Title: Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilised institutional building in the UK

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Abstract: This paper presents a systematic, socio-technical and empirical evaluation of the actual energy and environmental performance of a sustainably-designed institutional building (Southeast England), intended to be a teaching tool and 'living laboratory' of sustainability. Despite the building being designed to high sustainability standards (Energy Performance Certificate rating of A, low reliance on fossil fuels, natural ventilation and rainwater harvesting) and also being under-utilised during the in-use stage (lower hours of occupation and number of occupants), its actual energy-related carbon dioxide-equivalent emissions are four times more than predicted. This is due to poor energy management of the building, underperformance of the biomass boiler and wasteful energy practices in terms of excessive winter overheating in the atrium, inappropriate lighting controls, and electrical equipment being left on standby. Due to lack of training and understanding of the energy manager, the building management system was not used adequately and issues with installation, commissioning and maintenance of the biomass boiler led to its disuse; however the photovoltaic system generated electricity as expected. Findings from the study show how a mixed-methods approach of building performance evaluation (BPE) should be embedded as part of the build process, to ensure that performance outcomes are met in reality.

Keywords: Building performance evaluation, low carbon non-domestic, performance gap, BREAAM, institutional building, sustainable education

1. Introduction

The UK Government is legally bound to reduce UK greenhouse gas emissions by 80% by 2050 in relation to 1990 levels [1]. Forty five per cent of UK CO_2e emissions are attributed to the building sector. Though only 3% of these CO_2e emissions are from the public sector (institutional buildings) [2], the public sector has a responsibility in demonstrating leadership and leading the way in reduction [3]. Institutional buildings in particular can act as teaching tools wherein actual performance matters publically. Furthermore, the health and performance of institutional buildings can be a key indicator of socio-economic development of a nation, creating long lasting influence on users [4]. In part, to these ends green building rating and certification systems have been created in many countries with varying approaches and methodologies but with the common objective to reduce the overall impact of the built environment on human health and the natural environment [5]. A few multi-attribute systems (meaning they regulate more than just one environmental concern like energy or water) are: Leadership in Energy and Environmental Design (LEED[1]) based in the USA but worldwide, Green Globes (USA and Canada), Hong Kong Building Environmental Assessment Method (HK-BEAM), Building Research Establishment's Environmental Assessment Method (BREEAM) based in the UK but worldwide, Green Star in South Africa, Green Mark Scheme in Singapore and Institute for Innovation and Transparency in Government Procurement and Environmental Compatibility procedure (ITACA) in Italy. As an example of impact, more than 200 higher education institutions in the USA now have at least one LEED certified building [6].

Institutional buildings present a unique situation where a number of resident and transient users come together in often large public buildings with high sustainability goals. These users can have differing

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[1] **Abbreviations:**
BER: Building Emission Rate
BREEAM: Building Research Establishment's Environmental Assessment Method (UK)
BRUKL: Building Regulation UK Part L
BMS: building management system
BUS: Building Use Study (UK)
CIBSE: Chartered Institution of Building Services Engineers (UK)
EPC: Energy Performance Certificate
FM: facility manager
HK-BEAM: Hong Kong Building Environmental Assessment Method
ITACA: Transparency in Government Procurement and Environmental Compatibility procedure (Italy)
LEED: Leadership in Energy and Environmental Design (USA)
O&M: operations and maintenance
PROBE: Post-occupancy Review Of Buildings and their Engineering

comfort expectations which can be at odds with the energy management staff or system in place to control energy consumption. To further complicate this energy or facility managers (FM) for institutional buildings are often responsible for a large collection of buildings on campuses or even dispersed collections. Expectation from users and building management can be further complicated by poor installation and commissioning practices, poor material or control choices and poor communication of use [7]. For these and the reasons and the delivery expectations from rating systems mentioned in the introduction, it is important to demonstrate the real results and perception of the buildings built to embody exceptional performance.

A number of articles have been published demonstrating the approach to evaluate institutional buildings certified by green building rating systems. As examples, a university building in Melbourne, Australia rated by Green Star involved analysis of performance data, interviews with design stakeholders, and a building user satisfaction survey [8]; in the USA, a university building was subjected to quantitative and qualitative data collection via investigative and diagnostic techniques including temperature and relative humidity (RH) measurements, water and energy consumption, feedback from FM, departments and almost 600 occupants. Findings revealed degradation in sustainable attributes over time, poor indoor environmental quality (IEQ) and an indication that LEED has poor consideration of occupant behaviour [6].

It is all too common to find a significant gap between predicted and actual energy consumption [9]. Continually, literature demonstrates that green building rating and certification systems do not ensure greater energy performance [10], occupant satisfaction [6] or better IEQ over conventional buildings [11]. Building rating and certification systems are in a constant state of refinement to reflect new standards and goals for achieving progressively higher levels of sustainability [5]. Most important to the issue of the performance gap, systems such as BREEAM and LEED have begun to include measurement and verification of certification indicators. Measurement and verification is important for these systems since previous version of the systems like LEED demonstrated little correlation between measured energy consumption, certification level and most problematically, the number of energy credits achieved at the design stage [12].

Before these standards and systems were widely used, quantification of progress in building performance was considered to be important. Early on, initiatives such as *Post-occupancy Review Of Buildings and their Engineering* (PROBE) [13] revealed that actual energy consumption in buildings is usually twice as much as predicted and that common issues found in building performance evaluations (BPE) today (including this study) were being discovered in institutional buildings in the 1990s (table 1). Examples include unexpected occupant influence on energy consumption in schools [14] and the strikingly common theme of lack of handover, guidance and training, inadequate commissioning of systems and poor calibration of sub-meters in two different buildings [15]. More recently, this gap was found to be two – nine times higher than predicted in a select 29 non-domestic buildings (16 institutional buildings) from the BPE programme funded by the UK Government's innovation agency, Technology Strategy Board (now Innovate UK) from 2010 to 2014 [16]. In addition, Burman *et al.* [17] reviewed 600 non-domestic buildings on the CarbonBuzz database of design and actual energy consumption figures in the UK and found that for education buildings the mean performance gap factor was 1.5 (that is, actual consumption is 50% higher than designed consumption) and for offices this factor was 1.6. In other European countries this factor is reportedly 1.3 for non-domestic buildings [17]. In the USA, one study comparing the energy model predictions with actual energy performance of a LEED certified university building, found the building consuming twice the predicted energy usage while causing a high level of occupant dissatisfaction [18].

Table 1 Summary of findings from the PROBE studies of select institutional buildings

	Centre for Mathematical Sciences – Cambridge [19]	Queens Building – de Montfort University [20]	The Learning Resource Centre – Anglia Polytech. [21]	John Cabot City Tech. College [22]	Elizabeth Fry Building – University of East Anglia [23]
Occupancy below design intent	Not clear	✓	✓		
No commissioning issues					✓
Energy performance better than 'good practice'	✓	✓	✓		✓
Overall satisfactory	✓	✓		✓	✓

internal conditions		
Responded well to high summer temperatures	✓	✓
Building operator skills and or resources sufficient for management		✓

Studies show that the reasons behind the performance gap vary from issues with building energy modelling at the design stage, changes prior to or during construction, detailing and construction omissions, commissioning and installation omissions, to unanticipated user behaviour after handover [16,24]. Specifically, within the non-domestic BPE programme, buildings experienced problems with integration and operation of new technology, less than optimal performance of technology and metering problems [16]. Also, there was no obvious correlation between airtightness and emissions performance, common findings of overly-complicated controls actually standing in the way of efficient operation, and poorly considered and integrated building management systems [16]. Understanding why the gap occurs and how it can be minimised is a precursor to making real improvements in building performance. This is why BPE adopts a systematic approach for collection and evaluation of data in a rigorous and consistent way on the performance of fabric and systems, energy consumption, environmental performance and occupant opinion. BPE helps to inform the design, modelling, construction, commissioning processes, and operation of buildings, consequentially reducing the potential performance gap in future buildings.

