Understanding Unregulated Energy Use in University Buildings

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Common terms abbreviations

- **CDD** - Cooling Degree Days
- **CHP** - Combined Heat and Power
- **DB** - Distribution Board
- **EMS** - Energy Management Systems
- **EUI** - Energy Use Intensity
- **GIA** - Gross Internal Area
- **Guide F** - Refers to the document “Energy Efficiency in Buildings: CIBSE Guide F”.
- **HDD** - Heating Degree Days
- **HVAC** - Heating, Ventilation and Air Conditioning
- **MELs** - Miscellaneous Electrical Loads
- **NIA** - Net Internal Area
- **Part L** - Refers to a series of governmental documents, titled “Approved Document Part L”.
- **POE** - Post-Occupancy Evaluation
- **TM54** - Refers to the document “CIBSE TM54”.

University name abbreviations

- **AU** - Aston University
- **MMU** - Manchester Metropolitan University
- **NT** - Nottingham Trent University
- **UoM** - The University of Manchester
- **UoS** - The University of Sheffield
- **UoR** - The University of Reading

Terminologies

- **Three-phase (or 3-phase) equipment** – A type of equipment that has three live wires, allowing for a constant current. Three-phase equipment is typically hardwired into buildings, and most large laboratory equipment will be three-phase.
- **Building Regulatory Standards** – A series of UK government-mandated building requirements set in various documents. These include the "Approved Document Part L" (Part L) documents and can be applied to both new and existing buildings.
- **Energy Use Intensity (EUI)** – A measurement of a building's total energy use relative to the building's gross square footage. It can also be referred to as energy per square foot per year. Typically, it is not used frequently within UK building-related studies. Instead, $kWhm^{-2}$ per annum is the primary measurement most studies will use.
- **Gross Internal Area (GIA)** – Refers to total building space per m^2. No spaces within the building are excluded from these calculations (for example, non-useable balance spaces are included).
- **Heating, Ventilation and Air Conditioning (HVAC)** – A common umbrella term used to discuss building-level electrical consumption. HVAC can also be referred to as regulated energy.
- **Net Internal Area (NIA)** – Useable building space per m^2. This is similar to GIA; however, balance spaces and server rooms are excluded from this calculation. This measurement is best used to calculate electrical consumption values across specific rooms and floors.
- **Plant room** – This refers to a mechanical or boiler room that contains necessary equipment used to supply ventilation, electrical distribution, and water distribution.
- **Regulated energy** – Energy sources measured and set to a specific requirement under the UK Building Regulatory Standards are regulated energy. This includes HVAC systems, internal lighting, and hot water.
- **Retrofit** – This is the process of changing building components after the initial construction and operation of the building.
- **Single-phase equipment** – A type of equipment that has one live wire. Most small power loads will be single-phase equipment, such as benchtop laboratory equipment and desktop computers.
- **Small power loads** – Equipment with low energy consumption values, such as phone chargers and laptops. These types of equipment are typically single-phase.

- **Unregulated energy** – Refers to user-related energy sources which are not necessarily set to a specific requirement under Building Regulatory Standards. These include small power loads, catering, server rooms, external lighting, and laboratory equipment.

Unit measurements

- **kW** – A Kilowatt, a measure of power consumed.
- **kWh** – Defined as kWhours, where one unit of energy is equivalent to one kWh.
- **$kWhm^{-2}$** – A kilowatt per hour per m^2, which is energy consumed within a set unit of time per one m^2 area. This is a standard measurement used within building services.
- **$kWhm^{-2}$ per annum** – A kilowatt per hour per m^2 per year, which is the energy consumed per one m^2 area per annum. This standard measurement assesses annual consumption within a m^2 space.
- **m^2** – Metre squared.

Abstract

Across the UK, building regulatory standards apply expectations on how buildings should perform. However, they do not always accurately resonate with actual energy consumption across many sectors, particularly the Higher Education sector. The Higher Education sector is the sole focus of this work, in part due to its significant contributions to the UK's CO_2 emissions; consequentially, all UK universities have set ambitious targets to reduce said CO_2 emissions. One method of reducing CO_2 emissions, so that UK universities can begin to achieve these ambitious targets, is by reducing unnecessary energy consumption within buildings. From a social, sustainable, and economic viewpoint, every university in the UK should aim to reduce its CO_2 emissions. One method of reducing CO_2 emissions is to target energy consumption, such as electrical consumption within buildings. By targeting unregulated energy consumption specifically, universities will achieve a potential substantial reduction in unnecessary electrical consumption.

Unregulated energy, defined briefly here as energy consumption within a building that does not have to perform to a mandated requirement under building regulations, represents a substantial proportion of energy. Specific assessment methodologies, such as CIBSE TM54, aim to include this type of energy within building modelling guidelines. However, unregulated energy remains misunderstood, and little is known about the topic under the Higher Education focus.

This thesis research assesses granular unregulated electrical consumption within several case study universities. Using different Energy Management Systems, floorplans, contextual discussions, and semi-structured interviews, the research quantified unregulated energy across the universities. Sub-metering data across the universities were assessed, quantified, and compared to other energy benchmarks and methodologies.

The research concluded that user activities, types of equipment, operational hours and occupancy levels have a significant effect on unregulated energy consumption. Based on the research findings, a series of recommendations were produced for the universities to help reduce unnecessary unregulated electrical consumption. The primary motivator for these recommendations was to help reduce CO_2 emissions and improve overall energy efficiency.

Declaration

I declare that no portion of the work referred to in the thesis has been submitted to support an application for another degree or qualification or any other university or institute of learning.

Copyright Statement

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Chapter 1 - Introduction

1.1 Problem Statement

Across all types of buildings, electricity is consumed through different devices. Heating, Ventilation and Air Conditioning (HVAC), lighting and hot water, are classified as "regulated energy", which according to the literature accounts for up to 50% of a building's overall energy consumption. However, this figure does vary considerably depending on building type (Pérez-Lombard et al., 2008). Regulated energy is monitored closely by regulatory bodies, such as the Ministry of Housing, Communities & Local Government, which sets specific lighting, hot water, and heating regulations. Other types of energy consumption, which are not measured to a specific requirement under current building regulatory standards, can be considered unregulated energy. Comparatively, "unregulated energy" is primarily user-related and depends upon occupant activities within the building to best describe this energy.

If regulated energy represents approximately 50% of a building's total energy consumption, the remaining 50% must be made up of unregulated energy, as suggested within other literature (Dougherty, 2018). At present, the topic of unregulated energy is under-researched, particularly within the Higher Education sector. To reduce this information gap, this research focuses on several universities and assesses levels of unregulated energy consumption.

Unregulated energy, and to a lesser extent regulated energy, is examined across several UK universities as a part of this work. The scope, primary objectives, and research questions are explored further within this chapter. After an initial contextual discussion, the thesis discusses how unregulated energy functions within UK buildings before discussing the thesis's aims, objectives, and goals. Finally, the overall structure of the thesis is outlined at the end of this chapter.

1.2 Research Context

Prior to expanding on the research aims, objectives and questions, the topic of unregulated energy needs to be understood. Therefore, this section explores how building regulations function within the UK before delving into the topic of unregulated energy consumption; to begin, different emissions targets and building energy assessment methods frame an understanding of how buildings within the UK operate.

1.2.1 Regulatory Sustainability Goals

Within the European Union, CO_2 reduction targets have been set for both 2030 and 2050, respectively (European Parliament, 2019). In line with these targets, the UK government had previously set a target to cut CO_2 emissions by 80% by 2050, set against a 1990 baseline level (Department of Energy and Climate Change, 2011). This initial target has now been altered, and the UK government has set a new goal: to reduce emissions by 78% by 2035 and be Net Zero by 2050 (Department for Business, Energy & Industrial Strategy, 2021a). These specific targets have been set to help ensure global temperature levels will not rise above a 2°C increase (Department of Energy and Climate Change, 2011). To help achieve these targets, building regulatory standards must target CO_2 emissions and reduce unnecessary electrical consumption within buildings.

The Department for Business, Energy & Industrial Strategy (2021a) released a Net Zero Strategy, which produced a plan on how the UK government would reach Net Zero emissions by 2050. To summarise the strategy, the initial aim of the strategy is to reduce CO_2 emissions by 50% between 2020 to 2033 (2021a). Significant financial contributions would be required for such a reduction to happen, and social behaviours of the general population would need to change, for this strategy to succeed. In addition, the strategy outlines a goal to reduce energy consumption in commercial and industrial buildings in England and Wales by 2030 (2021a). From a building perspective, reducing unnecessary energy consumption would partially help towards reaching this target, such as by reducing both regulated and unregulated energy consumption, and by focusing on reducing out-of-hours consumption.

1.2.2 UK Building Regulatory Standards

For a more specific assessment of energy consumption within buildings in England, Approved Document Part L (Part L) is considered here. This series of documents apply regulatory requirements for both new and existing builds. The documents layout mandatory UK building requirements: these requirements are then checked by either the relevant local authority or an approved license inspector (Ministry of Housing, Communities & Local Government, 2020). For the Guide F documents, categories L1A and L1B refer to dwellings whilst L2A and L2B refer to non-dwellings and are particularly relevant given the focus of this research upon non-dwelling properties (Ministry of Housing, Communities & Local Government, 2016a; Ministry of Housing, Communities & Local Government, 2016b). These documents provide various guidelines on approximately how much lighting, heating and ventilation, and hot water are required for different UK buildings, and provide various performance ranges.

Additionally, the Part L documents assess how energy devices should be sub-metered within buildings. From a sub-metering perspective, the L2A document states that all new buildings must have at least 90% of total annual energy consumption measured (Ministry of Housing, Communities & Local Government, 2016b). Additionally, retrofitted facilities are required to meet the 90% sub-metering rate, as outlined in the L2B document (Ministry of Housing, Communities & Local Government, 2016a). This sub-metering assesses distinct types of consumption, so both regulated and unregulated energy would be measured under this 90% target.

It is imperative to understand that this prominent level of sub-metering is required to assess electrical consumption within different buildings. The requirement sets a 90% monitoring rate, but high-level data granularity is unnecessary. Thereby, a building could have only a handful of electricity and heating sub-meters, whereas, for detailed analysis of the building's various energy and heating sources, it would benefit from having 50-100 sub-meters instead. Without the functionality of decent sub-metering, most building managers would struggle to assess building-wide electrical consumption. However, the L2A document does not specify how sub-metering within buildings should be implemented; thereby, it only acts as a rough guide. In conjunction with this standard, the non-mandatory CIBSE TM39 document (CIBSE, 2009) outlines how to implement sub-metering successfully. According to the document, successful sub-metering can help to reduce energy consumption by up to 60%. The main processes required to implement sub-metering, as outlined in TM39, include listing energy-using items in the buildings and selecting which systems and devices need sub-metering. The last step of the process requires documenting the sub-metering strategy. Thereby sub-metering in buildings must be to a high-quality standard and must capture most energy-using devices. However, this document is only a guide and is not a government-mandated regulation. Therefore, this limits the overall impact the various CIBSE documents provide, as there is no financial incentive nor governmental pressure into following these guidelines. In this instance, whilst TM39 provides detailed sub-metering guidance, any recommendations given by CIBSE are simply that – recommendations.

1.2.3 Building Energy Assessment Methods

As outlined above, building regulatory standards set various mandates on sub-metering levels in buildings. Various methods can be used in order to monitor energy consumption, such as through benchmarking. Energy benchmarks provide a useful guideline of how much energy a building should consume, on a general level (Menezes et al., 2013). Benchmarking also enables organisations to share their best practices and identify energy usage trends (Stern, 2007). As universities have varied and heterogeneous buildings, following just a single set of benchmarking targets is often insufficient (ECON 19, 2000). However, benchmarking guides enable the energy consumption of buildings to be understood in the context of other buildings.

A good benchmark will also present a range of information, including plug load densities, to produce a more accurate benchmark (Srinivasan et al., 2011). However, it must be stated here that using benchmarks allows for building managers to gain a preliminary idea of how much energy a specific type of building should ideally consume. Some examples of universally accepted Higher Education benchmarks include the CIBSE Guide F benchmarks (CIBSE, 2012) and the CIBSE TM46 benchmarks (CIBSE, 2008).

Comparatively, the Non-domestic National Energy Efficiency Data-Framework (ND-NEED) represents one of the most detailed UK energy comparison frameworks; the framework assesses electrical consumption (typically using TWh as the unit measurement) to compare how different UK sectors are performing (Department for Business, Energy & Industrial Strategy, 2020). Using this framework, they assess different types of education buildings (covering nurseries, state schools, private schools, and universities). From 2016 to 2018, education buildings consumed approximately 5.94 TWh, 6.06 TWh and 6.02 TWh, respectively (Department for Business, Energy & Industrial Strategy, 2020). For each of these years, the respective sample sizes were 23,000, 24,000 and 24,000 (these figures have all been rounded to the nearest thousand). For more detail on typical benchmarking figures across various sectors, Table 1-1 presents the electrical intensity of different sectors, including Education buildings.

Table 1-1: ND-NEED's electrical intensity figures for different sectors (Department for Business, Energy & Industrial Strategy, 2020).

Building sector	kWhm^{-2} per annum		
	2016	2017	2018
Arts, Community and Leisure	33	34	34
Education	63	63	61
Emergency Services	75	61	65
Factories	35	36	34
Health	95	93	91
Hospitality	196	207	204
Offices	84	85	81
Shops	143	144	137
Warehouses	31	32	32
Other	55	56	55

According to the ND-NEED framework, education facilities are not as electrically intensive as other building types, such as factories, although they do consume a substantial amount of electricity within England and Wales. However, the issue with this framework is that it is not presented at a level of granularity that allows it to be used to understand the regulated and unregulated energy consumption across education buildings. Henceforth, whilst both benchmarks and the ND-NEED framework are useful guideline tools, it is imperative that other analysis techniques are used to assess energy consumption across different types of buildings.

1.2.4 Justification for the Focus on the Higher Education Sector

Incorporating the different building regulatory standards into building design can be difficult for many Higher Education organisations. For example, because sub-metering is often generic and outdated, as will explored throughout this work, and the buildings inside these organisations are not typically designed to be energy efficient.

University Estates also contain a wide array of types of buildings. Older building stock can be modified or retrofitted to ensure all buildings comply with the UK building regulatory standards and remain functional and fit for purpose. However, historic buildings can be challenging for Higher Education Estates services to manage. For example, installing double-glazing may not be allowed if the building is grade-listed, as it may change the building's artistic and architectural purpose (Berg et al., 2017; Historic England, 2017). Certain buildings, therefore, do not have to comply with certain building regulations due to these reasons. Even the University of Manchester contains several buildings which have these specific requirements, which means that retrofits cannot be completed within certain buildings, as around 35 buildings are grade listed (The University of Manchester, 2019a).

Hence, whilst university building may offer a challenge for detailed analysis, there also exists an opportunity in furthering understanding of building stock within the Higher Education sector. As highlighted previously, the primary focus of this work is on Higher Education university buildings. This is due to a few reasons. The first reason is that HESA data suggests that in 2020/21 that UK universities collectively consumed approximately 6,936,360 MWh of energy (HESA, 2022a). This substantial energy consumption is a profound issue, as the UK is aiming to become Net Zero Carbon by 2050 (Department for Business, Energy & Industrial Strategy, 2021a). By focusing solely on Higher Education buildings, a potential reduction of energy consumption could consequentially also potentially cause a substantial reduction in CO_2 emissions.

Secondly, universities also typically are well-monitored in terms of different management systems, where standards such as ISO 14001 are commonplace; using 2020/21 data, there were 57 universities and colleges using this standard, and 79 universities and colleges in total used some kind of EMS (HESA, 2023). Sub-metering is required in every building, though the sub-metering itself does not have to be particularly granular. However, with access to such sub-metering, different high-consumption areas can be identified within sections of various buildings. This thereby presents an opportunity as an ideal case study area for this research.

1.2.5 The Focus on Unregulated Energy

As suggested earlier (and referred to in Section 1.1 Problem Statement), the definition of unregulated energy can vary amongst the literature. However, one of the clearer definitions, taken from BREEAM (2011), can be paraphrased as the following:

Unregulated energy represents energy consumption within a building, which building regulations do not mandate a specific requirement upon.

Simply put, unregulated energy covers a range of types of energy. For example, catering facilities, server rooms, supplementary heating, equipment loads, external lighting, emergency lighting, lifts, and escalators, are all considered unregulated energy (Carbon Trust, 2011; Mulville et al., 2014; Van Dronkelaar et al., 2016). Under current building regulatory standards, different types of unregulated energy are typically captured under sub-metering guidelines. However, they must adhere to no minimum or maximum performance standards.

Across the literature, as is primarily explained in Section 2.1 and Section 2.2, regulated and unregulated energy are categorised as separately from one another. Whist the two categories are intertwined, they are inherently defined as two separate categories of energy consumption. The paraphrased definition above focuses on the lack of a mandated requirement, or a mandated performance range. It is argued here that an addendum is needed to this definition of unregulated energy, in order to sufficiently explain what unregulated energy is:

Energy consumption, within a building, that is linked directly to a building user, or in the control of the user.

Conversely, regulated energy can be defined as energy consumed through controlled systems and not related specifically to the user. It may meet the needs of the user (such as meeting thermal temperature needs), but it is in fact not typically in direct control of the user. Where regulated energy (HVAC, internal lighting, and hot water) represents the energy required to make a building compliant, unregulated energy represents the energy needed to run a building to occupant satisfaction. Evidence of the interlinked relationship between unregulated energy consumption and the effects of the user will be explored throughout this research, particularly in Chapter 3 and Chapter 6, in order to argue the need to expand the definition of what unregulated energy actually is.

As outlined previously, there is currently a knowledge gap concerning understanding unregulated energy. The current UK building energy assessment methods do not focus on unregulated energy. Furthermore, the topic is typically focused on the private sector (such as office buildings). Due to these existing knowledge gaps, this work intends to develop an approach to assess unregulated energy consumption across a series of Higher Education buildings. Due to the sector's overall high energy-consumption, high numbers of energy-inefficient building stock and its availability of EMS data, the research for this thesis is focused on the Higher Education sector. It is believed that these factors would allow for a detailed energy analysis of variable building stock, and thereby present detailed information about unregulated energy in particular. The topic of unregulated energy is further expanded on in Chapter 2, however prior to this in-depth literature analysis, the thesis aims, objectives and questions must first be outlined.

