Narrowing the Energy Performance Gap in Non-Domestic Buildings with Aspirational Sustainability Targets

A Case Study of the Institute for Manufacturing

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Abstract

The non-domestic building sector has in recent years witnessed a boom in the number of ostensibly 'green' buildings certified under the Building Research Establishment Environmental Assessment Methodology (BREEAM) and similar rating schemes. Despite the proliferation of aspirationally sustainable building designs, the actual energy performance of certified buildings is generally little better and sometimes worse than the building stock average. The actual energy consumption of non-domestic buildings is typically 1.5 to 5 times greater than designer estimates, resulting in a phenomenon termed the 'energy performance gap.'

One of the central contributing factors to the energy performance gap is the restricted scope of energy estimate, based around so-called 'regulated' loads, so named because of their frequent inclusion in national building regulations. The result of regulation is the near universal exclusion of 'unregulated' loads such as office equipment, plug loads, lifts, catering and IT servers from energy estimates. For an unbiased quantification of the performance gap, it is necessary to develop estimates for these unregulated loads or to exclude such loads from the actual consumption comparison.

Drawing upon data from the University of Cambridge Estate Management, the highly regarded Institute for Manufacturing building was evaluated to further explore the energy performance gap. Assessment of the underlying causes of the performance gap revealed a design-stage optimism bias in the building development process and lack of prioritisation towards the utility of available energy data. Temporal analysis of sub-metered energy consumption data revealed the usefulness of a simple peak-baseload ratio as a preliminary indicator for building energy performance, with significant energy optimisation potential. Lastly the Estate's implementation of Soft Landings is critically evaluated against University policy together with the approaches to incentivise energy efficiency across the building portfolio.

Findings from energy-focussed Building Performance Evaluation of the case study building and associated development context are consolidated to produce recommendations for Estate Management. These recommendations have particular relevance for university estates, but are applicable also for other non-domestic building portfolios, such as schools and government offices.

Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

The word count for the main body of work is 12122 and the count for the entirety of this research is 14979.

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Nomenclature

BMS	Building Management System
BPE	Building Performance Evaluation
BRUKL	Building Regulations United Kingdom Part L
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BSRIA	Building Sciences Research Information Association
BUG	Building User Guide
CIBSE	Chartered Institution of Building Services Engineers
DECC	Department of Energy and Climate Change
DEC	Display Energy Certificate
DSM	Dynamic Simulation Model
EIS	Electricity Incentivisation (sic) Scheme
ECRP	Energy and Carbon Reduction Project
ECON19	Energy Consumption Guide 19 for offices
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive (European Union)
EUI	Energy Use Intensity
EMBS	Estate Management and Building Service
EU	European Union
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
IfM	Institute for Manufacturing
IESVE	Integrated Environmental Solutions Virtual Environment
LEED	Leadership in Energy and Environmental Design
LTHW	Low Temperature Hot Water
M&E	Mechanical & Electrical
ND-NEED	Non-Domestic National Energy Efficiency Database
POE	Post-Occupancy Evaluation
PROBE	Post-occupancy Review of Buildings and their Engineering
RIBA	Royal Institute of British Architects
TM22	CIBSE Technical Memorandum 22: Energy Assessment and Reporting

	Methodology
TM54	CIBSE Technical Memorandum 54: Evaluating Operational Energy Performance of Buildings at the Design Stage
TSB BPE	Technology Strategy Board Building Performance Evaluation project
USGBC	United States Green Building Council

Chapter 1

Background to Building Energy Efficiency

1.1. Buildings: An Energy Efficiency Opportunity

Thirty-eight per cent of all end-use energy consumption in the European Union occurs within buildings of which one third is used in the operation of non-domestic buildings (European Commission 2013). On a global scale this figure is similar at 32% of final energy consumption (IEA 2014). Given the potential to reduce operational energy consumption by 30-50% by 2020, new and existing buildings collectively represent one of the world's largest energy efficiency opportunities (IEA 2014). Since energy consumption is directly correlated to carbon emissions (albeit variable in different countries), the development of energy efficient buildings represents one of "the most environmentally and cost-effective instruments for emission reductions" (IPCC 2014).

Government-led measures to reduce the energy intensity of UK non-domestic buildings over the past two decades have led to advances in building energy efficiency, however the rate of improvement remains well below the acknowledged potential (Cohen 2014). The same period has seen the rise of design-focused green building certification schemes such Building Research Establishment Environmental Assessment Methodology (BREEAM) in Europe and Leadership in Energy and Environmental Design (LEED) in North America.

The energy consumption of these ostensibly 'green' buildings is generally little better and sometimes worse than the building stock average. Building professionals are now becoming increasingly aware of a sizeable disparity between designer energy performance expectations and as-built energy consumption. This disparity, the 'energy performance gap,' is highly variable but typically ranges from 1.5 to as much as 5 times the energy estimate (Carbon Trust 2012a). For the realisation of sustainable low-energy, low-carbon buildings, the energy performance gap must be understood and resolved.

1.2. UK Actions Under the EU Energy Performance of Buildings Directive

The UK government is taking action to improve the energy performance of its building stock through its commitment to the European Union Energy Performance of Buildings Directive (EPBD), effective since 2002 (Sutherland et al. 2013). In England and Wales, the energy performance of buildings is governed under the Building Regulations UK Part L (BRUKL) (DCLG 2012). It comprises the methodology through which building energy consumption is estimated using an Energy Performance Certificate (EPC).

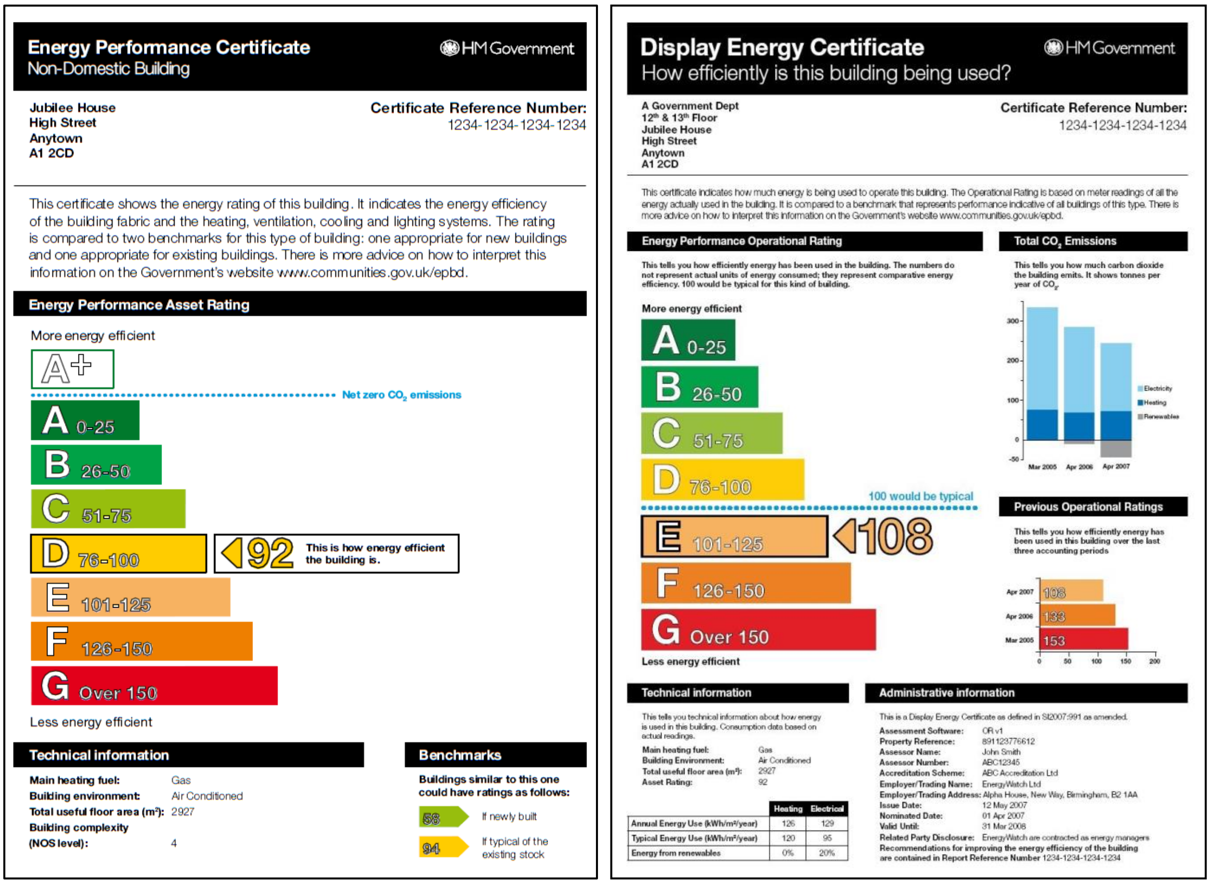


Figure 1. Comparison of UK Energy Performance Certificate (EPC) with Display Energy Certificate (DEC) (CP Creative 2014; Better Buildings Partnership 2012).

The BRUKL further stipulates that a Display Energy Certificate (DEC) is to be displayed in all public buildings larger than 500m^2, which benchmarks the actual energy consumption. The most common quantification of the energy performance gap is the difference in energy estimated by BRUKL and the metered consumption which underlies the DEC. Although the EPC does not display the equivalent kilowatt hour consumption estimated by the BRUKL methodology, a graphical representation of the performance gap can be seen in the difference between EPC and DEC (Figure 1).

1.3. The 'Perception Gap': Comparing Actual Energy Use with Regulated Energy Estimations

The EPC is a misleading representation of a building's estimated energy consumption as the certificate is inclusive only of the 'regulated' energy consumption (that which is measured by the Building Regulations). This means that the EPC estimates only the energy associated with the Heating, Ventilation and Air Conditioning (HVAC), hot water and lighting (DCLG 2012). This leaves a significant number of energy end-uses unaccounted for through the direct comparison with metered energy consumption.

The EPC is the only statutory design stage energy estimate required by BRUKL, with the result that there are very few buildings where the estimate scope covers 'unregulated' energy end-uses such as office equipment, plug loads, lifts, catering and IT servers. Hence when comparing energy reported by an EPC and DEC, a significant proportion of the difference can be attributed to the disparity of scope. This difference in scope leads to an artificial contribution to the performance gap termed the "perception gap," illustrated in Figure 2.

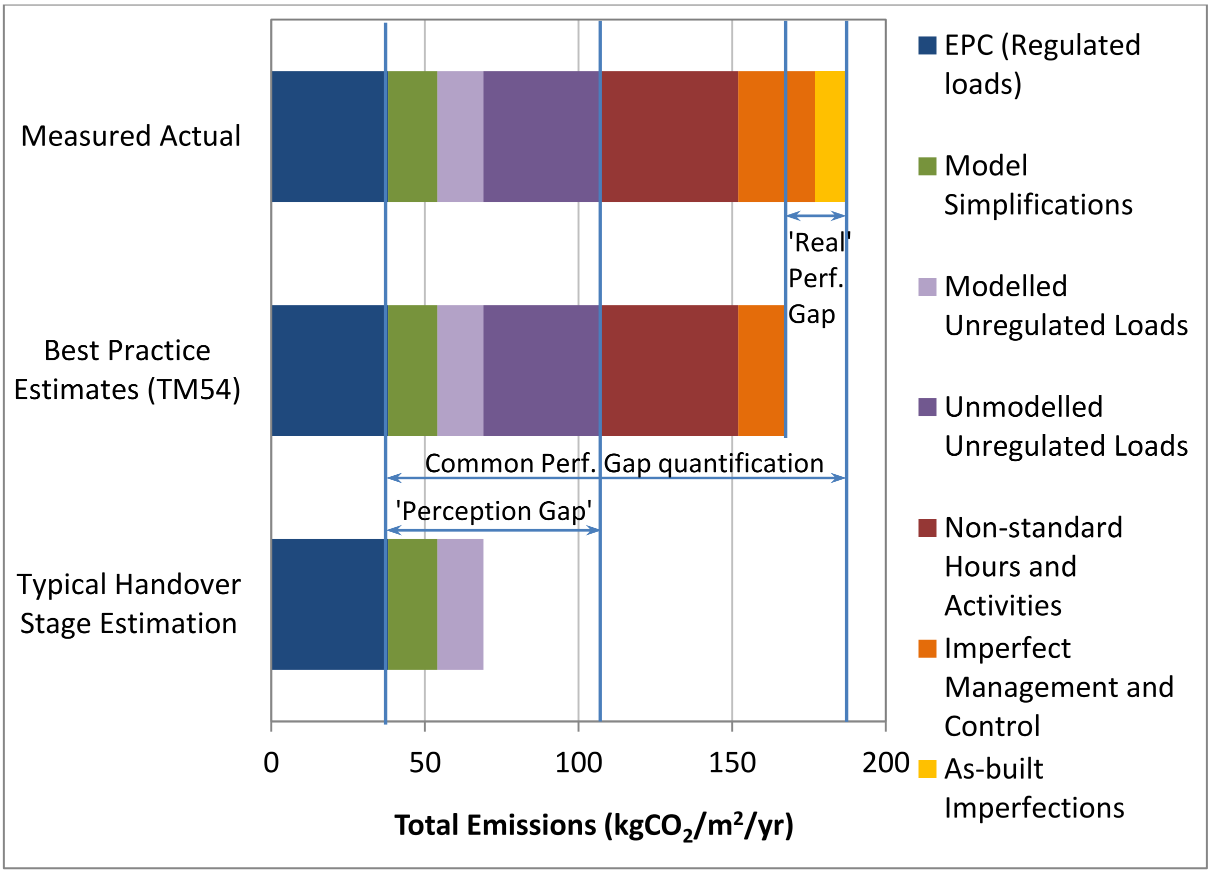


Figure 2. The Energy Perception/Performance Gap relative to Best Practice Performance Gap (adapted from Cohen 2014).

1.4. Detailed Energy Analysis

The EPC scheme adopted by the UK Government under the EPBD allows for the benchmarking of buildings against a national metric however there remains significant scope to improve the depth of analysis. Fortunately most new non-domestic buildings have relatively sophisticated building data available through a user-sensor interface called a Building Management System (BMS). Such data is not standardised in its presentation or scope, which makes broad scale analysis very challenging, and is likely a major contributing factor to why this data is rarely utilised for routine energy analysis.

BMS data represents a virtual goldmine of building performance information that can be used to inform the design of future buildings. A suite of tools have been produced by the Chartered Institute of Building Services Engineers (CIBSE) to standardise the BMS data analysis as part of a broader Building Performance Evaluation (BPE) process. Three of the most relevant CIBSE Technical Memoranda for BPE are TM22 for assessment of energy consumption, TM46 for energy benchmarking of building typologies and TM54 for evaluation of operational performance at building design stage. All of these have been used or proposed for use in existing BPE studies (de Wilde 2014; Burman et al. 2012; Liddiard et al. 2008).

1.5. Research Questions

This research draws upon energy performance data and qualitative information from the Estate Management of a case study building in the University of Cambridge. A holistic approach that capitalises upon these complementary data sources is then taken in order to answer the following research questions:

1. Can investigation of the underlying causes of the performance gap be used to identify early stage building problems?
2. How can presently available energy consumption data assist Estate Management to optimise building energy performance?
3. Does the implementation of Estate Management building development policy enable low-energy building operation?

1.6. Structure

In order to address the research questions, the background to the energy performance and perception gaps in the non-domestic building industry is first addressed in Chapter 2. The energy analysis and policy evaluation methods are detailed in Chapter 3, together with the building development context for the case study building.

Quantitative results are presented in the beginning of Chapter 4, followed by a critical evaluation of the implementation of the building development and management policies in the University of Cambridge.

Recommendations for the building and the Estate Management are made in Chapter 5 and conclusions and future research guidance in this topic area is provided in the final chapter.

Chapter 2

The Energy Performance Gap

2.1. Background

The field of building performance evaluation has been suggested to have originated in the 1960s, when the US military began to assess its facilities in terms of energy consumption (Churcher 2011). Much of the early work in this field centred on assessment of operational energy or energy estimations, but the comparison of both has only become widespread since the Post-occupancy Review of Buildings and their Engineering (PROBE) studies in the mid-1990s (McClurg 2013). These studies have raised awareness within the buildings industry of the energy performance gap, however the phenomenon has not yet been resolved.

Following the PROBE studies, the quantification of the energy performance gap has largely relied upon a case study approach or broad comparison of legislated energy performance reporting requirements, such as the difference between EPC and DEC ratings (de Wilde 2014). A group of industry experts recognised the lack of reporting on building energy performance against designer estimations and established CarbonBuzz, a collaborative online platform for the anonymous sharing of building data (CarbonBuzz 2014). The platform allows building energy professionals, whether they are architects, engineers, energy consultants or clients to share specific building project information on an anonymous basis. This helps to build up a knowledge base on the performance gap for new buildings.

As evidenced in Figure 3 below, the energy performance gap is the difference between the left and right columns under each of ten building typologies. Eight of the ten typologies prominently feature this gap. In this graph, the energy performance gap is displayed in terms of units of carbon dioxide produced, rather than kilowatt hours, which increases the percentage contribution from electricity (relative to kWh metric) because of its higher carbon emission factor (DEFRA 2014).

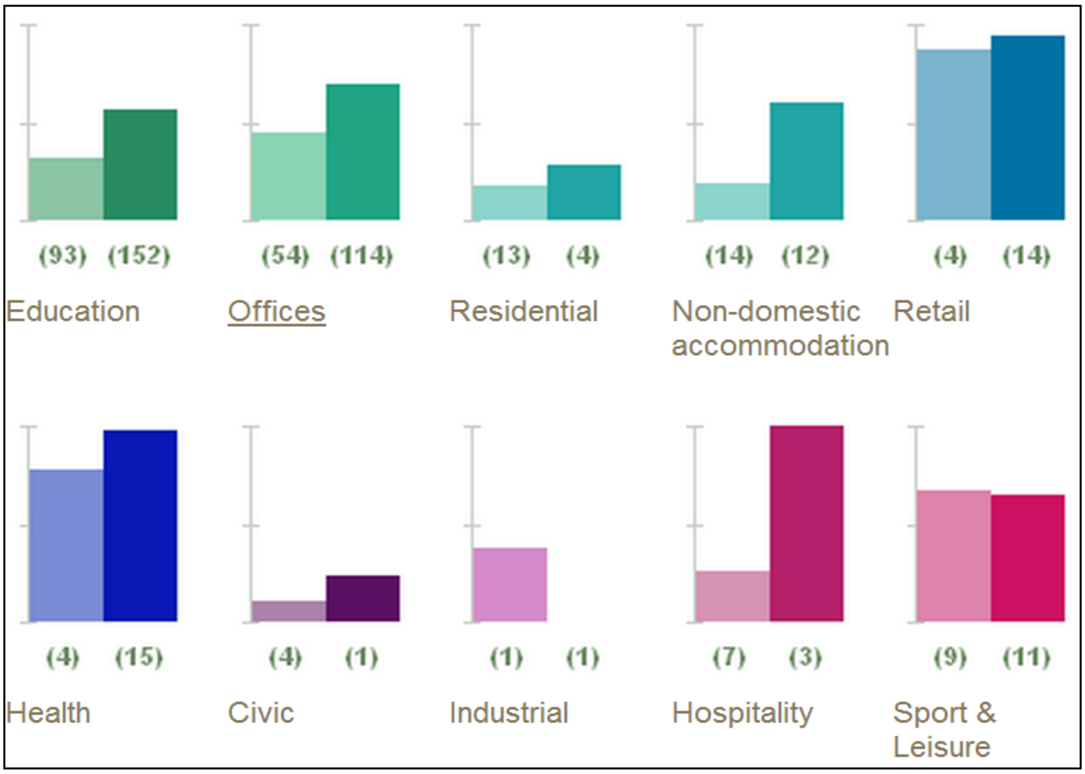


Figure 3. Building energy performance, measured in CO_2 equivalent emissions by building classification. The left column in each category represents the design stage estimate whilst right represents actual. Bracketed numbers show the size of the dataset (CarbonBuzz 2014).

Within the education sector, university buildings have a particularly pronounced difference between estimate (34 $kgCO_2/m^2/yr$) and actual energy consumption (77 $kgCO_2/m^2/yr$). This is equivalent to an additional 130% energy consumed relative to the estimate, as displayed in Figure 4.