The present paper provides a case study approach to addressing the issue of *energy management in institutional buildings*. This is done through BPE of a new non-domestic building located in Southeast England, an institutional building (higher education) designed as an exemplar to demonstrate sustainable building materials, technologies and techniques. This paper addresses two themes on energy management in institutional buildings:

- The paper presents an empirical evaluation of an exemplary designed building and outlines the necessary transformations, both specifically for the building and for industry, owners and building management, to support the roadmap towards zero energy.

- The study covers building management and the empirical evaluation of energy consumption and IEQ in an institutional building to identify the reasons for the mismatch that occurs between design intent and actual outcomes, and proposes methods for improvement.

2. Methods and case study building

The Technology Strategy Board's BPE programme mandated a prescribed protocol for evaluation and reporting to maintain consistency and comparability in benchmarking and analysis. BPE study elements included: review of design intent through relevant documentation; review of handover, aftercare, operation, maintenance and management procedures; review of installation and commissioning of building services and technology; qualitative review of operation and usability of systems and controls; physical assessment of the building fabric using diagnostic field tests (air-permeability tests and thermographic surveys); occupant satisfaction; and finally, energy and environmental performance (including temperature, RH, and CO_2 concentrations) metered and collected for 19 months from March 2013 to September 2014. Energy data was collected by remotely accessing the building management system (BMS). Environmental data was collected every five minutes from wireless sensors and was transmitted wirelessly from a RT:Wi5 data-hub. These physical data were cross related with qualitative data gathered through Building Use Study (BUS) questionnaires evaluating occupant satisfaction and perception. The BUS analysis method is a quick and thorough way of obtaining feedback data on building performance through a self-completion occupant questionnaire; the results of which can be compared against a national non-domestic benchmark database. The questionnaire prompts the respondents to comment on the building's design and image, occupant control, comfort and daily use of the building features [25]. Table 2 graphically shows the workflow of the BPE.

Table 2 Detailed workflow of non-domestic retrofit BPE (adapted from [26])

Design and Construction	
Design and construction audit	Review of drawings, environmental assessment standards, interviews/ feedback from design and construction teams to compare design intentions to built reality (and later performance)
Fabric performance testing	Air-permeability test, infra-red thermography
Systems installation and commissioning review	Installation and commissioning checks; measurement of performance of systems
Control interface(s) review	Review of the usability of control interfaces
Handover and written guidance evaluation and review	Review of handover process and user guide documentation
In-use evaluation/ POE	Review of occupant and manager feedback - walkthroughs, interviews and BUS questionnaires
	Years 1-2 Monitoring of environmental conditions, energy consumption, sub-metering and energy conversion from renewables, and occupant feedback review
Final analysis, feedback and dissemination	

Using the case study approach in this paper the authors agree with Flyvbjerg [27] that a detailed examination of a single example can provide reliable information about the broader class and that this is particularly true regarding the life cycle process of institutional buildings, furthermore,

> *One can often generalize on the basis of a single case, and the case study may be central to scientific development via generalization as supplement or alternative to other methods. But formal generalization is overvalued as a source of scientific development, whereas "the force of example" is underestimated. ([27] p.228)*

The great value of BPE case studies is that they add to a collective process of knowledge accumulation on the subject; one that has been accumulating since the mid-1990s [28] in the UK. An important value in such case studies is that the same methods to design, model, construct, commission and manage are being used time after time in many locations and there are numerous lessons to learn in approaching these methods with more care.

2.1 Case study building details

The case study building was designed to be an exemplar institutional building to inspire and educate trainees in the construction industry with a focus in sustainability. It was designed with the dual purpose of an educational environment and a case study for sustainable construction in which all elements of the building and its services provide a real world living laboratory. The building was designed to operate with minimal reliance on fossil fuels. Construction materials were selected based on embodied carbon profile, thermal efficiency and thermal mass. Design maximises use of daylight and potential need for cooling was designed out through solar shading, natural ventilation and thermal performance measures. The building achieved the BREEAM rating of Outstanding (BREEAM version: BREEAM 2008 – Further Education). Energy use reduction credits have the greatest impact on the overall assessment score; therefore, in 2011 BREEAM logically began to require in-use assessment of energy use through monitoring to prove energy performance for *Excellent* and *Outstanding* rated buildings [29]. Though BREEAM in-use assessments were not in place for the case study building, the owner and operator rightly considered subjecting the building to a BPE study an appropriate undertaking for the overall ambition of the building. The authors were unable to find a published review of the actual energy performance of any BREEAM Outstanding buildings to date.

The building is three stories, comprised of ground floor with a café, teaching/meeting rooms, three story atrium/exhibition area, one and half story workshops; second floor with offices, teaching/meeting rooms and third floor only accessible to staff with storage, server room, and a plant room. Table 3 displays physical characteristics. Figure 1, 2 and 3 show the massing of the ground floor plan, the massing of a section of the building and images of the exterior and interior of the building respectively.

Table 3 Physical characteristics of the case study building

Buildings type	Institutional / Higher education
Date of completion	March 2011
Sustainability rating	BREAAM Outstanding, A rated Energy Performance Certificate (EPC)
Area (m^2)	Gross internal area: 2,612 Net internal area: 1,752 Envelope surface area: 6,188
Main construction elements (design intent)	**Walls:** Timber frame with continuous external insulation layer; airtightness layer on the inside of the frame / block wall at workshops Proposed area-weighted U-value: 0.18 W/(m^2.K) **Roof:** Timber frame Proposed area-weighted U-value: 0.18 W/(m^2.K) **Windows:** double glazed, timber frame. Proposed area-weighted U-value: 1.8 W/(m^2.K) **Doors:** Glazed pedestrian entry doors and large garage doors to workshops Proposed area-weighted U-value: 1.8 glazed and 0.4 W/(m^2.K) garage doors **Floors**: Proposed area-weighted U-value: 0.2 W/(m^2.K)
Air tightness (m^3/(h.m^2)@50 Pascal)	Target air permeability: 7