1.3 Overall PhD Research Questions, Aims and Objectives

This section explains the key aim of the thesis and a series of objectives to outline how this outcome was achieved. During the beginning stage of this research work, a series of research questions were considered, based on existing literature review gaps. The initial research questions are first considered here:

Research questions:

- What are the unregulated energy profiles for different types of building stock?
- What factors influence unregulated energy consumption in different types of buildings?
- As the current literature suggests, do occupancy and operational hours impact unregulated energy?
- Do building users have a direct impact on unregulated energy?

Key Aim:

- To answer the above questions, the work aims to create a methodological approach, including both quantitative and qualitative data, to assess unregulated energy consumption across various Higher Education buildings. The work also seeks to answer how unregulated energy differs across heterogeneous building stock through existing sub-metering and contextual information.

Objectives:

- Identify suitable case-study candidates, based on their available data streams such as Energy Management Systems (EMS) data, historical energy consumption data, floorplans, and occupancy numbers. Using the available data, trends will be identified across different unregulated energy uses, such as lifts, catering facilities, and small power loads.
- Use Net Internal Areas (NIA) to disaggregate unregulated profiles for different rooms, using $kWhm^{-2}$ as a standardised measurement. EMS and floor plan measurements will also be used to separate regulated and unregulated energy.

- Using all validated data, create a series of unregulated energy benchmarks on a room level and a building level, similar to the Guide F document (CIBSE, 2012).
- Compare levels of unregulated energy across all the case study universities with any existing sub-metering data and benchmark data. Overall levels of unregulated energy should be compared, such as the percentage breakdown of unregulated energy across all studied buildings.
- Obtain contextual data, such as equipment lists, actual operational hours, and identifying energy barriers, by conducting a series of interview with different building managers and building users.
- Provide a written conclusion for all university buildings, identifying potential reductions for unregulated energy.

1.4 Thesis Structure

To conclude this introductory chapter, this thesis aims to expand the topic of unregulated energy consumption within university buildings. It has been suggested in this research that the matter remains underdeveloped. There is an idea that regulated energy represents primary energy consumption use within buildings. However, it is argued here that unregulated energy can also be defined as primary energy consumption. Where regulated energy could be defined as the "barebones" energy required to make a building functional, unregulated energy can be defined as the "necessary" energy needed to run a building effectively.

To finish this section, a brief overview of every forthcoming chapter is as follows:

Chapter 2 – Regulated and Unregulated Energy

This section compares types of regulated and unregulated energy, though the primary focus is on the latter. Different categories of unregulated energy are assessed, such as server rooms, small power loads and external lighting. This section also clarifies the difference between the two categories and argues why there is a knowledge gap on the topic of unregulated energy.

Chapter 3 – Review of the Higher Education Sector

This section provides an in-depth literature review focused on universities, laying out typical policies and initiatives in place across UK universities. Energy consumption and energy demand in UK universities is then discussed in detail. The main portion of the chapter discusses unregulated energy studies and clarifies why this research is focused on the Higher Education sector.

Chapter 4 – The Case Study Universities

This chapter discusses the case study universities, such as the different energy consumption levels and the various sustainability targets within each university. Finally, the case study buildings are described, and the reasons for their selection are discussed.

Chapter 5 – Methodology

The initial hypotheses of the research are considered based on information gathered during the literature review. The quantitative and qualitative data collection methods are expanded upon here, and the primary methods used include EMS, historical .csv files, floorplan designs, semi-structured interviews, and other sources of contextual data.

Chapter 6 – University Practices, Policies and Energy Demand

This chapter breaks down information gathered from a series of semi-structured interviews, conducted within the University of Manchester. These interviews were used to obtain detailed room information, but to also highlight the impact different building users have on energy consumption within the university. Academic and research practices, energy initiatives and the overall impact of building users are discussed in this chapter.

Chapter 7 – Unregulated Energy Consumption in UK Universities

This chapter discusses unregulated energy consumption for different types of unregulated energy consumers, rooms, and buildings for all the case study universities. Unregulated energy is broken down on a building and room-level, and this chapter interweaves sub-metering data with contextual information, gathered during the interview process.

Chapter 8 – Conclusions

This final chapter revaluates the initial research problems and how the research observations have answered such questions. The research hypotheses are considered one final time; broader beneficial implications of the research are outlined, and a series of generalised recommendations are presented here.

Chapter 2 - Regulated and Unregulated Energy

Within this chapter, the issues of regulated and unregulated energy are initially defined. Regulated energy is initially described in detail as a method of understanding how it relates to unregulated energy.

This chapter then discusses, in detail, what unregulated energy is defined as, the different types of unregulated energy, and how it varies amongst different building studies. Indirect factors affecting both unregulated and regulated energy, referred to as operational hours and occupancy levels, are then addressed within this chapter. These factors are critically important, particularly for unregulated energy. Unregulated energy consumption is interlinked into occupancy behaviours, where these behaviours can provide insight into how buildings are being used (opposed to how designers may predict a building may be used).

The work's definition of what unregulated energy is, as outlined previously in Section 1.2.5 to a lesser extent, is also discussed within this chapter. The last part of this section outlines different complexities when calculating unregulated energy and lists other studies which have attempted to calculate such energy consumption.

2.1 Regulated Energy

Regulated energy is typically well understood and well documented across many modern building regulatory standards and building services documents, such as the CIBSE Guide F document (2012). Through definitions gathered within the literature, regulated energy can best be described as energy consumption caused directly by controlled building systems and included in current building design standards (Department for Communities and Local Government, 2008). All types of regulated energy must adhere to a specific range within buildings within the Part L documentation. Regulated energy must therefore have a minimum and maximum performance range.

Regulated energy is comprised of three key areas: Heating, Ventilation and Air Conditioning (HVAC), internal lighting, and hot water (Department for Communities and Local Government, 2008). Combined together, these three categories represent large consumers across all types of buildings, not just in the Higher Education sector. As such, a brief overview of HVAC, lighting, and hot water, is provided here.

2.1.1 Heating, Ventilation and Air Conditioning (HVAC)

HVAC systems represent one of the highest energy consumers within most buildings. According to Pérez-Lombard et al. (2008), HVAC systems represent approximately 50% of a building's energy consumption, at least within the US, though this figure varies depending on the type of building. Comparatively and nationally, HVAC represents 20% of the US's total energy use (Pérez-Lombard et al., 2008). Out of all the regulated energy categories, HVAC is often defined as the highest energy consumer, based on different studies (CIBSE, 2012; Kampelis et al., 2017). Future predictions suggest that HVAC consumption is likely to increase within specific sectors in the UK, particularly regarding ventilation and air conditioning needs. For example, Zeferina et al. (2019) have predicted that annual cooling demand requirements within UK office buildings will increase by up to five times within the future, compared to the current peak demand, due to global temperature increases.

However, there is a potential to reduce overall HVAC consumption, though the process can be expensive and complicated. For example, Agarwal et al. (2010) noted, within a US university, that HVAC systems were left frequently running during out-of-hours. They noted that the HVAC schedules for different offices could be reduced by 10-15% by targeting unoccupied office spaces. So, it can be assumed that reducing HVAC consumption is possible, though it is highlighted here as being potentially difficult.

Ventilation is also integral when calculating a building's total energy consumption, as it varies immensely depending on the building type. Ventilation within existing buildings is primarily monitored by Approved Document Part F (Ministry of Housing, Communities & Local Government, 2021). For older buildings, prevalent standards of the day are commonly used instead. For a standard office with air conditioning, approximately 80-90% of total energy costs and CO_2 emissions are attributed to ventilation (ECON 19, 2000). However, according to the Department for Business, Energy & Industrial Strategy (2016), the education sector displays some of the lowest levels of mechanical ventilation. Therefore, there could be an assumption that ventilation may be a relatively low electrical consumer within certain buildings.

From a Higher Education perspective, ventilation rates differ depending on the building type. It is expected, for example, that a laboratory building will require a higher ventilation standard than an office building due to health and safety reasons. Ventilation helps remove pollutants from the air, although unfortunately, this conversely increases a building's energy consumption (Menezes et al., 2013; Morgenstern et al., 2016). Thus, there is a constant balance between the need of the occupants and balancing ventilation levels to the extent where they will not consume a large amount of electricity.

2.1.2 Lighting

Internal lighting represents another integral type of regulated energy. Assessing numerous studies across the Higher Education sector, internal lighting consumption is estimated to represent 18-35% of a building's total energy consumption (McDowall, 2007; Dasgupta et al., 2012; Escobedo et al., 2014; Jafary et al., 2016). While internal lighting is regulated, external and emergency lighting is typically unregulated, primarily as emergency lighting is battery operated (rather than mains operated). External lighting varies, though again, these usually are battery operated. However, both external and emergency lighting are necessary for a building's overall safety and are vitally crucial for running buildings. This can make measuring emergency and external lighting difficult, however. Additionally, they may be measured under general lighting sub-meters instead of specifically separate emergency/external lighting sub-meters.

Reducing internal lighting consumption is potentially a more complex matter to address when compared to reducing HVAC consumption. This can be for several reasons, such as targeting occupancy behaviours. For example, lights are known to typically be left running constantly, have a significant impact on total energy consumption, and can vary depending on the shape of the building (Junnila, 2007; Dasgupta et al., 2012; Van Someren et al., 2017). In addition, internal lighting is strictly monitored under different building regulatory standards; for example, other rooms must adhere to specific luminaries (lux) ranges to ensure staff and students have adequate lighting within their workspaces. An office room, for example, will require to adhere to a lux value of approximately 300 (BSRIA, 2001). This is easy to achieve, assuming the office space has access to natural light. Higher Education buildings must also ensure not to go over this lighting range. Too much light in buildings can cause health issues, such as headaches and eye strain. As with HVAC, matching the needs of the occupant frequently outweighs the need to limit the amount of energy consumed. Unlike HVAC though, lighting can typically be limited during out-of-hours periods, such as night-time and weekends.

2.1.3 Hot water

Hot water represents the final main category of regulated energy. Within public institutions, such as universities, hot water must be constantly available and monitored for health and hygiene reasons. Energy Management Systems (EMS) measure water, electrical and gas consumption. They can be invaluable in understanding how hot water is used on a building or campus level. As with the other categories of regulated energy, hot water is primarily controlled for older buildings under the building regulatory standards Approved Document Part G (Ministry of Housing, Communities & Local Government, 2016c). This building regulatory standards document outlines specific running and hot water requirements. However, the document does not primarily focus on energy consumption; instead, it outlines health and safety requirements (such as stored hot water not exceeding 100°C).

Numerous studies have been amalgamated to assess how much energy is consumed through hot water. Depending on the building, hot water can represent approximately 9-53% of a building's total energy (Pérez-Lombard et al., 2008; Dasgupta et al., 2012; CIBSE, 2014).

2.1.4 Understanding the Impact of Regulated Energy

Using BSRIA (2001) to provide an insight into how much energy should be consumed by heating, cooling, and electrical systems for education buildings, the information is as follows:

Cooling loads:

- Computer suites: 400 Wm^{-2} Offices (general): 125 Wm^{-2}

Heating loads:

- Educational buildings: 100 Wm^{-2}
- Offices: 70 Wm^{-2}
- Office equipment: 15-25 Wm^{-2}
- Lighting in offices: 12 Wm^{-2}

Education comfort levels:

- Ventilation fresh air rates: 8 l/s/person
- Ventilation air change: 6-10 ac/h
- Lighting levels: 300 lux (factories/warehouses 750-1000 lux, offices 300-500 lux, fitness/health clubs 300 lux, computer rooms 300 lux)

Electrical systems service loads:

- Lighting: 10-12 Wm^{-2}
- Small power: 15-45 Wm^{-2}
- Air conditioning: 60 Wm^{-2}
- Passenger lifts: 10 Wm^{-2}
- Small computer room: 200-400 Wm^{-2}

BSRIA (2001) outlines that cooling, and heating loads, are highly dominant electricity consumers. Lighting, in comparison, is a lot smaller in terms of overall lighting demand. What is particularly interesting, from this information, is that computer rooms, offices and passenger lifts seem to vary immensely regarding electricity demand. These areas indicate a mix between both regulated and unregulated energy. However, this BSRIA document is quite out-of-date and should be compared to more recent documents, such as TM54 (CIBSE, 2013).

When the three categories of regulated energy are combined, they can consume approximately 50% of a building's total energy (Ministry of Housing, Communities & Local Government, 2016b; Dougherty, 2018). Other studies suggest that regulated energy consumption may represent 65% of a building's total energy use (Cohen, 2013). Regulated energy represents a considerable proportion of buildings total energy consumption, as suggested in the earlier studies. The actual percentage of consumption of the average building varies depending on the study. However, it has been commonly stated that approximately 50% of a building's energy consumption is regulated energy. If a building's energy consumption is approximately 50% regulated energy, conversely the remaining 50% must be due to unregulated energy. A massive amount of energy consumption will therefore not be granularly monitored under building regulatory standards, which at present do not require unregulated energy to perform within a specific range. To better understand why unregulated energy is not thoroughly addressed by building regulatory standards, the topic must first be understood better.

2.2 Unregulated Energy

Unregulated energy can now be defined, seeing as regulated energy has been determined. Defining unregulated energy provides insight into how unregulated energy consumption varies substantially across different sectors.

2.2.1 Defining Unregulated Energy

Unregulated energy inherently acts as an interim category, which captures all types of energy not intrinsically defined as regulated energy. In comparison, regulated energy represents energy consumption that must perform within a range set by strict building regulations standards. Whilst unregulated energy is typically captured under building sub-metering, there are no specific requirements for how they must perform. Unregulated energy is often collected through EMS and Building Management System (BMS), the same way in which regulated energy is measured. EMS are primarily used to capture, monitor, and control energy consumption (Sequeira et al., 2014). BMS are also necessary for a broader building level to ensure buildings run smoothly. Therefore, a BMS, EMS and Building and Energy Management System (BEMS) provide a standardised process, which is vital when assessing unregulated energy consumption.

Unregulated energy can also be classified as user-related energy consumption, as previously mentioned in Section 1.2.5. Where regulated energy is represented by HVAC, internal lighting, and hot water, unregulated energy is represented by smaller and often overseen areas. Things that are defined as unregulated energy include the following (Carbon Trust, 2011; Mulville et al., 2014; Van Dronkelaar et al., 2016):

- Office equipment and small power loads
- Laboratory equipment
- External lighting and emergency lighting
- Lifts and escalators
- Catering facilities
- Server rooms
- Supplementary heating (such as plug-in heaters – this includes sockets used for additional heating and cooling equipment).

The literature suggests that operational hours and occupancy levels also affect unregulated energy. Between 20-50% of a building's total energy use is controlled or impacted by occupants (1E and The Alliance to Save Energy, 2009; Foster et al., 2012). As might be expected, if a building is heavily occupied and open for long periods of the day, an increase in energy consumption can be noticed, though this increase in energy may simply reflect an efficiently used building. Entwisle (2016) argues that a successful building could be defined as a building that is intensely used, with long operational hours and with significant occupancy levels.

However, understanding the topic remains challenging as unregulated energy differs considerably depending on the building type. For example, Guide F (CIBSE, 2012) states that for a typical air-conditioned office, 55% of CO_2 emissions are due to unregulated loads; in this calculation, 37% of total emissions are due to office equipment, 13% due to lifts and 5% due to catering (CIBSE, 2012). Other literature review studies indicate the total impact of unregulated energy to be slightly different. For example, Menezes et al. (2013) state that small power load consumption within UK office buildings is substantial. They note that small power load consumption is approximately 20% of the office building's total electrical consumption.

Previous studies indicate that unregulated energy is typically left out of prediction models due to a lack of relevant data and numerous uncertainties (Marszal et al., 2011; referred to as user-related energy within the study). The issue is that unregulated energy does not adhere to a specific requirement under UK building regulatory standards. As of the writing of this thesis, there is not a formalised national calculation methodology tool used to assess all types of unregulated energy. Hence, other documents, such as CIBSE TM54 (2013), must be used as a methodological tool instead if a building designer wishes to calculate a building's total unregulated energy.

To thoroughly assess unregulated energy in the Higher Education, each of these unregulated energy categories are considered in further detail throughout the rest of this chapter.

2.2.2 Equipment and Small Power Loads

Equipment and small power loads are prevalent within all buildings and tend to be found across all rooms in the Higher Education sector. Within a standard office building, there tend to be numerous pieces of office equipment. However, there is also an assumption that small power loads and office equipment only consume a small amount of electricity. Current energy efficiency methods and papers focus on significant energy consumers instead of small power loads (New Building Institute, 2012).

This is not the case for laboratories, however. A piece of laboratory equipment, whether it is single-phase or three-phase, for example, can be incredibly energy-intensive; yet this is, in theory, okay as building regulatory standards do not mandate how this piece of equipment should perform. It is also essential to try and capture plug load consumption directly, as plug load consumption cannot be assessed without also obtaining measurement readings (Christiansen et al., 2015). In their work, Christiansen et al. (2015) previously assessed energy consumption patterns and values for over 10,000 medical devices at the University Medical Center Hamburg-Eppendorf. Whilst the results of this study are interesting, they only measured kWh values from the devices for one week; hence the data sample size is small. They also did not separately cluster three-phase vs single-phase equipment, which may have been beneficial to the work. According to them, ultra-low freezers, refrigerators, and regular freezers were responsible for 60% of the total consumption among all the laboratory devices. Another 20% of the total consumption was miscellaneous pieces of equipment or Miscellaneous Electrical Loads (MELs). Finally, the remaining 20% consisted of incubators and exhaust ventilation systems, considered a mixture of regulated and unregulated energy consumption. The small power loads consumed a minimal amount compared to the larger ultra-low freezers.