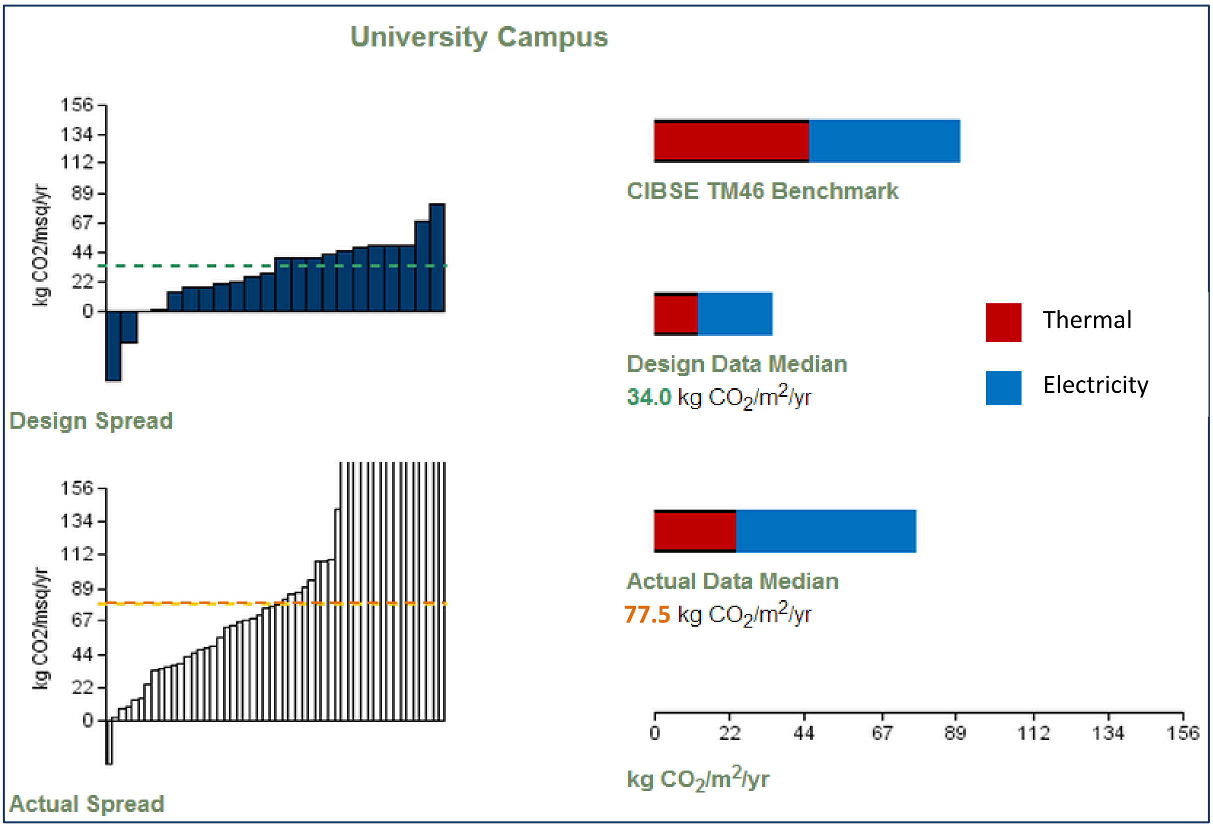


Figure 4. The Performance Gap for University Buildings by CO_2 equivalent emissions. (n_{design} = 22, n_{actual} = 52) (CarbonBuzz 2014).

The data provided in CarbonBuzz is a small representation of the total non-domestic building stock and does not necessarily represent buildings with aspirational sustainability targets that are the focus of this research. The PROBE studies examined 23 well-regarded new commercial and public buildings across the UK (Cohen et al. 2001). A subsequent analysis revealed a collective performance gap of approximately two times as much energy used as predicted (Menezes et al. 2012). The PROBE studies also found that 29% of building CO_2 emissions (based on 2001 emission factors) come from uses that are considered outside the scope of 'normal building services' (Bordass et al. 2001). The authors defined 'normal building services' in the same manner as the BRUKL 'regulated' scope.

2.2. Comparing Like for Like Emissions

The energy performance gap is adversely skewed by inequality of scope, so to develop a 'like for like' comparison, one of two approaches must be taken. Either the regulated actual consumption needs to be used for the comparison or the estimate needs to include the full range of energy end-uses.

The former of these approaches was used in the Technology Strategy Board Building Performance Evaluation (TSB BPE) project, due for completion in late 2014 (Bunn 2010). Preliminary results from 15 of the 56 non-domestic buildings studied suggest that between 30-40% of building energy use is made up of 'unregulated' loads (Cohen 2013a).

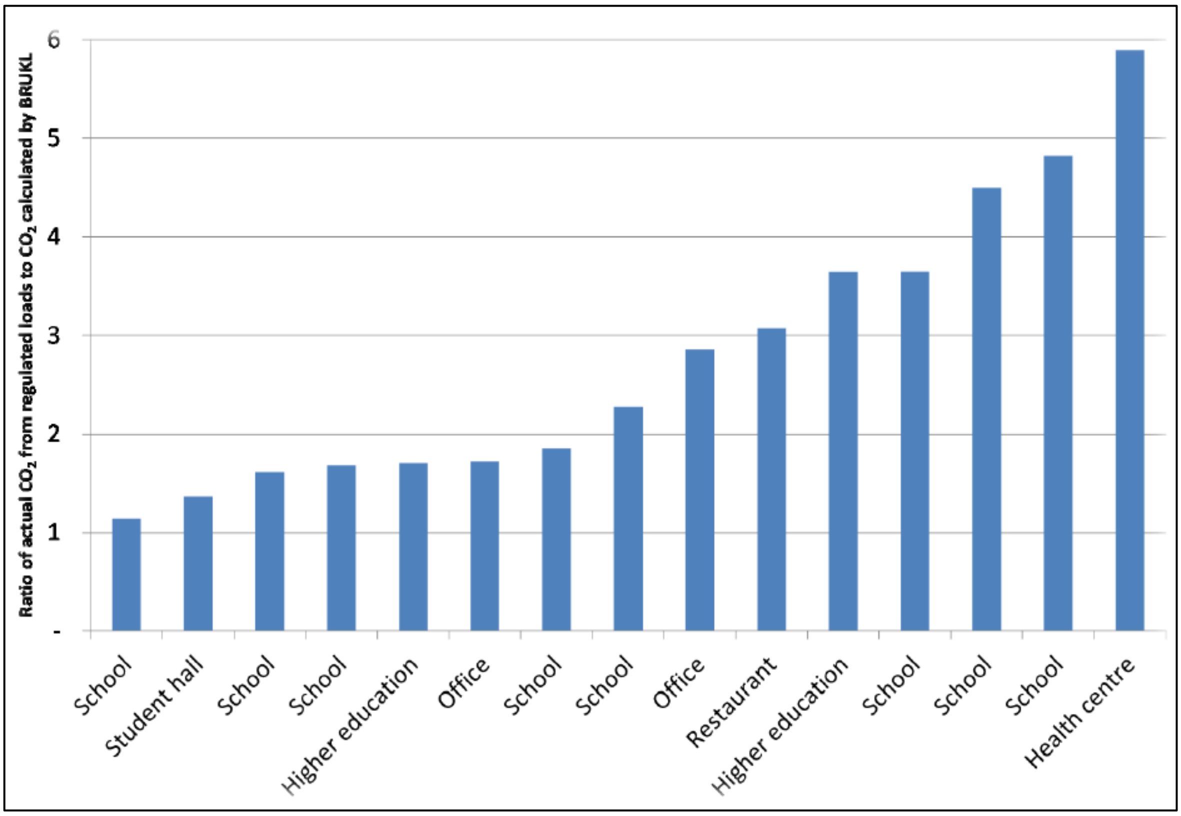


Figure 5. Preliminary data from the TSB Building Performance Evaluation programme displaying the ratio of actual 'regulated loads' with the predicted loads for the same scope of end-uses (Cohen 2013a).

The graphical output of the comparison between 'regulated' estimate and 'regulated' actual consumption is shown in Figure 5. The graph displays the ratio of 'regulated' energy consumption to the BRUKL prediction (converted to CO_2 equivalent emissions). It should be noted that building energy performance often uses CO_2 as an energy metric but can equally be displayed using kWh, since each energy end-use has an equivalent 'emission factor.'

2.3. Developing a Fully Inclusive Energy Performance Estimation

The issues surrounding the scope of energy performance in buildings have been well established for over a decade, and indeed pre-date the EPBD Directive 2002/91/EC

(European Parliament 2010). The Carbon Trust's Energy Consumption Guides published in the early 2000s pinpoint energy consumption end-uses and fuel types in great detail as displayed in Figure 6.

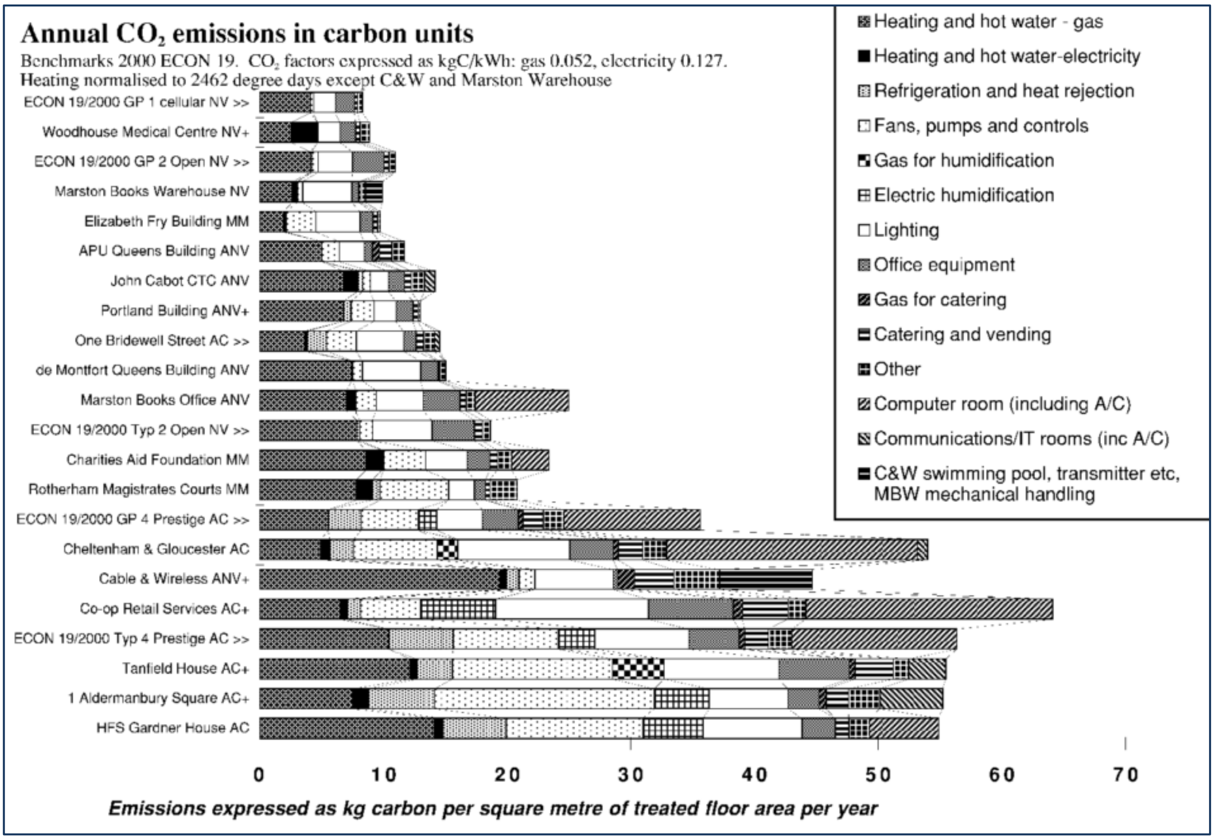


Figure 6. Breakdown of annual carbon dioxide emissions (expressed in kg of carbon content per m² of treated floor area) from gas and electricity consumption (Bordass et al. 2001).

CIBSE collated ECON19 benchmarks together with much of the existing knowledge on the performance gap problem in order to release TM54 'Evaluating Operational Energy Performance of Buildings at the Design Stage' in late 2013 (Cheshire & Menezes 2013). The technical memorandum aims to create a holistic energy prediction inclusive of sensitivity analysis such that the uncertainty associated with end-use energy prediction is clearly apparent.

The TM54 analysis relies on close collaboration and discussion with the building end-users and management team. This eliminates many of the issues associated with the BRUKL standardised assumptions on occupant behaviour. Figure 7 compares the BRUKL 'regulated' energy estimation (same scope as the EPC) to the TM54 methodology and actual energy consumption for a case study building.

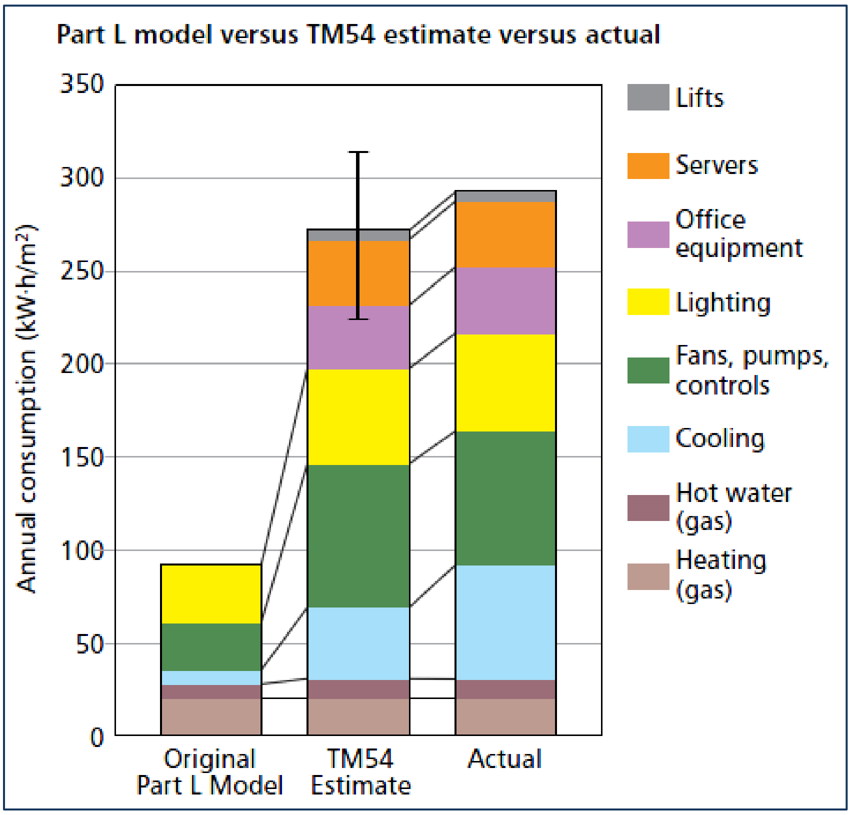


Figure 7. The results from applying the TM54 methodology on a case study office building with comparison to Building Regulations estimation and actual energy consumption.

2.4. Trends in Non-Domestic Building Energy Performance

In May 2014 the UK Department of Energy and Climate Change (DECC) released the first report in an ongoing series of statistical reports titled the Non-Domestic National Energy Efficiency Data framework (ND-NEED) (DECC 2014). NEED was established by DECC to enhance understanding of energy use in domestic and non-domestic buildings in the UK. The report illustrates strong improvements in the energy efficiency of buildings by gas intensity between 2006 and 2011, and a weaker improvement in electricity intensity. As an exploratory piece of work by DECC, no attempt is made to establish the reasons for the difference in rate of improvement of the two energy use types.

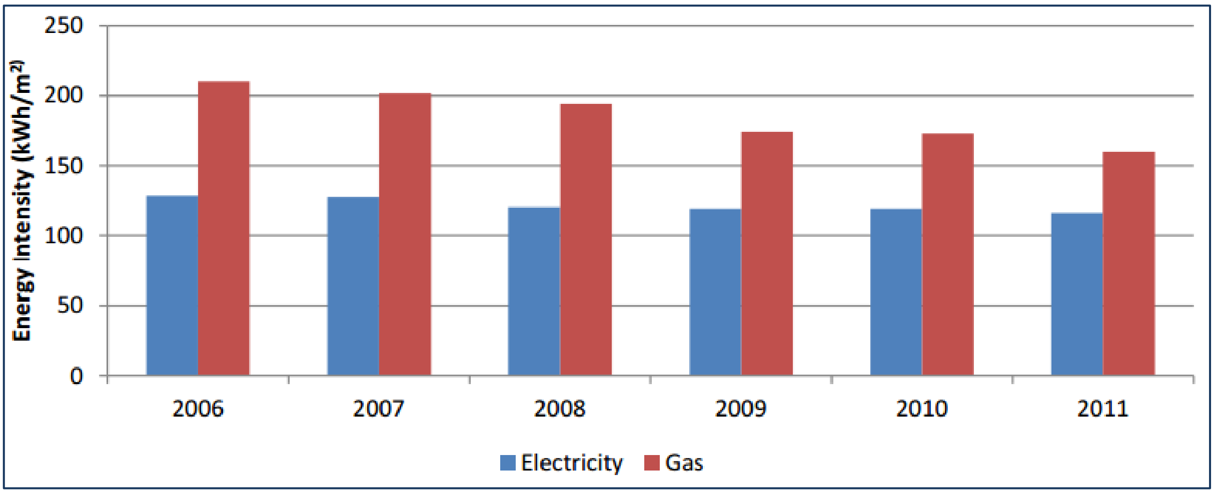


Figure 8. Median electricity and gas intensity for non-domestic buildings between 2006 and 2011 in England and Wales (DECC 2014).

The recent trends (Figure 8) show that there have been significant improvements in the building stock in a relatively short period of time, with a representative sample of almost 30% (n = 488,000) of all the non-domestic buildings in England and Wales. In the six years of available data, gas intensity has decreased by 24%, whilst electricity intensity has dropped by 10% (DECC 2014).

Parallel to the general improvement of building stock energy efficiency has been a significant growth of green building rating certification methodologies, such as BREEAM (see Figure 9 below). The US Green Building Council (USGBC) which administers the LEED certification methodology has witnessed a similar pattern of high growth, with 41% of all non-residential building project starts in 2012 being considered 'green,' as compared to 2% in 2005 (Katz 2012). Whilst the correlated trend may suggest causality, changes in the price of electricity and gas is a greater factor influencing building energy performance (Sunikka-Blank & Galvin 2012).

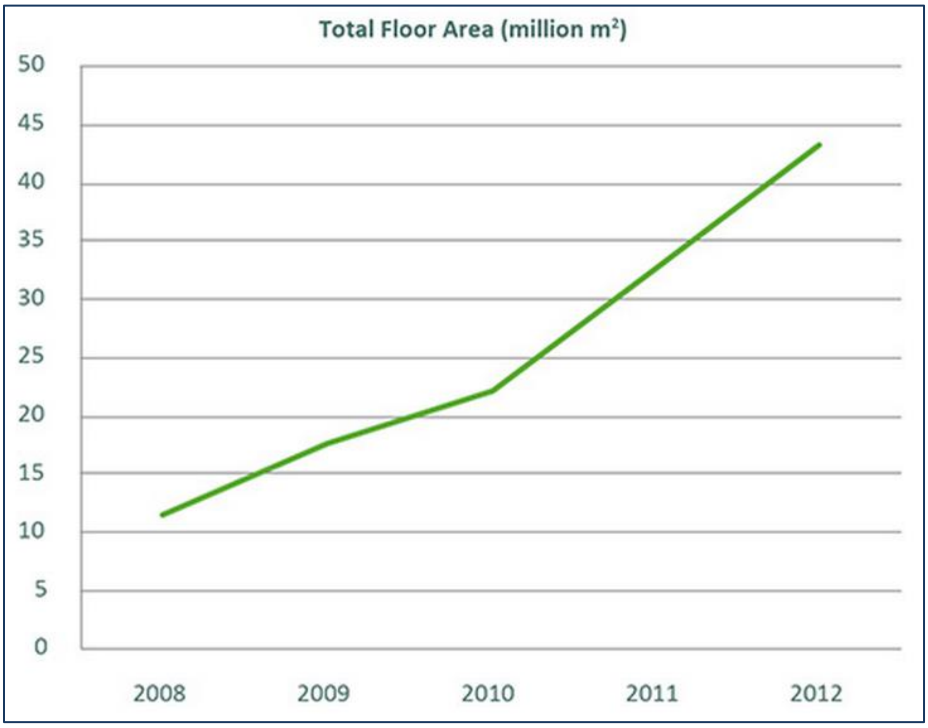


Figure 9. Cumulative Floor Area certified under the BREEAM Certification Methodology (BRE Global 2014).

2.5. Certification of Aspirationally Sustainable Buildings

BREEAM, LEED and similar green building certification schemes have to date focused predominantly on new construction projects, rather than on retrofits. One study of over 100 LEED New Construction (NC) buildings in the US showed that on average, the buildings consumed 18-39% less energy (per unit floor area) than their conventional counterparts. However no statistically significant correlation was evidenced for individual buildings between the certification level and the measured energy performance (Newsham et al. 2009).

The study further assessed whether the specific numbers of energy credits achieved under the LEED rating methodology had any relationship to energy performance and concluded that the correlation was highly tenuous. The only statistically significant results (R^2 = 0.11) of this analysis stemmed from the comparison of Energy Use Intensity (EUI) with Energy Performance Credits, and revealed a weak correlation in the expected direction (Figure 10).

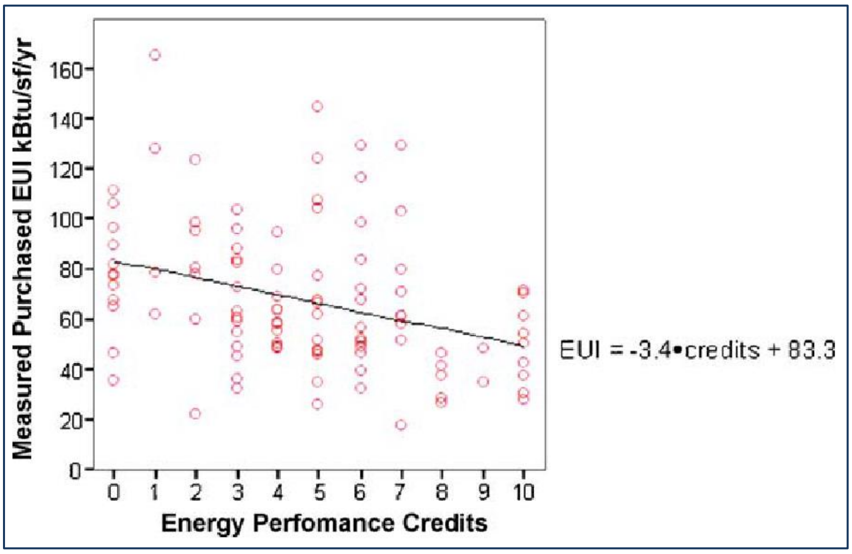


Figure 10. Measured EUI vs. energy credits achieved, for LEED certified buildings. Individual building values and best-fit regression line are shown (Newsham et al. 2009).