Actual air permeability: 7.08

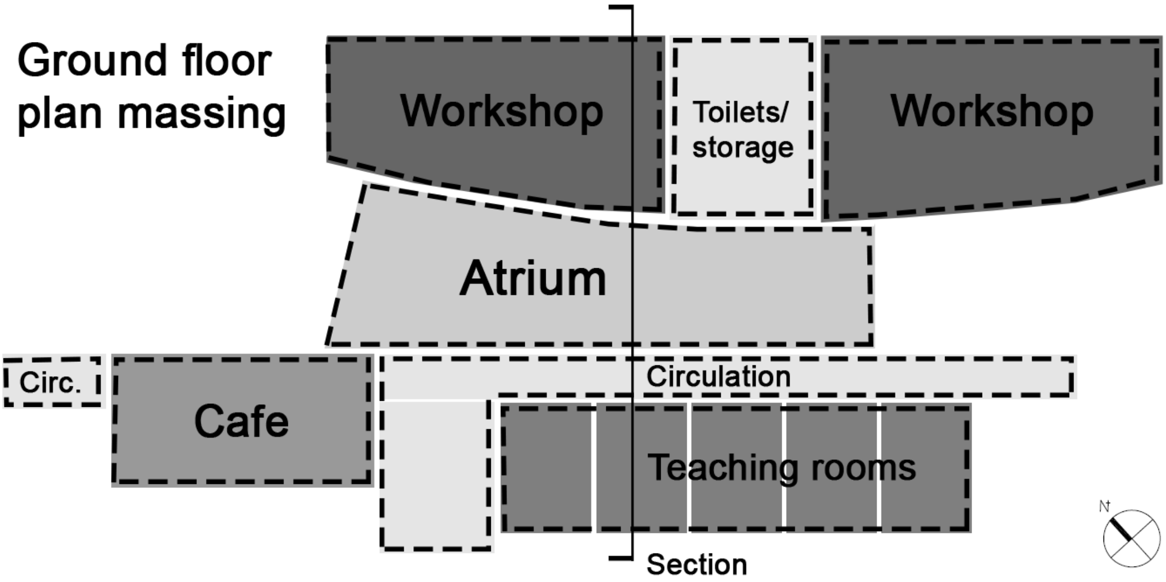

Figure 1 Ground floor plan

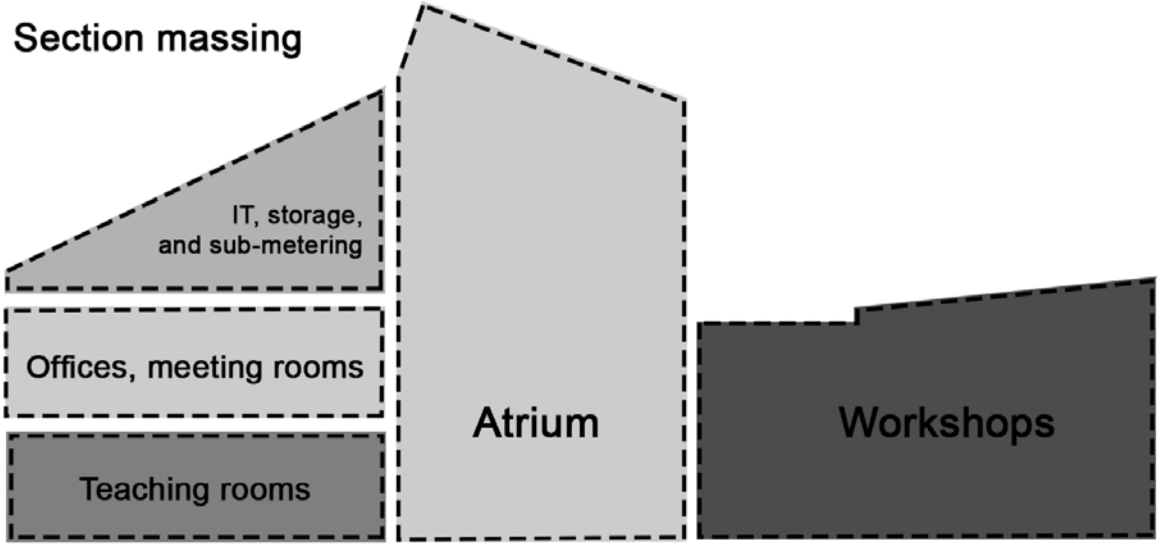

Figure 2 Section

Figure 3 Exterior detail (left), three story atrium/exhibition hall (right)

The building was oriented to maximise daylight, winter solar access and prevailing winds (for summer ventilation) in the offices, meeting rooms, and teaching rooms. The offices, teaching rooms and PV on the roof have a south east orientation. The design maximises use of natural ventilation, thermal mass, and daylight with external shading to reduce summer solar gain. Table 4 provides details of the systems and services installed.

Table 4 Energy systems and services

Space heating and hot water system	**Biomass boiler** (pellets; energy density: 4.9 $\text{kWh}_{\text{thermal}}/\text{kg}$) designed to be primary (base load) system. **Gas fired boiler** (high efficiency condensing boiler designed as backup system when the buffer vessel drops below 65°C and for extreme weather conditions. The atrium is heated 24 hours every day by an **underfloor heating** system. Most rooms are heated by **wall mounted radiators**. Apart from the underfloor heating, the heating schedule is from 7:05 – 17:05.
Space cooling	Mechanical cooling is provided for the server room via wall mounted air conditioner. Advertised energy efficiency ratio: 3.26
Ventilation strategy	Cooling is designed out for the rest of the building through solar shading, **natural ventilation** (manually operable windows and motor driven louvers) and thermal (e.g. mass) performance measures. Natural ventilation is assisted by passive stack in the atrium. Mechanical ventilation in toilet rooms.
Renewables	29.68 kWp solar PV panels (106 panels) on south east face of roof.
Water systems	**Rainwater harvesting** system collects rainwater run-off from the roof and then stores it for WC flushing.
Lighting	**Interior lighting**: High efficiency fluorescent (T5 and T8): entrance lobby, atrium and corridors on time schedules with daylight sensing override; occupancy sensors in most rooms with dimmable controls and automatic daylight dimming controls / **Exterior lighting** is set on a timer with daylight sensor overrides.

The measured air permeability of 7.08m³/(h.m²) @ 50Pa was found to be better than the building regulations target (10m³/(h.m²)@50Pa) and could be better, but there were no expectations beyond the design target of 7m³/(h.m²) @ 50Pa. Thermal imaging showed a number of thermal anomalies resulting from design detailing and installation during construction. Heat loss was identified through the roof connection to the exterior wall and the corner exterior wall (Figure 4), leakage was also revealed around windows and cold bridges at the wall/ceiling junction in a number of rooms (figure 5).

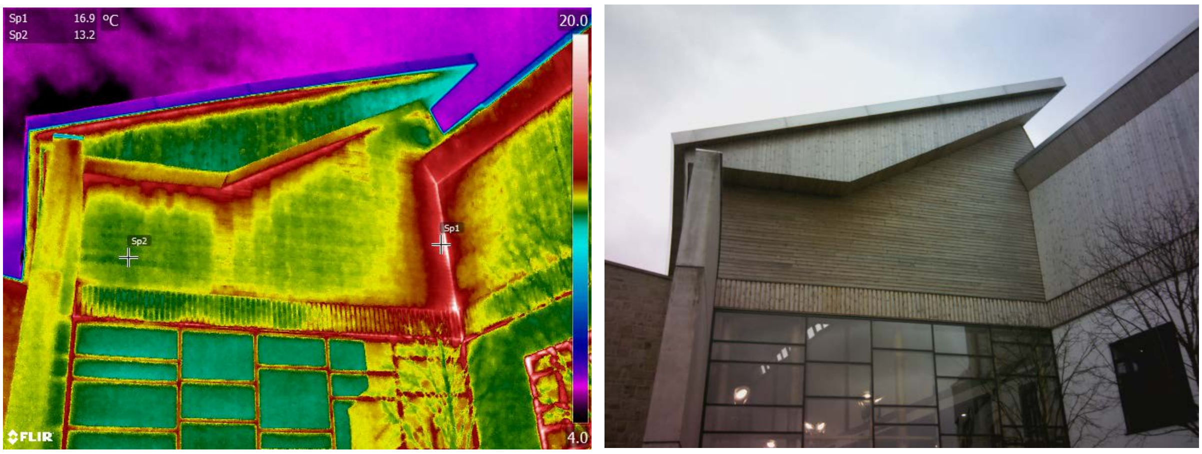

Figure 4 Thermogram of external roof/wall

Figure 5 Thermogram of interior wall/ceiling junction

3. Building usage, aftercare and maintenance

The building was designed primarily as a teaching facility with a large majority of transient users. In reality the building has not been used as planned and occupancy has been far lower than assumed in design (table 5). Though a total of ten rooms were designed and modelled as teaching spaces, four of these rooms later became two offices and a storage room (leased space). Eventually after staff redundancies, the originally dedicated large office space was left empty. Furthermore, use of teaching and workshop space is highly inconsistent.

Table 5 Occupancy and building use details

	Occupancy	**Building usage**
As-designed (modelling)	Maximum daily occ. modelled : **498 people** (no differentiation between staff and visitors)	Modelled operational from 8:00 – 20:00
Actual (Mar 2011 – Jun 2013)	20 staff / 60-80 visitors daily	Core operational hours 9:00 – 17:15 Monday – Friday
Actual (Aug 2013 – Oct 2014) – following staff redundancies	14 staff / 20-60 visitors daily	Hours and days are flexible and events are sometimes held on weekends.

According to the handover assessment (held before management changes) the seasonal commissioning and maintenance of the building was considered to run smoothly under the FM team; however, the FM should have been recruited earlier in the process to enable them to attend meetings during planning and implementation. Handover documentation was available to all key stakeholders immediately and O&M manuals were considered useful and are used regularly, but could be more user-friendly. Reconciliation and calibration of sub-meters with the BMS should have been checked during handover and early occupancy, whereas problems were caught only after the BPE team became involved. There was inadequate training for the FM team which were responsible for the energy management of the building; this was especially apparent following the continual breakdown of the biomass boiler. Overall, aftercare, maintenance, operation and management have not lived up to expectations partly because the use of the building did not turn out as expected; however, building occupants are satisfied with the speed of response with regard to requests for indoor environment changes or repairs. Though the FM team expressed concern over excessive energy use in the atrium (explained later), there appears to be either an issue with knowledge on how to investigate the issue, motivation, or permission to change energy and heating schedules, as the underfloor heating regime was not addressed again during the two year study.