Fitting in with this idea, Escobedo et al. (2014) have previously considered how lighting, refrigerators and computer equipment vary across university buildings, on a purely kWh and MWh level. Their study focused on the National Autonomous University of Mexico and assessed the different effects equipment could have on total energy consumption. As indicated by their study, lighting represented approximately 28% of total energy use by sampling different university buildings, matching previous literature review studies for lighting consumption values. Special research equipment represented 17% of total energy use for unregulated energy, while refrigeration represented 14%. A further breakdown of the power consumption ranges for these various categories are presented here in Table 2-1.

Table 2-1: $kWhm^{-2}$ measurements for various types of equipment, categorised into different Higher Education facilities (taken from Escobedo et al., 2014).

Building category	**$kWhm^{-2}$ per annum**		
	Computer equipment	**Miscellaneous**	**Special equipment**
Classrooms	-	-	-
Classrooms with laboratory	2.2	0.5	12.1
Libraries	2.2	-	-
Maintenance areas	2.4	6.9	20.2
Medical units	2.8	1.4	9
Offices	2.2	-	-
Restaurants and cafés	0.8	31.9	1
Science & engineering research	11.3	5.1	39
Social science research	0.5	-	-

Laboratory equipment, miscellaneous catering equipment, and maintenance equipment are all substantially higher than for other Higher Education facility areas. Escobedo et al. (2014) demonstrate in their work the benefits of separately assessing single-phase equipment and larger specialist equipment, in order to quantify the different effects equipment and small power loads have in terms of unregulated energy consumption. As a comparison, small power load can also have a substantial impact on electricity consumption, depending on the type of building. According to Rodriguez et al. (2016), small power load equipment consumes up to 50% of a building's total electricity. Using a Non-Intrusive Appliance Load Monitoring machine learning approach and focusing on an office building, their approach tested various workstation and kitchen appliance loads. Their work outlines the importance of assessing multiple categories of small power loads, as the accuracy of the results obtained were evidently higher within the latter category. Hence, this thesis outlines here the importance of assessing both higher-consuming equipment (such as three-phase laboratory equipment) and small power loads (such as microwaves and kettles). Other studies also assume that approximately 20% of energy consumption in offices is related to office equipment; out of this percentage, desktop PCs represent the highest amount and consume approximately 66% (CIBSE, 2012; ECON 19, 2000).

When focusing on small power loads, it has been calculated previously that approximately 20% of energy within offices is due to MELs (Kamilaris et al., 2015; Menezes et al., 2013). For example, this is a relatively small proportion of energy consumption compared to HVAC consumption. Junnila (2007) assessed four office buildings and concluded that electrical consumption could be decreased by up to 70% by focusing on sustainability using equipment. Personal office workstations, such as desktop PCs, were the largest energy user in each organisation. Other sustainability initiatives, such as applying energy management software, caused an average saving of 35%. Comparatively, turning PCs off overnight accounted for a 20% saving. This study indicates that substantial reductions can be made by specifically targeting unregulated energy and equipment consumption.

2.2.3 Server Rooms

Server rooms represent one of the more energy-intensive unregulated energy categories. Server rooms also typically have higher cooling loads because they are energy-intensive and emit vast amounts of heat (CIBSE, 2013). Therefore, the mix between regulated energy (the cooling loads) and unregulated energy (the servers themselves) is intertwined. Across different studies, the total electrical consumption of server rooms varies from low figures, such as 15-18 W at peak (Kazandjieva et al., 2011), to a much higher potential 50-270 W (Kawamoto et al., 2004).

Kamilaris et al. (2015) indicate that IT equipment alone, such as servers, routers, and PCs, can consume half of a building's electricity. PCs and routers also fall into the small power load category rather than within the server unregulated energy category. Kamilaris et al. (2015) emphasised the benefits of reducing small power load IT equipment, such as double-sided printing (which consumed only 0.058 kWh per printed copy compared to 0.124 kWh per single-sided printed copy) and applying power management software. These kWh savings were small, however. Reducing larger server room consumption, on the other hand, can also be a much more challenging task. There are unforeseen events that server rooms need to be prepared for, such as most staff working from home, as was the case during the COVID-19 crisis. As will be demonstrated within the thesis work (in Chapter 7), server room electrical consumption is typically substantial with a consistent baseload.

2.2.4 Catering Facilities

Universities represent an interesting category regarding the forms of catering available on-site. Typically, catering facilities are outsourced to external organisations (Hoolohan et al., 2021). These external organisations are responsible for the maintenance and running of catering facilities on-campus, though the university would oversee paying for the energy consumed within these facilities. Nevertheless, some assumptions can be made for catering facilities, such as that energy use within catering facilities is expected to be dominated by cooking, water heating and general heating needs, as demonstrated in Figure 2-1.

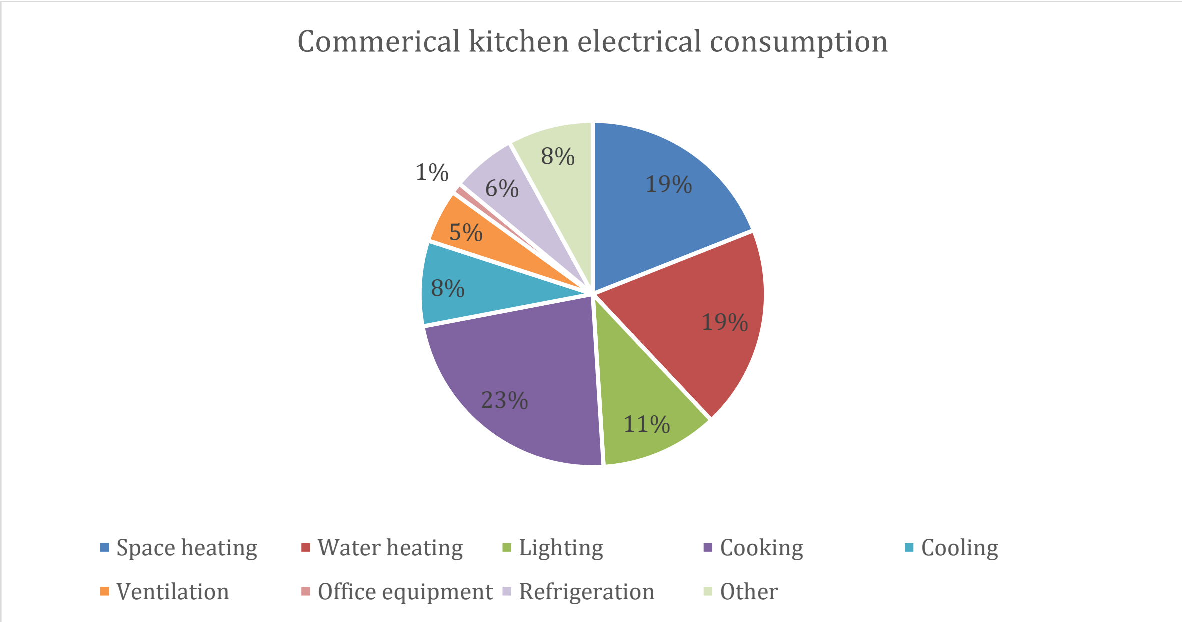

Figure 2-1: Energy consumption in commercial kitchens across the USA (adapted from data in CIBSE, 2010).

TM50 (CIBSE, 2010) outlines how to run a functional commercial kitchen. The document discusses the complexities of applying sub-metering within catering facilities, as sub-meters can typically monitor multiple zones within buildings, rather than just the catering facility in question (2010). Generally, it is accepted that catering consumption is high within education buildings, according to the Department for Business, Energy & Industrial Strategy (2020).

University catering is overlooked in modern literature. The best method of comparing this energy consumption is to look at energy benchmarks used for different industries. Using the Guide F document (CIBSE, 2012) as a, it is assumed that the average university catering facility consumes approximately 149 $kWhm^{-2}$ per annum (for bars/restaurants) and 218 $kWhm^{-2}$ per annum (for fast food venues). For offices, the annual electrical consumption for a typical catering facility varies from 2-15 $kWhm^{-2}$ per annum (2012). For hotels, typical catering consumption is 32 $kWhm^{-2}$ per annum. The figures outline that typical consumption within university catering facilities massively outperform offices and hotels, even though it was initially assumed these venues were easily comparable. Universities are most akin to hotels regarding catering facilities (such as their peculiar opening times and variable usage across various times of the year, for example, catering facilities are much less frequently used in universities during summer holidays). It is imperative that catering electrical consumption within universities is further assessed to update the current literature.

2.2.5 External and Emergency Lighting

Whereas internal primary lighting is regulated energy, both emergency and external lighting are categorised as unregulated energy.

CIE (2017) provides a guide on how to implement external lighting. This form of lighting is typically used for safety, work, and display reasons. Depending on the lighting environment, different areas are classified as separate zones, going from E0 (Intrinsically dark) to E4 (High district brightness) (CIE, 2017). For emergency lighting, the required luminary levels vary depending on the building. Objective illuminance must, at a minimum, be between 0.2-5 lux (for corridors) to provide the necessary lighting levels (Lyons, 1992a). The official minimum lux value for escape routes is 0.2 lux, though many design standards assume a minimum of 1 lux (Lyons, 1992b). This is vastly different from the average lux required to light a room nominally, such as an office. For a Higher Education office building, lux readings should be approximately 300 lux (BSRIA, 2001). Therefore, emergency lighting is a tiny output, in terms of lux and kWh levels, compared to other types of indoor lighting. Whilst the Lyons and BSRIA documents are out-of-date, there have been no significant lighting updates regarding required luminary levels. Hence, these documents best outline suitable lux levels for all types of lighting.

A more current document, the code of practice BS 5266-1, covers all necessary information required for emergency lighting (Watts, 2012). The standard outlines different emergency lighting requirements, such as ensuring emergency signs are visible from a distance and open areas larger than 60 m^2 have emergency lighting (Watts, 2012). Schools, technical institutions, and research laboratories may fall into the remit of the 60 m^2 measurement. A classroom under this size does not require emergency lighting, whereas the BS 5266-1 standard notes that lighting may be required for laboratories. It does not, however, mandate that it is necessary. However, there is no emphasis on how much energy emergency lighting should consume within the standard. Focus is primarily placed on lux levels, the length of time it takes the lighting to start up (in emergencies), and the duration for which the lighting must remain on (Watts, 2012). Little emphasis is placed on how much energy both emergency and external lighting consume, hence there appears to be a limited literature review on this particular topic.

2.3 Operational Hours and Occupancy Levels

The main categories of unregulated energy have been assessed in Section 2.2. However, there remain two indirect categories, which have a substantial impact on unregulated energy consumption. These two categories also remain essential to regulated and unregulated energy; they act as intermediaries. These secondary categories are known as operational hours and occupancy levels.

Operational hours refer to the period that a building remains open and operational. A substantial percentage of university buildings operate under a typical 09:00-17:00 schedule. However, many campus buildings may remain open outside of these core hours.

In their work, Gul and Patidar (2015) monitored and calculated operational hours for different Higher Education activities. It needs noting that their study did not specifically compare different building types; instead, they compared activities related to other operating systems running in different Higher Education buildings. Their results indicate the variable operational hours required for various activities, such as cleaning the building (an early morning activity) compared to running hot water (an all-day activity). Indeed, the length of time of activities being run is not entirely surprising. Hot water is required to run for longer than the building remains open to the staff and students; the same goes for lifts and lighting as well. Their works did emphasise a surprise, though, in that the air handling units only began running late in the morning, not long before users would have occupied the buildings.

Occupancy levels are also heavily tied to operational hours. When occupancy is highest, such as during the daytime, electrical consumption is also typically highest. Energy consumption and occupancy levels are heavily tied to one another where it is well-understood that higher occupancy typically means higher energy consumption. According to the Department for Business, Energy & Industrial Strategy (2016), education buildings peak operating hours are under eight hours a day. Approximately 80% of education buildings have peak opening hours of under eight hours a day, whilst 19% of buildings have a peak operation between 9-15 hours a day.

It is also necessary to include occupancy levels in building-specific studies. Occupancy has a more significant effect on energy consumption than external factors, such as weather (Guan et al., 2016). To understand overall energy consumption, occupancy factors can be applied to buildings. For example, Davis and Nutter (2010) created a series of occupancy factors for six types of universities. They used various visual analysis techniques such as cameras, manual collections, door-way sensors and scheduling data. Through these methods, their work concluded that university spaces were typically severely underused. Administration buildings had the most variable occupancy diversity factors, whereas laboratories had minor variable occupancy diversity factors. They also concluded that a more accurate occupancy level could be calculated if course lists, and timetabling information could be obtained for classroom buildings (Davis and Nutter, 2010). If accurate occupancy information cannot be collected, it is determined that applying inaccurate occupancy schedules can cause an underestimation or overestimation in energy consumption (Van Someren et al., 2017).

When assessing unregulated energy, it is integral to incorporate operational hours and occupancy levels into building calculations. One example of this would be the Demanuele et al. study (2010); their work focused on conducting a sensitivity analysis within 15 schools to measure occupant behaviours. They concluded that elevated levels of unregulated energy were prevalent within the schools, primarily due to operational issues and occupant behaviour. Variable occupancy levels led to increased total unregulated energy levels amongst the schools. They also noted that average office equipment loads, and average class IT equipment loads, were 4.7 Wm^{-2} and 7.3 Wm^{-2}, respectively. While these figures are quite small, they also outline occupants' effects on small power load consumption.

Both operational hours and occupancy levels play a large part in determining total unregulated energy consumption. If these factors cannot be understood, considerable challenges will be presented in the research. Other challenges and opportunities should also be considered in further detail.

2.4 Opportunities and Challenges

Many challenges are faced when calculating unregulated energy consumption (and indeed, regulated energy consumption as well). One example of an issue facing these calculations include the difference between predicted and actual consumption; this term is referred to as the Performance Gap (De Wilde, 2014). Certain studies have shown the potential impact of the Performance Gap, focusing specifically on unregulated energy. Menezes et al. (2012) believe that energy consumption within office buildings can be up to four times larger than the initially predicted energy consumption. In their study, this was deemed partly due to the exclusion of certain types of energy consumption during the design process. Additionally, within the office building assessed within the study, they found that floor-by-floor consumption varied significantly. In this study, the 2nd floor consumed up to 60% more than the 5th floor. This happened even when the equipment used and occupant density across the floors was similar. This consumption difference could be attributed to occupant behaviours (Gaetani et al., 2016).

The Menezes et al. study assumes that actual consumption can be up to four times greater than predicted consumption, and the Pegg et al. study (2007) concurs. Their work assumes that actual energy can be >50% greater than predicted energy. They focused on assessing benchmarks across five primary schools and noted a predicted and actual consumption disparity. This disparity was due to three primary reasons:

- Firstly, the introduction of modern IT equipment was unexpected during the initial predictions; hence the unregulated IT equipment consumption impacted the total energy consumption.
- Secondly, improved regulated air quality standards required increased ventilation rates.
- Thirdly, the variable operations and multi-use nature of the school buildings (such as operating out of hours for school clubs) made it harder to predict what the buildings would need to be used for.

Whilst there is a consensus across the research that the performance gap is a prevalent issue, some researchers argue that unregulated energy should not be considered during the design stage (Dasgupta et al., 2012). The reasoning provided is that including such energy would ensure that future designs remain conservative and would potentially not replicate actual operational consumption. However, it is argued here that the challenge of the performance gap must be faced head-on. For example, the Part L methodology (Ministry of Housing, Communities & Local Government, 2016a; Ministry of Housing, Communities & Local Government, 2016b) and the TM54 methodology (CIBSE, 2013) varies immensely from one another. One reason for this is that the latter method includes unregulated energy during its calculations and is deemed more representative of actual consumption, compared to the former method. It is, therefore, necessary to include all types of energy consumption to reduce the performance gap.

To reduce the performance gap and address the challenges of assessing data in the Higher Education Sector, granular data, such as room-by-room or floor-by-floor level, helps building managers to understand energy-intensive building areas. Simply comparing building-wide data provides limited insight into how buildings perform. The comparative methodologies currently used (such as Higher Education benchmarks) do not capture all the intricacies of heterogeneous and multipurpose buildings. However, granular room-level data can be challenging to obtain. For example, applying such high-level sub-metering is an expensive process; 30-minute reading sub-meters are expensive and are only mandated for large businesses (Janda et al., 2014). A further challenge when assessing energy consumption across different universities is that it is commonly accepted that many universities suffer from inadequate sub-metering (Entwisle, 2016). Even when data are available, there can be a lack of desire to act, which is common among many sectors when applying sustainability initiatives. Accessing data can be complex for many staff members, and only a baseline of information is available to the general populace (Janda et al., 2014).

2.5 Calculating Unregulated Energy

There have been several attempts to calculate unregulated energy consumption across the literature, though the calculations tend to be sparsely allocated compared to the regulated energy. Unregulated energy calculations are rare in the research, potentially due to the complexities of obtaining accurate unregulated energy data.

Perhaps the most well-known calculation method, is the TM54 methodology (CIBSE, 2013). This methodology makes a series of calculations to assess different types of unregulated energy, though they are not explicitly described in the document. The relevant calculations from TM54 (2013) are listed here. To begin, annual lift consumption is broken down in the following equation:

Lifts (E_L) = $(S\ P\ t_h / 4) + E_{standby}$

Where E_L = Energy used in a year by one lift

S = Number of starts per year

P = Drive motor rating

t_h = Time to travel between the main entrance floor to the highest floor

$E_{standby}$ = Standby energy used in a year by one lift

Small power office equipment, such as desktop PCs, use the following equation:

Office equipment = number of workstations × {[average power consumption during operation × annual hours of operation] + ['sleep mode' consumption × (8760 – hours of operation)]}

Small server room annual energy consumption can be calculated using the following equation:

Small server rooms = number of rooms × rated power demand × ratio of rated to operational power demand × hours of operation

The Department of Energy and Climate Change has previously aimed to calculate unregulated energy by assessing appliances and cooking consumption, as indicated in Formula 2.5 and 2.6 (2014). These are simple calculations; however, they only focus upon two specific areas of unregulated energy. The Department of Energy and Climate Change does not explain where these specific calculations come from in the first place.