Other more broadly focused research (de Wilde 2014) in comparing notionally green buildings with both Energy Performance Certificates and Display Energy Certificates in the UK clearly illustrates the disconnect between certification and realised energy savings (Figure 11).

	Credentials	Building type	EPC	DEC
building 1	BREEAM Excellent	court	B	D
building 2	BREEAM Excellent	court	B	E
building 3	BREEAM Excellent	data centre	A	F
building 4	BREEAM Excellent	education	B	F
building 5	BREEAM Excellent	education	B	D
building 6	BREEAM Excellent	education	B	D
building 7	BREEAM Excellent	office	B	C
building 8	BREEAM Excellent	office	A+	E
building 9	BREEAM Outstanding	education	B	G
building 10	BREEAM Excellent	court	D	D
building 11	BREEAM Excellent	education	C	C
building 12	BREEAM Excellent	education	B	C
building 13	BREEAM Excellent	education	B	E
building 14	passivehouse	education	A+	B
building 15	concrete center case	education	B	E
building 16	concrete center case	education	B	F
building 17	RIBA prize	office	A	B
building 18	RIBA prize	office	B	C
building 19	RIBA prize	healthcare	B	E
building 20	RIBA prize	education	B	D

Figure 11. Comparison of sustainability credentialed buildings in the UK against their EPCs (Building Regulations) and DECs (measured energy performance) (de Wilde 2014).

2.6. Soft Landings

‘Soft Landings’ was conceptualised by Mark Way when working as a principle architect on the construction of the Centre for Mathematical Sciences at the University of Cambridge in 2002. His intention was to extend the service provided by building designers and contractors such that feedback from occupants and managers can become a natural part of the project delivery process (Way & Bordass 2005).

David Adamson, the then Director of EMBS supported the formalisation of this highly successful approach, enabling a project team to draw together a preliminary guide for Soft Landings in 2004 (Way & Bordass 2005). Since this time, the process has been adopted by the Building Sciences Research Information Association (BSRIA) who have authored a series of public documents that raise awareness of this methodology in the building industry. Soft Landings provides a framework to assess the stages of building development from design briefing through to operational feedback (Usable Buildings Trust et al. 2014). It additionally assists in closing the loop between the different phases of building development and feeding back the lessons learnt into the briefing stage of future buildings.

Chapter 3

Case Study Building Performance Evaluation Methodology

3.1. Why Use a Case Study?

Non-domestic buildings are developed in highly context specific environments and are tailored according to user needs, financial constraints, geographical factors and regional legislative conditions. This unique combination of factors is very significant for a building's final energy performance, meaning that the field of Building Performance Evaluation (BPE) lends itself well to analysis through a case study approach. A case study can assist to develop a detailed understanding of the intricacies of an individual building's technical systems, operational environment, user behaviour and building management processes. These combined techno-social characteristics often would not surface through purely quantitative cross-sectional research methods.

For this research, the case study approach is used to provide insights not only to building energy performance, but also the building development and management context. Early findings from this approach can then inform semi-structured interviews that delve deeper into the role of people; including project managers, facilities management and users.

3.2. Case Study Selection

The criteria for a building to be used as a potential case study were:

- a BREEAM or similar 'green' certification;
- at least 12 months metered operational energy data;
- availability of building management staff and occupants for interview.

Initially a number of British engineering consultancies and property developers were contacted in an attempt to source commercial building data. Contacted individuals were highly reluctant to release information due to concerns with how the energy performance research could adversely portray the company in question.

The focus for sourcing potential data then shifted towards public sector building owners and managers, starting with university estates. The University of Cambridge established the Living Laboratory for Sustainability (the Living Lab) in 2012 after recognising the student-led research interest in the Estate's building portfolio. The Living Lab is overseen by the Environment and Energy division of the University's Estate Management and Building Service (EMBS) group. It was set up specifically to meet the goal of providing "opportunities for Cambridge students to propose and carry out projects across the University to improve Cambridge's sustainability" (University of Cambridge Estate Management 2014b).

Staff from the Living Lab have access to data from more than 300 buildings in the University Estate, and were thus able to shortlist a number that met the above criteria. In a subsequent meeting with the Coordinator and Environmental Manager of the Living Lab, it was revealed that some of the shortlisted buildings had been analysed in previous student dissertations. Two buildings remained unanalysed: the Institute for Manufacturing Alan Reece Building (IfM) and the University Sports Centre. The IfM, having more operational energy data available was hence selected as the case study building upon which to focus this research. Findings from the aforementioned student dissertations are discussed in Section 4.3.

3.3. Building Development Context

3.3.1. Sustainability Policies of the University

The University of Cambridge EMBS has two central policy documents that are used to guide the development of sustainable new buildings. 'The Design and Construction of Environmentally Sustainable New Buildings' (henceforth 'Design Guide') provides guidance for the procurement of new buildings based on a set of design principles (University of Cambridge 2008). This is supplemented by the more detailed but broader scope 'Design and Standards Brief for University Services and Construction

Works,' (henceforth 'Construction Manual') intended for use by tendering design and construction companies (University of Cambridge Estate Management 2013a). The main energy-related sustainability considerations from the aforementioned documents are summarised below:

- Maintain focus on whole life costs (design, construction and operation)
- Use integrated passive design principles such as natural ventilation and orientation to provide solar gains in winter
- Design reviews to take place with an EMBS Review Panel at suitable points when still flexible to change
- Soft Landings policy engaged for construction and refurbishment work worth > £0.5m
- Target to achieve BREEAM Excellent on all new buildings > 1000m^2
- Adopt energy efficiency measures if they meet the client department's brief and have payback period < 15 years
- Installed appliances to have minimum A rating European Energy label
- Ensure building will perform under higher future climate scenarios of + 3.5°C by 2080
- Post-Occupancy Evaluation to be performed after building occupation

3.3.2. The Institute for Manufacturing

The IfM is a 4380m^2 multipurpose laboratory-office space on the University of Cambridge West Cambridge site. The £15m building's design was conceptualised in early 2005 when a pre-feasibility study was prepared by the University to gather information for tendering design teams (Woods 2009). After some delays to the building's development due to funding constraints, a 13 month construction programme commenced in February 2008 and the facility was officially opened in November 2009 (The Institute for Manufacturing 2009b). The building is the first BREEAM Excellent rated building in the University Estate and showcases many sustainable features including a biomass boiler for heating and naturally ventilated open plan offices (Woods 2011).

From the conception of the present-day IfM, sustainability aspirations have played an important role in shaping the building's form and operation, allowing it to exceed a number of the Estate's sustainability requirements for new buildings. Materials sourcing, construction methods and layout of the building were all actively and regularly reviewed by the project team with a sustainability focus (Woods 2009). During the construction of the IfM building, the University's Design Guide stipulation for a target BREEAM rating of Very Good was upgraded to Excellent for all new buildings (Grozeva 2013). The building was exempt from this change as building works had already commenced, however the project team was able to incorporate design changes to meet the new criteria.

Figure 12. The Institute for Manufacturing (IfM) features natural ventilation and is the first BREEAM Excellent rated building in the University of Cambridge (Macintosh & Pugh 2007; The Institute for Manufacturing 2009a; Marriott Construction 2009).

The EMBS maintains its own Soft Landings Work Plan for implementation on all new buildings with a value >£0.5m, meaning Soft Landings was employed in the building development process of the IfM (Darwin Services & Way 2006). The IfM designers, project management team and builders were contractually required to participate in Soft Landings meetings regularly during a three year 'extended aftercare' period following the construction completion. This was intended to promptly amend problems that occur during early occupancy and to maintain a regular presence in the building to gather feedback on operation.

A strong emphasis was placed on ensuring adequate time for the commissioning phase of the IfM build due to the importance of this process in troubleshooting and signing off on the building's correct operation. An independent commissioning manager was appointed whose secondary remit was to ensure design consultants and EMBS energy and facilities managers "had adequate opportunity to review documentation ahead of schedule, and to comment accordingly" (Woods 2009).

Lastly, a Post-Occupancy Evaluation (POE) report was created after the building's completion, two years after occupancy in October 2011 (Woods 2011). This was performed as a part of the implementation of Soft Landings midway through the 'extended aftercare' period.

3.4. Mixed Methods Approach to Building Performance Evaluation

A mixed methods approach was taken for the analysis of the building energy performance of the IfM facility. The approach encompassed a combination of metered energy consumption analysis and benchmarking; and qualitative evaluation of reports held by EMBS. In order to structure the methodology, it was necessary to determine the principle objectives and analysis types that allow the study to best answer each of the three research questions from Section 1.5. This is illustrated in Figure 13 below.

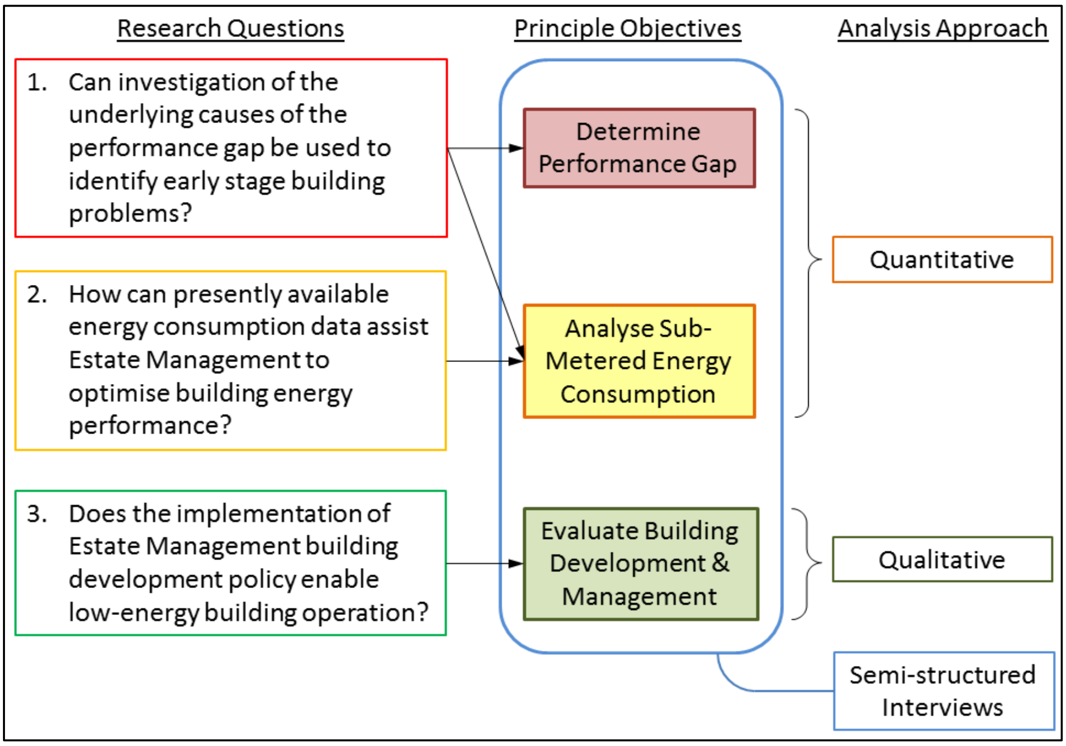


Figure 13. Methodology Overview: how the analysis approach is informed by the research questions

Following the methodology overview, the three principle objectives are individually mapped out in Figure 14, Figure 15 and Figure 16. Each objective is broken down systematically to reveal the data sources or available documentation in the rightmost column of each figure. The preliminary actions that stem from the data sources are then presented in the comments on the far right.

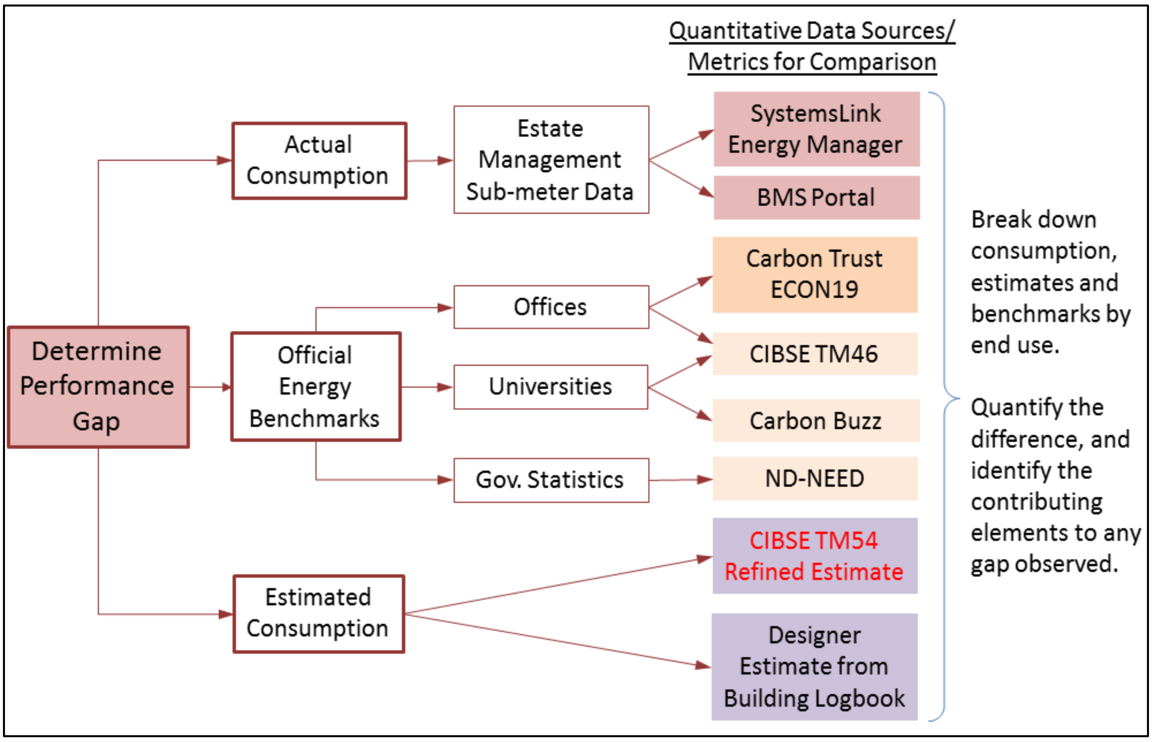


Figure 14. (Research Objective 1) Determination of the performance gap and energy benchmarking.

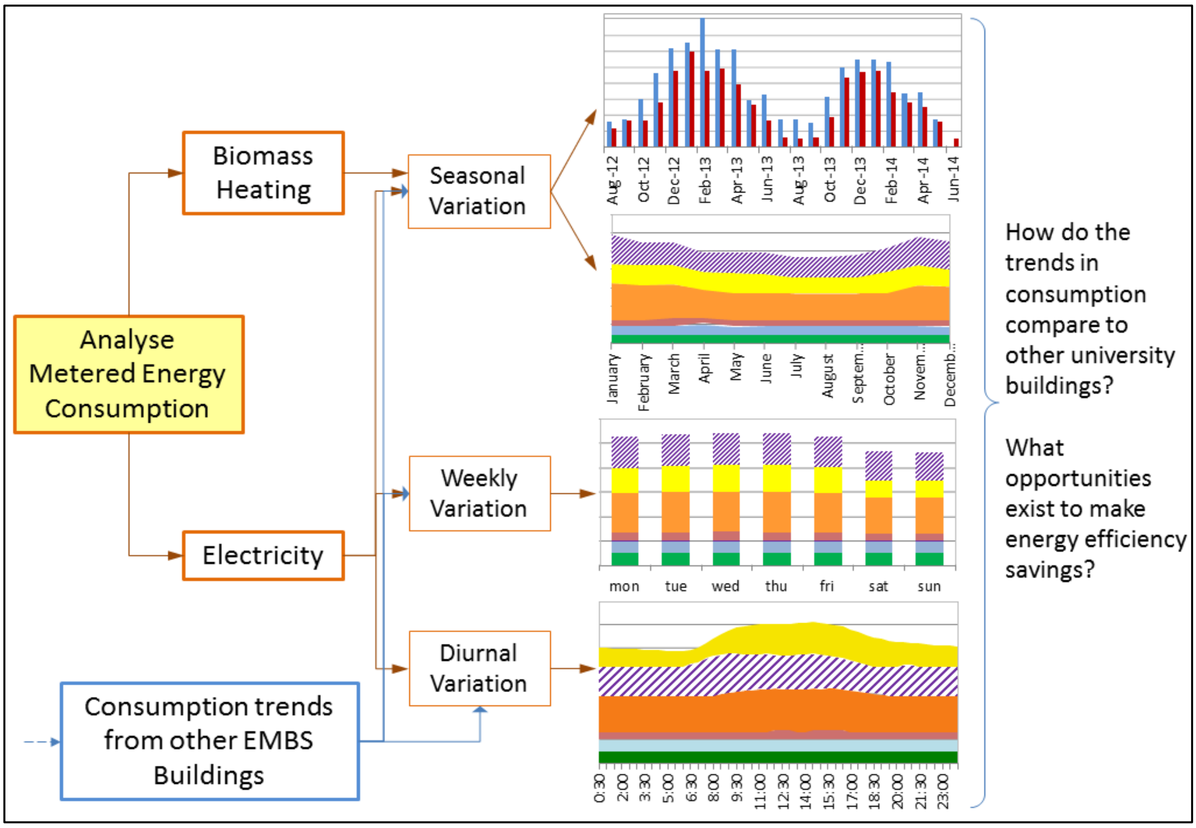


Figure 15. (Research Objective 2) Analysis approach for metered and Sub-Metered energy consumption.

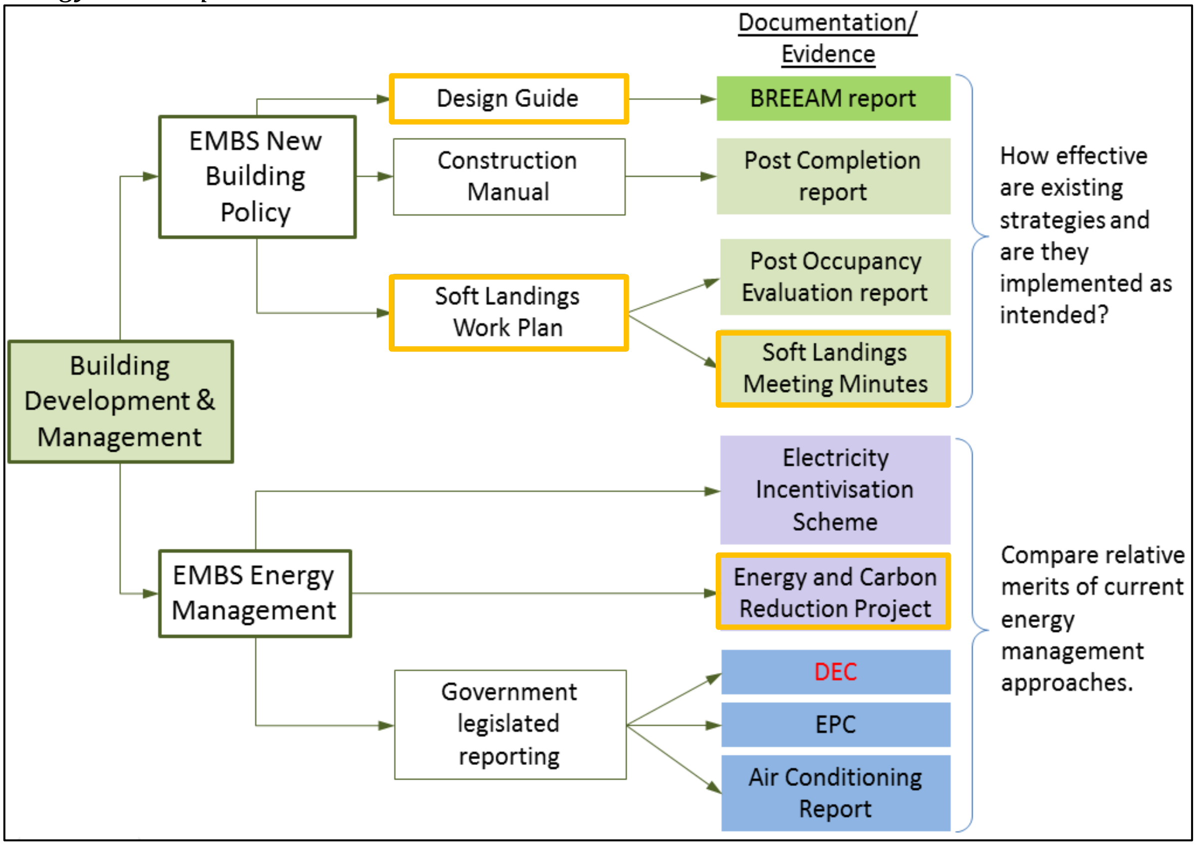


Figure 16. (Research Objective 3) Assessment of the present Estate Management approach to sustainable building design and operation. The outlined items indicate areas of particular focus of the critical evaluation.