Due to changes in senior management and budget cuts, the dedicated FM/energy manager for the case study building was made redundant and no training in the use of BMS and heating systems was provided to the person who took over. In addition, the new FM was not dedicated to this building only, but for a large number of buildings located five miles away. Due to a number of other issues including a commissioning fault (continual shutdowns), lack of knowledge regarding operation and maintenance (lack of proper handover and training), and operator's concern over fuel cost, the biomass boiler was decommissioned in April 2013. This resulted in the gas boiler replacing the biomass boiler as the primary system as it was familiar and considered easier to operate, maintain and repair.

4. Energy performance

The energy analysis covers the period from 1st October 2013 to 1st October 2014, after the occupancy change and biomass boiler decommissioning which were both complete by summer 2013. For this period, a majority of the energy supplied to the building was from mains gas. Gas supplied to the building was 236,607 kWh_{gas} per annum (p.a.) (90.6 kWh_{gas}/m^2 p.a.); 45,902 $kgCO_2e$ p.a. (carbon factor for natural gas of 0.194 $kgCO_2e/kWh_{gas}$). Grid electricity consumption for the 12 months was 87,932 $kWh_{electric}$ p.a. (33.7 $kWh_{electric}/m^2$ p.a.); 48,363 $kgCO_2e$ p.a. (carbon factor for electricity of 0.55 $kgCO_2e/kWh_{electric}$). PV panels are performing well, with annual PV generated electricity covering 20% of the electricity used in the building, despite the fact that lower electricity demand is experienced during the summer months when PV generation is highest (figure 6).

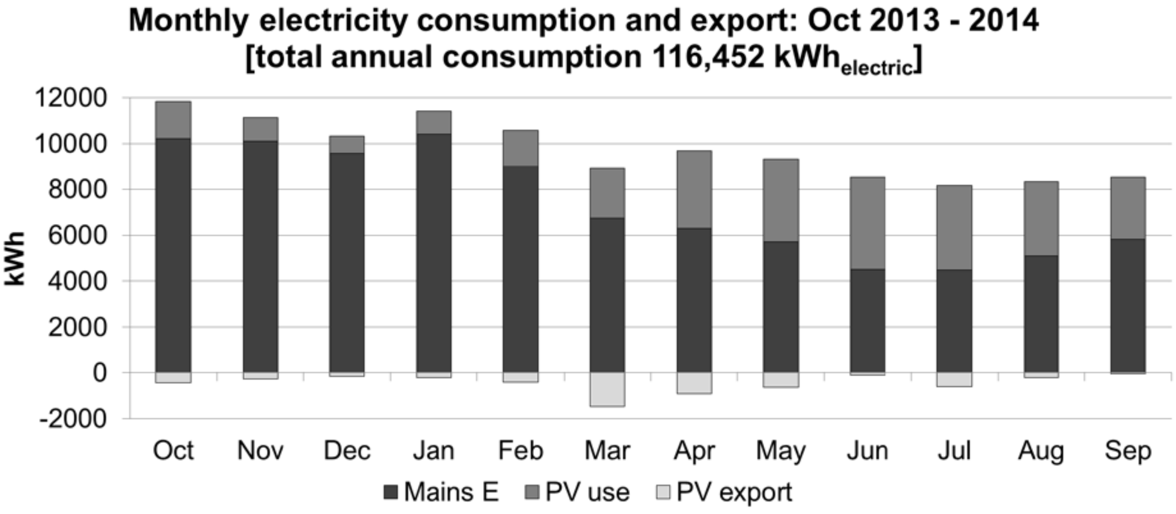

Figure 6 Monthly electricity consumption and export

Predicted regulated emissions from the building were 9.4 $kgCO_2e/m^2$ per annum. This represents an expected annual saving of 55tCO_2e (70%) compared to a Building Regulation compliant benchmark and 124tCO_2e (84%) compared to an existing building (pre-1995). This aligned the project with the UK Government's 2050 target of an 80% reduction in national CO_2e emissions compared with 1990 levels. However, the supplied (actual) CO_2e emissions rate is found to be nearly four times greater than the building emissions rate (BER) (design aspiration) despite the fact that the building was under-used. To be considered:

1. The BER design prediction was estimated using Building Regulations UK Part L [30] compliance tool calculations from the Simplified Building Energy Model (SBEM). SBEM is a state model that provides an analysis of a building's energy consumption for compliance only and does not account for all end-uses and include only heating, hot water, cooling, fans and pumps and fixed internal lighting (excluding other end-uses such as small power, server looms, lifts, catering and external lighting). This excluded electricity consumption is estimated to be at least 30,000 $kWh_{electric}$ per annum (16,500 kgCO_2e p.a.).
2. The building is classified as 100% 'further education university building' which is different from reality.

Comparison of the CO_2e emissions of the buildings with the design estimate and benchmarks is shown in Figure 7. For reference, Higher education building 1 (BREEAM *Very Good*) is similar to the case study building in that they both house architectural/ construction workshops, office and meeting rooms. The case study building is distinct in its large atrium and openness to public visitors. Note that due to unavailability of modelled energy breakdown, only the total CO_2e emissions are given for the modelled building.

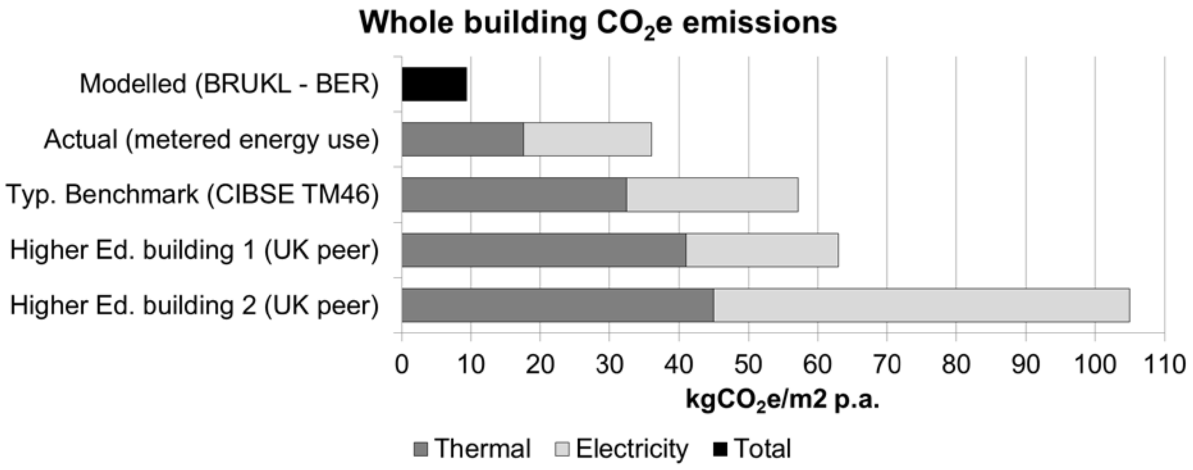

Figure 7 CO_2e emissions (typical CIBSE benchmark [31]; Higher education benchmarks [32])

Figure 8 below shows energy consumption for two periods of analysis. As can be seen, the first period (pre-staff redundancies) consumes more energy than the second period (post-redundancies). In addition, though the first period covers before the biomass boiler was decommissioned; the biomass boiler was not carrying the majority of the heating load as it was designed.

