.27	1.2
	BH Offices	242	137	5.3	46.1	8.8	0.38	0.44	0.22	2.0
Average (other)			126	8	28	4.3	0.35	0.38	0.27	1.4

speciality and the needs of the patient population. With respect to electricity use, some clinics such as renal dialysis can be expected to be more energy intensive than others for which (verbal) consultations are the focus of the clinical activity.

For this study, three outpatient departments in three different hospitals have been investigated (Table 9). All of them show a pronounced weekday weekend difference with regular operating hours whereby for the RLH Outpatient Dialysis department Saturdays are a working day and the department remains closed only on Sundays. As the only department type with such distinct after hours, some savings potential from operational improvements may be suspected here as indicated by differences in weekend electricity levels (see Fig. 6b for an example at RLH where median daily electricity use on Sundays is 14% higher than for the first quartile).

The electricity profile of the RLH Outpatient dialysis department during the week (Fig. 6a) shows distinct peaks at 6am, 12 noon and 5pm which can be attributed to the heat disinfection of the approximately 50 dialysis machines. According to Connor [45] and other unpublished data by the same author, dialysis machines use 0.6–1 kWh during 30 min of heat disinfection while the electricity use during the actual treatment is with 1.5–2 kWh per four hours much lower. This is in line with measurements by [36] (1.8 kW during heat disinfection, 0.6 kW during treatment) and taking into account some diversity in machine use explains the observed profile well. Understanding such characteristics of hospital departments can be important from an energy management perspective when making sense of the increasingly available smart and sub-meter data.

4.6. Other departments

In addition to the above departments, data was available to this study from four further departments (Table 10). They have been grouped together for convenience and contain each some office spaces but are otherwise not really comparable.

The RLH day theatres have a much lower consumption than average as well as RLH theatres due to lower operating hours (12 h per day, Monday to Friday only) while base and peak loads are also lower due to less energy intensive procedures being carried out here. In line with findings for day clinics, there seems to be some savings potential from improved switch-off after hours.

The LRI Maternity department also contains two theatre suites, as well as a great number of supporting spaces. Its function dictates a 24 h operation and results in a remarkably constant electricity consumption pattern across all weekdays and times. Given the large size of the department and the variety of contained spaces, it is however suspected that not all spaces will actually be in use quite as continuously.

The NUH Radiology department was initially meant to complement the evidence for imaging and radiotherapy departments. Due to practical obstacles from sub-station layout and circuit documentation, however, the electricity use by imaging and nuclear medicine equipment could not be measured. The obtained electricity use largely corresponds to lighting loads, IT equipment and low intensity medical equipment such as ultrasound scanners and results comparable to an office space rather than other radiology departments.

At 137 kWh/(m^2.yr), the BH oncology offices seem to fairly intensive use compared to the well-established CIBSE TM46 benchmarks for offices of 95 kWh(m^2.yr), an interpretation also supported by the high peak load. The high load factor of 8.8 nevertheless suggests good management of lights and equipment after-hours.

5. Discussion

5.1. Evaluating current UK hospital energy benchmarks

The above findings suggest that while total electricity consumption in english hospitals tended to exceed established benchmarks (Fig. 1), a clear distinction can be made when analysing individual departments. There are a number of department types, mainly wards and day clinics as well as some other departments whose consumption was found by this study to be roughly in line with recommendations (Fig. 7). Although sample sizes are small, this finding to some extent strengthens the confidence for example in CIBSE energy targets used as basis for DEC ratings; especially since additional electricity use from ventilation can be expected to be moderate for these department types.

There are, however, a number of areas which much exceed the prescribed electricity consumption targets, including those specifically defined for laboratories and operating theatres (Fig. 8). All of the (admittedly few) theatres and laboratories analysed proved more electricity intensive than the CIBSE target including full occupancy adjustment of 328 kWh/(m^2 yr). At the same time, an annual occupation of 8568 h/year seems generous while actual figures were found to be lower even for emergency theatres. Hospital laboratories on the other hand will indeed be occupied year around but service provision is somehow lower during nights and weekends. The observed difference results even more pronounced given that measured consumption figures do not account for ventilation electricity use which for these space types will be especially prominent.

On the whole, these findings suggest that a review of current electricity targets based on a large study may be worthwhile to improve their potential as a tool for reducing operational energy use. In addition, the study identified saving opportunities from reducing after-hour electricity use for day clinics and other departments with defined operating hours as well as investigating high base loads in laboratories. In elective and day theatres, the demand driven operation of air handling units seems a crucial strategy to reduce energy use. Timer settings with explicit manual override options given the demand driven nature of hospital operations may be viable here.

5.2. The case for composite energy benchmarks for hospitals

It has been variously been suggested [14–16] that hospital energy benchmarks need to be resolved more specifically to account for differences in service provision between trusts. These observations are supported by the findings of this study, which show a pronounced difference between standard and high energy intensity spaces. This implies disadvantages for certification, and limited usefulness of targets for those acute hospitals providing a disproportionate amount of the latter.