Results that stem from the above quantitative and qualitative building assessment approaches were used to inform building users and EMBS staff. This guided the discussion during semi-structured interviews, which helped to reveal the user insights of the building and to develop an understanding of the approach taken by EMBS to building energy management. Appendix 1 summarises the interview data from building occupants.

3.5. Determination of the Performance Gap

3.5.1. Avoiding the 'Perception Gap'

In the quantification of the performance gap, it is important to compare like for like emissions to avoid the inclusion of the 'perception gap' as discussed in Section 2.2. The simplest manner of doing this is to compare the same scope of metered end-uses as the estimate scope (generally the BRUKL 'regulated' loads). However for a more representative quantification, the 'perception gap' illustrated in Figure 2 needs to be addressed through refining of the estimate methodology. This can be guided through the use of CIBSE TM54 'Evaluating Operational Energy Performance of Buildings at the Design Stage' (Cheshire & Menezes 2013).

Full implementation of TM54 requires the input of refined building specific assumptions into a Dynamic Simulation Model (DSM), through the use of software such as Integrated Environmental Solutions Virtual Environment (IESVE) and Thermal Analysis Simulation (TAS) (Lillicrap & Das Bhaumik 2014). The intention of such an approach is to collectively assess the building energy performance in a full building simulation tool, as is often done when seeking compliance with the legislated requirements of BRUKL.

For the IfM building, a verified IESVE model was developed by the building designers for the purpose of producing the EPC (McKerrow 2009). Despite repeated attempts to contact the design engineers about the DSM model of the IfM, no response was elicited. This meant that the methodology could not be pursued without the creation of a DSM from As-Built drawings and specifications. The undertaking of such a task requires extensive modelling experience and availability of all the building specification data. The author's lack of building modelling experience and difficulty with sourcing the requisite information (such as building fabric specifications) meant that the TM54 methodology was not able to be implemented in the course of this research.

The lack of rigorous estimation methodology meant that the perception gap could only be avoided through the comparison of 'regulated' energy consumption with the existing designer estimates.

3.5.2. Energy Benchmarking for Performance Gap Qualification

Energy benchmarks were used to qualify the relative performance of the IfM, in the absence of a TM54 guided estimate. CIBSE TM22:2012 Energy Assessment and Reporting Tool for the TSB BPE recommends the use of the first three benchmarks from Figure 14: ECON19, CIBSE TM46 and CarbonBuzz (Cohen 2013b). The fourth benchmark uses statistical building performance data from the Non-Domestic National Energy Efficiency Database (ND-NEED) (DECC 2014). The relative merits of each benchmark are detailed in Table 1 below.

Table 1. Energy Benchmarks for comparison

Benchmark Name	Institution, Year	Type of data	Resolution by end-use	Strength of Benchmark
Energy Consumption Guide 19 (ECON19)	Carbon Trust, 2003	• Typical and good practice • 4 types of offices (2 naturally and 2 mechanically ventilated)	High (11 end-uses)	• Good practice & typical metrics • High end-use resolution
TM46 Energy Benchmarks	CIBSE, 2008	• Typical practice • 29 building categories (inc. university campus and general office)	Low (electricity and thermal comfort)	• Official guide document • Frequently cited
CarbonBuzz	RIBA & CIBSE, 2014	• Typical practice • 31 building categories (inc. university campus and general office)	Low (electricity and thermal comfort)	• Highly accessible • Collaborative/ participatory
Non-Domestic National Energy Efficiency Database (ND-NEED)	DECC, 2014	• Typical practice • Large dataset UK Govt. statistics (n=488,000) for 5 building categories (inc. general office)	Low (electricity and natural gas)	• Large dataset (>25% of all English office buildings of same area)

The ECON19 benchmark contains data for two types of naturally ventilated offices and two types of air conditioned offices. Because the IfM is a mixed-mode system with both ventilation types, a weighted average based on floor area can be used to make a directly comparable metric. This approach is sanctioned in the ECON19 guide itself. The remaining three benchmarks can be directly compared without weighting.

3.6. Analysis of Sub-Metered Energy Consumption

The sub-metered energy consumption data from the IfM holds a vast amount of information on the temporal trends of energy use. The existence of high resolution energy consumption data in non-domestic buildings is increasingly common in new buildings and a number of approaches exist to guide the analysis of this data. CIBSE TM22:2012 is one such guidance document. At the time of writing, TM22:2012 was being trialled on the TSB BPE case studies as a non-public beta release (Cohen 2013b).

The beta version of this tool was made available for research feedback via CIBSE, however it remains in confidence until publication. The approach used in this technical memorandum nevertheless guides the analysis of available energy consumption data. Two customised spreadsheets underlie TM22:2012, making use of half-hourly sub-metered energy data together with a framework for making credible energy estimates. The spreadsheets demonstrate the importance of assessing energy consumption both during the primary hours and out-of-hours operation. It is thus important to display data to show the relative difference between normal hours of use with night time usage, weekend usage, and to observe what seasonal trends may appear.

The difference between baseload and peak energy consumption can provide indication of the effectiveness of the energy management of the building, when compared to well-performing buildings in the University Estate. The Gurdon Institute, as one of the more successful pilot buildings in the University’s Energy and Carbon Reduction Project was selected for this intra-Estate benchmarking. Making such comparison can assist EMBS to determine how optimally the building is presently performing and to pinpoint opportunities for improvements to the building energy efficiency.

3.7. Evaluation of Building Development and Management

A significant amount of qualitative data was available for the IfM in the form of reports and documentation provided by EMBS on the building development process and energy management. The available data is summarised in Figure 16.

For the building development process, two University policies of particular significance relate to BREEAM and Soft Landings. The University Estate maintains a policy where all new buildings are required to target a BREEAM 'Excellent' rating and to achieve a minimum rating of 'Very Good' "in cases where there are good and explicit reasons why an Excellent rating could not be achieved" (University of Cambridge 2008). This policy complements a separate sustainability requirement for the Soft Landings approach to building development, introduced in Section 2.6. The EMBS Soft Landings Work Plan has been in effect since 2006, with a contractual requirement for new buildings to undertake this process, most notably including a three year 'extended aftercare' process to resolve inevitable post-completion building issues.

For the IfM building, reports and documentation detailing the process of building development have been critically evaluated in terms of adherence with EMBS policies. Amongst the available documentation, the first 12 months of Soft Landings meeting minutes best illustrates the actual implementation of a building development policy. Other documentation available includes reports for BREEAM certification, post completion and post occupancy evaluation.

The present energy management policies of the EMBS (as distinct from building development policies) are summarised in Figure 16, and detail how the University is taking action to improve energy efficiency in its building portfolio. These include both EMBS specific policies and legislated requirements from the UK Government towards building performance. In particular the effectiveness from the first 2.5 years of the University's pilot ECRP projects is reviewed in Section 4.5.1.

The Living Lab, as mentioned in Section 3.2, has findings from previous student dissertations regarding some of the University's notionally sustainable buildings. One study analysed the energy reporting and monitoring of three BREEAM Excellent rated buildings (Norris 2014) whilst another undertook more detailed energy performance analysis and Post-Occupancy Evaluation on the highly regarded Sainsbury Laboratory (Lee 2014). Both projects are helpful in providing intra-Estate benchmarks since preliminary analysis of the performance gap was performed in both.

Chapter 4

Results and Discussion

4.1. The Energy Performance Gap in the Institute for Manufacturing

4.1.1. Metered and Estimate Energy Consumption

The IfM building has a total of 28 electrical meters and sub-meters, one biomass heat meter and two gas meters. The majority of data from these meters is automatically exported and recorded in an online platform called SystemsLink, which is primarily used by EMBS energy managers to ensure compliance between utility invoices and metered data. More comprehensive Building Management System (BMS) data was accessible via an online portal to supplement some of the gaps in SystemsLink data. The combination of these two data sources allowed for 'as performing' energy consumption to be broken down by end-use. Correction by floor area allowed for a simple comparison to be drawn with energy benchmarks and a design stage estimate from the Building Logbook (using the same units of kWh/m^2/day).

The facility's Building Logbook (a requisite component of BRUKL compliance) contains a design stage energy estimate for the IfM, as do many new University of Cambridge buildings at the request of EMBS (Marriott Construction 2009; Norris 2014). This energy estimate does not precisely detail the end-uses that are recorded by the building electrical sub-meters, however provides a guide to the expected annual energy consumption. The estimate is broken down into three categories:

- electricity for naturally ventilated spaces;
- electricity for mechanically ventilated spaces;
- natural gas for hot water use.

Users of the Logbook are cautioned about the exclusion of laboratory loads and biomass heating energy consumption from the collective estimate.

4.1.2. Energy Consumption Guide 19 for Offices (ECON19)

Four different energy consumption benchmarks are used for comparison with the estimated and actual energy figures, the merits for which are discussed in Table 1 of the Methodology. The first of these, ECON19, is especially useful due to high end-use resolution and ability to develop a mixed ventilation benchmark through weighted floor area averages. Two thirds of the IfM floor space is naturally ventilated (the remaining third is air-conditioned), so a 2:1 weighting of the two most representative office types was used to customise a mixed ventilation benchmark, as shown below in Figure 17. This is repeated individually for both the 'good practice' and 'typical' energy consumption. When compared with metered consumption in Figure 18, laboratory energy use is separated to allow comparison of the office component of energy performance.

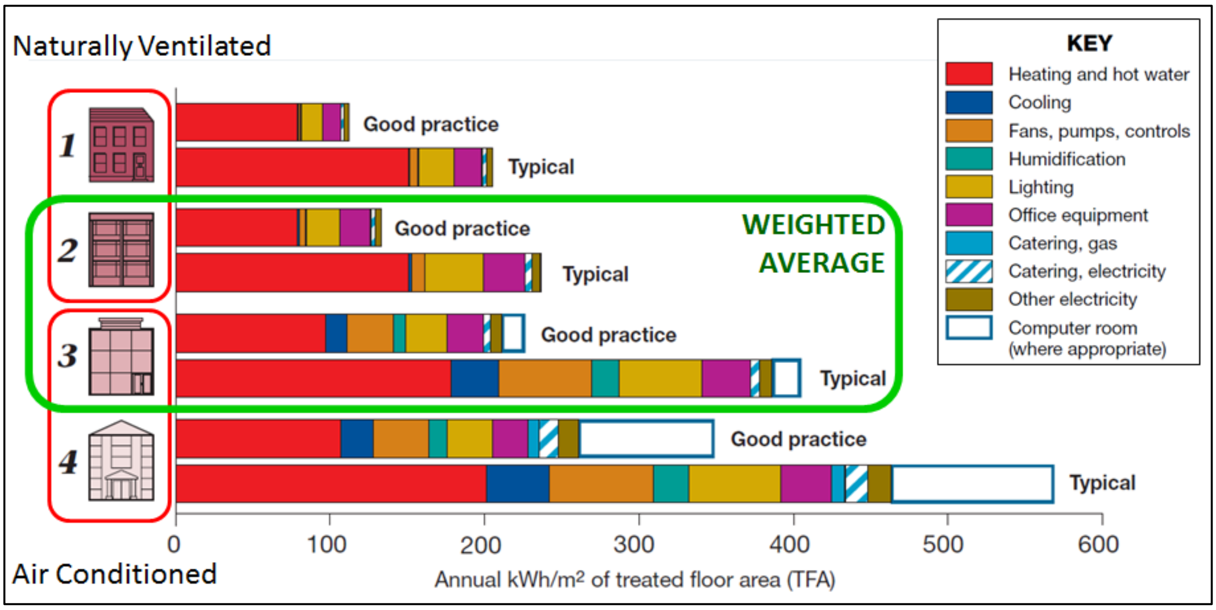


Figure 17. Energy use intensity for good practice and typical examples of four office types. Office types 2 (naturally-ventilated open plan) and 3 (air-conditioned standard) are most representative of the IfM building (Carbon Trust 2003).

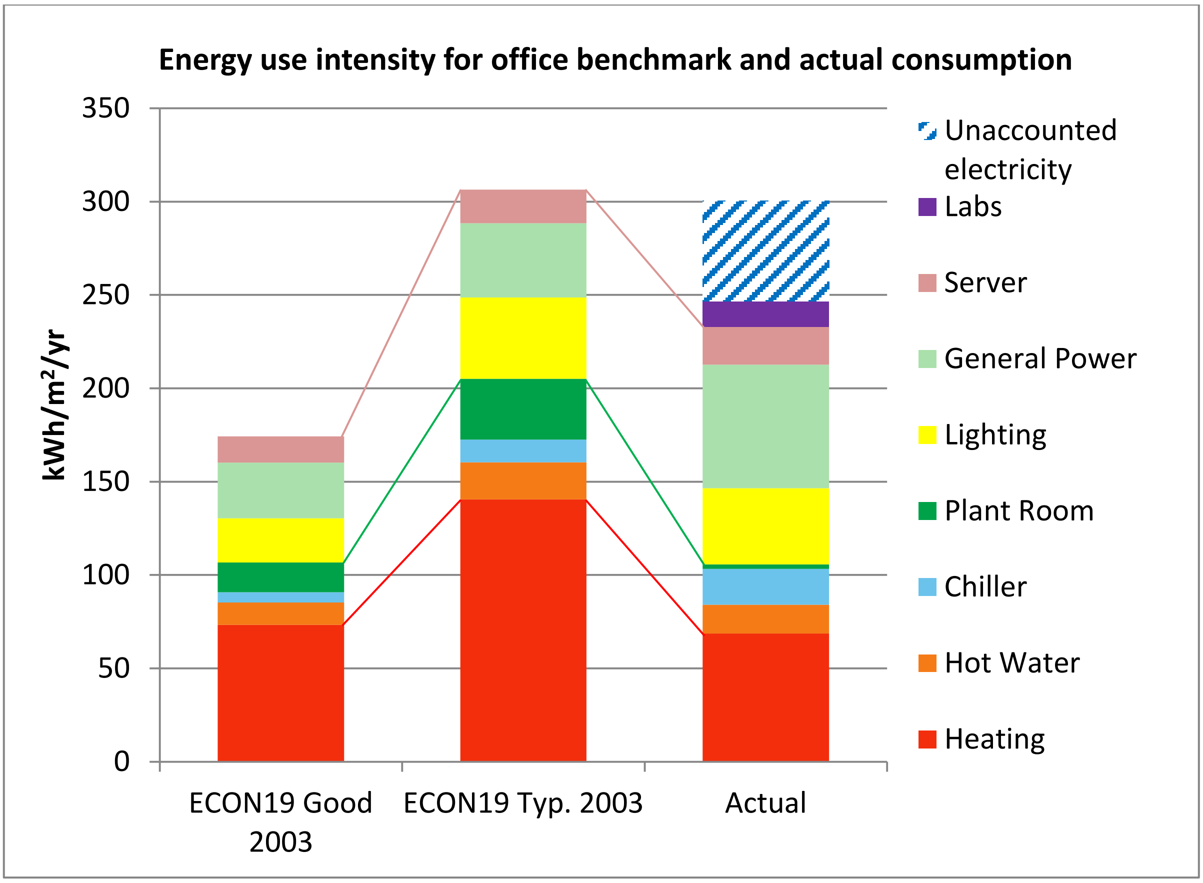


Figure 18. IfM building end-use energy consumption with Energy Consumption Guide 19 'Good Practice' and 'Typical' benchmarks for offices.

4.1.3. Other Benchmarks

The remaining three energy benchmarks from Table 1 are directly comparable to the main metered consumption types of electricity and heating fuels (gas and biomass). Although the end-use resolution is considerably lower than ECON19, each benchmark is useful for different reasons:

- The ND-NEED statistical dataset reveals non-domestic building energy use intensity for electricity and gas. The relevant data for this research was collected in 2011, for office buildings between 1000 – 4999 m^2 (DECC 2014).
- CarbonBuzz draws upon open source case study building data contributed by building professionals and represents a dynamic database for university buildings (see Figure 4).
- CIBSE TM46 describes the statutory building energy benchmarks to complement the DEC rating procedure, again for university buildings (Field 2008).

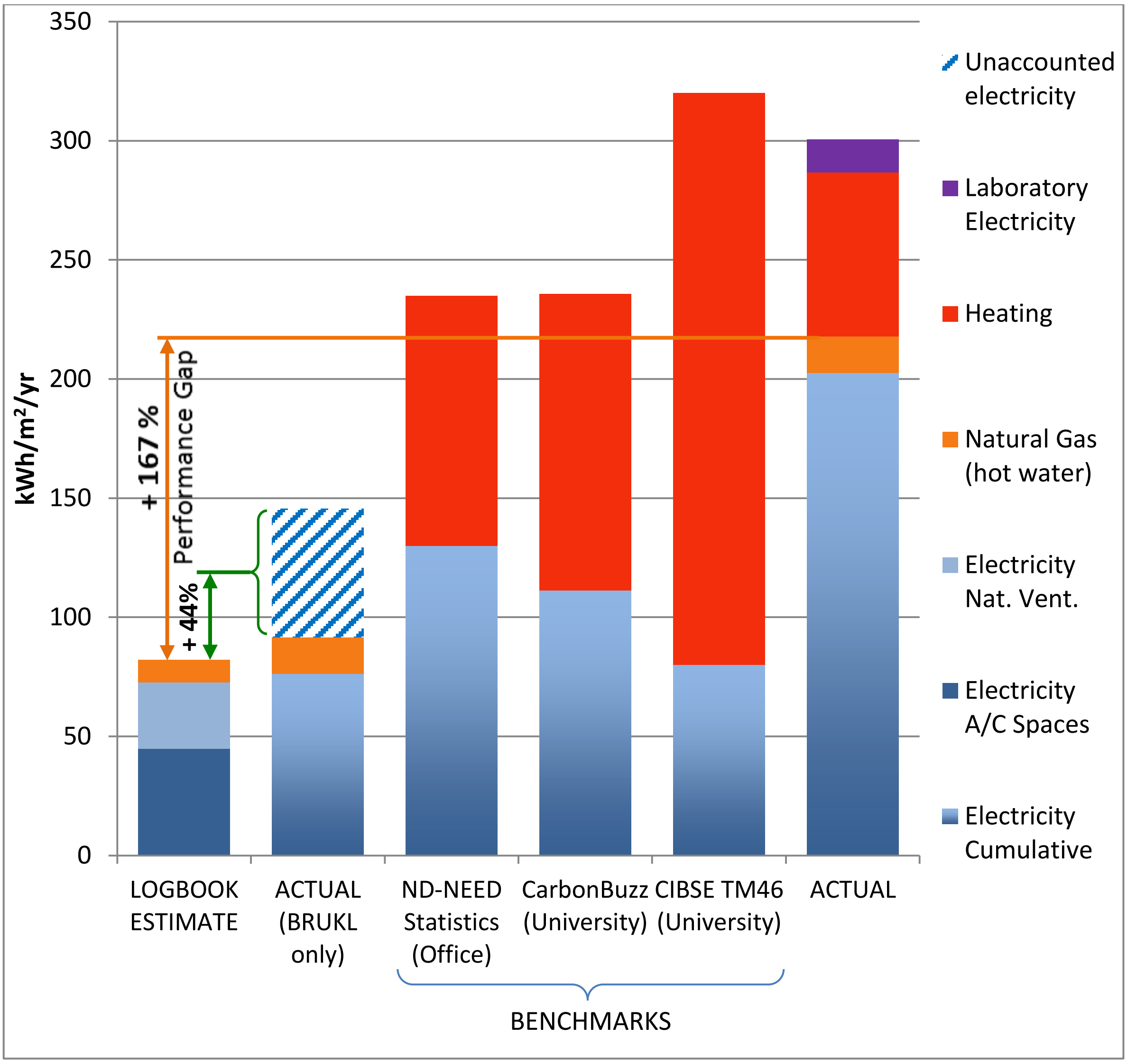


Figure 19. Energy Consumption of the IfM building and comparative energy benchmarks/logbook estimate.

The three energy benchmarks from Figure 19 above illustrate that the IfM building performs worse than the non-domestic building stock average, despite being a notionally high performance building. Total metered consumption is 29% higher than both the ND-NEED statistics for offices and the CarbonBuzz metric for university buildings, whilst the actual performance is only marginally better than the benchmarks provided in CIBSE TM46. The biomass heating energy however is very low relative to the benchmarks, meaning that the high total energy consumption is mostly the result of substantially inflated electricity consumption above both benchmarks and the Logbook estimate.

A large disparity between the estimated electrical and gas consumption relative to the actual usage is immediately apparent from Figure 19 (indicated by the orange arrow). Taking the assumption that the electricity estimate was fully inclusive (i.e.: both regulated and unregulated energy end-uses were included), then a quick comparison can be made to quantify the performance gap. The sum of the 'Estimate' loads is 82kWh/m^2/year whilst the same scope from metered consumption measures 219kWh/m^2/year. This means that the performance gap can be quickly estimated as 167% additional energy consumed compared to Building Logbook estimates.

A concern with this quantification approach is that there is no way to verify the assumptions that were made in developing the Building Logbook estimate. However it is likely that the estimate electricity consumption is inclusive only of 'regulated' loads given that the Logbook is a statutory requirement of the BRUKL. This would mean that the 167% performance gap quantification includes some elements of the 'perception gap.' Thus a second quantification demonstrates the performance gap using only regulated loads plus half of the unaccounted electricity (taking the assumption that part of this will be regulated). This suggests a more modest 44% increase energy consumption above the designer estimate.