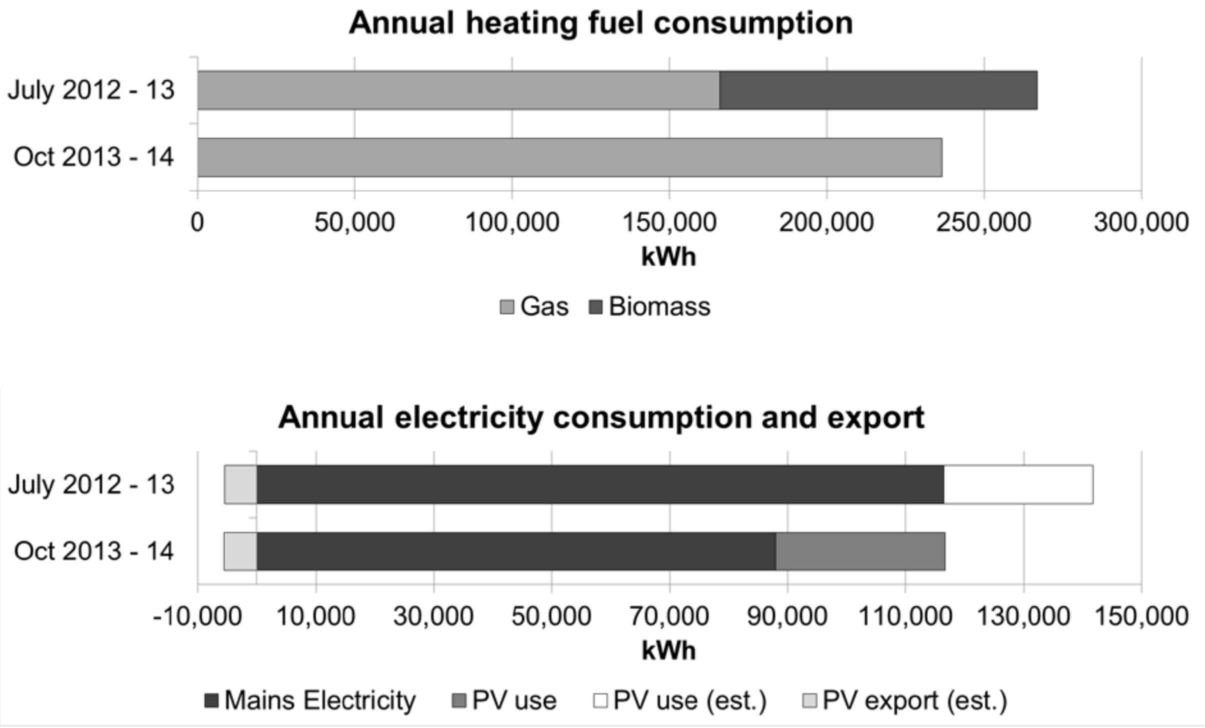

Figure 8 Annual heating fuel consumption for two periods and annual electricity consumption and export for two periods

Looking at two years of energy data, the case study building was found to manage space heating in relation to weather more effectively as time progressed. As can be seen in figure 9, in relation to heating degree days, the first year was more erratic that the second, whereas the least control appears on Oct 2013 and Apr 2014, cancelling each other out. The remaining months in the second year remain relatively close to zero difference between actual and predicted heating consumption. Though year one was more erratic than year two, overall energy consumption at the end of both years evened out to equal zero annual cumulative sum of the difference between actual and predicted heating requirement.

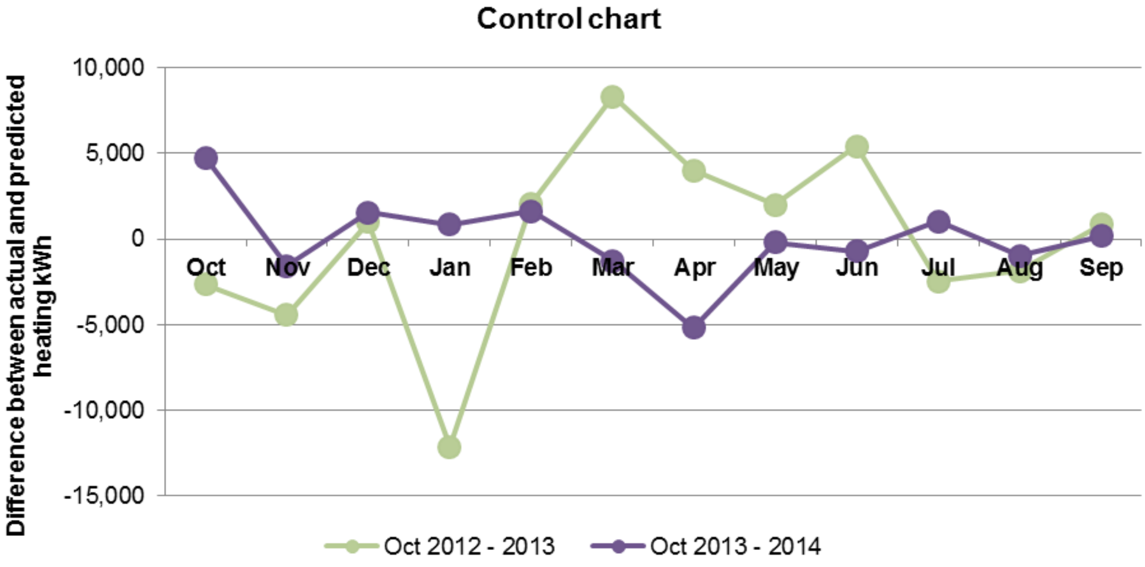

Figure 9 Control chart

4.1 Sub-metering energy end uses

It was found that 18 sub-meters in the building were not connected to the BMS as originally intended, likely because of a lack of communication, co-ordination and follow-up between the installer of the BMS, installer of the sub-meters, commissioning agent, the design team, and other stakeholders. This reveals the communication gap that can occur between different trades during construction and commissioning of buildings. At the beginning of the study, the BPE team discovered that the BMS did not capture all required data; therefore, the team commissioned pulse meters to be installed on seven of the sub-meters so that data could be monitored (though still not connected to the BMS). Finally after months of attempts, the BPE team arranged for the contractor to connect all sub-meters to the BMS. The job was performed in May 2014 but was incomplete (e.g. ground floor light and power not connected). Without an active BPE study of the project this problem potentially would have not been discovered or rectified; this demonstrates the importance of BPE or similar in evaluating all phases from briefing to in-use. Lack of sub-meter data restricted comprehensive TM22 assessment and will limit future load isolation analysis for the building.

With the short period of available data, the following conclusions could be drawn (figure 8):

- The single largest (metered) electricity consuming sub-meter is the first floor power distribution board (26%). This covers the offices which are the most regularly occupied and used spaces. First floor lighting (17%) is second in consumption.
- Roughly one-quarter of electricity consumption falls among the remaining un-connected sub-meters: ground floor light and power, fire alarm system, surge suppression system, and rainwater harvesting pumps.

As mentioned earlier, summer consumption is lower; reduced summer consumption is greatest in exterior lighting and the café. Ground floor light and power is also expected to be lower as this is where most teaching and meeting rooms are located, however, these data (including both regulated and unregulated loads) were not metered (i.e. *non-submetered electricity* in figure 10)

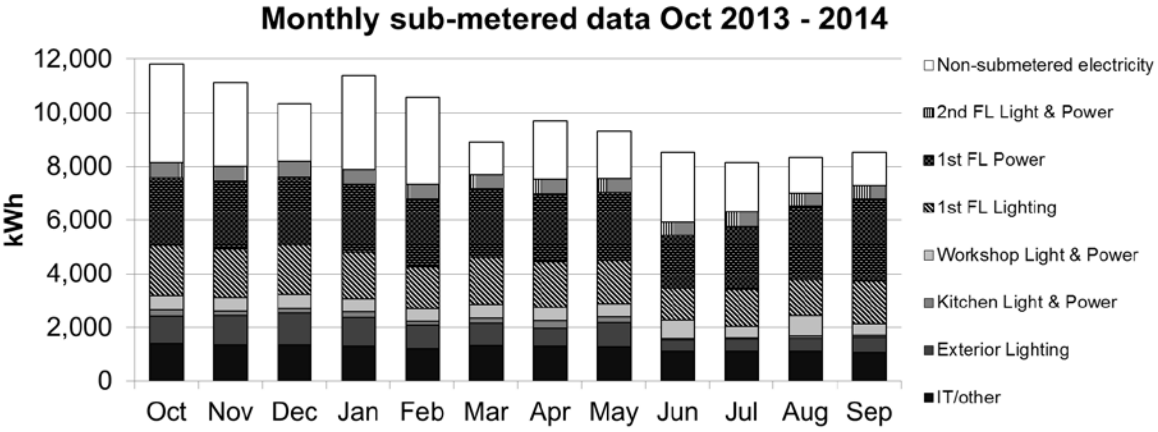

Figure 10 Monthly sub-meter breakdown *Note: IT/other covers the server room, the lift and plant MCC; the server is responsible for a majority of consumption in this category.*

4.2 Wasteful energy practices

Energy waste is commonly found throughout the building during site visits. Key aspects, most of which can be easily addressed through good house-keeping and careful management of the building, include: lack of appropriate lighting controls across different spaces, electrical equipment often left on stand-by continuously for long periods of time, and over-heating in the atrium causing occupant discomfort in addition to energy waste.