Appliances (EA) = $207.8 \times (TFA \times N)^{0.4714}$

Where N = Assumed number of occupants

TFA = Total Floor Area (m^2)

Cooking consumption within household buildings are also calculated using the following equation:

Cooking = $(119 + 24N) / TFA$

Finally, perhaps the most up-to-date and detailed method of calculating unregulated energy consumption, Frimpong and Twumasi (2021) conducted a much more involved process as a method in calculating unregulated energy consumption, which can be summarised within the following equation:

$$E_{kn} = P_{akn}T_{akn} + P_{ikn}T_{ikn} + P_{okn}T_{okn}$$

Where E_{kn} = Energy consumed by device k in week n

P_{akn} = Power drawn by device k, in week n, in active mode

T_{akn} = Operational period of device k, in week n, in active mode

P_{ikn} = Power drawn by device k, in week n, in idle mode

T_{ikn} = Operational period of device k, in week n, in idle mode

P_{okn} = Power drawn by device k, in week n, in off mode

T_{okn} = Operational period of device k, in week n, in off mode

Whilst this process requires more detailed input data, it does provide an adaptable approach in calculating different types of unregulated energy.

Through using all these equations, certain areas of unregulated can be calculated. However, specific categories remain uncalculated, including catering facilities, emergency and external lighting, and non-office types of equipment consumption. At present, there is no single widely used national calculation method used to determine all types of unregulated energy. Therefore, it is suggested here that obtaining live data would be invaluable as a method to help further understanding on how to calculate various categories of unregulated energy. A vast array of data, such as from different types of buildings, would be beneficial in this endeavour.

Whilst unregulated energy within the Higher Education sector is currently not well-represented across existing research, an opportunity to better understand unregulated energy now exists. With the sector-wide push towards reducing CO_2 emissions, there has never been a better opportunity to assess Higher Education-specific unregulated energy consumption, and in turn to reduce unnecessary energy consumption.

Chapter 3 - Review of the Higher Education Sector

As covered in the previous chapter, the literature focused on unregulated energy is a developing topic, through there has been an expansion of building-wide monitoring studies and higher numbers of modelling studies. This chapter focuses on the Higher Education sector, providing an both overview of the sector and a detailed understanding of energy consumption, including unregulated energy.

To begin, the impact of the Higher Education Sector on the UK, in terms of energy consumption and financial contributions, is considered. Overall energy demand across different universities is also considered.

University-specific energy consumption studies are then considered in greater detail in order to understand how energy consumption varies in UK universities, including differences between predicted and actual energy consumption. This section also includes the comparison of different unregulated energy studies.

3.1 Universities

This section presents an over overview of the Higher Education sector. The Higher Education sector has seen expansion over the past 30 years. Altan (2010) surmises that there has been an overall increase in student numbers between 1997-2006, and also an increase in research activities. The incorporation of IT and state of the art equipment has also seen an increase during these periods (2010). To go into depth and understand these trends, different factors can be addressed that provide a narrative into how the Higher Education sector performs.

In 2020-2021, there were approximately 452 Higher Education providers within the UK, including colleges, universities, and other Further and Higher Education facilities (HESA, 2021b). There were approximately 165 Higher Education institutions (HESA, 2021c), hosting approximately 2,532,385 students (as of 2019/2020) (HESA,2021d), of which 74.61% were undergraduate students, and 25.39% were postgraduate students. Total student populations for the UK are listed in Table 3-1, using data obtained from HESA (2021d). For the case study universities, Table 3-2 lists total student figures from 2014 up to 2020.

Table 3-1: Total university undergraduate and postgraduate figures, across the UK, according to HESA (2021d).

Level of Study	2015/16 figures	2016/17 figures	2017/18 figures	2018/19 figures	2019/20 figures
Research postgraduate students	113,145	112,520	111,755	112,985	110,675
Taught postgraduate students	418,115	445,885	470,705	490,025	532,235
Other undergraduate students	205,465	187,775	176,055	163,805	154,695
Undergraduate students	1,801,570	1,818,565	1,833,205	1,854,140	1,889,475
Total	**2,332,825**	**2,376,975**	**2,415,660**	**2,457,150**	**2,532,385**

Table 3-2: Total undergraduate and postgraduate figures for the case study universities, across the UK, according to HESA (2021d).

University	2014/15 figures	2015/16 figures	2016/17 figures	2017/18 figures	2018/19 figures	2019/20 figures
Aston	11,070	12,475	13,610	14,615	14,990	15,385
Manchester Metropolitan	31,355	32,485	33,010	33,080	33,050	33,420
Manchester	38,590	39,700	40,490	40,140	40,250	40,485
Nottingham Trent	26,890	27,920	29,370	30,890	33,255	35,785
Reading	14,325	14,980	15,840	16,995	17,805	18,735
Sheffield	27,195	27,925	28,715	29,675	30,195	30,055

Universities are also integral to the UK's economy, contributing over £21.5 billion to the UK's gross domestic product in 2014/2015 (Universities UK, 2017). Furthermore, universities represent the 4th highest category of industrial turnover (following motor vehicle manufacturing, civil engineering, and computer consultancy). Comparing the case study universities, the relative income streams are displayed here in Figure 3-1. The data from Table 3-1, Table 3-2 and Figure 3-1 indicate the scale of the case study universities in terms of student numbers and financial outcomes.

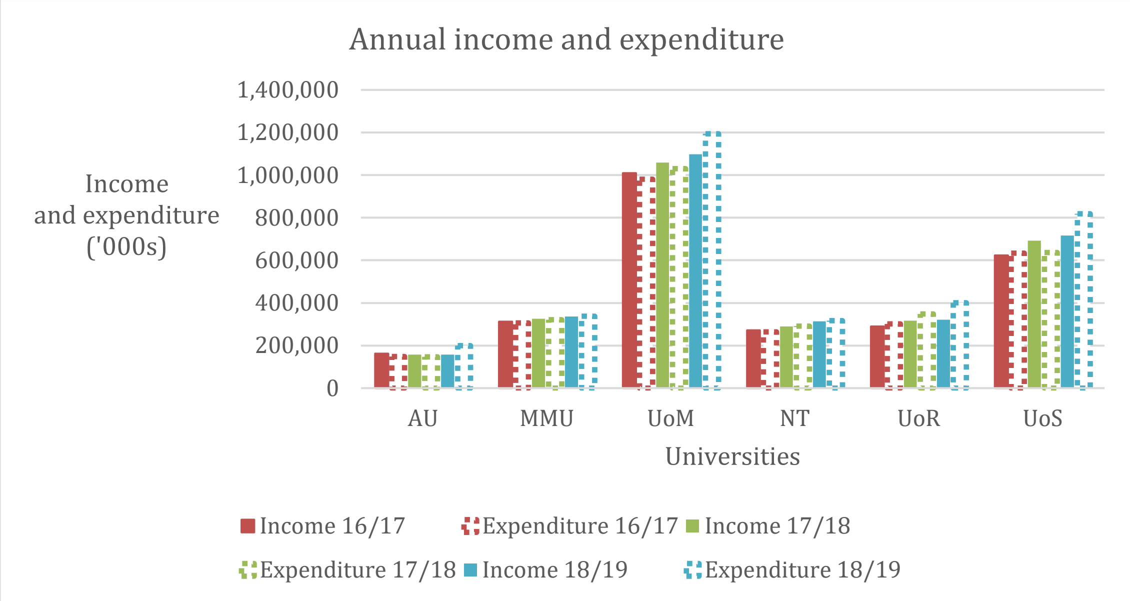

Figure 3-1: Total annual income and expenditure at the case study universities (HESA, 2021e).

3.1.1 Carbon Emissions and Policy Changes

Beyond its financial importance to the UK economy, the Higher Education sector has a role to play in meeting climate change targets, as previously suggested in Chapter 1 and Chapter 2. In accordance with the UK's government's future goals in reducing CO_2 emissions by 2050, all UK universities must aim to reduce their CO_2 emissions by 2050. To reach this target, many universities have set personalised targets and timelines, such as to become carbon neutral by 2035, including some of the case study universities analysed during this research (which will later be discussed in Table 3-3). In terms of CO_2 emissions, UK universities currently emit approximately 1,433,605,175 $KgCo_2e$ per annum in Scope 1 and Scope 2 carbon emissions (HESA, 2022b). To understand this comparison to the UK as a whole, the UK emitted a total of 427 $MtCO_2e$ per annum in 2021, in territorial greenhouse gas emissions (Department for Business, Energy & Industrial Strategy, 2021b).

Unfortunately, the sector is currently struggling to reduce its emissions. For example, in 2012-13, out of 126 universities, 39 universities increased their CO_2 emissions (Britegreen, 2014). In their updated subsequential report, in 2014-15, only 37 universities (out of 126 universities) were on track to meet or exceed their 2020 carbon reduction targets (Britegreen, 2016). As a percentage, this would be 29% of UK universities, meaning 71% of universities, at the time of the report, were not on target according to the Britegreen reports. Comparatively, when using a different and more modern dataset, HESA (2022b) the data suggests a mixed response into how universities are performing in terms of Scope 1 and 2 emissions. Comparing data between 2019-20 and 2020-21, out of 125 universities (that had datasets for 2019-21), 60 universities emitted more CO_2 in 2020-21 compared to 2019-20, whilst 60 universities reduced their 2021 CO_2 emissions. The COVID-19 pandemic may play a part in these figures; however, the HESA data does suggest that universities generally continue to struggle to reduce their CO_2 emissions.

These failures to reach these CO_2 reduction targets may be due to overly optimistic targets or lack of funding required to install necessary technological changes. Alternatively, it may be due to a lack of top-down planning, or a lack of achievable goals required to make these changes and as a whole, there remains a need for considerable change in the Higher Education sector, to reduce its' CO_2 emissions and help the UK to reach its' ambitious 2050 target.

Common to other sectors, universities face many challenges in implementing climate change mitigation policies, including internal structures and procedures, which vary across the sector. With a high number of relevant "players" in an average university's hierarchical structure, there can be substantial oversight in the application of policy. In terms of energy consumption research, most studies focus on those at the top of the university hierarchy system, or those that represent the bottom, such as typical staff members with little ability in applying or instigating policy changes. By focusing on the two ends of the spectrum, these studies overlook the importance of middle-management players (Goulden and Spence, 2015).

Typically, sustainability-focused policies in universities centre predominantly on decarbonisation or increasing efficiency of energy use, whilst overlooking the need to enforce policy (Royston et al., 2019). There is also a tendency for universities to focus on building improvements, such as retrofits or upgrading buildings. Focusing just on technological advancements or on building retrofits alone does not always lead to a reduction in energy consumption (Darby, 2006). The introduction of new policies only results in reductions in energy usage if the policies and regulations themselves put into place new infrastructure, changes in technology design, or describe ways of changing social practises (Royston et al., 2019). Additionally, for most staff members within universities, their main focus is their work rather than ensuring that wider university policies are achieved (Gormally et al., 2019).

As Sorrell (2015) notes, lack of time for staff members is a large contributing factor as to why different energy saving initiatives may not be partaken in or implemented. As the workplace is a "hybrid space", a public and yet private place, staff members may feel a lack of ability to control or change their environments and thereby they feel limited by their environment (Gormally et al., 2019). In fact, to achieve longstanding behaviour change amongst staff may require substantial changes in workplace practices, which staff may not feel able to apply, as it may be simply out of their control (Gormally et al., 2019).

3.1.2 Sustainability and Energy Initiatives

Energy initiatives within universities also vary considerably and can include the implementation of energy saving campaigns, the retrofitting of buildings and the replacement of inefficient equipment, saving a considerable amount of energy. For example, Altan (2010) produced a survey which analysed various sustainability interventions across various UK Higher Education Institutions. Their survey results show that 83% of their survey respondents conducted both technical and non-technical initiatives, 13% conducted just technical initiatives and only 4% of UK universities conducted no initiatives, between 2001-2006. All together, they conclude that equipment efficiency improvement initiatives saw a 10-46% reduction in energy demand.

Comparatively, Chung and Rhee (2014), in a study of a South Korean university, estimated that savings between 6-30% could be achieved through behavioural and technological initiatives, for example the replacement of windows. Their research indicated that, out of the 11 buildings studied, the energy-intensive buildings were in use irrespective of occupancy hours. They also indicated that older buildings could save between 10-22% in energy consumption, by replacing old windows and laying insulation.

Multiple universities run different behavioural campaigns in order to help reduce energy consumption usage. For the case study universities, Table 3-3 outlines some of these initiatives. Many of the case study universities run both bottom-up and top-down sustainability activities (such as green impact campaigns and university-wide carbon management plans). Cornell University (2023) pioneered an online energy dashboard that is accessible to the public, staff, and students alike. This dashboard shows total energy consumption on an hourly basis, thereby allowing different trends to be analysed across different periods. Several UK universities employ a similar feedback mechanism, such as the University of Manchester (2023) and the University of Sheffield (2023).

Common across most UK universities, the case study universities have adopted sustainability procedures, initiatives and strategies which provided insight into how each university processes sustainability and energy concerns (Hoolohan et al., 2021); these are presented in Table 3-3. Additionally, Table 3-4 provides a breakdown of carbon emission reductions within the case study universities, from 2015 to 2021.

Table 3-3: Sustainability information, such as CO_2 reduction targets and historic Scope emissions, for the case study universities.

University	CO_2 reduction targets	Scope emissions	Sustainability initiatives
Aston University (2019; 2021)	78% reduction in Scope 1 and Scope 2 emissions by Carbon neutral by 2050	In 2005/6, the university's Scopes 1 and 2 emissions were 11,382 tonnes CO_2e, whereas, in 2017/18, they managed to reduce emissions by 38.4%.	They have a CHP and have created a series of sustainability campaigns, such as Go Green Week, Go Green Network and the 'Kitty the Kestrel' mascot.
Manchester Metropolitan University (2020)	Zero-carbon by 2038	Between 2015/16 to 2019/20, the university has reduced its Scope 1 and 2 emissions from 15,779,784 Kg CO_2e to 7,810,843.391 Kg CO_2e (HESA, 2021a).	The university uses various electricity generation methods (such as solar panels, ground-source heat pumps, and a CHP plant).
Nottingham Trent University (2021a; 2021b; 2021c)	29% CO_2 emissions by 2021 (using a 2005/06 baseline) 50% total carbon emissions by 2030 Net Zero carbon emissions by 2040	Between 2015/16 to 2019/20, the university has reduced its Scope 1 and 2 emissions from 14,013,991 Kg CO_2e to 9,554,240 Kg CO_2e (HESA, 2021a).	The university has solar PV installations with a capacity of 396kW (2021b). It is also ranked 3rd place in the People and Planet University 2019 League.
The University of Manchester (2021a, 2021b, 2021c)	Zero carbon by 2038	Using 2007/08 as a baseline, the university has achieved a 37% absolute carbon reduction (using 2018/19 data). From 2007/08 and up to 2019/20, the university has reduced electrical emissions by 46.35%.	The 10,000 actions campaign is the university's primary campaign, encouraging staff to take personal actions in and out of the workplace.
The University of Sheffield (2020)	Carbon-neutral by 2038 Net Zero in Scope 1 and Scope 2 emissions by 2030	They reduced Scope 1 and Scope 2 emissions by 35% between 2005-2019.	Sheffield uses a CHP system for heating the university.
The University of Reading (2020)	Carbon neutral by 2030	They have managed a 40% carbon emissions reduction between 2008/09-2020.	There are >500 solar panels placed across the campus.

Table 3-4: Total Scope 1 and Scope 2 carbon emissions for the case study universities.

University	Total scope 1 and 2 carbon emissions (Kg CO_2e)					
	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21
Aston	7,665,910	7,545,490	7,012,947	6,398,042	5,418,958	5,438,457
Manchester Metropolitan	15,779,784	13,443,511	11,801,395	10,803,622	7,810,843	8,066,614
Manchester	67,596,583	60,233,305	53,838,765	50,673,673	49,377,118	52,215,856
Nottingham Trent	14,013,991	12,315,252	11,354,324	10,922,535	9,554,240	10,117,837
Reading	13,606,023	12,406,840	11,292,451	10,693,415	10,586,663	10,984,881
Sheffield	40,350,276	35,549,360	31,945,445	26,265,982	22,530,886	24,529,410

The case study universities have adopted ambitious carbon emission reduction targets, with many aiming to become either carbon neutral or zero carbon between 2030-2040. Whilst all the case study universities demonstrate Scope 1 and Scope 2 carbon emission reductions (as indicated in Table 3-4) there are a few potential issues where the universities may not be able to achieve their CO_2 emissions reduction targets. For example, there appears to be an oversight in reducing Scope 3 emissions; this is perhaps due to the inherent difficulty in reducing these types of emissions or due to the wide range of what is defined as a Scope 3 emissions, which include capital goods, travel, generated waste, and various other categories (Greenhouse Gas Protocol, 2013). Additionally, the universities themselves, whilst outlining their targets and timeframes clearly, do not always have clearly laid out plans which describe how these targets will be reached.

In order for the case study universities to reach these targets it is suggested here that a sustained reduction in unnecessary consumption, such as out-of-hours unregulated energy consumption, could help. Therefore, the following section explores the topic of energy consumption in universities further, to ascertain whether such a policy focus could help universities substantially reduce their energy consumption.

3.1.3 Energy Consumption

In terms of energy consumption and as with other public institutions, universities must monitor at least 90% of all energy consumers within modern and retrofitted buildings (Ministry of Housing, Communities & Local Government, 2016a). This sub-metering typically captures unregulated energy consumption; however, it does not necessarily mean the captured data are granular enough to assess unregulated energy consumption.

Across the Higher Education sector, energy consumption is typically dominated by gas rather than electrical consumption. Over 65% of all energy use is non-electrical consumption, whereas approximately 35% is due to electrical consumption (Department for Business, Energy & Industrial Strategy, 2016). In laboratories, consumption is highly dominated by plug loads; for example, at the University of Stanford, laboratory equipment consumed 16% of the university's overall electrical consumption (Hafer, 2017). Focusing on the University of Stanford, approximately 110,529 plug load devices were recorded through visual observations and energy audits. The Hafer study (2017) measured these devices and calculated that they consumed approximately 50 million kWh per year. For the university, this accounted for approximately 32% of the university's total electrical consumption during this time. In addition, Hafer noted a substantial Energy Use Intensity (EUI) measurement for laboratories. The other building types within the study performed similarly with computers and monitoring equipment dominating their overall plug load consumption. Laboratories were particularly energy-intensive, and their plug load consumption was unsurprisingly dominated by laboratory equipment. In addition to the unregulated energy, the regulated energy use within these building types would also be substantial (particularly the Heating, Ventilation and Air Conditioning (HVAC) consumption in laboratories).