4.2. Design Stage Energy Prediction

The energy performance gap quantified earlier in this chapter relies upon a Building Logbook estimate provided by the designers of the IfM building. Subsequent to the creation of the Building Logbook, the EMBS created an energy-focussed Key Performance Indicator (KPI) report for the IfM (University of Cambridge Estate Management 2013b). These KPI reports are commonly produced for new Estate buildings as a form of reporting and feedback with the building designers in the three year post completion period governed by Soft Landings (Norris 2014).

In the first full year of operation (2010), the KPI report held by EMBS shows a large energy performance gap against the Building Logbook estimate (dated 11/03/2009). The designers were asked on at least two subsequent occasions to recheck their estimates based on findings from the report (actual consumption is indexed and reported each year), as illustrated below in Figure 20.

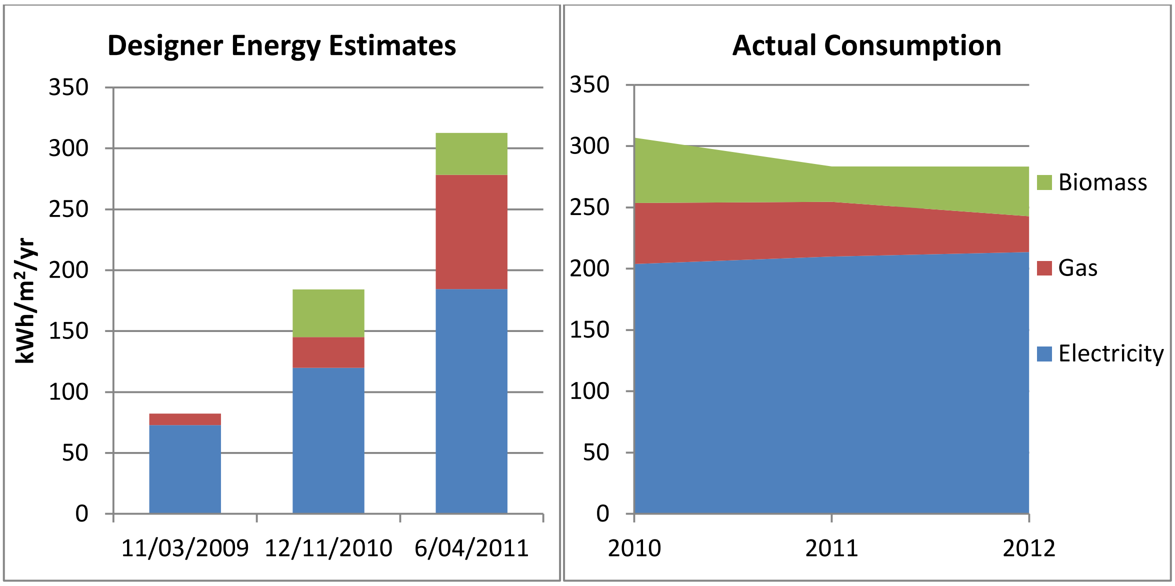


Figure 20. Designer energy estimates compared to actual consumption. Adapted from (University of Cambridge Estate Management 2013b).

The finding that designer energy estimates increase in response to feedback about actual performance suggests building designers experience a form of optimism bias. This concept is typically used in reference to risk-taking in finance and project management, but for the case study building there is a clear trend that initial designer estimates fall far short of actual consumption. Unlike optimism bias for high risk decision making, the consequence to the designer from making a poor energy estimate is very low. This is largely because of heavy focus on design-based rating schemes such as BREEAM and LEED, which do not test the operational accuracy of energy estimates. This allows for many overly optimistic assumptions to be made repeatedly concerning occupant behaviour, building operation and model simplifications.

4.3. Intra-Estate Performance Gap Benchmarking

Two previous student projects through the Living Lab have made observations of the energy performance gap in three BREEAM Excellent buildings in the University Estate (Norris 2014; Lee 2014). The performance gap for these notionally green buildings is benchmarked against the IfM building on the far right of Figure 21. Whilst not a statistical dataset, it is clear to see that the electricity performance gap of the IfM (excluding laboratories) far exceeds the equivalent metric for the three other University buildings.

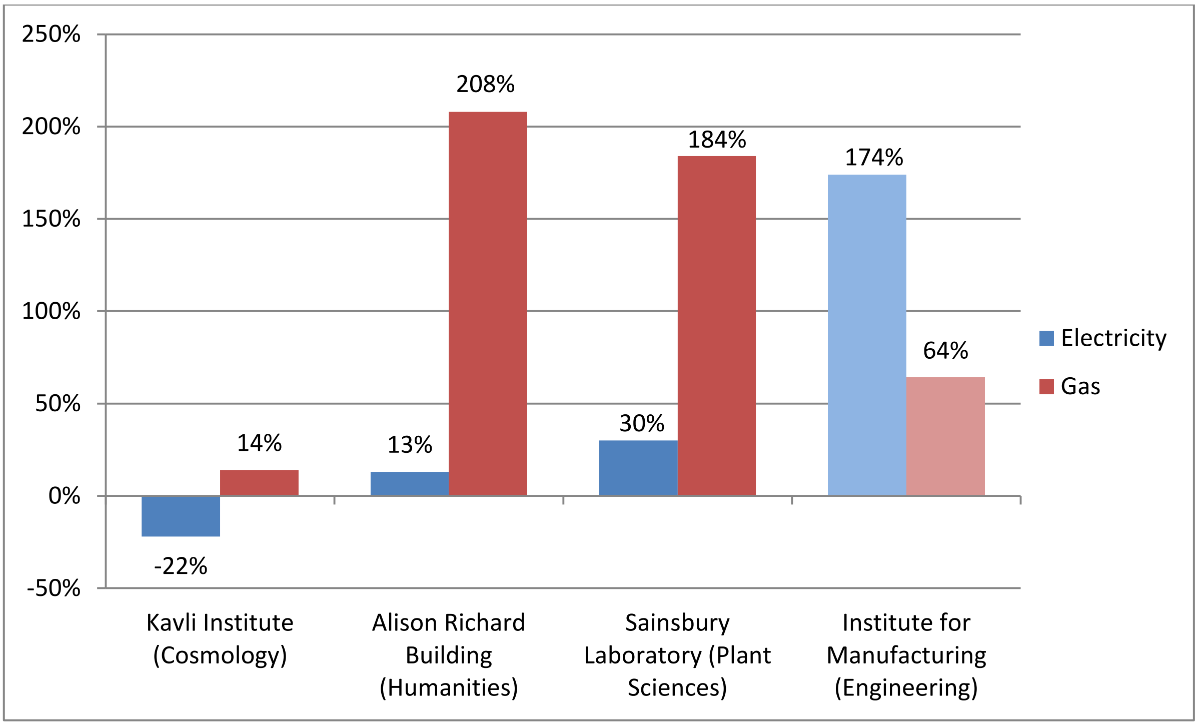


Figure 21. Comparison of Energy Performance Gap between BREEAM Excellent buildings in the University Estate (% difference between Logbook estimate and actual consumption) (Norris 2014; Lee 2014).

4.4. Electrical Sub-Metering Strategy and Reality

The Construction Manual from EMBS outlines a metering strategy which recommends that a minimum of 90% net energy consumption should be assigned to the various end-uses (such as lighting, servers, heating etc.). The strategy, depicted in Figure 22 also promotes the use of tiered metering for electricity, which provides redundancy. This arrangement allows for simple pinpointing of measurement errors, because intermediate meters are placed between electrical end-uses and the main electricity incomer (gas and biomass are not tiered because of the low diversity of end-uses).

The Building Logbook for the IfM has a similar metering schematic that shows how the 26 electrical sub-meters are arranged, as illustrated in Figure 23. There are two marked differences between the Construction Manual metering strategy and the actual metering schematic. Firstly the IfM metering schematic has only 2 tiered groups of meters, leaving the majority of meters 'un-tiered.' Secondly the descriptions that are provided in the IfM metering schematic are very brief, making it troublesome to understand how and where the energy is used (for instance sub-meters 4, 6, 10 and 12 all measure 'General Lighting').

To illustrate the first of these points, the kilowatt hour energy consumption from the tiered sub-meter group for HVAC consumption in Figure 23 (SM11) is plotted in a stacked column graph, as shown in Figure 24. The sum of the readings from 'second tier' sub-meters 21 to 26 should be equal to (or slightly less than) the reading obtained from 'first tier' sub-meter 11. This comparison reveals that there is four times greater cumulative meter readings from the 2nd tier relative to the 1st. This is impossible if the actual wiring of the sub-meters is configured in the same manner illustrated the metering schematic from Figure 23. Because the majority of 2nd tier sub-meters record very high values, this suggests one of two potential errors:

- The 1st tier sub-meter, SM11, routinely under reports electricity consumption
- A systemic problem exists with the configuration of the 2nd tier sub-meters

When the meter readings from the six 2nd tier meters are used to replace the contribution from SM11 in Figure 18, the "unaccounted for" electricity becomes negative, indicating that the first of the two potential options is unlikely to be the source of error. Thus the presence of a systemic problem with the sub-metering configuration is more likely. It is not uncommon for problems of this nature to occur with metering due to either mis-matching of sub-meter data pulses with the BMS system or inappropriate current-transformer ratios being used during meter configuration (Bunn 2014). This type of problem is often characterised by an integer multiplier of the actual meter readings. This is evidenced in both the second tier sub-meter groups of the IfM building, where the 2nd tier group from SM11 is four times greater than the 1st, whilst the SM20 is 100 times larger SM15 (see Figure 23).

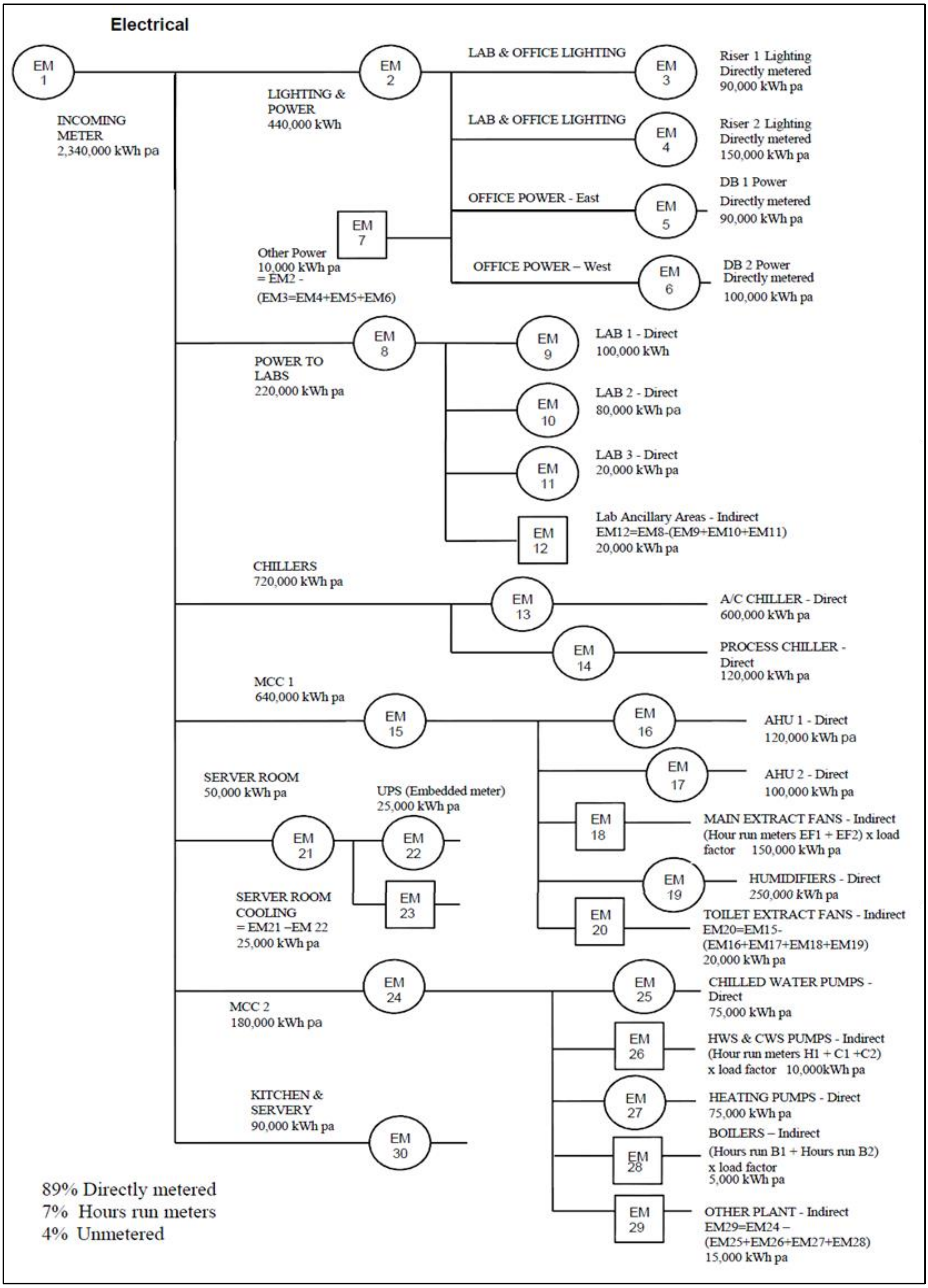


Figure 22. Metering strategy document (University of Cambridge Estate Management 2013a).

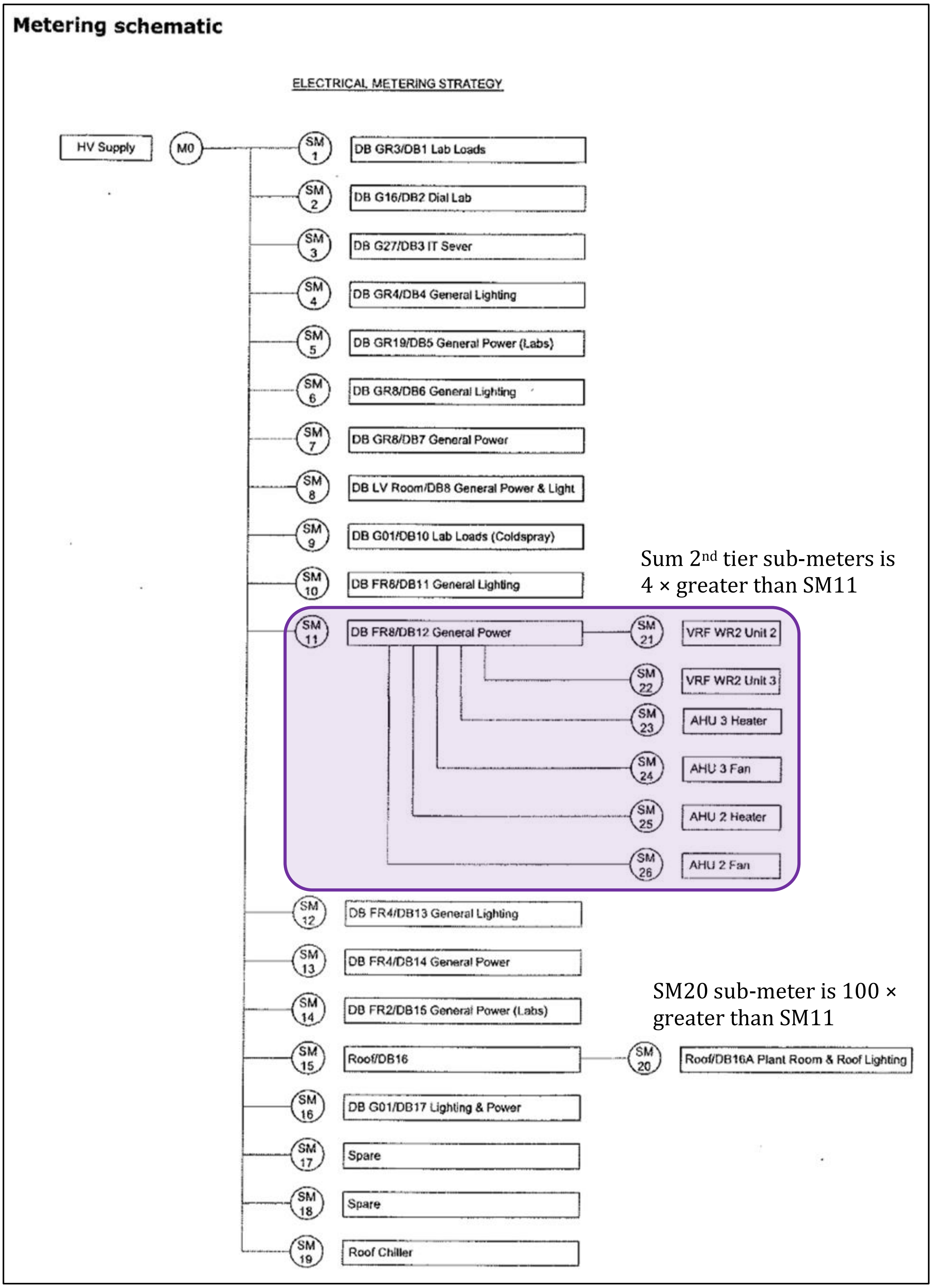


Figure 23. IfM Building Electrical Sub-Meter Schematic. The tiered sub-meters for HVAC energy consumption are highlighted in purple (Marriott Construction 2009).

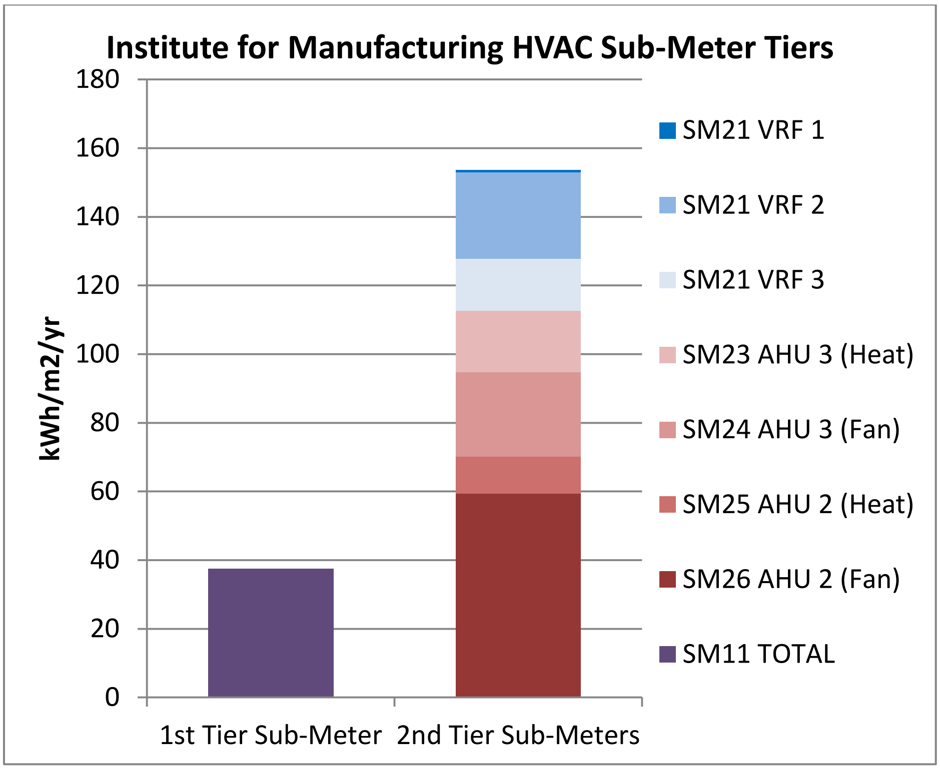


Figure 24. Disparity between Sub-Meter tiers for HVAC energy end-uses.

4.5. Temporal Analysis of Electrical Sub-Meter Data

4.5.1. Peak-Baseload Ratio

The IfM electrical sub-meter data, as mentioned in Section 3.6 of the Methodology has a vast amount of temporal data which is not extracted when quantifying the performance gap. The four years of half-hourly sub-meter data had outliers removed (data errors discussed in Section 4.10) and was then plotted to show the trends in daily, weekly and monthly consumption (Figure 25, Figure 29 and Figure 30). Only first tier electrical sub-meters are used to create graphs, due to 2nd tier meter errors discussed in Section 4.4. The graphs are plotted with consistent end-use classifications, based on the descriptions of the sub-meters in the Metering Strategy document in Figure 23.

Figure 25 for daily sub-meter profile illustrates that the relative difference between operational hours and out-of-hours building energy consumption is small. This can be quantified as the ratio between peak and baseload energy consumption. Over an averaged 24 hour period the ratio is 1.26 for the whole week, however average weekdays exhibit a higher ratio of 1.35, whilst Saturdays and Sundays have a ratio of 1.07 (Figure 26).