Ceiling luminaires in teaching rooms, workshops, offices and meeting room areas are switched on and off via remote controls available to the FM and reception staff. Although teaching and meeting rooms are not occupied during the whole day, lights remain switched on. Setting lighting in teaching and meeting rooms on occupancy sensors or requiring better management of lighting by on-site staff would reduce this consumption. The first floor kitchenette would also benefit from an occupancy sensor in the same way. Lighting in the workshops is however on occupancy sensors. The workshops receive a large amount of daylight given the large high windows (figure 9). To add to this, when weather permits, the workshop doors could be opened to allow more daylight into the space further negating the need for electrical lighting at least in the summer. Setting lighting in workshop areas on daylight sensors could help further reduce lighting energy consumption.

In most meeting/teaching rooms (including the workshops) equipment was found to be left on in rooms not used, including computers, projection system and audio systems. In almost every room, all equipment is left on standby (at least); wall switches were in the on position. This would not be as problematic in rooms occupied regularly; however, meeting rooms can go weeks without being used. As examples, in one ground floor computer lab, three of the 16 computers and the audio system were left on. According to the room booking schedule, this room has not been occupied (officially) since November 2013 and was not scheduled for use through to the end of March 2014. Estimated energy waste of 698$\text{kWh}_{\text{electric}}$ over the unoccupied period. In the first floor computer lab all of the 17 computers were left on. According to the room booking schedule, this room has not been occupied (officially) since November 2013 and was not scheduled for use through to the end of March 2014. Estimated energy waste of 3,917$\text{kWh}_{\text{electric}}$ (standby) over the unoccupied period. A mini-refrigerator in an unoccupied office was left plugged in and on though the office (and the fridge) have been unused for nine months. Estimated energy waste 323$\text{kWh}_{\text{electric}}$ over the unoccupied period of the office.

The FM team and reception staff have expressed from the beginning concern that the underfloor heating in the atrium is a high energy consumer. The mean winter temperature (24 hours/day) in the atrium is 23°C. This is between 2-4°C above the CIBSE [33] recommended operative temperature for this type of space. This operative temperature could be reduced during occupied hours and should be reduced further outside of occupied hours. In addition, the atrium is heated 24/7; the need for continual heating is questioned by both BPE team and users. In the atrium lights are also on when daylight is sufficient for the space: 210W per post x 10 posts and a television is left on in atrium (figure

11) which is a questionable use of energy even if the atrium space was heavily occupied which it is often not.

Figure 11 Workshop (left), TV in atrium (right)

5. Occupant feedback, control and environmental performance

The BUS methodology was used to evaluate user satisfaction in the building to indicate whether it was providing a comfortable and productive internal environment in the summer, winter and overall. Overall, users are especially satisfied by the design, image of the building to visitors and the suitability of facilities in satisfying their needs (the three areas of the survey that received the highest rating; above benchmark). Overall, health perception is the only factor that scored lower than the other factors and not above the BUS benchmark. Among the 27 respondents to the BUS, it was found that overall comfort was rated positively, with the building scoring significantly better than the benchmark. Overall the air quality in both winter and summer is rated significantly better than the BUS benchmark.

5.1. Thermal comfort

Overall summer and winter temperatures are perceived to be ‘comfortable’ and better than the benchmark (figure 12). However, when investigated deeper with directed questions toward too hot, too cold, etc., the responses are less desirable. In depth interviews found that heating within the offices is found to be uneven. Occupants sitting near the radiators are too hot and those further away are cold. Those occupants that consider it ‘cold’ use portable heaters. For in-location control of heating, the radiator valves provide a good level of control and are intuitive, accessible and easy to use. The room thermostats which are controlled by the BMS, on the other hand are confusing for the occupants as they provide no indication of purpose, control or responsiveness. Regardless, BUS responses indicate occupants feel they have a poor level of control over heating.

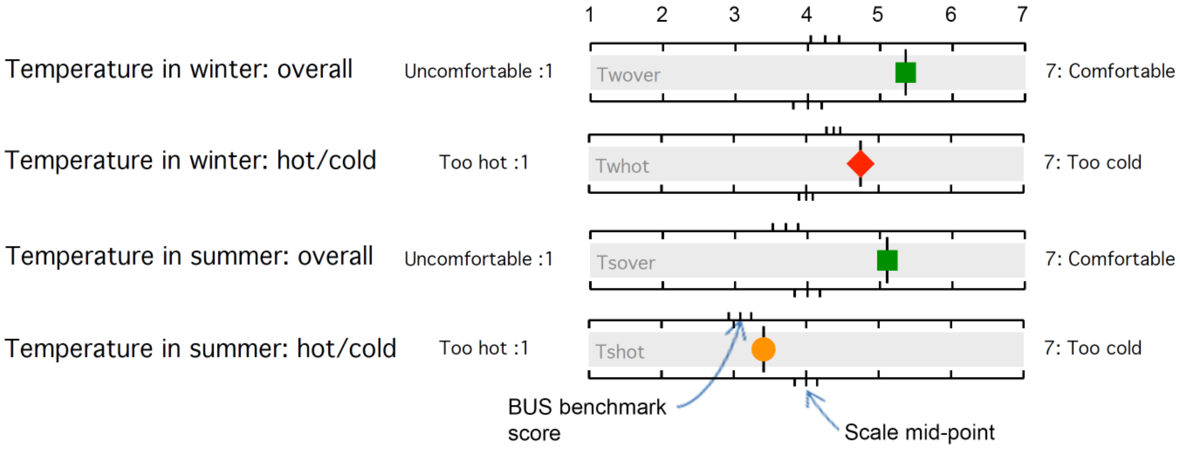

Figure 12 BUS temperature results. *Note: square is above, circle is within, and diamond is below the BUS benchmark.*

Table 6 presents summer and winter temperature ranges. The café is most successfully kept at operative temperature for both seasons; however, 15% of occupied hours are over-heated in the winter. A majority of winter RH is also too low. Characteristics of the café include openness to underfloor heated atrium and kitchen, high level of thermal mass, large sliding glass doors for ventilation when needed, and large overhang blocking direct solar radiation in the summer. One third of the office's winter temperatures are below the CIBSE [33] recommended operative temperature; this would likely contribute to a 'too cold' vote on the BUS and further comments in occupant interviews suggesting that heating may not be sufficient at times in the office. The office is also almost 15% over-heated in the winter and is experiencing summer overheating. Overheating in a particular space in schools or offices is any percentage above 1% annual occupied hours over operative temperature of 28°C [33]. Note: dry bulb temperature (as monitored) was used in lieu of operative temperature. BUS votes indicate 'too warm' in summer and one office occupant interviewed uses a portable fan. The design of the building failed to consider the impact of location and orientation of teaching, office, and meeting rooms along the side of the building located 40 meters away and facing a heavily travelled A-road. The impact of the noise has led occupants not wanting to keep the windows open when doing so would benefit ventilation. However, environmental analysis revealed that when windows were left open overnight in the summer there was a reduction in daytime temperature peaks; therefore, introduction of night-time ventilation to cool the building in summer would be effective (figure 13). One teaching room (ground floor), a space not used every day, should be of concern considering that it is being over-heated 85% of the time. Though the recommended operative range is lower than that of the office, a significant proportion of the teaching room temperatures were far above even 23°C in January. Radiators were found to be left on the highest setting in meeting/teaching rooms that were not occupied or booked during the entire day of site visits. Average use is five days per month (max=eight; min=one). In January the room was occupied six days for the entire month. One of these days, shown in figure 14, demonstrates high temperatures (including times not occupied) and high CO_2 levels during occupancy. According to CIBSE standards [33], the teaching room's operational temperature could be reduced, thereby saving heating energy; the heating regime of the teaching spaces should be reviewed for potential energy reduction especially considering the intermittent use of the spaces. Though the teaching room is also experiencing summer overheating, it is also potentially the most comfortable among the three in the summer with 56% of hours at or below the recommended operative temperature.