Given the diversity of universities Estates and areas of work, energy consumption within buildings varies across the Higher Education sector. Table 3-5 provides an overview of the total MWh consumption of the case study universities. Table 3-6 also provides an overview of total student figures and total research income, as a comparison to total energy consumption.

Table 3-5: Total MWh per annum and $MWhm^{-2}$ per annum consumption for the case study universities (HESA, 2021a).

University	MWh per annum						$MWhm^{-2}$ per annum					
	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21
Aston	30,484	30,165	30,692	30,044	26,809	28,419	0.28	0.28	0.29	0.28	0.25	0.27
Manchester Metropolitan	52,481	52,097	51,599	49,602	37,783	41,355	0.20	0.20	0.19	0.18	0.16	0.16
Manchester	239,372	233,913	237,359	235,524	241,060	269,289	0.27	0.26	0.27	0.27	0.26	0.29
Nottingham Trent	46,601	45,689	49,166	50,343	45,223	52,074	0.24	0.24	0.25	0.25	0.21	0.24
Reading	45,911	45,874	48,189	46,476	48,636	51,355	0.23	0.23	0.24	0.23	0.24	0.25
Sheffield	133,810	131,771	137,641	134,825	122,427	125,469	0.25	0.24	0.25	0.25	0.23	0.23

Table 3-6: Total student numbers and research income levels for the case study universities. Research income comprises of funding body grants, and research grants and contracts.

University	Total student numbers						Total research income (£ 000's)					
	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21
Aston	12,475	13,610	14,615	14,990	15,595	16,795	29,769	31,007	32,481	33,883	35,705	42,152
Manchester Metropolitan	32,485	33,010	33,080	33,050	33,420	35,940	32,248	37,421	41,025	38,688	39,856	41,645
Manchester	39,700	40,490	40,140	40,250	40,485	44,635	403,066	396,007	425,840	455,181	398,222	375,035
Nottingham Trent	27,920	29,370	30,890	33,255	35,785	38,995	27,868	27,856	27,565	28,000	29,150	35,432
Reading	14,980	15,840	16,995	17,805	18,735	19,980	63,741	64,553	68,653	69,926	69,521	73,733
Sheffield	27,925	28,715	29,675	30,195	30,055	30,605	269,608	239,667	280,853	269,336	264,364	259,685

As is shown in Table 3-5, the case study universities consume a substantial amount of energy. There is also a clear considerable energy consumption reduction for each university between the 2018/19 and the 2019/2020 datasets, which is attributed to the occurrence of the COVID-19 pandemic during which time each of the case study universities closed a high proportion of their buildings during 2020.

Universities typically have fluctuating operational schedules, where a building may be open from 09:00-17:00 or run 24/7 (Gul and Patidar, 2015). Additionally, it is typically expected that most buildings will have lower occupancy during weekends and holiday periods, although laboratory buildings may be used over more extended periods depending on the nature of the research conducted. Based on these variable operational hours, it can be difficult to determine standardised energy performance ranges for different types of university buildings. Out-of-hours baseload consumption can also be higher than initially designed or anticipated for. For example, Soares et al. (2015) monitored a single university teaching building and found that the out-of-hours consumption remained constant yet higher hypothesised. They concluded that the out-of-hours consumption was primarily due to catering equipment, several types of lighting, and a handful of heating devices being left on (Soares et al., 2015). This equipment, in theory, sometimes must be left running depending on what it is used for. However, it also indicates the potential effects of unregulated energy on a standard university building's baseload consumption.

Baseload consumption can be defined as the lowest typical consumption within a building (Costa & Matos, 2016), whereas peak demand primarily focuses on two factors, quantity (of energy) and timing (of energy consumption) (Yarbrough et al., 2014). This consumption includes appliances that require to be left on such as refrigerators, security systems, and routers, and any equipment also left in a standby mode (Costa & Matos, 2016). Targeting out-of-hours baseload consumption provides one method for universities to reduce unnecessary energy consumption and consequentially reduce CO_2 emissions. If a university's Estates team can understand their baseload consumption, for example where and what contributes most of a building's electrical baseload, the university can then assess whether baseload could be reduced. A high baseload out-of-hours is a concern, whilst a low baseload with high daytime consumption indicates that a building is being run efficiently. To demonstrate this concept, Figure 3-2 presents two energy performance scenarios for a university building. This is a representative figure and is not based on data obtained from the case study universities. In this instance, Building 2 depicts a higher peak in electrical consumption, yet across the day it consumes less than the consistent baseload for Building 1. As with in the Soares et al. (2015) paper, a constant baseload in-hours and out-of-hours is typically due to different pieces of equipment being consistently left on.

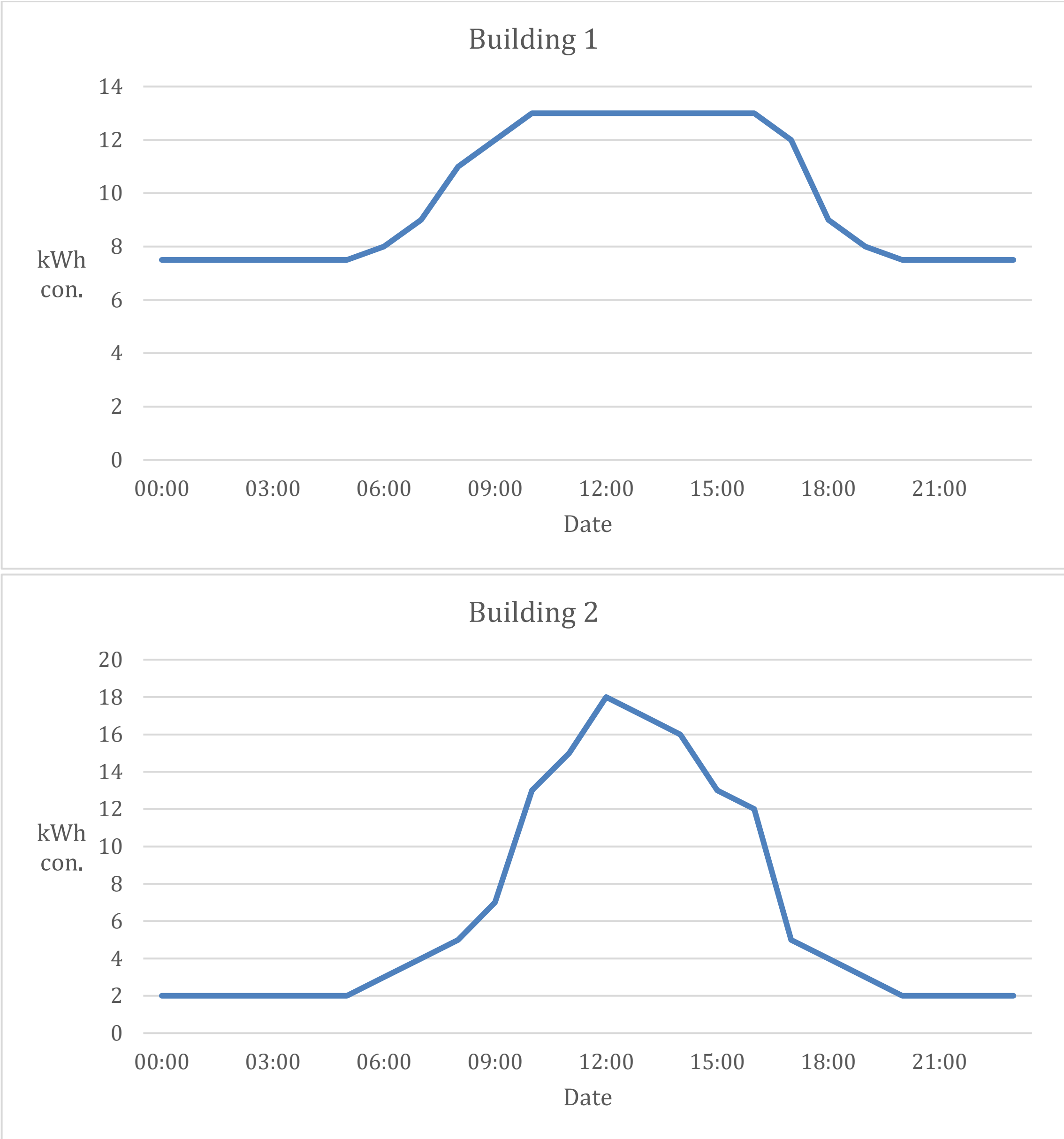

Figure 3-2: A demonstration of two potential baseload scenarios.

In summary, the Higher Education sector consumes a considerable amount of energy, for both gas and electric. As previously outlined, the need to reduce carbon emissions is integral, and one proposed method of reaching this goal would be reduce energy consumption wherever possible. As shown in Table 3-5, reductions in energy consumption were observed during the

COVID-19 pandemic, showing a potential for reducing said energy consumption when occupancy of buildings are heavily reduced.

3.1.4 University Benchmarks

To better understand energy consumption in Higher Education buildings, different tools can be used to calculate and assess energy consumption. Benchmarking, as described in further detail in Chapter 1 and Chapter 2, can be used to assess building-wide energy consumption. Benchmarking, however, cannot be used to understand granular data and should only be used as a generalised comparison tool, for example to compare two library buildings. Obtaining benchmarking data can also be difficult, as typically a wide array of studies is required in order to obtain meaningful results (Leaman et al., 2010).

One of the most widely accepted benchmarks is the Guide F document (CIBSE, 2012), as previously described within Chapter 1. The guide comprises multiple benchmarks for numerous sectors, including the Higher Education sector, although the data used to create the benchmarks are outdated. The originating document made by HEFCE (1996) is no longer in print, making it difficult to review the accuracy and scope of the research. However, the CIBSE benchmark is one of the most in-depth energy consumption guidelines for the Higher Education sector. Table 3-7 lists the CIBSE Guide F benchmarks for university buildings (2012).

Table 3-7: Fossil fuels and electricity benchmarks, for different categories of university buildings. The data were taken from HEFCE (1996), as displayed in Guide F (CIBSE, 2012).

Building type	Fossil fuels (kWhm^{-2} per annum)		Electricity (kWhm^{-2} per annum)	
	Typical	Good	Typical	Good
Catering, bar/restaurant	257	182	149	137
Catering, fast food	618	438	218	200
Lecture room, arts	120	100	76	67
Lecture room, science	132	110	129	113
Library, air conditioned	245	173	404	292
Library, naturally ventilated	161	115	64	46
Residential, halls of residence	290	240	100	85
Residential, self-catering/flats	240	200	54	45
Science laboratory	132	110	175	155

As demonstrated in Table 3-7, most benchmarks offer a performance range for universities to target, adhering to typically including typical and good ranges, however the Guide F benchmarks are out-of-date, and the breakdown of building data are limited. For example, laboratory buildings are not separated into different laboratory types (such as biological, chemical, and engineering laboratories). Additionally, administration spaces, sports centres, and computing spaces are amongst the room types excluded from the benchmarking guide.

Other benchmarking schemes, such as TM46 (CIBSE, 2008), offer another insight into how electrical and gas consumption may vary depending on the building type. Accordingly, TM46 indicates typical catering facilities, research laboratories, and lecture room performance ranges for different buildings, though not explicitly focused on higher education. In terms of university campuses, they state that 80 kWhm^{-2} per annum is typical electrical consumption (CIBSE, 2008). This figure is not broken further into modern or historical university campuses, nor are other types of consumption in universities assessed per se.

Khoshbakht et al. (2018) have previously created university benchmarks using data from 80 universities. Accordingly, data from 80 Australian universities were compiled, and a statistical model was created to assess typical benchmarking levels. This is partially demonstrated below in Table 3-8. Their observed EUI figures are similar to the predicted EUI figures, indicating their model is relatively accurate. The primary purpose of Khoshbakht et al. paper is to demonstrate the similarity across different Higher Education buildings, where UK and Australian buildings can be compared.

Table 3-8: Calculated EUI values for different university building types, according to Khoshbakht et al. (2018).

Building type	kWhm^{-2} per annum		
	Average observed EUI	**Average predicted EUI**	**Benchmarked EUI**
Academic office	121	142	137
Administration	134	148	140
Library	147	160	145
Research	379	279	216
Teaching	145	149	149
Mixed	148	171	142

They concluded that activities within the buildings presented one of the best indicators for how much energy a building should consume. For example, research buildings (wet and dry laboratories, cold rooms, workshops, and computer terminals) and academic offices had the highest and lowest EUI benchmarks, 216 $kWhm^{-2}$ per year and 137 $kWhm^{-2}$ per year, respectively. The study would have benefitted from breaking down the differences between the types of laboratories assessed to understand why their electrical consumption was higher than for previously mentioned benchmarks. However, it provides insight into potentially more up-to-date energy benchmarks, which this research can use as a comparative tool.

Other relevant comparison documents include TM54 (CIBSE, 2013). TM54 is one of the best documents that outline typically benchmarking levels for a variety of sectors. The 17-step methodological process is involved; if the input data are reliable, then TM54 can calculate a series of $kWhm^{-2}$ values for the designed building. Unlike Part L, TM54 integrates all types of energy consumption within facilities, such as small power loads and lifts; it also considers factors such as operational hours and occupancy levels. Between the two documents, there is a significant focus on capturing all types of energy consumption rather than just regulated energy. The Part L documents primarily focus on HVAC, internal lighting, and hot water; thereby, the Part L documents do not sufficiently consider unregulated energy consumption or mandate any specific requirements.

The CIBSE document TM46 (CIBSE, 2008) provides another insight into how university campuses perform. However, the study is limited and provides only one figure for university benchmark performances. Consequently, whilst it is not as detailed as CIBSE Guide F (2012), it does provide advice on how benchmarks can be made. It also illustrates typical electrical and fossil fuel measurements for university campuses, 80 and 220 $kWhm^{-2}$, respectively.

Finally, the HEEPI classification system (HEEPI, 2006) involved benchmarking data obtained from over 30 universities providing data on 223 buildings. The study also compared its' benchmarking system to other existing benchmarks available at the time, as presented in Table 3-9. The HEEPI study offers some of the most detailed data available for the Higher Education sector, and as such is highlighted here as one of the sector's best examples of different building performance ranges.

Table 3-9: Typical fossil fuel and electricity performance ranges for different University buildings, using data from HEEPI (2006).

Building Template	Fossil Fuels – kWhm^{-2} per annum			Electricity – kWhm^{-2} per annum		
	HEEPI	Value for Money (1)	Carbon Trust	HEEPI	Value for Money	Carbon Trust
Offices	166	108	136-168	90	68	80-288
Sports Centres	325	238-356	217-1336	199	79-217	105-258
Libraries	176	145-221	No data	186	58-364	No data
Residences	240	216-261	No data	57	49-90	No data
Teaching	240	108	No data	118	68	No data
Admin	166	110-177	136-168	90	50-158	80-288
Laboratories	256	119	No data	325	158	No data

Whilst the HEEPI benchmarking system is a useful benchmarking tool, it is unfortunately no longer available; hence assessing the data available is complicated. As such, there is a need to have access to a more up-to-date benchmarking scheme for the Higher Education sector, a goal that was set for this thesis work. The HEEPI categories are some of the most descriptive for the Higher Education sector. Compared to the CIBSE benchmarks (2012), the HEEPI benchmarking process does break down laboratories into three main categories and considers computing and administration buildings. This literature considers smaller benchmarking studies to assess kWhm^{-2} per annum readings across universities.

3.2 Energy Demand in Universities

In relation to energy consumption, it is necessary to also consider energy demand. In essence, energy demand is the energy required to meet its' users' needs, for individuals and organisations alike (Hasanuzzaman et al., 2020). Energy demand refers to "the amount of energy required by a country" and consequentially also "the amount of energy supplied to consumers" (Hasanuzzaman et al., 2020, p. 41). Overall, energy demand should be considered to be dynamic (Hargreaves and Middlemiss, 2020).

When looking at future scenarios, Van Ruijven et al. (2019) note that future energy demand will increase due to climate change. In their study, which looked at 210 socioeconomic and climate scenarios, they determined that energy demand will grow by a factor of 1.4-2.7 for industrialised regions with an even more rapid growth in China. In addition to this energy demand, they estimated an increase in the global population, where they estimated a global population figure of between 8.4-10 billion in 2050. Sorrell (2015) agrees that increases in the global population have historically shown a large correlation with a substantial increase in energy consumption, particularly due to an energy surplus in fossil fuels. Thereby, it is also likely that energy demand will increase across various sectors, including the Higher Education sector. As such, it is necessary to understand energy demand in the present, in order to predict further future energy demand trends.

Energy users do not usually consider energy demand, instead they will focus primarily about the utility or fulfilment of purpose which is obtained from using said energy (Haas et al., 1998; Hasanuzzaman et al., 2020). To clarify and for the purpose of this thesis research, this work will primarily assess energy demand focused on the amount of energy supplied to consumers in the context of the Higher Education sector. Royston et al. (2018) perceive that existing demand-side approaches focus primarily either on the efficiency of equipment and technology or on consumption figures alone. The focus on these areas causes an oversight on other areas, which leads to organisations missing their carbon reduction goals. Thus, a refocus on overall energy demand is needed.

Whilst much is known about energy use and carbon emissions in the Higher Education sector, there is an apparent lack of research and knowledge on the topic of energy demand, or the links between energy demand and policy (Wadud et al., 2019; Gormally et al., 2019). However, by both improving energy efficiency measures and reducing energy demand, then a substantial reduction in short-to-medium term carbon emissions can be expected (Sorrell, 2005). Any reductions in energy demand must be carefully considered and matched to the needs of the user. For example, Wadud et al. (2019) notes that income, size of the university and research intensity are the primary factors which effect energy consumption, with the ever growing need to increase income and research outputs driving an increase in energy demand (Wadud et al., 2019). As a sector, universities need a better understanding on the drivers of energy demand and associated impact on demand reduction interventions (Altan, 2010). In all, through understanding different energy demands for users and organisations, a better understanding can also be gained on how unregulated energy in particular may vary in terms of demand.