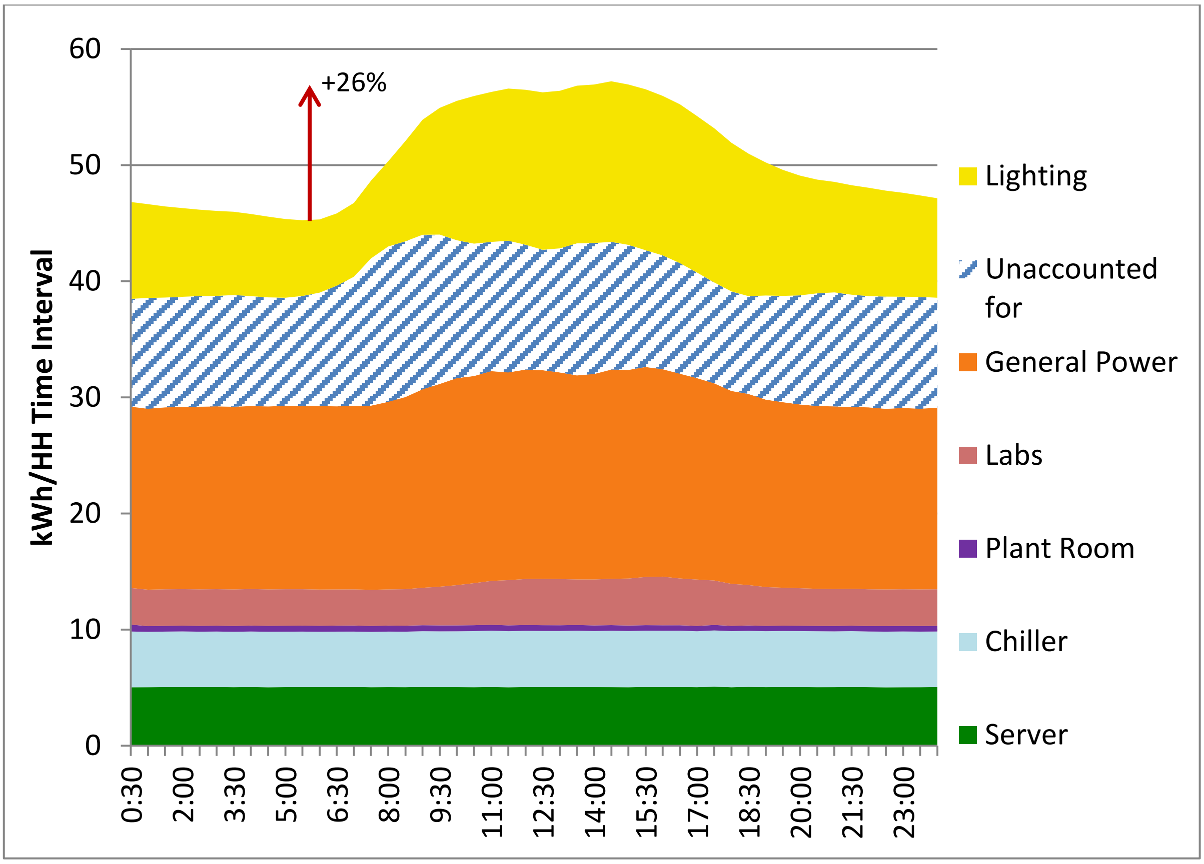


Figure 25. Daily Electrical Sub-Meter Profile (inclusive of all days of the week)

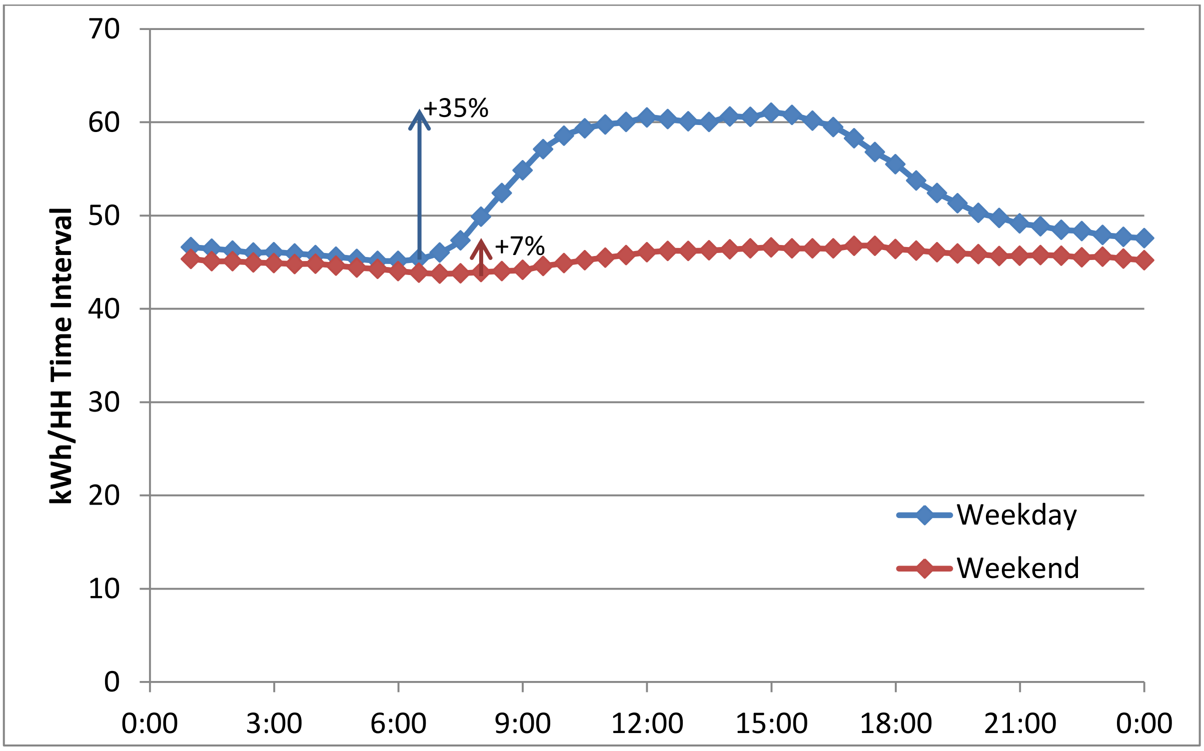


Figure 26. Daily electricity consumption on average weekday and weekend in the Institute for Manufacturing.

The low variability between peak and baseload consumption can be indicative of minimal energy management. This hypothesis is supported by many observations from building occupants that services such as lighting and air conditioning continue at all hours despite the occupancy being very low out-of-hours and on weekends (Appendix 1).

An analysis of EMBS electrical sub-meter data from the Gurdon Institute is used to observe this ratio of peak to baseload consumption. The Gurdon Institute houses a cancer research team, and is one of most successful of the five pilot buildings in the University's Energy and Carbon Reduction Project (ECRP) (University of Cambridge Estate Management 2014a). After commencing early in 2012, the ECRP has caused a drop in both the average maximum and minimum daily energy consumption, as indicated by the red and blue lines in Figure 27 below. However the percentage difference between these two lines (illustrated in green) clearly shows that the ratio between the two is getting larger since introduction of the scheme. From a historical baseline of 36% peak-baseload difference, this is now over 50%, because of the higher energy savings potential with out-of-hours energy consumption.

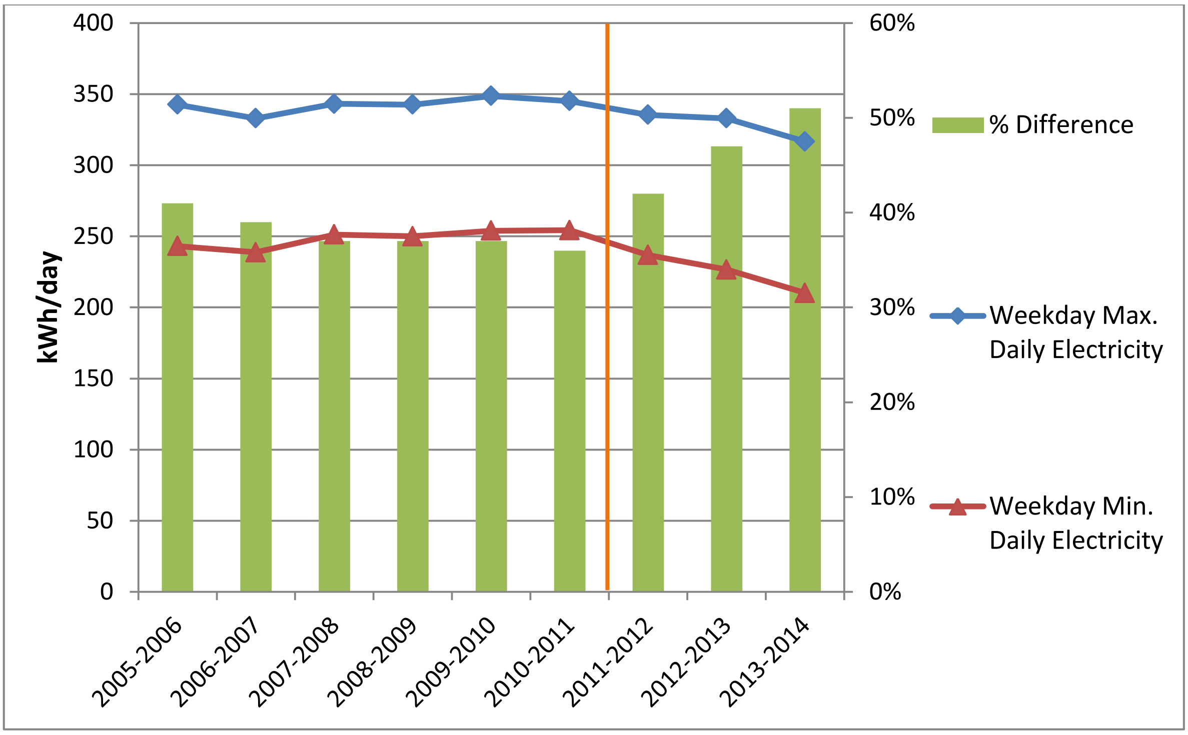
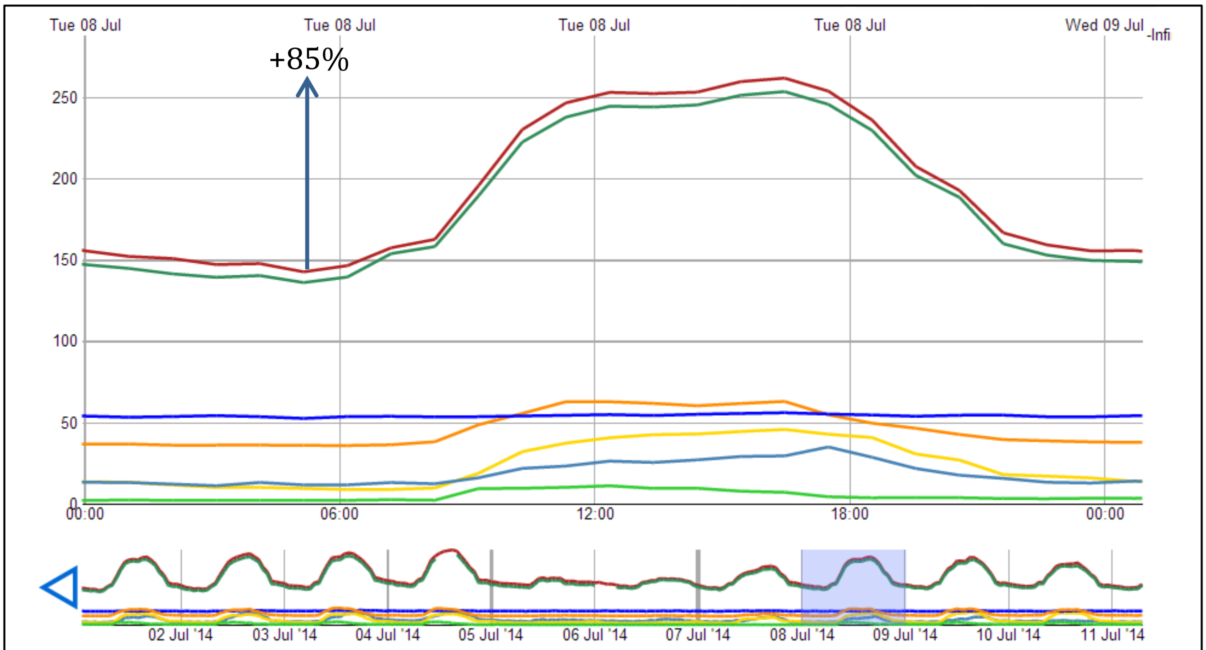


Figure 27. Gurdon Institute variation in daily electricity consumption by academic year (weekdays only). The vertical orange line indicates the commencement of the ECRP project.

In August 2014 the IfM building had a similar weekday peak-baseload ratio as the Gurdon Institute in 2011. The Gurdon Institute has undertaken many simultaneous initiatives ranging from behaviour change to equipment upgrades, and the combination of measures has to date resulted in an average 4.5% reduction in consumption year-on-year. Since the IfM building consumed 1,016,000kWh of electricity in 2013-2014, a 4.5% saving is equivalent to 45720kWh or £4600 in saved electricity costs for the first year alone (at the University rate of 10p/kWh). Although the IfM is a much newer facility than the Gurdon Institute, the existence of a large energy performance gap makes it reasonable to consider 4.5% energy saving reductions per annum.

A University of Cambridge research project called Joule@CL illustrates the potential of affordable, high resolution sub-metering through the use of Raspberry Pi micro-computers (Leslie 2014). The system is installed on the William Gates Building (considered to be a low energy building when constructed in 1999) and data collected is displayed online in real time using javascript. As seen in an extract from this online portal in Figure 28, the weekday peak-baseload ratio is 1.85. The potential therefore exists to continue to decrease baseload consumption in order to reach ratios of this magnitude, and likely higher, Acting upon POE-informed user feedback would provide a starting point from which to begin IfM energy saving initiatives.



Col…	Description	Start	End	Avg kW Selected	Avg kW Entire	Total Energy (kWh)
	Entire Building	Jul 2014	Jul 2014	191.29	188.40	46,347
	Logical Sum of Sub Meters	Jul 2014	Jul 2014	184.22	179.80	44,230
	Building Operations: Chiller	Jul 2014	Jul 2014	18.65	20.91	5,144
	Lighting	Jul 2014	Jul 2014	23.73	20.80	5,116
	Machine Rooms	Jul 2014	Jul 2014	54.45	54.76	13,472
	Sockets	Jul 2014	Jul 2014	45.73	43.41	10,680
	Miscellaneous	Jul 2014	Jul 2014	5.04	4.75	1,169

Figure 28. Joule@CL Energy Data Visualisation Tool for the William Gates Building (Leslie 2014).

4.5.2. Weekly and Seasonal Variation

Weekly and monthly/seasonal patterns of consumption can be plotted using the same approach as the daily data. For the weekly consumption, in Figure 29 below, the variability is again unexpectedly low considering the user interview finding that less than 5% of staff work on the weekend (Appendix 1).

A significant seasonal variation is observed in Figure 30 which is unexpected because the electricity does not provide heat to the building, and therefore should not fluctuate greatly due to changing seasons.

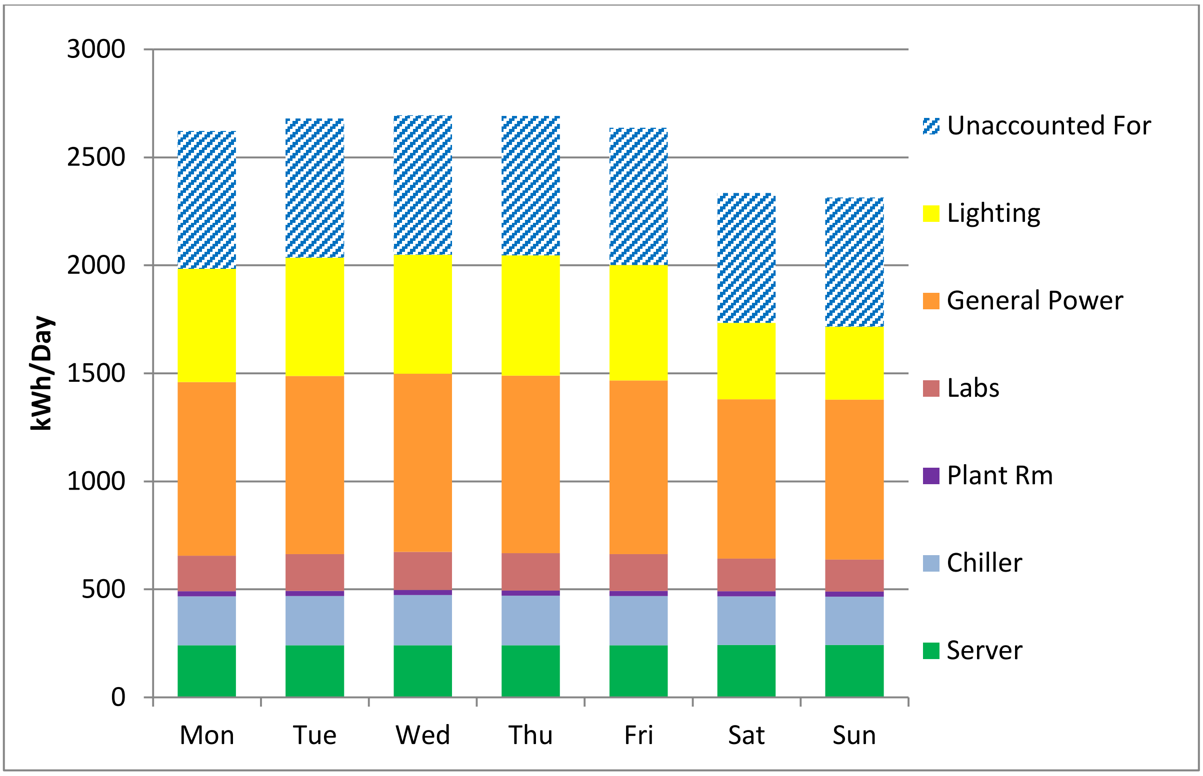


Figure 29. Weekly Sub-Meter profile.

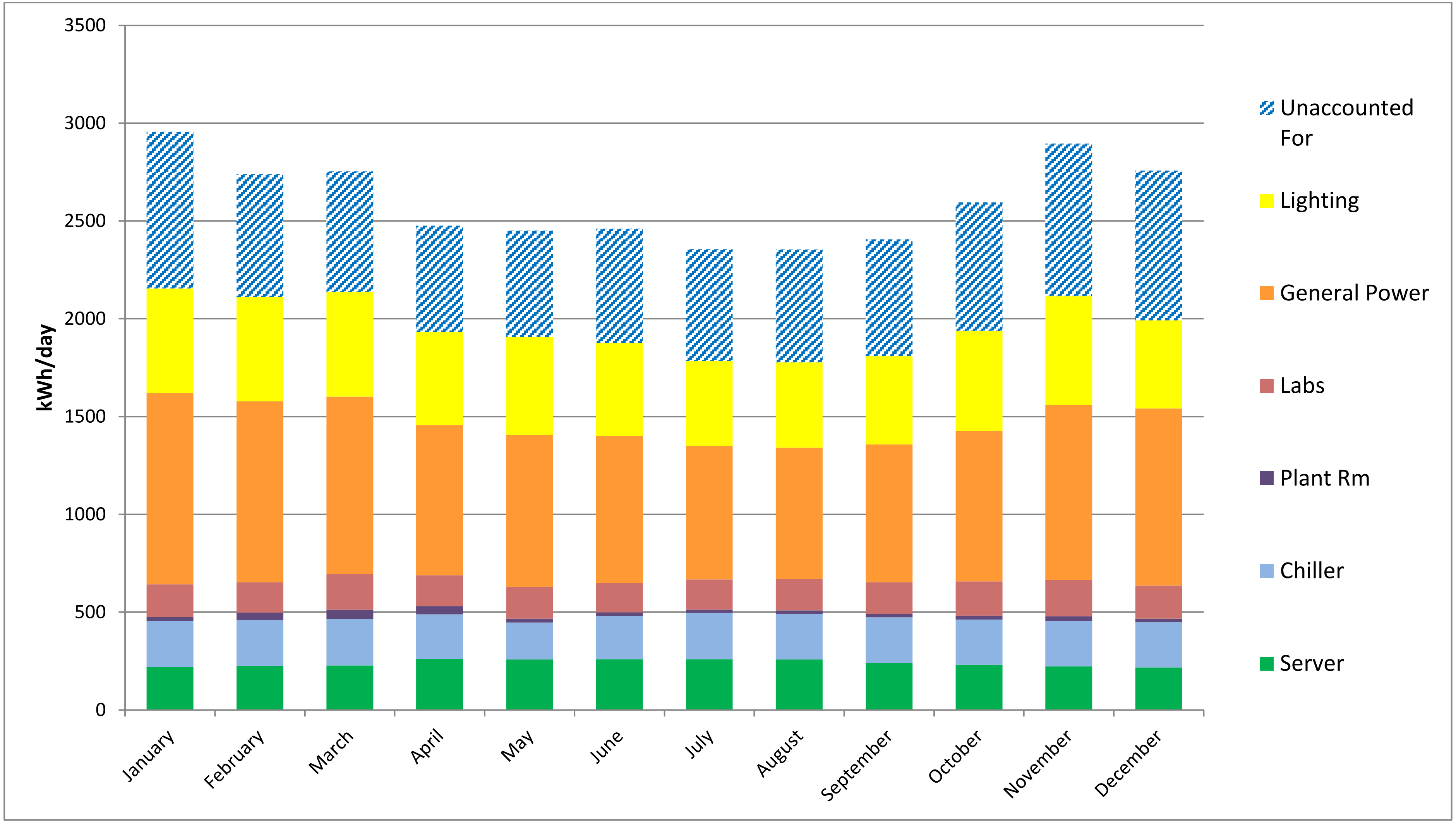


Figure 30. Seasonal Sub-Meter Profile

It is difficult to interpret the potential for energy saving actions from either the weekly or seasonal sub-meter profiles shown in Figure 29 and Figure 30. This is largely due to the poor end-use resolution available in the sub-metering. For the weekly sub-meter profile, lighting is the primary fluctuating variable (a reduction is observed during most out-of-hours times). This correlation should be especially strong for the IfM due to the installation of Person-In-Room lighting sensors in the open office areas (Clean Room Construction 2009).