Table 6 Occupied hours at the recommended operative temperatures for the café, office, and teaching room

	Winter			**Summer**		
	Café (21-23°C)	**Office (21-23°C)**	**Teaching (19-21°C)**	**Café (25°C)**	**Office (25°C)**	**Teaching (25°C)**
Overheating (1% annual occ. hrs. over operative temp. of 28°C)	-	-	-	-	**2.1%**	**1.5%**
Percentage of hours **above** operative temps.	15.2%	14.6%	84.9%	51.7%	65.6%	44.2%
Percentage of hours **within** operative temps.	82.1%	51.5%	9.3%	34.2%	30.4%	25.4%
Percentage of hours **below** operative temps.	2.7%	33.9%	5.8%	14.1%	4%	30.4%

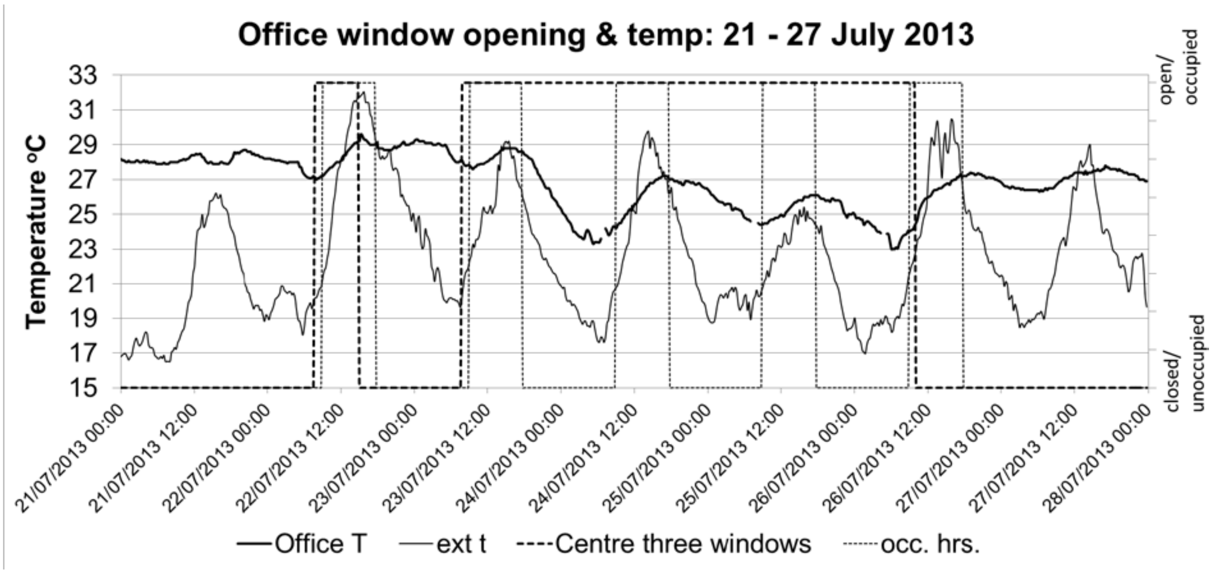

Figure 13 Temperature and window opening in office

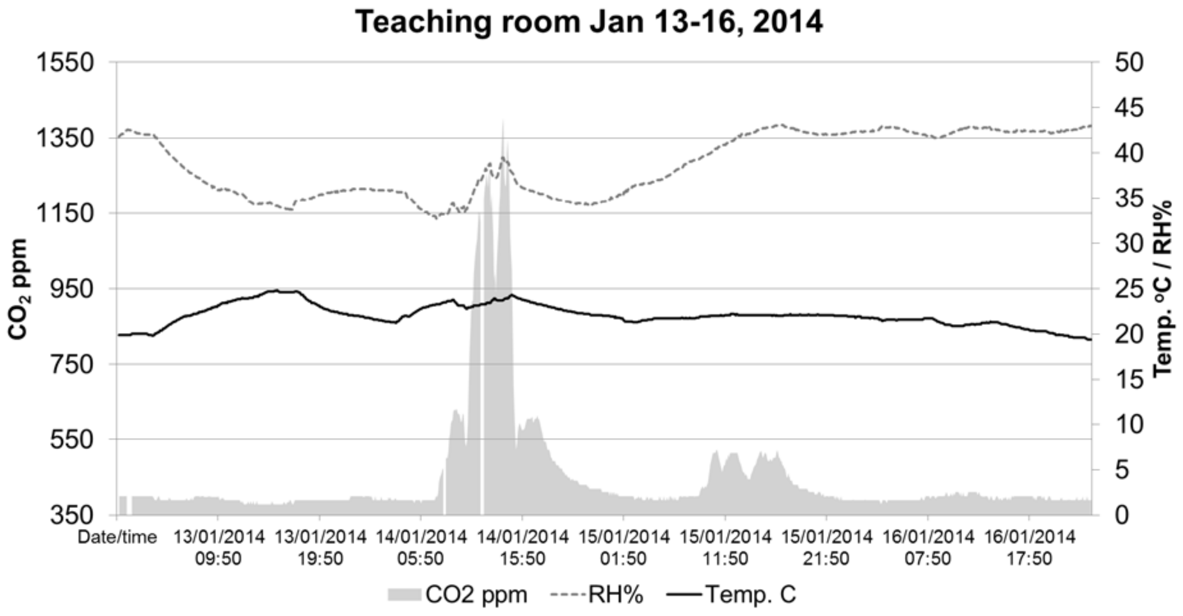

Figure 14 CO_2, RH and temperature in teaching room

5.2. Indoor air quality

According to the BUS, air in both winter and summer is perceived as fresh and odourless; scoring significantly better than the BUS benchmark. Summer ventilation is highly effective at keeping CO_2 concentrations below 500ppm for over 90% of occupied hours in all spaces; CO_2 levels are kept reasonably low corresponding with the ‘fresh’ air votes in the BUS, demonstrating that the natural ventilation strategy is effective in providing fresh air to the building in most spaces. Interestingly however, manual windows only open to a maximum of 6-8 inches. There is no degree of fine control and it is doubtful that the windows provide the occupants with an adequate sense of control over ventilation. This lack of control is reflected in BUS responses (below BUS benchmark).

In the teaching room there are peaks of CO_2 concentrations over 1000ppm when occupied (figure 12). This is expected considering the potential high occupancy of teaching rooms and the transient nature of the occupants (visitors). Visitors are less likely to know or attempt to open windows for ventilation when only present for short periods and when unfamiliar with their surroundings. According to occupant interviews, a regular user of the teaching room states that, in their opinion, there has not been a need to control the local environment, therefore these is a lack of knowledge in how to do so. To add to this, the natural ventilation override switch is poorly labelled and is confusing for visitors (often mistaken for a light switch). Signage and labelling on the natural ventilation override switch could be improved; likewise, the control of vents could be more flexible; occupants can use the switch to close them, but cannot open them again, unless they are automatically triggered again or manually opened via the BMS.

6. Discussion

In the case study building, actual energy use was measured to be four times more than predicted, although better than typical benchmarks and comparable peers. Though the building appeared to perform quite well as compared to benchmarks there were issues with modelling estimations, management of the building, heating system failures, wasteful practices in terms of winter over-heating, inappropriate lighting controls, and electrical equipment left on standby throughout. An important point this study revealed is how reduced occupancy, occupation hours, and change in use did not have the expected effect (reduction) on energy performance; however, in one institutional building study [20], it was theorised that underuse of the building lead to higher heating demand due to insufficient internal gains in reality. There could be a small impact of this present; however, due to mismanagement of the building, heating is often found to be on in unused spaces for long periods of time. Not only is there an expectation for sustainably certified buildings to excel in performance, the particular case study in question was designed to be the epitome of sustainable performance, a living study. A number of failures prevented this outcome in reality.