3.3 Unregulated Energy in Universities

Building on the overview of the Higher Education sector and discussion of energy consumption in university buildings, Section 3.3 focuses in more detail on unregulated energy within university buildings. Energy-specific university case studies are first elaborated ahead of unregulated energy-specific university case studies. Both operational hours and occupancy levels are discussed in detail, as these factors have been found to have a significant impact of unregulated energy.

3.3.1 Methodologies Used to Assess Unregulated Energy Consumption

The current literature suggests different ways of assessing and measuring unregulated energy consumption, which varies according to the use of different buildings and implies that the purpose and functional usage of the buildings are the critical factors when assessing unregulated energy consumption. Post-Occupancy Evaluations (POEs) are one method of collecting relevant unregulated energy information. One of the best examples of POEs conducted within the Higher Education sector was produced by Lawrence and Keime (2016). They conducted a POE within two university buildings at the University of Sheffield and calculated both electrical and gas readings for the two buildings, as indicated in Table 3-10. As noted, there was a significant electrical consumption difference between the Arts Tower and the Information Commons. The latter building contained numerous HVAC devices, chillers, and office electrical devices, such as desktop computers. Although this study would benefit study from a further breakdown of the total energy consumed within the buildings, rather than just an overall building kWhm^{-2} per annum calculation, they outline how POEs can be used to break down energy consumption post-occupancy.

Table 3-10: Electrical and gas consumption for the two university buildings at the University of Sheffield (Lawrence and Keime, 2016).

	Annual consumption (kWhm^{-2} per annum)	
Building	**Electric**	**Gas**
Arts Tower	67	49
Information Commons	233	32

Using a different approach, collecting electrical consumption data, and assessing it using various existing methodologies (such as TM46), Pritchard and Kelly (2017) analysed energy consumption in an office and laboratory building at the University of Cambridge. They noted that the logbook estimates wildly differed from the actual consumption, due to the exclusion of unregulated energy consumption in the logbook records. Unfortunately, many methodologies struggle to include unregulated energy; hence, they do not accurately represent total energy consumption.

3.3.2 Building Uses and Energy Consumption

Comparatively, Miscellaneous Electrical Load (MEL) consumption within universities can be substantial, according to Kamilaris et al. (2014). Within this study, total energy consumption measurements were made for a series of small power loads and IT equipment. Potential energy consumption kWh savings were also calculated, based on the number of IT devices located within the study at the university. The study then compared potential sustainability practices which could easily be implemented. The focus on changing types of MEL technology, from desktop PCs to laptops, presents the most significant potential financial and energy savings within the study. From a university perspective, reducing IT equipment usage seemed to reduce overall electrical consumption. Theoretically, there are likely to be 1000s of laptops in use in a larger university, including desktop PCs. Hence, the potential in reducing electrical consumption by swapping from desktop PCs to laptops would be potentially substantial.

Understanding the consumption patterns of different types of laboratory equipment is also integral to this thesis research. Hafer (2017) indicates that laboratory equipment usage within universities is particularly energy intensive. As mentioned previously, approximately 11,529 MEL devices were categorised into different MEL groups. For all these devices, total electrical consumption values were estimated. The plug loads assessed within this study accounted for 48,214,900 kWh per annum, which is a substantial amount. Hafer also assessed plug load densities across several buildings. According to this study, plug load energy use intensity was estimated to be 5.42 kWh per square foot per year, which is a low figure when compared to regulated consumption.

3.3.3 Differences Between Predicted and Actual Energy Consumption

Brady and Abdellatif (2017) incorporated a wider methodological approach and used digital surface models, surveys, and TM54 to assess energy consumption within a university workshop; they then compared their results to other Higher Education benchmarks. Their calculations indicated an under-prediction in the predicted electrical consumption as with previous studies. Figure 3-3 displays their energy consumption predictions using different benchmarking schemes.

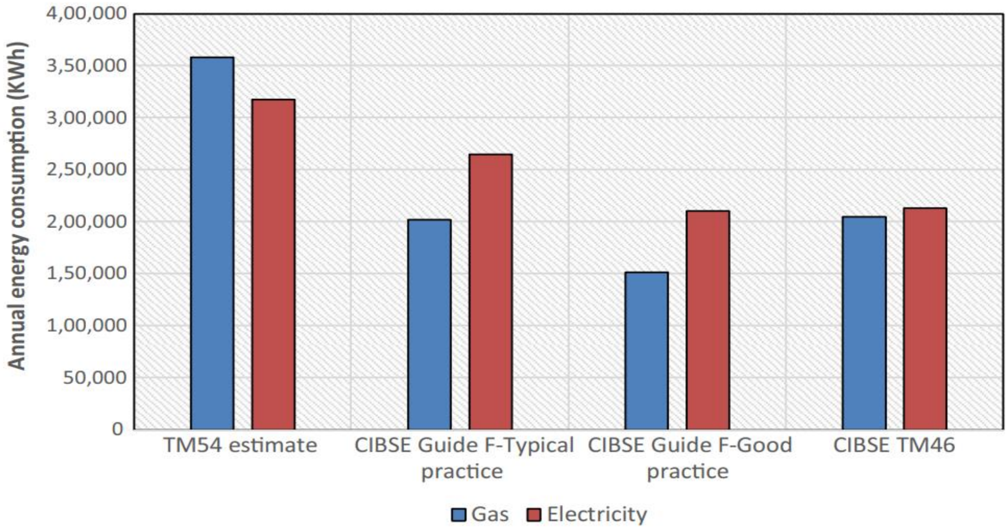

Figure 3-3: Predicted and actual energy consumption for Higher Education buildings, calculated using a variety of benchmarking schemes (Brady and Abdellatif, 2017).

As with the Pritchard and Kelly study (2017), the Brady and Abdellatif (2017) study provides insight into the difference in estimated kWh measurements based on the methodological approach. Their work excluded unregulated energy consumption, so their predictions varied when comparing actual versus predicted consumption. Equally, as the Display Energy Certificate readings and utility readings were based on estimated readings, rather than being live data, there was a discrepancy in some measurements Unfortunately, the building was not metred on its own circuit, hence why this study's live data were difficult to obtain. This highlights the need for a granular level of sub-metering as outlined by Brady and Abdellatif (2017) and the need to carefully select the correct methodological approach when comparing regulated and unregulated energy.

Through assessing the current literature, it became apparent that small power load consumption and MEL consumption was only a small proportion of the total electrical consumption. For example, Vadodaria (2014) found that small power and IT loads consumed 5% of total electrical fuels. On the other hand, Hafer (2017) notes considerably higher MEL consumption, as their study outlined the impacts of various MELs, based on the building type. Within this study, laboratory equipment indicated the highest plug load density, which consumed 50% of the total plug load's energy consumption, followed by computers and monitors, which consumed 36% of the total plug loads.

Their work also aimed to analyse general energy consumption within a medium-sized student accommodation block at Queen Mary University. By comparing building sub-metering against the Guide F benchmarks (CIBSE, 2012), Vadodaria (2014) found a significant gap between predicted and actual energy consumption. Most of the electrical consumption was due to three main categories: space heating (regulated), services and pumps (regulated), and catering (unregulated). The identified unregulated energy categories included small power loads, IT equipment, catering facilities, and lifts. These categories consumed approximately 5%, 25% and 8% of the total electrical fuel consumption. The regulated energy categories, identified as space heating, internal lighting, and service pumps, consumed approximately 31%, 6%, and 25% respectively of the total electrical fuel consumption.

3.3.4 Factors which Impact Unregulated Energy Consumption

3.3.4.1 Equipment Usage

Considering the flexible work patterns that come with working within Higher Education, it could be assumed that equipment must be left-on constantly, in-order to deal with these work demands. However, several studies outline a potential for IT equipment consumption to be reduced out-of-hours (Brown et al., 2012; Schoofs et al., 2011; Webber et al., 2006). Schoofs et al. (2011) noted that, across 450 networked machines with a university department, 38% of machines indicated wastage during the night whereas 35% of the machines indicated energy wastage across weekends. Their findings indicate IT equipment were left on unnecessarily during these periods, and indicated a relatively high baseload, further suggesting equipment was not being switched off. This is demonstrated in Figure 3-4.

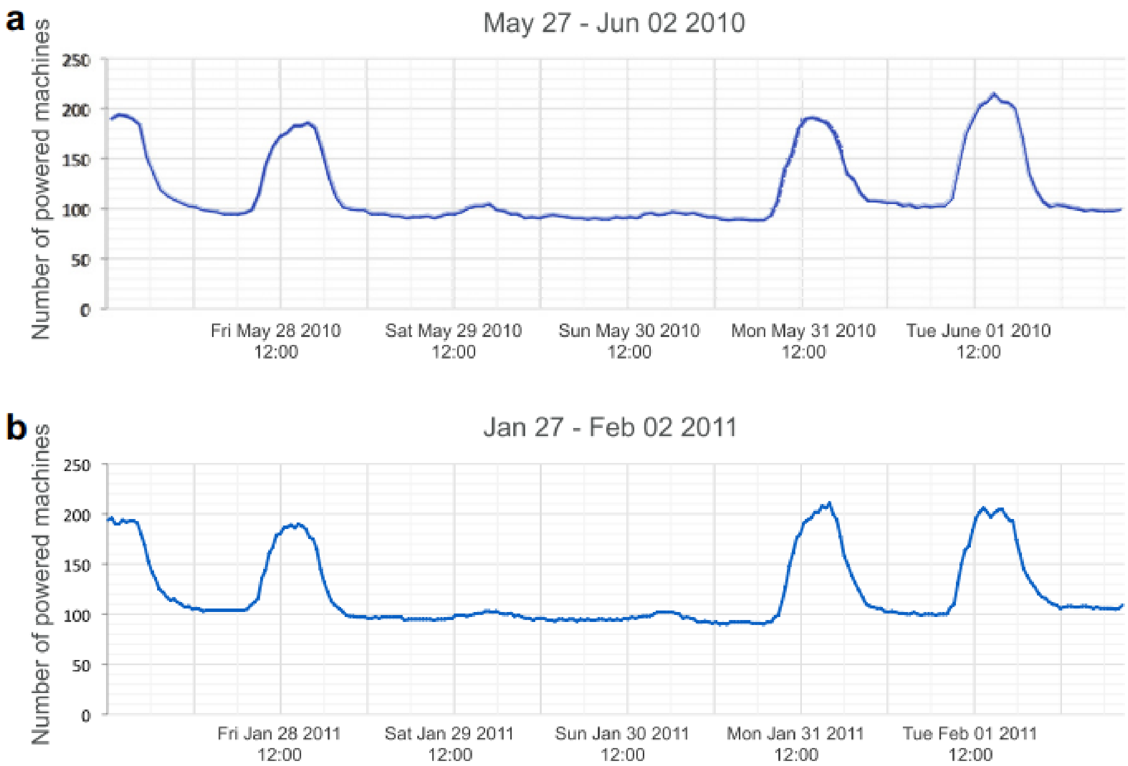

Figure 3-4: Demonstration of IT equipment being left on during out-of-hours periods, within the Schoofs et al. study (2011).

Comparatively, Webber et al. (2006) previously assessed equipment switch-off rates across different sectors within America to further develop this idea. High schools had a noticeable low monitor switch-off rate, whereas universities had the highest Power Management software rate for monitors. This study focused on 16 buildings, however as part of this approach they only assessed two university buildings. So, the limitations of this research must be considered, and it cannot, therefore, be easily applied to all UK universities. However, it indicates the benefits of assessing sustainability initiatives to reduce energy consumption across different universities. Focusing on just the education buildings, which had a sample of 260 monitors, 13% were left on out-of-hours, 74% were on standby mode, and 13% were off (Webber et al., 2006). Many machines were assumed to be left on, indicating a substantial potential saving if all monitors and desktop PCs were either turned off or left idle across campus, during out-of-hours periods.

3.3.4.2 Operational Hours in Universities

Within the literature, "after-hours" consumption is a frequently used phrase when determining energy usage outside of typical work hours (Aljabr et al., 2021; Webber et al., 2006; Schoofs et al., 2011; Brown et al., 2012). However, the use of this term is not accurate for the purposes of this thesis research. However, it is argued here that as energy consumption occurs at all hours of the morning, day, evening, and night, “out-of-hours” consumption is deemed to be an all-encompassing descriptor as opposed to “after-hours”. As such, the term “out-of-hours” is used throughout this thesis in order to identify periods where buildings are predominantly unoccupied.

Electrical consumption, both regulated and unregulated, is typically assumed to be highest during the typical workday and lowest during out-of-hours periods, as has been found to be the case across numerous sources of literature (Schoofs et al., 2011; Brown et al., 2012; Menezes et al., 2014). This is a standard perception, however, the Higher Education sector is atypical in this sense, as buildings remain operational longer than other types of buildings, such as office buildings or school buildings. As such, for the purpose of understanding unregulated energy usage across a full 24-hour day, this section assesses typical operational hours within universities and explains after-hours electrical consumption.

Defining out-of-hours consumption seems easy initially, as it could be assumed that any energy consumption outside of an organisation’s core operational hours might be considered to be out-of-hours. For example, office buildings are typically stated to be operational from 09:00-17:00 on a Monday to Friday basis, where it is assumed office buildings are typically fully occupied and will be at zero occupancy at nights and weekends (Ekwevugbe et al., 2017). So, the assumption here would be that, for a typical office building, out-of-hours consumption would occur after 17:00 and up until 09:00 on weekdays, and all day on weekends. For the Higher Education sector, however, operational hours for different buildings vary dramatically. For example, Table 3-11 indicates typical variable operational hours for Higher Education buildings based on the activities conducted within the buildings (Gul and Patidar, 2015).

In all, operational hours in universities seem to vary considerably and it can therefore be a complex process to determine when in-hours and out-of-hours consumption occurs. This topic is therefore explored within this research and is discussed in detail in Chapter 6 and Chapter 7.

Table 3-11: Typical air conditioning operating periods and activities conducted in various Higher Education buildings (Gul and Patidar, 2015).

Systems	Start	Finish	Operator
Air handling unit			
Teaching rooms	08:00	21:00	Estates
Study/social	08:00	00:00	Estates
Toilet extract	08:00	00:00	Estates
Hot water	06:00	00:00	Estates
Lighting	Depends on requirement		Staff/students
Activities			
Cleaning	07:00	09:00	Staff
Café	08:00	15:30	Staff
Teaching	09:30	18:00	Staff
Support services	09:00	17:00	Staff
Lift	07:00	00:00	Staff/students

3.3.4.3 Effects of the User

As ascertained throughout this chapter, unregulated energy consumption varies based on a number of factors, however what has yet to be discussed in detail is the "effects of user". A user is simply defined here as a person who typically inhabits or uses a building, in the context of a university, this applies predominantly to staff and students. The users of a building can have a substantial impact on how buildings are used, for example Gaetani et al. (2016) note that the large discrepancy between predicted vs actual building performances noticed within their study was due to occupant behaviour. Yan et al. (2015) concurs with this opinion and concludes that occupant behaviour is a major contributor in the difference between predicted and actual energy consumption.

The idea that user behaviour can affect a building's energy consumption is understandable particularly in older buildings with less automated processes. In this type of building, the user has direct control of their environment, so can choose when to turn a light on or off, can choose to keep a piece of equipment running 24/7 or can choose what temperature to set their supplementary heating at. In more modern, automated buildings the direct impact of a user is reduced in certain ways, such as through lighting or heating, however equipment usage typically remains in control of the user. Nguyen and Aiello (2013) note that, through their survey approach, that occupant behaviours have a significant impact upon HVAC, lighting, and equipment energy consumption. Their simulation results indicated that by using occupancy-based control systems, a 10-40% energy saving can be created for HVAC systems. According to their findings, a saving of up to 40% could also be obtained for lighting, using a similar control system approach. Obtaining accurate occupancy input data is thereby necessary, in order to comply with an occupancy-based approach (2013). An automated approach may therefore be preferable for universities' Estates teams, in order to remain in control of building processes.

The literature denotes that various factors impact energy consumption, including both physical and behavioural factors (Uddin et al., 2021). Elements such as everyday life outside of work impacts not only user behaviours inside the workplace, but also on how academic work itself is perceived. For example, Rafnsdóttir and Heijstra (2013) state that a typical workday in academia does not exist. Their 42 semi-structured interviews, with a series of Higher Education academics, outlined that it was common for academics to enjoy high levels of working hours flexibility.

Other researchers strengthen this concept; for example, O'Laughlin & Bischoff (2005) attest that the academia work model allows for evening-time or weekend work, thereby altering typically traditional boundaries. However, Rafnsdóttir and Heijstra's (2013) research noted, staff commonly felt a burden to work constantly even outside of core work hours. Hence, the lack of a rigid workday can affect staff members abilities to "switch-off" from work. Comparatively, Aljabr et al. (2021) note that the use of technological boundaries allows staff members to minimise work connectivity and provide staff with a high level of autonomy, giving a level of flexibility and allowing for variable working patterns. Overall, it is stated here that academia allows for flexible work patterns and thereby, suggests also flexible operational hours for university buildings.

Social relationships can also impact how much energy could be consumed, as well as how an individual may also react and respond to a specific initiative (Hargreaves and Middlemiss, 2020). A summary of these intermingling relationships, and how they may have an impact on energy demand, is highlighted within Table 3-12 below.

Table 3-12: A breakdown of different social relationships and their impact on energy demand, taken from Hargreaves and Middlemiss, 2020.

Social relation type	Definition	Examples	Impacts on energy demand
Relations with family and friends	Relationships of care and intimacy	Parent, child, husband, partner, sister, cousin, aunt, friend, housemate	Learning and shaping practices, sharing energy services, energy consumption advice, lending money
Relations with agencies and communities	Relationships of service provision and activism	Landlords, energy companies, energy advice agencies, tradespeople, community energy groups	Energy consumption advice, energy efficiency support, constraints on choice of tariff or efficiency measure
Relations of identity	Relationships of solidarity and oppression	Age, gender, class, race, disability status, single-parent household, welfare recipient	Access to support due to membership (or not) of a specific category, practices shaped by belonging to that category

Building users can act in a variety of ways which make it hard to predict users' activities and energy consumption usage. Most studies, according to Uddin et al. (2021) use quantitative methods, mostly focused on defining occupant behaviour as opposed to understanding why certain occupant behaviours are developed.