In the seasonal sub-meter profile, a significant proportion of the variability is witnessed in 'General Power' which is presumably comprised mostly of plug loads such as computers and desktop appliances. However there is no further breakdown potential for general power provided in the metering schematic, distribution board diagram or electrical specification documents. This is a weakness of the implementation of the sub-metering implementation, as the room or exact end-use cannot be pinpointed for further investigation. There is also variability in the 'Unaccounted For' component of energy use across the seasons, which is higher in winter than summer. This could be the result of discretionary temperature linked equipment such as over-door heaters or portable radiators. Again, the lack of sub-meter resolution makes the determination of potential errors a source of great uncertainty when attempting to locate problems for further attention.

4.6. Biomass Heating Energy

Biomass is used as the primary heating source in the building whilst natural gas is used for hot water provision and back-up heating (Marriott Construction 2009). Heat is produced from the combustion of wood pellets in a 220kW biomass boiler, which is distributed through the building via a Low Temperature Hot Water (LTHW) radiator loop.

Whilst all of the IfM electrical sub-meters record data at half hourly intervals, the available data for biomass has much less precision. Historical delivery invoices for the wood pellets are available from SystemsLink, but have a variable frequency ranging from two weeks to three months (due to variable heating demand). The mass of delivered biomass (converted to kilowatt hours using the calorific value provided on the invoices) was used to assist the performance gap quantification in Section 4.1.1.

The biomass heating output is also measured with a variable temperature heat meter, which records the flow rate and temperature of hot water entering the LTHW circuit. This information is available only from manual readings of the BMS web interface (no provision is made to export BMS data into spreadsheets). Two years of heat meter data is available from the BMS with a recording frequency of every half hour, however due to the need to take manual readings, data was extracted for each month. In an interview with the building M&E project manager, heat meter readings were said to be unreliable and required legitimisation through comparison with invoice data.

After conversion to kWh, wood pellet invoice data as plotted using a three month moving average. This allowed seasonal heating consumption trends to appear, but to smoothed the highly variable delivery frequency. The graph of this comparison is displayed in Figure 31.

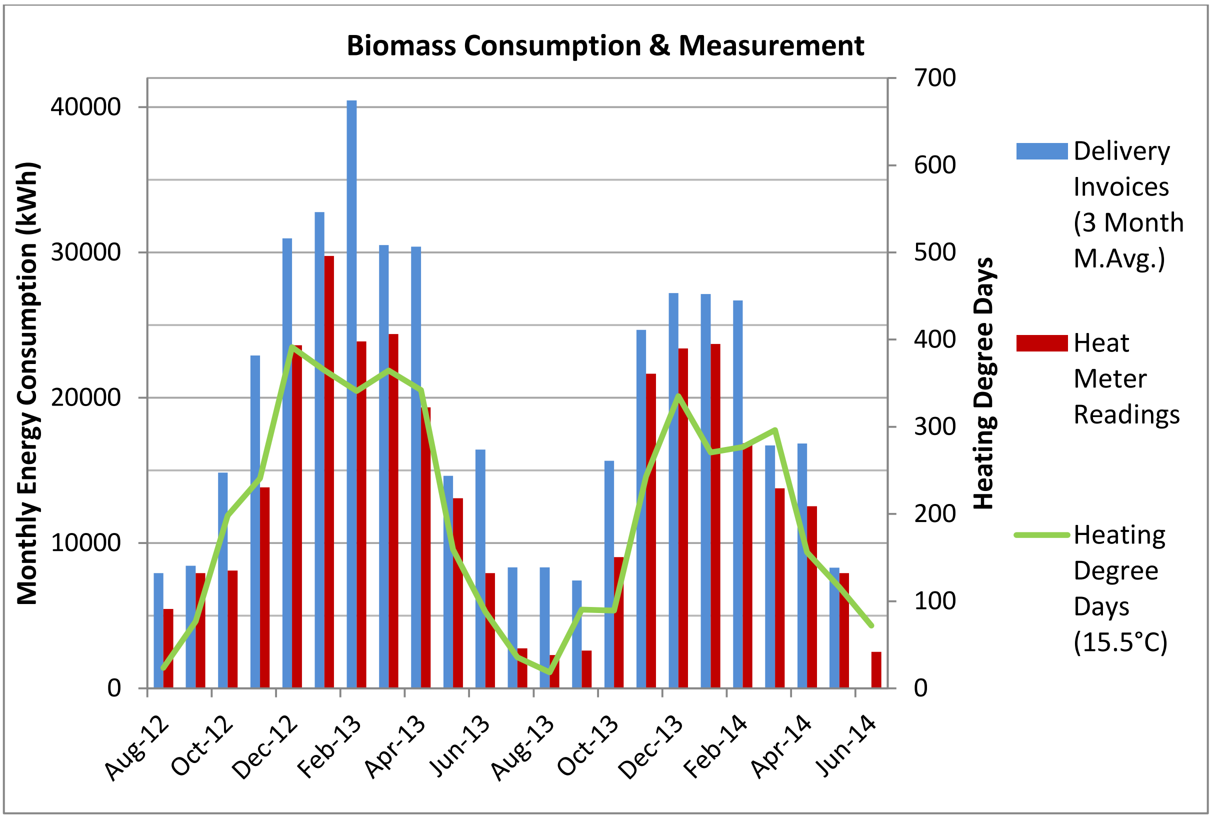


Figure 31. Biomass deliveries (calorific value) compared to heat meter readings.

The first observation that can be made from the comparison above is that there is a shortfall in the heat meter readings against the calorific value of the delivered biomass. Over the two year period there is an average difference of 29% which can be attributed to three main reasons:

- The combustion process has efficiency losses either equal to or greater than the stated efficiency of the boiler
- The heat meter does not accurately record heat flowing into the LTHW circuit
- The actual calorific value of the delivered biomass is less than the theoretical value (e.g. due to water ingress into pellet store)

The IfM's Herz BioMatic-220 boiler does not have a stated combustion efficiency in the operating manual or sales brochure, however a number of commercial installers of Herz biomass boilers in the UK suggest a typical efficiency range of 85-95% (Hamworthy 2012; Forest Fuels 2012; GreenWarmth 2007). This can account for approximately half of the shortfall highlighted above; leaving a 15% deficit that can be attributed to the other two reasons.

The second observation from Figure 31 is that for the two heating seasons represented; there was higher consumption of biomass in 2012-2013 than in 2013-2014. This is usually the result of variations in the weather between different years, and can be taken into account using Heating Degree Days (HDD), plotted in green. Heating Degree Days measure the difference between a base building temperature, (typically 15.5°C is used in the UK) and the exterior temperature over time, as shown by the shaded blue region in Figure 32 below (Carbon Trust 2012b). HDD weather data was for Bedford, the nearest available weather station to Cambridge with records of degree days (Oxford Environmental Change Institute 2014). Because the biomass consumption is solely used to heat the building, there should be a strong correlation between the consumption of biomass and the building's heating requirement.

Whilst HDD are useful as a powerful tool for assessing heating energy consumption, this research uses the HDD to affirm the relationship between weather and heating (Figure 31). This helps to eliminate other potential reasons for the difference in heating seasons (such as an extended period of inactivity in the biomass system).

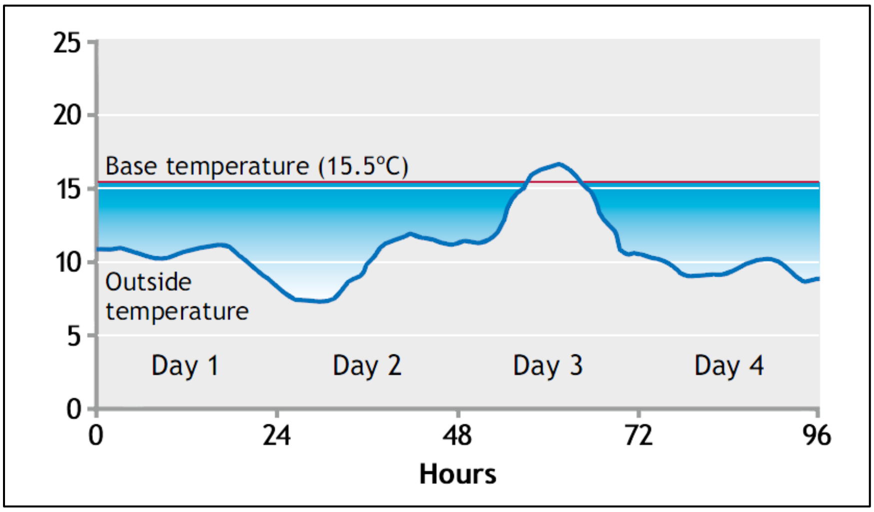


Figure 32. Heating degree days represent the summation of differences between exterior temperature and a baseline temperature (indicated by the shaded region) (Carbon Trust 2012b).

4.7. Gas Hot Water and Back-Up Heating

The gas meters, similar to electricity meters record data with a half-hourly sampling frequency. Unfortunately however the raw data from SystemsLink is very unclear, with significant unresolved and inconsistent discrepancies observed in the monthly totals for the 'direct' measured data compared to the invoice data. This made the available information unreliable. The gas consumption did not, however, warrant particular attention based on the ECON19 benchmarking to ECON19 in Figure 18 (actual usage between the typical and good practice consumption).

4.8. Soft Landings

The most notable of the Estate's sustainable design principles outlined in Section 3.3.1 was the adoption of the Soft Landings methodology. This has been a requirement since the Estate developed a customised Soft Landings Workplan in 2006 (Darwin Services & Way 2006). This approach was a contractual requirement for the IfM building development, and the first 12 months of Soft Landings meeting minutes were able to be critical evaluated against the EMBS Work Plan. A summary comparison of these two documents is presented in Table 2. The comparison revealed a poor match between the Soft Landings intentions and executed actions.

The minutes also reveal that the attendance at Soft Landings meetings is highly variable, with a range of 3 to 12 attendees per session (run two times per month initially and monthly or bimonthly thereafter). This is highly likely to be positively correlated with the agenda for any particular meeting, with higher attendance correlated with the perceived importance of the meeting. The first two meetings and the one year Soft Landings review meeting had the highest meeting attendance, further supporting the above statement. This suggests that the Soft Landings process was not treated as a priority amongst the designers and contractors at the IfM.

Table 2. Comparison of Soft Landings Work Plan requirements and Meeting Minutes in the first year after Practical Completion

Key Deliverables	**Details (Design Intent)**	**Observations from Minutes**	**Compliance**
Pre-Handover Stage	**Before user occupancy**		
Commissioning time.	Commonly an area that gets compressed in the interests of time constraints.	The commissioning report is an item on every meeting agenda, and with a few exceptions where the re-testing and replacement of failed equipment is required, the commissioning phase appeared to be well executed.	Good
Training programme for FM staff.	To ensure that FM staff are adequately prepared for post-handover.	Training from specialist installers such as Chubb (security systems) and Clean Room Construction (laboratories) arranged.	Good
BMS demonstration for FM staff.	Demonstrate key facilities and trend logging to allow for future reviews of the actual performance and fine-tuning of systems.	BMS training discussed from June meeting minutes and scheduled for October. Minutes after October continue to state that BMS training is outstanding.	Poor
User migration planning.	Design team to assist mitigate the impact of any ongoing site activities with incoming user requirements.	No evidence	N/A
Arrange aftercare team 'home.'	Aftercare team required to assist with issues in the first weeks of occupation, and should be seen by occupant from an accessible 'home' from the beginning of occupation.	A semi-permanent aftercare team home is not discussed, and meetings are held on an infrequent basis in different rooms.	Poor
Compile Building User Guide.	To help building users to better understand and operate the building efficiently as envisaged by the design team.	Draft version of the Building User Guide is circulated and Arup to update with feedback, however this item remains outstanding at every subsequent meeting.	Poor

Operations and Maintenance (O&M) Manual Review.	Verify content of O&M guidance to ensure completeness.	Discussed at length, and scope expanded to include the work of sub-contractors.	Good
Early Aftercare Stage	**Immediately post-occupancy for 4-8 weeks**		
Provide Resident on-site attendance.	To respond to a spot emerging issues. Expectation to be in attendance 1-2 days per week.	No mention of regular attendance planned during the occupancy phase-in. Additional meetings scheduled in response to particular issues that require resolution.	Poor
Building user guidance.	Provide focus group meetings with new users to disseminate building operation information.	No evidence	Poor
Technical guidance.	To allow for smooth transition to operation by client's FM team.	Training from pre-occupancy phase appears to cover the specialised technical information handover.	Good
Communications and walkabouts.	To encourage feedback and observe occupation usage	No evidence	N/A
Aftercare Remainder Year 1	**After the 'Early Aftercare Stage' until 1 year post-completion**		
Aftercare review meetings.	Continue to have designer and constructor presence in monthly Soft Landings Meetings.	Meetings continue to be held on site after occupancy commences and official opening occurs.	Good
Log and review energy usage.	Provide comparison against energy targets and assist fine tuning.	BMS data manually read prior to datalink establishment to Laundry Farm, where all BMS data is managed. Energy targets are not mentioned.	Poor
Fine tune systems and make records	To adjust for seasonal change as necessary, and make notes of any	Seasonal commissioning scheduled for August as part of preventative maintenance. Records from this are not	Poor

including usage changes	changes to system operation in the building logbook.	kept in the logbook or mentioned in later minutes.	
Commission Occupant survey	Independent survey of occupant overall satisfaction	No mention of formal survey. Instead general opinions of some user representatives are used (not independent).	Poor
Year 1 review	To review overall building performance and collate information from first year of Soft Landings	No evidence, however the meeting records cease in January, 10 months after practical completion.	N/A

4.9. Post Occupancy Evaluation

A supplementary document to Soft Landings related to the building's Post-Occupancy Evaluation. The report features only one half of an A4 page regarding 'Feedback from users and problems post completion,' with highly informal consultation of a small number of user representatives, and no mention of concerns with building operation. The report did not detail a structured methodology despite the guidance provided in the University's own Soft Landings Work Plan (Darwin Services & Way 2006) and academic literature (Bordass & Leaman 2005; Way & Bordass 2005). The highly positive findings of the report may have been the result of the building project managers performing the survey on a select group of users rather than appointing an independent assessor, as recommended by the guidance documents from the University.

4.10. Data limitations from the Case Study Approach

Despite notionally having five years of operational energy performance data, the IfM facility had significant gaps in sub-metered electricity data, impeding the ability to perform detailed quantitative analysis guided by TM22:2012. Figure 33 and Figure 34 illustrate the concerns with electrical sub-meter data, whilst Section 4.7 has already highlighted the problems with gas meter readings.

Date	16:00	16:30	17:00	17:30	18:00
24/08/2013	0	0	0	0	0
25/08/2013	0	0	0	0	0
26/08/2013	0	0	0	0	0
27/08/2013	0	0	16409.9	0.09375	0.0625
28/08/2013	0.09375	0.0625	0.09375	0.0625	0.09375
29/08/2013	0.0625	0.09375	0.0625	0.09375	0.0625
30/08/2013	0.0625	0.0625	0.09375	0.09375	0.0625
31/08/2013	0.09375	0.0625	0.09375	0.0625	0.0625

Figure 33. A sample of consistent outliers in SystemsLink Sub-Meter Profile Data. These errors are replicated in all electrical Sub-Meters for the same dates and times.

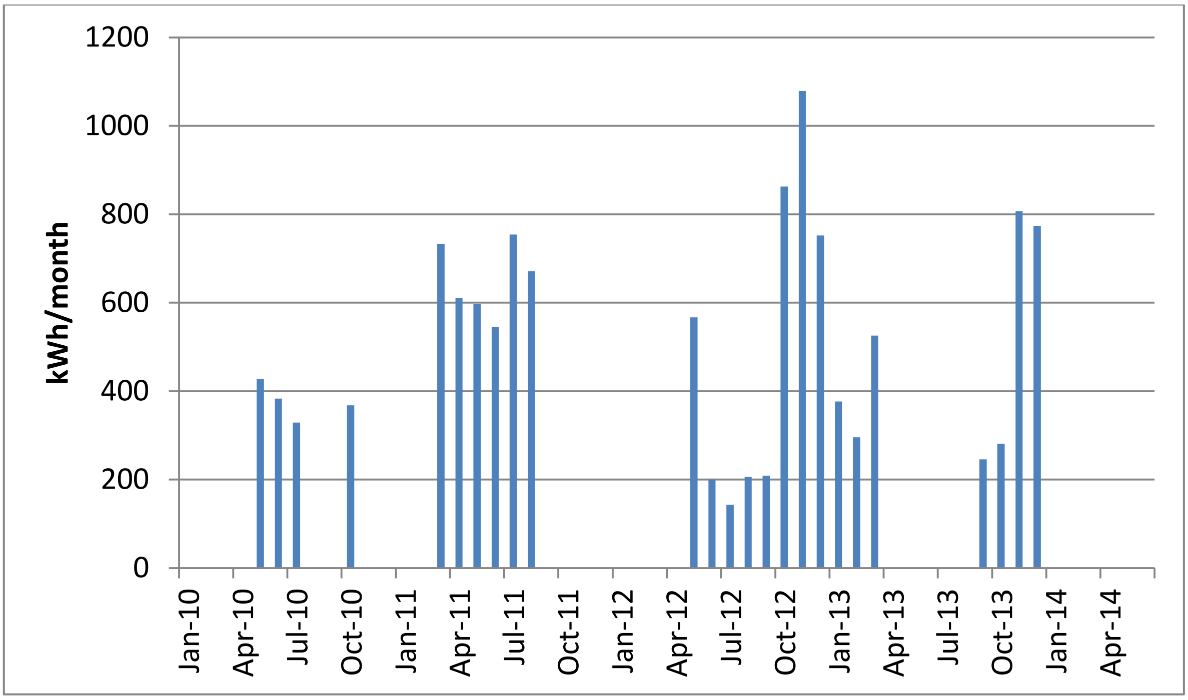


Figure 34. Data Availability for SM02: Distributed Information Automation Laboratory.

Whilst a significant number of building development documents were made available through the Living Lab and EMBS, some information remained unobtainable, such as the IESVE Dynamic Simulation Model developed for the creation of the IfM EPC (McKerrow 2009). The model was withheld by the consultants who performed the analysis, which limited the full utilisation of the TM54 methodology.

Lastly, IfM building has a legislated Air-Conditioning Certificate and Report required in parallel with an EPC and DEC. The report makes comments on the management of the building, and highlighted that the building exhibits poor records keeping with many of the expected maintenance logs missing or empty (Graham 2013).

Chapter 5

"No industry owning capital equipment of a similar cost to buildings could survive unless it had more data on performance"

(Markus & Building Performance Research Unit 1972)

Recommendations

5.1. Micro-level Recommendations: Institute for Manufacturing

The analysis of the operational performance of the IfM building has uncovered a number of building-specific problems. These relate to a lack of requisite documentation and problems with energy consumption data.

5.1.1. Building User Guide

The Soft Landings minutes for the IfM building showed that a draft Building User Guide (BUG) was created but never finalised and distributed (Table 2). Additionally, the distribution of a BUG to building occupants was an awarded credit point in the BREEAM Excellent certification received by the IfM building, however none of the 13 surveyed building occupants were aware of this document (Marsden 2009). As the name suggests, this document is tailored to meet the needs of users, providing guidance on building operation to ensure thermal comfort and efficient use. Thus the operation of the IfM building is presently poorly understood by many building occupants, a finding supported by interviews (Appendix 1).

The development and distribution of a BUG would hence be highly recommended for improving user engagement and understanding of the building. The distribution of building guidance to all IfM occupants is important for ensuring energy efficient operation, particularly in the context of the manually operated naturally ventilated spaces (Marriott Construction 2009). Upon finalisation, the document should be included in the induction procedure for incoming staff and students, together with making a copy available to all the present building users.

5.1.2. Display Energy Certificate

The prominent display of a verified DEC (updated annually) is a legislated requirement for public buildings larger than 500m^2, and is a verifiable and familiar form of building energy benchmarking (Figure 1). The IfM's lack of DEC was confirmed through searches of the public Non-Domestic Energy Performance Register and in conversations with EMBS staff and building occupants

When implemented and updated each year, the DEC will reveal the trends in energy consumption over time and provide building occupants with information on their facility's energy performance. This would also form a verifiable means through which performance-based certification and building design can occur (Tweddell 2014).

5.1.3. Sub-Meter Data

Sub-meter tiers provide redundancy in metering, allowing for verification of energy consumption (Section 4.4). The IfM tiers exhibit a large mismatch in energy consumption suggesting that there are systemic problems with metering installation and commissioning (Figure 24). The issue requires resolution in order to more accurately account for energy consumption, particularly that which is presently 'unaccounted for.'