The performance gap, a consequence of weaknesses across the entire design, build and management process, can be rooted in combination of issues, such as these recognised in this study:

- the biomass boiler, an important icon for the project's sustainability objectives and overall performance in reduced emissions did not remain the primary heating system as designed due to improper installation and commissioning leading to breakdowns, insufficient training for the FM team leading, inability to service the system, and insufficient design phase calculations and consideration regarding either the real cost of procurement of fuel or the higher than expected energy consumption all leading to cost-concerns.
- Considering the significance of the performance promises made, follow-up to ensure proper installation and commissioning of sub-metering should have been taken more seriously to assist in monitoring, demonstrating and improving performance.
- Poor handover practices resulting in users and managers misunderstanding design and performance features, and operating them inefficiently.
- Where design and construction workmanship meet– more attention to joints and junctions to prevent cold bridging, and heat loss.
- Poor management resulting in instances of energy waste such as meeting and teaching rooms heated when unused for days, and equipment and lights left on for long periods of non-use.

In general the building was designed to serve as a teaching facility on sustainable construction; a live teaching tool. In reality, from a visitor's point of view, there is much to be done in linking operations of the building to informing and teaching. As an example, the rainwater harvesting system, considered among occupants as an element of sustainable credentials, demonstrates a missed opportunity whereas it (and its display) was isolated to the workshop store instead of a public space. Not only is the system display out of public view but it is also predictably for this reason not maintained. The purpose of the display is to be exhibited publically to make occupants aware of the use of the system and amount of rainwater harvested and potable water saved. As a suggestion for this building and those like it, similar to an exhibition space, the atrium should be equipped with public display screens (with presence sensors) presenting open information on the type of systems in the building (e.g. operation and performance of the boiler, rainwater harvesting and PV), how the building operates, and day-day performance of the building (including energy use metrics, carbon metrics, comfort metrics and benchmarks). To maximise dissemination sub-meters need to be linked to the BMS or logged in a way to show where and how energy is used in the building and accessible to students and visitors. Student projects could provide ongoing BPE to close the gap for the life of the building.

Though the building consumed less than certain benchmarks, there was ultimately a large performance gap likely causing the cost-related shutdown of the biomass boiler. Theoretically if the biomass boiler were responsible for 80% of the thermal energy for the year of analysis (October 2013 - 2014), the total supplied BER would be 23.8 $kgCO_2e/m^2$ p.a. As electricity alone is 18.5 $kgCO_2e/m^2$ p.a. of that figure (or around 10-12 $kgCO_2e/m^2$ p.a. less unregulated loads), the boiler change does not explain the entire gap. There appears to be much more consumption of both heating fuel and electricity, e.g. miscalculated heat loss/ heat demand. To close the energy gap it would be helpful to assign a willing and knowledgeable individual to direct efficient use and maximise the sustainable features of the building, continually guiding it in the direction of as-designed performance. This person will act as the sustainability champion. The FM and sustainability champion could together develop technically detailed but user friendly O&M / building user guide (including a user guide for the BMS) which will ensure efficient use of equipment to minimise energy used by the building, well informed maintenance of equipment and building elements, and well-timed and appropriately performed seasonal commissioning. These tools are essential for current and future FMs. A user friendly manual / user guide will also be useful for visiting students or trainees as the building is intended to be an exemplar teaching tool for sustainable construction.

To address energy waste, there are two potential solutions:

1. Involve reception in this localised energy management, e.g., first thing in the morning, turn on radiators at thermostatic radiator valves in rooms that are to be occupied that day (and turn off at end of day or ideally after the meeting or use) or,
2. Retrofit radiators with ‘smart’ radiator valves which allow scheduling. These can be installed over existing radiator valves.

For meeting and teaching rooms, as with managing heating by room scheduling, the receptionist could manage lighting, computers and equipment. A more costly solution would involve installing typical light switches in the rooms for visitors.

6.1 Wider lessons for industry, clients and building operators

Wider lessons are extracted from the case study for industry (including designers, constructors and suppliers), clients, building operators and users, during the briefing, design, construction, commissioning, handover and in-use stages (table 7).

Table 7 Wider lessons

Wider lessons by stage	Industry	Clients / developers	Building operators
Briefing: Identify actions and stakeholders needed to support procurement, integrated participation, aftercare and BPE.	✓	✓	
Briefing / Design: Protect the efficient and long-term use of unconventional systems (e.g. biomass boiler) by ensuring the client has staff on hand who can use and maintain or will be trained on the use and maintenance of the system, ensuring this staff or FM are a part of the early discussion and present during commissioning, and by discussing all costs, maintenance regimes and fuel procurement processes thoroughly with the client.	✓		
All stages: Design, the procurement process and cost of fuel (e.g. biomass), and the route and method of storage and supply to the system need to be detailed and discussed with FM and owner in the early stages. In addition, with all non-standard technology, extra care should be taken to ensure proper commissioning, training and aftercare.	✓	✓	✓
Design: Simplify external envelope to ensure minimal thermal bridging and optimised airtightness.	✓		
Design: Get to know the site personally, e.g. visit the site, including the smells and sounds. Investigate how nearby road noise, for example, can impact occupant satisfaction and willingness to ventilate (with unintended knock-on effects leading to discomfort and increased energy consumption).	✓		
Design / construction: Involve as many stakeholders as possible in as many meetings as possible to protect the future in-use life of the building and expected performance. E.g. bring the FM on early in the project, involving in meetings and providing appropriate training to ensure smooth running of the building and avoid issues.	✓	✓	✓ (request to be involved)
Construction / commissioning: The installation and commissioning process for services is critical; ensure	✓	✓	

technicians are knowledgeable about the process and documentation is thorough. Provide on-site training at all levels to ensure appropriate fitting of materials and equipment.			
Construction / Commissioning – Aftercare: Reconciliation and calibration of sub-meters with BMS should be checked during handover and early occupancy.	✓	✓	✓
Handover: Develop technically detailed but user friendly O&M / building user guide (including for the BMS) to ensure efficient use of equipment to minimise energy used by the building, well informed maintenance of equipment and building elements, and well-timed and appropriately performed seasonal commissioning.	✓		
Early occupation / In-use: Coordinate training and continued education for management staff after occupation.		✓ (encourage)	✓ (request)
Early occupation / In-use: Review building occupancy and use to ensure the building is being used as planned and designed; reconcile unresolvable changes with design targets.	✓	✓	✓
In-use / Aftercare: The design team should follow-up; assessing year-one and year-two energy consumption and re-model predicted consumption to evaluate where possible modelling mistakes were made to inform performance gap research and improved future performance of designs.	✓		✓ (provide data)
In-use: Provide hands on training for occupants for equipment and controls preferably after commissioning has been satisfactorily completed and the occupants have had time to settle in and develop personal queries around the operation of the building		✓	✓
In-use: Reach out and provide an atmosphere of openness where occupants can discuss concerns regarding their environment and control; find the most comfortable condition for the majority.		✓	✓
In-use: Follow up on installed systems and controls, investigate problems and report back to manufacturers / revise specifications for future projects accordingly.	✓		

7. Conclusion

This paper presented an empirical evaluation of an institutional building, designed to be an exemplary of sustainable practice, but requiring a BPE study to fine-tune its performance by identifying and addressing issues with services, systems and unwanted energy practices. It is found that BPE can help to identify and address the performance gap in the various stages of a buildings lifecycle to aid in maximising efficiency, reducing operating costs and improving the overall performance of a building. Future research is needed to assess more recent BREEAM buildings and their magnitude of performance gap (or lack of); specifically considering the in-use evaluation process that BREEAM currently has in place [29].

As is detailed above, there are steps that can be followed in each stage of the design and build process and throughout the life of a building to close the performance gap and to ensure more efficient management and use of a building. This is beginning to happen with the Soft Landings approach that is being adopted in the UK. The Soft Landings approach provides a five-stage alternative to the conventional brief, design, build and occupy system, which aims to close the performance gap [34]. Its key features include a focus on outcomes from inception and into operation; expectations management during design and construction; and a better handover, followed by a period of aftercare and post occupancy evaluation. Without BPE or Soft Landings, it is possible that some of the building performance issues would go unnoticed and widen the performance gap, thereby undermining the role that the building sector can play in meeting national carbon reduction targets.

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