Two approaches have been suggested to overcome this challenge: firstly, composite benchmarks based on floor area shares of different use intensity could be constructed. The consumption figures provided in this study can form the basis for such attempts which have previously primarily been applied to mixed use buildings. Sub-categories of the hospital category defining departmental activities would, however, need to be carefully defined. Guidance for low carbon hospital design such as [46] distinguish three space types in prototypical modelling (wards, diagnostic and treatment facilities, and nonclinical spaces)—potentially also a reasonable compromise between accuracy and costs for benchmarking. In electricity terms, the introduction of a medium-intensity space in addition to standard and high-intensity spaces characterising departments with long operating hours such as delivery suites and accident and emergency departments might be beneficial.

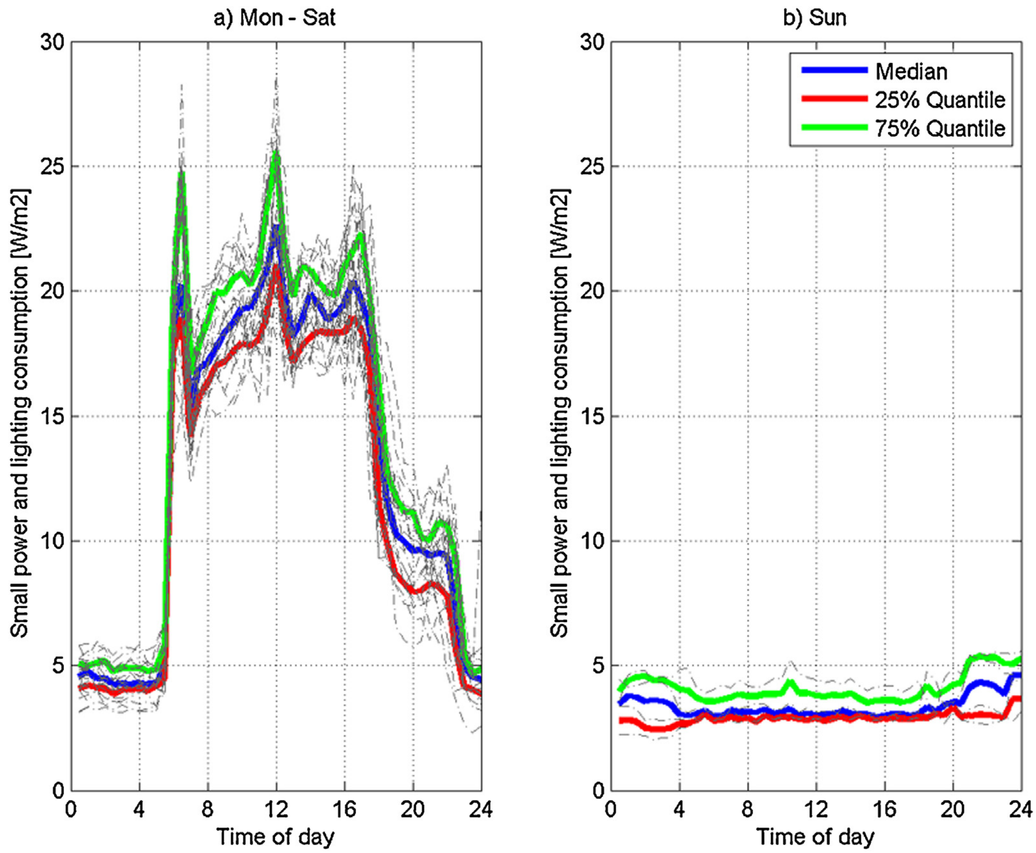

Fig. 6. Electricity consumption at RLH Outpatient Dialysis.

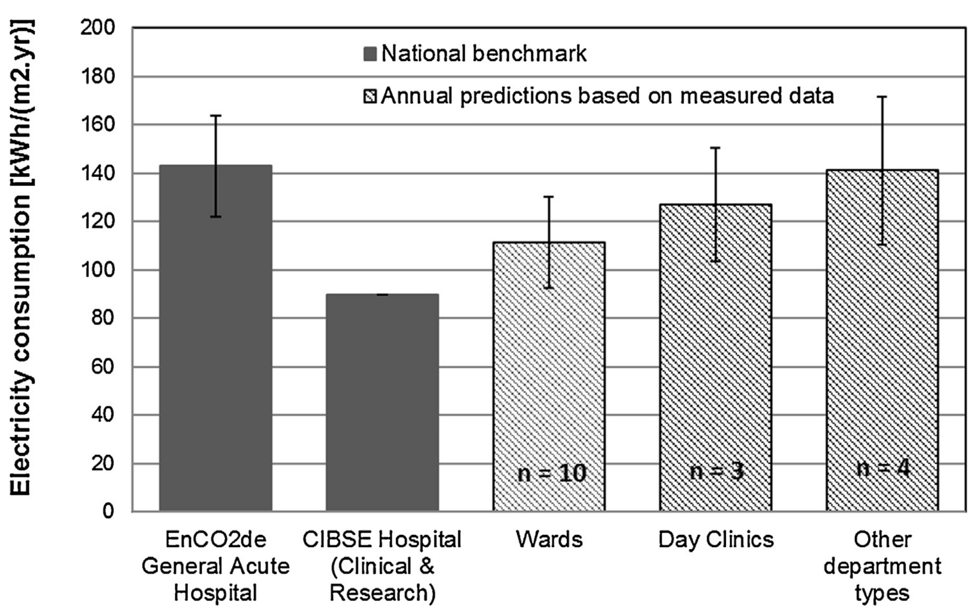

Fig. 7. Electricity consumption of wards, day clinics and other departments in relation to established benchmarks.