Approximately half of all sub-meter data is missing from the half hourly 'profile download' function in SystemsLink (Figure 34). In addition, the imprecise labelling of the IfM metering schematic prevented the pinpointing of potential problem areas as not all end-uses could be benchmarked to the resolution available in ECON19 (particularly 'general power'). The recommendation to improve sub-metered data resolution and amend metering errors echo findings from both the available past dissertations on the University's BREEAM buildings (Lee 2014; Norris 2014).

5.2. Macro-level Recommendations: Estate Management and Building Service

5.2.1. Implementation of Estate Policy

The present Soft Landings policy used by the EMBS dates from 2006 and the BSRIA has significantly advanced the available guidance since this time (Usable Buildings Trust et al. 2014). It is important not only that policy is up-to-date however, but that it is well implemented. The findings from the implementation of Soft Landings on the IfM building (Table 2) show that very little of the design intentions are well executed in reality. This is particularly the case for Post-Occupancy Evaluation (POE), which needs to be independently performed using formalised approaches from the Usable Buildings Trust or other sources (Bordass & Leaman 2005).

The effectiveness of Soft Landings is not widely published in the academic literature. However the UK Cabinet Office was at the time of writing developing an implementation plan for Government Soft Landings (GSL), for application to all government built assets (Rowland 2014). The key features of GSL and Soft Landings are very similar, so the widespread deployment of this methodology to the public sector building stock will allow for future indexing of EMBS Soft Landings implementation. It is therefore recommended that EMBS revises the Soft Landings Work Plan in line with GSL and produces an action plan for the improvement of policy execution in the University building development process. This will need to include EMBS staff training, consultation with BSRIA and GSL and potentially financial incentive mechanisms for best practice implementation.

5.2.2. Revision of Design Guidance for the University Estate

The EMBS Design Guide for new buildings presently stipulates that BREEAM Excellent ratings are targeted in any new construction development. However the energy performance of University BREEAM certified buildings remains poor (Figure 21). This is largely due to a lack of focus on operational energy performance in the design brief (de Wilde 2014).

The Building Research Establishment (BRE) developed BREEAM In-Use in 2009, partly in response to the lack of energy performance verification. The scheme's purpose is to provide "a consistent and credible means of determining the impact and performance of their buildings, and determining areas for improvement" (Summerson et al. 2012).BREEAM In-Use is amongst a number of initiatives being proposed to link a rating to the energy performance of the building in operation. LEED Existing Buildings in North America is a similar operational rating scheme whilst Passivhaus has revolutionised the development of low-energy domestic (and increasingly non-domestic) buildings in continental Europe.

This study recommends that the EMBS reviews its Design Guidelines in line with the burgeoning literature on operational performance-based rating schemes. In conducting this review, it will be necessary to consider how the attainment of certain levels of operational performance can be written into building contracts.

5.2.3. Facilities Management

Observations of the EMBS approach to energy management points strongly to a correlation between the motivation of key departmental staff and realised energy savings. In particular, this was observed for the Gurdon Institute where initiatives taken by the facilities manager and upper departmental managers has greatly impacted the success of energy saving measures (University of Cambridge Estate Management 2014a). Interviews with EMBS staff and the IfM facilities manager indicate that there is little focus on energy savings in the IfM building. This is the result of the large number of remits required of these staff. The staff are then generally highly reactive to the numbers of complaints or alarms, since there is a chronic lack of manpower in the facilities management profession (McClurg 2013).

The result of facilities management being placed under time pressure is that energy performance is not prioritised in daily work schedules, which is a requisite condition to find and implement energy savings. To avoid tasking time-poor facilities staff with additional remits, it is proposed that extra staff could be employed in the Estate's Building Maintenance Unit, who already manage the maintenance aspects of BMS systems for the University Estate. The specialised knowledge of such staff would allow quick identification of unusual energy trends and resolution through a centralised maintenance team.

5.2.4. Capitalising upon Energy Data

One of the principle findings from research into the IfM building has been that the EMBS does not capitalise fully upon the presently available energy data to assess building energy performance. Whilst Key Performance Indicator reports are created to compare estimated and actual consumption during the three year post completion period, there is no reporting at the sub-meter level or temporal data analysis of main energy meters.

This research demonstrates the potential however for the use of this data in real time feedback of energy consumption trends to users and detailed reporting against University-specific benchmarks and targets. The analysis revealed how a peak-baseload differential can be used as a simple diagnostic indicator for building energy performance (4.5.1). If the sub-metering resolution is improved in line with the earlier recommendations, the energy analysis potential can extend to cover the approaches outlined by TM22:2012 and TM54 amongst many others.

Chapter 6

Conclusion

Despite the recent proliferation of aspirationally sustainable building designs, the actual energy consumption of ostensibly 'green' non-domestic buildings is generally little better and sometimes worse than the building stock average. The metered energy use of non-domestic buildings is typically 1.5 to 5 times greater than designer estimates, resulting in a phenomenon known as the 'energy performance gap.'

6.1. Review of Objectives

The overarching goal of this research was to see how a building management team can utilise readily available data to reduce the energy performance gap in their building portfolio. This study applies techniques from the field of Building Performance Evaluation on the University of Cambridge Institute for Manufacturing (IfM) building in order to address this goal. The specific research objectives that stem from this, in the context of the case study building were:

1. Determine the underlying causes of the energy performance gap.

Using designer energy estimates, energy consumption benchmarks and sub-metered data, Sections 4.1 to 4.3 were able quantify and explore the performance gap of the IfM. The research demonstrated that much of the performance gap is attributable to design-stage optimism bias and a lack of rigorous means to report energy performance (Section 4.2). The Estate Management needs to revise its design guidance for sustainable buildings to ensure that operational energy performance is prioritised in future building works, as outlined in Section 5.2.2.

2. Analyse energy consumption data to determine opportunities for Estate Management to optimise building energy performance.

Detailed analysis of the metered electricity end-uses and biomass consumption revealed significant amounts of temporal data are automatically logged (Sections 4.4

to 4.6). Comparison of the energy use trends with well managed buildings in the Estate revealed the magnitude of energy optimisation potential for the IfM (Section 4.5). This research highlights the utility of available data in Section 5.2.4, despite the problems associated with data quality and capture (4.10). These data issues were demonstrated to be the result of systemic problems with the sub-metering 5.1.3, resolution of which will enable the use of advanced energy estimation methodologies, as shown in Section 3.5.

3. **Critically evaluate the Estate Management building development and management policy and the effectiveness of its implementation.**

The first research objective highlights already the need for a review of design guidelines produced by the Estate. Evaluation of policy implementation for the IfM building development process revealed that the Estate's design intent was poorly executed (Section 4.8). This research proposes that the Estate reviews contractual agreements made with third party building service providers to ensure best practice implementation (5.2.1). The Estate's building management approach was found to rarely address concerns with energy performance in the IfM, hence a renewed approach is proposed to improve the impact of the Estate's energy management remit (5.2.3).

6.2. Recommendations for Future Research

The time constraints of this research resulted in data limitations which inhibited the use of CIBSE's TM54 methodology for design stage energy estimation. Dynamic simulation models for building energy prediction are frequently created for the production of statutory Energy Performance Certificates, so future research in this area should start with attempts to source these models. Modelling can also be performed independently provided specifications for building envelope construction and mechanical and electrical plant are available.

Future work should also focus upon how energy consumption data analysis can be standardised and automated, such that the human task of managing the energy performance of a building portfolio is more manageable. An update to CIBSE's TM22 for building energy assessment and reporting is expected to be publically released by 2015, which could begin to inform how energy data can be systematically analysed.

Appendix 1: Semi- Structured Interview Findings

Theme	Role	Finding	Positive/ Negative
Labs	Researcher	Out-of-hours use not permited	P
	Researcher	10% utilisation 9-5pm	P
	PhD	Energy use not very high because short usage hrs	P
	PhD (former)	Energy use not very high because short usage hrs	P
	Researcher	Temperature sensitive equipment: constant A/C	N
Migration	Researcher	May 09 until Aug 09	-
	IfM Admin	Photonics moved in May, 1st half IfM June, 2nd half IfM July, new MET students October	-
Occupancy	PhD	150 people estimate total. Actual figure ≈ 330.	P
	PhD	50% occupancy estimate typical day	P
	Researcher	Computers frequently left on 24/7	N
	Researcher	Lights often on all weekend	N
	Researcher	Person In Room sensors unreliable	N
	PhD (former)	Late night and weekend use common but ≤ 5% occupied	N
	Researcher	Out of hours 'Quite a lot' but very troublesome to know (Chubb security)	N
	IfM Admin	14% increase in staff May 09 to Dec 13 (291 to 332)	N
	PhD	High occupant turnover (phd-3yr, research 1-2yr, lect 5-10yr, admin 5-10yr)	N
Operation	Researcher	Battery powered light switches do not work	N
	PhD	Complex, unlabelled or user-unfriendly controls (lights)	N
	Researcher	No Building User Guide	N
	Researcher	No Building User Guide	N
	PhD	No Building User Guide	N
	IfM Admin	No Building User Guide	N
	IfM Admin	No Building User Guide	N
	PhD	No Building User Guide	N
	IfM Admin	No time for energy performance evaluation in FM	N
	EM Energy	Energy not a priority for FMs	N
	EM Energy	Energy not a priority for FMs	N
	Buildings Specialist	FMs reactionary to alarms	N

Continued overleaf

Operation (cont.)	IfM Admin	Stays for Nat. Vent. window box openers all broken	N
	IfM Admin	Summers can be uncomfortably warm	N
	PhD	Automatic high level windows let in the rain	-
Energy	EM Energy	EIS makes the energy costs relevant to departments	P
	Buildings Specialist	ECRP funds retrofits. EIS provides money incentive	P
	EM Energy	DEC is unpublished. Seeking approval.	N
	PhD	IfM is a tenant of EMBS. Doesn't pay the direct energy bill	N
	IfM Admin	Reluctant to share information on equipment energy consumption	N
	PhD	EPC in building, no DEC seen.	-
	IfM Admin	EPC in building, no DEC seen.	-

Bibliography

Better Buildings Partnership, 2012. Display Energy Certificates. Available at: http://www.betterbuildingspartnership.co.uk/working-groups/sustainability-benchmarks/display-energy-certificates/.

Bordass, B. et al., 2001. Assessing building performance in use 3: energy performance of the Probe buildings. *Building Research & Information*, 29(2), pp.114–128.

Bordass, B. & Leaman, A., 2005. Making feedback and post-occupancy evaluation routine 1: A portfolio of feedback techniques. *Building Research & Information*, 33(4), pp.347–352.

Bunn, R., 2014. BSRIA Soft Landings - The Level 1 Course. Professional Development Training Course.

Bunn, R., 2010. *Building Performance Evaluation. An £8 million research programme by the Technology Strategy Board*, Available at: https://www.bsria.co.uk/download/asset/bpe-presentation-tsb-funding.pdf.

Burman, E. et al., 2012. Performance Gap and Thermal Modelling: A Comparions of Simulation Results and Actual Energy Performance for an Academy in North West England. In *Building Simulation and Optimization Conference, Loughborough, UK*. pp. 35–42. Available at: http://www.ibpsa-england.org/resources/files/bso-2012/1B2.pdf.

Carbon Trust, 2012a. Closing the Gap. Lessons learned on realising the potential of low carbon building design. Available at: https://www.carbontrust.com/media/81361/ctg047-closing-the-gap-low-carbon-building-design.pdf.

Carbon Trust, 2012b. Degree days for energy management. Available at: http://www.carbontrust.com/resources/guides/energy-efficiency/degree-days.

Carbon Trust, 2003. Energy Consumption Guide 19 - Energy use in offices. , pp.1–24. Available at: http://www.energybenchmarking.co.uk/Offices/ECON19reprintMarch03.pdf.

CarbonBuzz, 2014. Evidence for the Performance Gap. Available at: http://www.carbonbuzz.org/evidencetab.jsp.

Cheshire, D. & Menezes, A.C., 2013. *CIBSE TM54: 2013. Evaluating operational energy performance of buildings at the design stage*, The Chartered Institution of Building Services Engineers London.

Churcher, D., 2011. Building Performance Evaluation - Summary Report. , 27(1), pp.1–24. Available at: https://connect.innovateuk.org/web/building-performance-evaluation/article-view/-/blogs/bpe-summary-report-edition-1-;jsessionid=80D6E7AE2DA49F4F184983E9A3976014.1?p_p_auth=HvAj4uZx.

Clean Room Construction, 2009. Institute for Manufacturing Mechanical and Electrical Specification, Internal University of Cambridge Report.

Cohen, R. et al., 2001. Assessing building performance in use 1: the Probe process. *Building Research & Information*, 29(2), pp.85–102.

Cohen, R., 2013a. *The performance gap in non-domestic building : Evidence collected from the Technology Strategy Board's Building Performance Evaluation Programme*, Available at: http://www.greenconstructionboard.org/images/stories/pdfs/performance-gap/CPG Evidence Base from BPE Final Report 05Mar13_.pdf.

Cohen, R., 2013b. TSB BPE: Reporting Non Domestic Building Energy Performance after a TM22 Analysis. , (September), pp.1–8. Available at: https://www.innovateuk.org/documents/3270542/3713333/Reporting+Non-Domestic+Building+Energy+Performance+based+on+a+TM22+Analysis/28915f01-be79-4e8c-817a-41bc13580ea0.

Cohen, R., 2014. Understanding the opportunity and countering the barriers. In *Ecobuild 2014*. pp. 1–15. Available at: http://www.ecobuild.co.uk/files/rr__4_mar__10.45__robert_cohen.pdf.

CP Creative, 2014. Example Commercial Energy Performance Certificate. Available at: http://www.cpcreative.co.uk/wp-content/uploads/example_commerical_epc.pdf.

Darwin Services & Way, M., 2006. Estate Management and Building Service Soft Landings Workplan, Internal University of Cambridge Report, pp.1–17.

DCLG, 2012. *Improving the Energy Efficiency of Our Buildings. A guide to the energy performance certificates for the construction, sale and let of non-dwellings.*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/50268/A_guide_to_energy_performance_certificates_for_the_construction_sale_and_let_of_non-dwellings.pdf.

DECC, 2014. *The Non-Domestic National Energy Efficiency Data Framework (ND-NEED)*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/314725/non_domestic_need_framework.pdf.

DEFRA, 2014. Greenhouse Gas Conversion Factors. Available at: https://consult.defra.gov.uk/climate-change/ac04ad33.

European Commission, 2013. *EU Energy in Figures. Statistical Pocketbook 2014.*, Luxembourg. Available at: http://ec.europa.eu/energy/publications/doc/2014_pocketbook.pdf.

European Parliament, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings. , 1(May 2010), pp.1–16.

Field, J., 2008. *CIBSE TM46: 2008. Energy Benchmarks.*, The Chartered Institution of Building Services Engineers London.

Forest Fuels, 2012. Fuel Price Comparison - Biomass Installations. Available at: http://www.forestfuels.co.uk/about-wood-fuel/fuel-price-comparisons.

Graham, D., 2013. *Institute for Manufacturing Air Conditioning Inspection Report (RRN: 9319-5001-0978-0400-5301)*, Available at: https://www.ndepcregister.com/.

GreenWarmth, 2007. Biomass Wood, Pellet & Chip Boilers. Available at: http://www.greenwarmth.co.uk/biomassboilers.asp .

Grozeva, I., 2013. *Sustainable Design Guidelines for the University of Cambridge*, Available at: http://www.iaruni.org/images/stories/Sustainability/Sustainability_Fellowship_Reports/2013_Grozeva_Ivelina_Report.pdf.

Hamworthy, 2012. Hamworthy Herz BioMatic Biomass Boilers (BM-U Series). , pp.1–20. Available at: http://www.hamworthy-heating.com/Shared/Files/Hamworthy-Biomass-BioMatic-500002587A.pdf.

IEA, 2014. Frequently Asked Questions - Energy efficiency. Available at: http://www.iea.org/aboutus/faqs/energyefficiency/

IPCC, 2014. Summary for Policy Makers: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Mitigation of Climate Change. , pp.1–31. Available at: http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf.

Katz, A., 2012. USGBC Green Building Facts. Available at: http://www.usgbc.org/articles/green-building-facts

Lee, S.M., 2014. *Energy Performance Analysis of the Sainsbury Laboratory*. Undergraduate thesis, University of Cambridge.

Leslie, I., 2014. Joule - An Energy Data Visualisation Tool from the C-Aware Project. Available at: http://www.cl.cam.ac.uk/meters/tools/wgb-vis/current/#

Liddiard, R., Wright, A. & Marjanovic-halburd, L., 2008. A Review of Non-Domestic Energy Benchmarks and Benchmarking Methodologies. Available at: http://www.ucl.ac.uk/carb/pubdocs/CP-DMU-10-IEECB08-ReviewNDBenchmarks-2008-RL-LMH-AJW.pdf.

Lillicrap, C. & Das Bhaumik, C., 2014. How to avoid the “Performance Gap” between Design Predictions and Operational Energy Use. Professional Development Workshop for CIBSE TM54, pp. 1–53.

Macintosh, S. & Pugh, R., 2007. University of Cambridge Institute for Manufacturing Stage D Report by Arup Associates, pp.1–64, Internal University of Cambridge Report.

Markus, T.A. & Building Performance Research Unit, 1972. *Building Performance*, London: Applied Science Publishers.

Marriott Construction, 2009. *L2 Building Log Book - Alan Reece Building*, Internal University of Cambridge Report.

Marsden, K., 2009. *Final BREEAM Certification Report IfM Building Cambridge*, Internal University of Cambridge Report.

McClurg, C., 2013. *Bridging the Gap Between the Design and Delivery of Sustainable Buildings. Using Maintenance Tickets to Create a Data-Driven Feedback Loop*. Master Thesis, University of Cambridge.

McKerrow, H., 2009. *Institute for Manufacturing Energy Performance Certificate (RRN 0510-0931-9300-2022-4006)*, Available at: https://www.ndepcregister.com/home.html.

Menezes, A.C. et al., 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97, pp.355–364.

Newsham, G.R., Mancini, S. & Birt, B.J., 2009. Do LEED-certified buildings save energy? Yes, but…. *Energy and Buildings*, 41(8), pp.897–905.

Norris, T., 2014. *Bridging the gap between designed and real consumption: What can the University of Cambridge teach us about energy reporting and monitoring?* Undergraduate thesis, University of Cambridge.

Oxford Environmental Change Institute, 2014. Daily Degree Days for Energy Management. Available at: http://www.eci.ox.ac.uk/research/energy/degreedays-weekly-daily.php

Rowland, D., 2014. Government Soft Landings Explained. In *Ecobuild 2014*. Available at: http://www.ecobuild.co.uk/files/bp__5_mar__12.30__deborah_rowland.pdf.

Summerson, S., Atkins, J. & Harries, A., 2012. *Briefing Paper. BREEAM In-Use. Driving sustainability through existing buildings*, Available at: http://www.breeam.org/filelibrary/BREEAM In Use/KN5686---BREEAM-In-Use-White-Paper_dft2.pdf.

Sunikka-Blank, M. & Galvin, R., 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information*, 40(3), pp.260–273. Available at: http://www.tandfonline.com/doi/abs/10.1080/09613218.2012.690952

Sutherland, G. et al., 2013. *Implementing the Energy Performance of Buildings Directive. Featuring Country Reports 2012.*, Available at: http://www.epbd-ca.org/Medias/Pdf/CA3-BOOK-2012-ebook-201310.pdf.

The Institute for Manufacturing, 2009a. About the Institute for Manufacturing. Available at: http://www.ifm.eng.cam.ac.uk/aboutifm/.

The Institute for Manufacturing, 2009b. Royal opening for IfM's Alan Reece Building. Available at: http://www.ifm.eng.cam.ac.uk/news/royal-opening-for-ifms-alan-reece-building/#.U-S5ofldV1a

Tweddell, T., 2014. How to procure a DEC A building. In *Ecobuild 2014*. Available at: http://www.ecobuild.co.uk/files/bp__6_mar__14.15__tamsin_tweddell.pdf.

University of Cambridge, 2008. The design and construction of environmentally sustainable new buildings. Available at: http://www.environment.admin.cam.ac.uk/resource-bank/guidance-documents/design-and-construction-environmentally-sustainable-new-buildings#heading1.0

University of Cambridge Estate Management, 2013a. Design and Standards Brief for University Services and Construction Works.

University of Cambridge Estate Management, 2014a. Gurdon Institute pilot energy saving scheme hits major milestone. Available at: http://www.environment.admin.cam.ac.uk/resource-bank/case-studies/energy-and-carbon-reduction/pilot-energy-saving-scheme-hits-major

University of Cambridge Estate Management, 2013b. IfM Energy Key Performance Indicators, Internal University of Cambridge Report

University of Cambridge Estate Management, 2014b. Living Laboratory for Sustainability. Available at: http://www.environment.admin.cam.ac.uk/getting-involved/living-laboratory-sustainability

Usable Buildings Trust, Way, M. & Bunn, R., 2014. *The Soft Landings Framework - for better briefing, design, handover and building perfomance in-use*, Available at: http://usablebuildings.co.uk/UBTOverflow/SoftLandingsFramework.pdf.

Way, M. & Bordass, B., 2005. Making feedback and post-occupancy evaluation routine 2: Soft landings – involving design and building teams in improving performance. *Building Research & Information*, 33(4), pp.353–360.

De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41, pp.40–49.

Woods, J., 2011. Department of Engineering Institute for Manufacturing Post Occupancy Evaluation, Internal University of Cambridge Report.

Woods, J., 2009. *IfM Practical Completion Report*, Internal University of Cambridge Report