Targeting users' behaviours is complex, particularly on a campus-wide level. However, by targeting user behaviours and causing a change in those behaviours, energy consumption may consequentially also be reduced, thereby also removing the need to apply physical or constructive material changes to existing buildings (Berg et al., 2017). Even if physical changes are made to buildings, typically there is a need to also be a behavioural change, as staff and students need to accept, understand, and use these new changes (Steg and Vlek, 2009). Other factors which may affect a user's pro-environmental behaviour can also be linked to social, cognitive (such as environmental awareness and perceived behavioural control) and affective factors (such as values and attitudes to the environment) (Blok et al., 2015). In all, there are numerous factors that can affect a user and how they control their environment, however, what can be done in a university context to help change and alter these behaviours?

Whittle and Jones (2013) found, through their series of focus groups and questionnaire conducted in the University of Sheffield, a lack of awareness of energy use amongst the participants, although the participants also desired more university-led behavioural initiatives and felt a lack of control over their energy use. These findings suggest a few ways energy policies could be improved, for example through more communication and feedback from universities on users' energy consumption. However, it is important that energy feedback loops must incorporate various actors, and not just focus on the user. For example, including policy makers in the feedback loop is an important step in order to improves policy making decisions (Hargreaves, 2018). Additionally, feedback should also be used to both modify existing user behaviours but also to develop further questions and to further engagement between different actors (2018).

3.4 Review of the Higher Education Sector

Overall, this chapter demonstrates the importance of the Higher Education sector, and its effect on the UK overall. The magnitude of unregulated energy consumption within universities has been outlined There are also various factors found to have an impact on unregulated energy consumption, including operational hours and user behaviours. To that end, it is highlighted here that further research on the topic of unregulated energy consumption is vital; as such, this thesis aims to assess unregulated energy consumption across a series of case study universities, and to investigated further the effects of various factors upon unregulated energy consumption. Chapter 4 therefore discusses these case study universities and outlines key information for each.

Chapter 4 - The Case Study Universities

Research on the topic of unregulated energy has typically focused on other sectors, as discussed in Chapter 2 and Chapter 3, for several reasons. Other building types, such as private office buildings, tend to be more homogenous and thereby are easier to compare (for example, they will use similar constructive materials, have similar types of office equipment, and typically function on similar operational schedules).

Justification has been provided on why the Higher Education sector represents an engaging case study environment and why unregulated energy consumption studies typically focus on other sectors, such as private offices and several types of public institutions. Due to this gap in the current literature, this thesis presents a series of data from case study universities. It was determined that a specific unregulated energy study focusing on university buildings would be beneficial. Chapter 4 provides an overview of the selected universities. Further insight is also provided on how the case study universities were selected and how the universities' data framed the scope of the research thesis.

4.1 Initial Selection of the Universities

Various universities were approached during different key research stages, where approximately 15 universities were approached. Universities were initially approached via email through known Arup contacts and University of Manchester contacts. Universities were prompted at least twice to ask whether they would be interested in the research. However, not all universities approached and spoken to were included in this research. For example, the available data occasionally were insufficient for detailed study. Alternatively, sometimes the conversations indicated that specific research on unregulated energy would not be viable in these universities.

However, several universities provided a decent level of sub-metering data and were deemed suitable for some level of analysis as part of this work. The list of universities approached, who agreed to be a part of this research, were as follows:

- Aston University
- Manchester Metropolitan University
- Nottingham Trent University
- The University of Manchester

- The University of Reading
- The University of Sheffield

4.2 University Data

The universities assessed within this work varied quite considerably from one another. For example, they differed in their population sizes, building ages, and overall university demographics. To understand some of these varied data, this section assesses the case study universities' energy profiles, sustainability initiatives and general financial impacts of the Higher Education sector.

It is imperative to understand the financial providence given by the universities towards the Higher Education sector. By understanding the separate research and teaching incomes, each university can be classified as either a research or teaching-focused university. Some of these data are demonstrated in Table 4-1.

Table 4-1: Financial data, such as teaching and research incomes, for the case studies (HESA, 2021a).

University	Pounds (£)		
	Teaching income	**Research income**	**Total expenditure**
Aston	99,897,000	21,029,000	145,386,000
Manchester Metropolitan	253,170,000	12,050,000	269,697,000
Nottingham Trent	222,789,000	10,028,000	242,473,000
Manchester	484,856,000	342,200,000	943,172,000
Reading	197,743,000	56,815,000	391,460,000
Sheffield	332,223,000	211,251,000	596,881,000

The variable income streams provide an essential insight into how each case study university financially impacts the UK. For all the UK universities included within the HESA datasets, these case study universities only represent 7.04%, 7.75% and 6.03% of the UK's total teaching income, research income and total expenditure (which totals £23 billion, £8 billion, and £43 billion respectively). Overall, compared to other data streams, in 2018/19 the UK government stated that the income provided by the Higher Education sector was £40.5 billion, its' total expenditure was £39.1 billion, consequentially meaning that "a surplus of £1.4 billion or 3.4% of income" was generated (Bolton and Hubble, 2021, p.3).

The UK's Higher Education sector is an essential part of the UK's overall finances. Whilst the percentages may seem small, compared to other sectors, there is still a surplus of £1.4 billion. Though the focus of this thesis is to improve understanding of unregulated energy consumption, there is also an argument that some financial benefits can be attained by reducing unnecessary energy consumption and thereby reduce unnecessary financial spending. Therefore, reducing energy consumption should, in theory, implement financial cost savings. Table 4-2 demonstrates basic information about the universities, such as total annual kWhm^{-2} consumption and non-residential consumption, whilst

Table 4-3 breaks down student headcounts, Scope 1 and 2 carbon emissions, and the universities' management systems. Assessing the HESA data alone indicates some potential comparisons amongst the universities (such as the annual 2018/19 kWhm^{-2} per annum consumption). However, further comparative data must be considered to fully understand the case study universities' sizes, scopes, and purposes.

Table 4-2: Annual energy consumption readings for the case study universities (data taken from HESA, 2021a).

University	Number of buildings	Total site areas (Hectares)	2018/19 energy consumption (kWhm^{-2})
Aston	20	30	278
Manchester Metropolitan	55	37	182
Nottingham Trent	111	265	250
Manchester	211	164	266
Reading	183	131	228
Sheffield	349	124	249

Table 4-3: Environmental comparative data, including Scope emissions, for the case studies (HESA, 2021a).

University	2018/19 total teaching student headcounts	Scope 1 and 2 CO_2 emissions (Kg CO_2e)	Environmental external management system
Aston	11,505	6,398,042	ISO14001
Manchester Metropolitan	29,455	15,779,784	ISO14001
Nottingham Trent	28,205	14,013,991	ISO14001
Manchester	33,285	67,596,583	N/A
Reading	14,880	10,693,415	ISO14001
Sheffield	25,970	40,350,276	N/A

The universities within this study are diverse concerning the number of buildings, student populations and overall CO_2 emissions. Aston University and the University of Manchester perform vastly differently regarding population sizes and carbon emissions. Aston University emits the least and has the smallest student population size. The other universities, except for Sheffield, have relatively modest CO_2 emissions. The University of Reading, Nottingham Trent University, and Manchester Metropolitan University purchase the most significant amounts of green energy. Aston University and the University of Reading also do not capture any residential energy, primarily as they do not have university-owned residences.

In general, student populations are all high across the case study universities, and most of the universities have comparable numbers of "teaching students," except for Aston University. The University of Manchester emits the most CO_2 and consumes the most in terms of campus-wide electrical consumption. These data imply that comparing the universities would not be feasible due to the number of variable external factors prevalent across the buildings.

However, assessing granular data from selected case study buildings is suggested here, rather than focusing on campus-wide and building-wide levels. Concentrating on room-level and floor-level sub-metering makes it much easier to understand how unregulated (and indeed also regulated) energy varies across different academic rooms and institutions. Using a $kWhm^{-2}$ measurement system as well, wherever possible, allows for a standardised measurement comparison across the universities.

4.3 The Case Study Buildings

After selecting the case study universities, various data were provided for several buildings. To better understand the buildings in question, this section provides some brief information on each of the buildings assessed in detail within the research. To begin, the buildings from the primary case study university, the University of Manchester, is broken down into some detail within Table 4-4, which displays different case study building data In addition, Table 4-5 lists different heating systems across different case study buildings, for the University of Manchester. Building names have been anonymised within this dataset.

Table 4-4: Building data, such as building type, age of the building, and operational hours, for case study buildings at the University of Manchester.

Building	Type of building	Construction date	GIA	DEC rating	Operational hours (Weekdays)	Operational hours (Weekends)
UoM 1	Library	2012	5,697.19	E	00:00-23:59	00:00-23:59
UoM 2	Computing	2007	17,252.30	C	08:30-18:00	Closed
UoM 3	Teaching	2008	13,450.76	C	08:30-18:00	Closed
UoM 4	Biomedical lab	2008	10,252.77	G	08:00-18:00	Closed
UoM 5	Teaching	1874	11,134.25	B	N/A	N/A
UoM 6	Engineering lab	1969	4,713.36	E	08:00-17:30	Closed
UoM 7	Engineering lab	1974	10,316.75	B	08:00-17:30	Closed
UoM 8	Engineering and chemical lab	2015	9,043.96	N/A	09:00-17:00	Closed
UoM 9	Maths/computing	1950	2,868.81	D	09:00-18:00	Closed
UoM 10	Computing	1972	16,522.08	E	08:00-18:00	Closed
UoM 11	Teaching	2004	N/A	N/A	09:00-17:00	Closed
UoM 12	Biomedical lab	2014	3919.04	N/A	N/A	N/A
UoM 13	Engineering lab	1963	10,080.61	D	08:00-17:30	08:00-20:00
UoM 14	Lab/teaching	1895	52,823.72	B	08:00-17:30	Closed
UoM 15	Admin/teaching	1919	15,771.38	B	08:00-21:00	Closed
UoM 16	Physics lab/teaching	1967	17,565.20	D	08:30-18:00	Closed
UoM 17	Teaching/admin	1953	20,684.48	C	08:00-17:30	Closed
UoM 18	Biological lab/teaching	1969	56,370.37	G	08:30-21:00	Closed
UoM 19	Teaching	2008	13,370.42	C	08:00-19:00	Closed
UoM 20	Chemical lab/teaching	1964	22,157.55	G	08:00-19:00	Closed

Table 4-5: Annual electrical consumption figures and heating information for the University of Manchester.

Building	Type of building	Annual 2017 (kWh)	Annual 2018 (kWh)	Annual 2019 (kWh)	Heating information
UoM 2	Computing	1,408,890	1,357,212	1,441,794	Low Temperature Hot Water (LTHW) district heating supplied by the Scan boiler house; between mid-May to mid-September, the LTHW is shut down (referred to as summer henceforth).
UoM 3	Teaching	1,151,486	1,120,069	953,631	Steam district heating system, supplied by the Precinct boiler house/Ellen Wilkinson boiler house.
UoM 4	Biomedical lab	2,561,342	2,589,306	2,462,942	LTHW district heating, supplied by the Stopford boiler house; shutdown over summer.
UoM 7	Engineering Lab	659,190	637,374	638,370	The primary heat source is obtained from the John Garside LTHW heating system; heating pumps are closed over summer.
UoM 10	Computing	2,412,913	2,591,939	2,623,555	Standalone gas-fired boiler housed within Kilburn; heating turned off during summer.
UoM 13	Engineering lab	1,097,722	1,123,782	1,083,613	Steam district heating system, supplied by the Sackville main building boiler house; heating calorifiers are shut down over summer.
UoM 14	Lab/teaching	2,090,983	2,000,792	1,902,857	Steam district heating system, supplied by the Sackville main building boiler house; heating calorifiers are shut down over summer.
UoM 16	Physics lab/teaching	2,560,705	2,693,755	2,660,418	LTHW is supplied from a gas-fired boiler plant in the University Place energy Centre; heating is shut down over summer.
UoM 17	Teaching/admin	1,121,319	1,118,087	1,072,012	It is supplied from a large standalone gas-fired boiler plant.
UoM 18	Biological lab/teaching	10,651,758	10,532,008	10,026,851	LTHW standalone gas-fired boilers housed within Stopford; gas-fired steam production boilers are also housed within the building.

For the external universities, the building sample sizes were much smaller, so a brief breakdown for the buildings in question is provided here in Table 4-6:

Table 4-6: Building data for the other case study universities. This includes building type and occupancy periods.

University	Building code	Type of building	Construction date	Occupancy Times (Weekdays, Term Time)	Occupancy Times (Weekends, Term Time)
Aston University	AU	Bioenergy laboratory	2013		
Manchester Metropolitan University	MMU, B1	Teaching / administration	2012		
	MMU, B2	Laboratories / teaching	2014		
Nottingham Trent University	NT 1	N/A	N/A	N/A	N/A
	NT 2	Teaching hub (art/design)	1980	07:00-20:00	10:00-16:00 Sat. only
	NT 3	Conference centre	1990	07:00-20:00	N/A
	NT 4	Exhibitions / education	1969	07:00-20:00	10:00-16:00 Sat. only
	NT 5	Library	1998	Open 24/7 term time	Open 24/7 term time
	NT 6	Admin / offices	1974	07:00-20:00	09:00-16:30
	NT 7	Admin / offices	1978	07:00-19:00	N/A
	NT 8	Medical office	1972	08:00-19:00	N/A
	NT 9	Study / workshops / labs (arts)	1964	07.30-19:00	N/A
	NT 10	Lecture / teaching / admin	1958	07.30-21:00	N/A
	NT 11	Shared space	2013	08:00-22:00	N/A
	NT 12	Labs (physics)	1908	07:00-20:00	N/A
	NT 13	Offices	1863	07:00-19:00	N/A
	NT 14	Teaching (art/design)	1864	07:00-20:00	10:00-16:00 Sat. only
The University of Reading	UoR	Food and nutritional Sciences	1985		
The University of Sheffield	UoS	Research laboratory	2007		

In all, these case studies were selected primarily due to data availability. Each case study had several sustainability initiatives, whether energy-focused or not. Selecting universities with this environmental focus allowed the researcher to adapt the methodology and analytical approach. The process used to collect the data from the case study universities, and what approaches were applied to the data, are covered in further depth in Chapter 5.

Chapter 5 - Methodology

There is a gap within the current unregulated energy knowledge base, particularly from a Higher Education perspective. The literature also suggests that energy consumption within universities is dependent on user-related factors, such as occupancy hours, as opposed to building-related factors.

Based on this information, a methodological process was created using existing university sub-metering data to further add to this literature and to address the knowledge gap. This information was used to quantify unregulated energy consumption across a series of rooms and buildings and was then compared to previous Higher Education benchmarks.

This chapter identifies how the case study universities were selected and describes each university's important building factors. The use of energy management systems (EMS), floorplan designs and other contextual data are assessed in detail here. Finally, the analytical processes are considered to explain potential trends within the data.

5.1 Research Questions, Data Types and Methodological Approaches

To understand the gaps this thesis work aims to answer, a summary of the key research objectives, questions, types of data obtained, and methodological approaches applied to the work are summarised here in Table 5-1.

Table 5-1: A breakdown of the questions, types of data and methodologies used across the thesis work.

Research question	Answering the research question and methodological approach	Data type	Data required
What are the unregulated energy profiles for different types of building stock?	Use NIA and GIA figures, and combine with sub-metering and electrical data, to obtain a series of profiles for different types of rooms and buildings.	Primary	NIA/GIA; floorplans; sub-metering data; electrical figures
What factors influence unregulated energy consumption in different types of buildings?	Use the literature to obtain different potential factors, such as operational hours or types of equipment. Use sub-metering and electrical data to ascertain the effects of these factors.	Primary and Secondary	Literature review; sub-metering data; electrical figures
As the current literature suggests, do occupancy and operational hours impact unregulated energy?	Use information obtained through the interviews to ascertain actual operational hours and obtain occupancy figures. Then compare this information with the sub-metering data.	Primary	Interviews; electrical figures; operational hours; occupancy levels
Do building users have a direct impact on unregulated energy?	Similar to the approach above, use interviews to gather information on changes in room usage/room function, types of equipment used in rooms and changes in types of room occupants. Then use electrical data to observe whether these factors do have an impact on the unregulated energy consumption.	Primary	Interviews; electrical figures; equipment lists; room functions

5.2 Methodological Overview

To summarise the overall process, which is discussed in further detail throughout the rest of this chapter, the following section breaks down the key parts of the methodological process:

1. Case study universities were identified (using existing contacts). Universities were approached for data (including sub-metered unregulated energy data and contextual data).
2. The new obtained data were assessed for its validity, such as confirming the length of the datasets and the quality of room-level data.
3. Overall annual, monthly, and daily energy trends were compared on a building-wide level.
4. Unregulated sub-meters were categorised based on existing Higher Education benchmarks and current literature.
5. Unregulated annual, monthly, and daily energy trends were compared within the previously defined categories on a sub-metered level. Peak, average, baseload, and other performance ranges were analysed during this process. Similar room types were compared within the selected case study university against other buildings within that specific university.
6. Weekday and weekend profiles were compared for the unregulated sub-meters, again within the selected case study university. In-hours and out-of-hours periods were also compared.
7. Levels of unregulated energy were compared amongst the case study universities, and significant trends amongst the data were highlighted. Overall unregulated and regulated levels were broken down on a building-wide level.
8. Ways to reduce energy and other sustainability recommendations were drafted based on the noticed trends and varied among different universities.
9. Following this process, a series of interviews were set-up with different building users, building managers and facility management teams. These interviewees were identified using internal staff search engines.
10. The interview data were then compared to and considered in collaboration with the sub-metering data.