Alternatively, electricity intensive single users such as MRI scanners or linear accelerators could be sub-metered and subtracted from the whole building consumption. In the UK, BREEAM Healthcare somehow vaguely specifies that laboratory plant and large-scale medical equipment may be excluded from the assessment [47]; a clearer definition of separable energy uses might be necessary here. On the other hand, regression analysis by Energy Star for Canada have found that the number of MRI machines is no significant predictor of hospital electricity use [48] while the US Energy Star includes the number of MRI machines into their regression equation but excludes CT scans, PET scans, X-ray, Fluoroscopy and Linear Accelerators [49]. Generally, excluding special end uses will be more relevant when assessing smaller rather than larger hospitals or those with much specialist equipment due to the relative size of loads and floor areas.

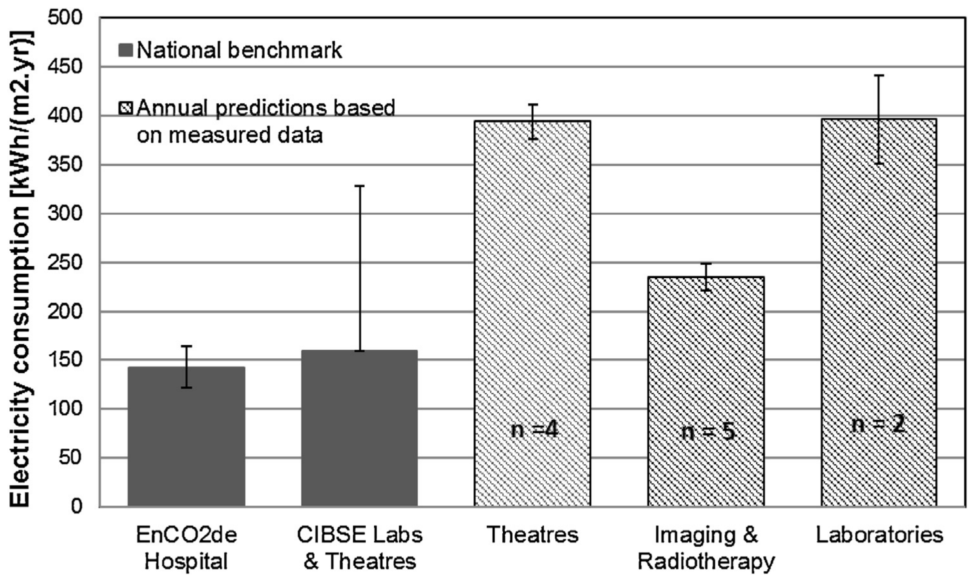

Fig. 8. Electricity consumption of theatres, imaging & radiotherapy departments and laboratories in relation to established benchmarks.

Both approaches are by no means mutually exclusive and may well in combination contribute to making hospital energy benchmarks more meaningful to building operators, owners and policy makers. One advantage of composites over separable uses seems to be that, given sufficient buildings were analysed to construct robust benchmarks, central energy requirements for environmental control crucial in many diagnosis and treatment spaces could be included into the benchmarks once more information becomes available. Doing so may be crucial in reducing aspects of the performance gap related to modelling the energy use of centralised HVAC plants feeding a multitude of different activity spaces.

6. Conclusions

The present study confirmed that different hospital departments have hugely varied small power and lighting electricity consumption characteristics. Wards, day clinics and some other departments have lower average consumption intensities which are reasonably well reflected by current hospital electricity benchmarks. Theatres, laboratories and also departments such as imaging and radiotherapy which were so far benchmarked as general clinical areas showed much higher consumption intensities exceeding those of available targets. A revision of current energy targets for the latter category is therefore strongly recommended, especially given their elevated air change requirements (the energy implications of which were not included in the figures measured by this study).

It is further proposed to develop composite benchmarks for hospitals taking into account differing energy intensities at a departmental level. Such an approach could greatly increase the meaningfulness of energy benchmarks by tailoring them to the service configuration of a respective hospital, accommodating the large heterogeneity between buildings of this category. This study has provided some initial evidence for what department types could be relevant in departmental benchmarking and for the range in which such targets could be set.

Further research is necessary to increase the reliability of the established consumption figures based on larger sample sizes. It is also recommended for future studies to include HVAC parameters of different hospital departments and investigate their energy implications. On a more fundamental level, questions remain about how consumption targets are established in complex buildings, whether based on statistical characteristics of a sample population only or also more closely related to consumption drivers and proven good practices for similar buildings and operations. In any case a balance needs to be struck between targets ambitious enough to drive improvements in operational efficiency and those realistic enough to be achievable taking into account current clinical practice.

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