5.3 Data Review from the Case Study Universities

5.3.1 Scope

Once the initial research questions were drafted, the project's overall scope was considered in detail. The research project primarily focused on a mixture of new and old buildings. The buildings themselves had variable levels of sub-metering available; hence, in older buildings, the sub-metering would potentially be less granular (as this assumption was based on observations from the University of Manchester data).

These buildings were also selected based on the availability of additional contextual data, such as occupancy levels, timetabling information, electrical consumption values, a basic idea of what the rooms are used for, and the availability of building contacts. The project's initial scope initially included 250 University of Manchester buildings; however, this scope was quickly reduced due to the lack of detailed electrical consumption data. Nottingham Trent University only provided monthly data readings, so a detailed analysis was therefore limited.

Ideally, this project's scope would have included a more extended period of data, such as five to ten years, in order to better identify annual trends across the datasets. Due to sub-metering data availability, most of the selected case study universities offered approximately one to two years' worth of data.

5.3.2 Data Accessibility

Electricity consumption data were collected using a variety of methodological steps. The methods varied from approaching different building managers and facility management teams to using EMS and historical data. Live data were available to the research through the University of Manchester's EMS, named Coherent. In general, 15-minute to 30-minute readings were available from the case-study universities. A brief overview of the available data is provided here in Table 5-2:

Table 5-2: A breakdown of the sub-metering data available at the case study universities.

University	Data availability	Number of buildings assessed
Aston University	Half-hourly data, granular sub-metering; equipment information	One
Manchester Metropolitan University	15-minute data, with limited granular unregulated energy; floorplan designs	Two
The University of Manchester	Half-hourly data, granular sub-metering; floorplan designs; equipment information	21
Nottingham Trent University	Limited monthly overall building consumption	14
The University of Reading	15-minute data, some room-specific data but limited unregulated energy research	One
The University of Sheffield	15-minute data, some room-specific data but limited unregulated energy research	One

The data obtained from the universities differed substantially; for example, the sub-metering data varied from overall floor level sub-metering up to granular room-level data. Readings also ranged from 15-minutes up to hourly readings. For some universities where the data were limited, the assessment levels were consequentially also limited. In comparison, at the University of Manchester, live EMS readings, floorplan measurements, and contextual were all available; hence the assessment levels available for this university were much more detailed. It is highlighted here, therefore, as being the primary case study within this thesis work.

Data collection did not stop during the COVID-19 pandemic, though it did stop any potential visual data analysis and meant that case study universities could not be visited during the pandemic. Electrical consumption data were still collected, as were other contextual documents.

5.3.3 Answering the Research Questions

A series of questions were considered before the data collection. Based on the existing literature, it became apparent that there remained a gap in assessing unregulated energy trends amongst different university buildings. Based on this insight, a series of simple questions were considered before data collection, as detailed previously within Section 5.1.

Once the questions were formed during this initial process, the analysis process was then modified to accommodate the answer these questions. It needs noting that the universities provided data from different years, and sometimes only one years' worth of data; hence the process detailed above was not always available. Daily and monthly trends were still calculated and assessed; however, they were not compared to other annual datasets.

5.3.4 Quantitative Data Collection

5.3.4.1 The University of Manchester

Due to the level of data from the University of Manchester, this section initially focuses on this case study university. Acting as the first university approached for any data, the University of Manchester represents the most extensive dataset assessed as part of this work. The university uses an EMS called Coherent, available to students and academics for research purposes. The system was used to collect building-wide consumption data. To test the system, building-wide electrical and heating readings for all the main buildings were gathered, targeting all buildings listed on the Main campus and the North campus. An example of this building-wide approach is demonstrated below in Figure 5-1, focusing on one of the case study buildings. Building codes can be found in Table 4-4.

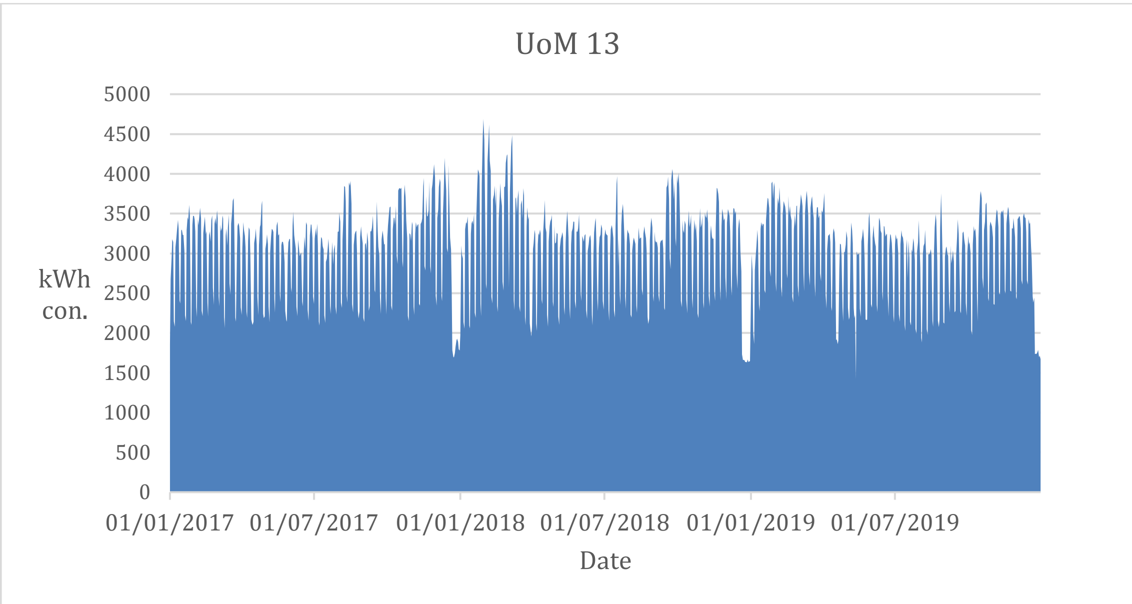

Figure 5-1: Daily electrical consumption for the University of Manchester's UoM 13 building, using data from 01/01/2017-31/12/2019.

The EMS system was then explored further to break down the specific sub-metering available in the campus buildings. Most sub-meters included a description of what the sub-meter linked to, such as it would relate to a specific room or piece of equipment. After a while, it was noted that a sizeable portion of distribution board (DB) sub-meters provided general data, which was not sufficiently granular enough for this research. Therefore, they were excluded from detailed analysis. Breaking down the regulated and unregulated sub-metering was sometimes a complex process, as not every sub-meter was clearly labelled (such as "MS2/L123"). Sub-meters that were not clearly labelled as unregulated energy or room-specific sub-meters were also excluded from detailed analysis.

Once the electrical data were gathered, the research broadened out to collect additional data streams. The university's Estates team were contacted to collect room measurement readings. Floor plan designs, m^2 measurements, total Gross Internal Area (GIA) and Net Internal Area (NIA) readings were collected for the buildings, using the Archibus system. These contextual data, coupled with the electrical data, allowed for $kWhm^{-2}$ per annum readings to be created for the selected university buildings. Leading on from the previous diagram, Figure 5-2 demonstrates how the data appeared once a kWh^{-2} measurement process was used instead of just using kWh.

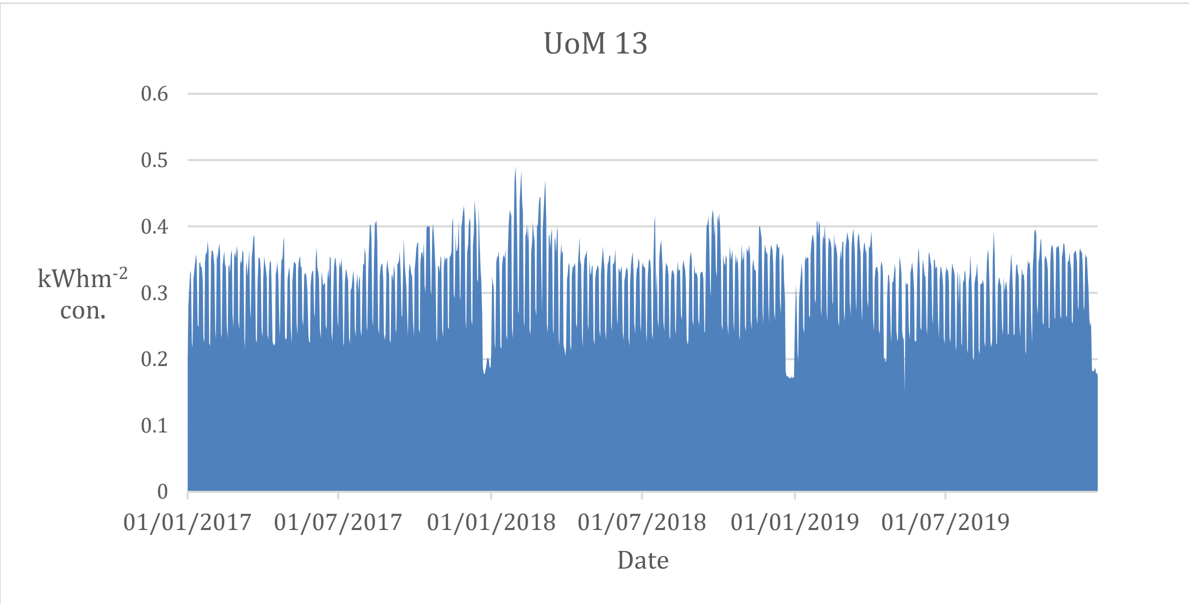

Figure 5-2: $kWhm^{-2}$ per annum readings for the University of Manchester's UoM 13 building, using data from 01/01/2017-31/12/2019.

A $kWhm^{-2}$ measurement allows the data to be compared across like-for-like buildings and other benchmarking schemes. The floorplan database was integral in understanding the purpose of different buildings. However, further contextual data were deemed necessary to properly understand how the rooms and other unregulated energy sub-meters were used.

Contextual data, such as occupant numbers, operational hours, and equipment lists, were deemed to be necessary for this work. Gathering these data were a complicated process due to a variety of reasons. At the University of Manchester, the different data streams were managed by different teams (for example, Coherent was organised by the Energy and Sustainability team, whilst the Estate & Space Management Unit controlled Archibus). It is worth noting here that the university was also approached regarding implementing single-phase data loggers on several occasions. It was decided that collecting live data would benefit this work, rather than just relying on EMS energy data. However, the allocation of such data loggers was deemed unviable by the university, due to equipment safety and access to laboratory area concerns.

5.3.4.2 The University of Sheffield

Outlined here as an example of the difficulty of collecting data, the University of Sheffield provided a potential case study where an additional data collection method was possible. Contacts within the university were helpful, and the university was visited several times to collect data from one of the university's modern research buildings. The building itself had over 3,000 sensors (including copious quantities of sub-metering, though most of it was primarily related to regulated energy). Whilst collecting vast quantities of data seems ideal in concept, if sub-metering were to collect data on a too granular scale, such as every 30 seconds, it creates a massive dataset that would require a data management system that could manage that amount of data.

Unfortunately, the data collection process was delayed due to issues with the building's data storage system. The EMS could not manage and sufficiently store the amount of data collected by the 3,000 sensors; hence enormous quantities of data were deleted from the storage system. Additionally, the data loggers available at the university did not work as initially planned and had to be tested to see why they were not working. While the data loggers were being fixed, the COVID-19 pandemic began, delaying future work within this building.

The difficulty of obtaining data from every university provided some unexpected insight into the challenges in getting sufficient levels of data (from a variety of streams). After these difficulties began, the research scope was re-examined, and the building was deemed unviable for future research. The levels of contextual data and the direct access to the EMS were also used as justification as to why the University of Manchester should remain as the primary case study university.

5.3.4.3 The Remaining Case Study Universities

The data collection process for the other universities was a much simpler and quicker process. For several universities (such as Manchester Metropolitan University), the external sponsor Arup and the supervisory team knew several potential contacts who could be approached for data. They approached members included energy team managers and other official Estates staff members. A data agreement form was sent to these initial universities to outline the data requests.

Some other universities were approached informally later than in this initial group (including Aston University and the University of Reading). These universities were approached based on a broader discussion on the EAUC platform, where different universities discussed how the COVID-19 crisis-affected energy consumption within various universities and campuses.

The data provided from the universities were provided via email (usually using encrypted data). The data consisted of historical .csv files from a set period from 2016-2018 or 2017-2019. Most of the data provided consisted of purely electrical readings, and little contextual information was provided initially. Each university was followed up with, in order to give an overview of the conducted analysis and in order to inquire about necessary contextual data. Obtaining this additional data typically took a long time and required several follow-up requests.

5.3.5 Qualitative Data Collection

After the unregulated energy and floorplan datasets were gathered, a series of informal discussions occurred with several building managers and technical operational managers. These discussions were framed around gathering information about understanding what types of equipment were used within the rooms. Some information regarding occupancy levels and m^2 measurements were also gathered from these discussions.

Building on from these initial discussions, it was determined that the information provided by these individuals was immensely useful, as it provided a level of contextual information not available from the existing datasets. As such, a series of interviews were set-up with different individuals at the University of Manchester.

The University of Manchester was selected for this purpose, due to the availability of other datasets and due to the existing working connections made with some of the interviewees. Potential interview candidates were identified using several methods, including using the university's internal staff network to identify individuals with specific roles, using terms such as "Technical Operational Manager" or "Energy Manager". Candidates were approached via email to enquire whether they would be interested in taking place in an interview process, detailing the purpose of the interview and the expected outcomes. An information sheet and consent form were sent to each potential interview candidate, detailing how their data would be handled and protected.

Seven semi-structured interviews were set-up, and these interviews were conducted virtually. Appendix B includes the list of questions asked for building managers, technical operational managers, and users of the building space (if information was required for certain rooms). Appendix C includes the list of questions asked for Facility Management Teams – this list of questions focused on key areas 1 and 4, as these individuals had information pertinent to understanding the challenges in applying sustainability initiatives in universities and provided important information on the role of Facility Management on a top-down level.

Each interview ranged from 30-60 minutes and covered topics generally focused on the following areas:

1. The role of different Facility Management teams and energy-saving initiatives
2. Understanding equipment usage and research areas
3. Operational hours and room usage
4. Implementing sustainability initiatives

Voice recordings were made of these interviews, where each recording was then transcribed using Descript. Once transcriptions were made of each interview, the voice recordings were then deleted, in line with necessary ethical approval considerations. Participant names and building names were also anonymised, again in order to comply with necessary ethical approval requirements.

Once all the interviews were completed, transcribed and the audio files had been deleted, the files were assessed for thematic patterns. Focus initially was to be placed on information related to equipment usage, occupancy patterns, challenges felt when applying sustainability initiatives, and general perspectives on energy usage within the university. These themes and findings are expanded upon in Chapter 6.

5.4 Relevant Literature

Prior to conducting the data analysis, relevant literature was considered in detail. Therefore, the thesis research was inspired by several authors, and a combined mixed-mode approach was adopted, based particularly on the works from the following authors:

- **Khoshbakht et al. (2018)** – This paper collected data from 80 university buildings and assessed Energy Use Intensity benchmarks (EUI), space types and total electrical consumption. They also used a stochastic frontier analysis model to compare benchmarking data. Data were collected via the university's metering system.
- **Lawrence and Keime (2016)** – Two university buildings were compared using post-occupancy evaluations (POEs), a field survey, and environmental measurements (such as a thermometer and anemometer).
- **Menezes et al. (2012, 2013)** – These series of papers document assessing unregulated and small power loads within office buildings to reduce the performance gap. Their 2012 study's methodology involved a two-model process: randomly sampling monitored data which was then compared to observed data, vs a 'bottom-up' system which required collection of detailed input data such as equipment used and usage patterns.
- **Mulville et al. (2014)** – This paper assessed energy use across 90 desks within two office buildings by allocating energy monitoring devices. Equipment profiles were created to identify various equipment's ages, types, numbers, and usage patterns.

An approach focused on assessing current unregulated energy consumption across various buildings was deemed suitable based on the existing literature. Using data obtained from the case study universities, a series of electricity benchmarks were created to act as a comparative tool when looking at different buildings through this process. Regarding other benchmarking schemes, a simple benchmarking range was made initially using data from the University of Manchester (due to the granularity of the available data). The benchmarking content was categorised into a similar format to the CIBSE Guide F Higher Education benchmarks (CIBSE, 2012) and the HEEPI benchmarks (obtained from Bennett et al., 2006), and assessed minimum, maximum, and average reading ranges. A demonstration of this breakdown is included in Table 5-3.

Table 5-3: An example of overall electrical consumption performance ranges for different University of Manchester buildings.

Building type	Sample size	Minimum ($kWhm^{-2}$ per annum)	Average ($kWhm^{-2}$ per annum)	Maximum ($kWhm^{-2}$ per annum)
Computing – Maths	2	483	592	701
Libraries	2	192	224	257
Teaching	4	74	151	339
Laboratories – Engineering & Physical sciences	11	70	120	253

When looking at the previous relevant research, it was decided that a benchmarking process like the Guide F/HEFCE benchmarks and the HEEPI benchmarks would be suitable, as they each represented some of the best Higher Education energy benchmarks currently available. Benchmarking, which previously explained includes the creation and comparison of a single building-wide electrical or gas reading against similar types of buildings, is not the focus of this work, however. As the focus of this work was on obtaining and assessing granular room-level data, it was hypothesised that focusing solely on a building-wide electrical reading would not be as useful as a detailed breakdown of different university spaces and case study rooms.

5.5 Data Analysis

Once the qualitative and quantitative literature review had been conducted, the following research stage required systematically assessing the data. To this end, a series of analysis techniques were applied to the datasets.

5.5.1 Assessing Unregulated Energy Consumption Profiles

The initial data breakdown began with assessing overall building-wide electrical consumption, typically across datasets from 2017-2019. To reiterate, these timeframes were used based on data available at the time of the core thesis research. The overall electrical consumption readings (including regulated and unregulated energy) were collected from EMS and excel data files. This process was conducted in order to understand how every case study building performed on a building-wide level. This same process was then conducted for the specific unregulated energy room-level sub-meters across all the universities. Once the data were collected, a series of graphs were created in order to demonstrate annual consumption on a building-level and a room-level. An example is represented in Figure 5-3 and Figure 5-4.

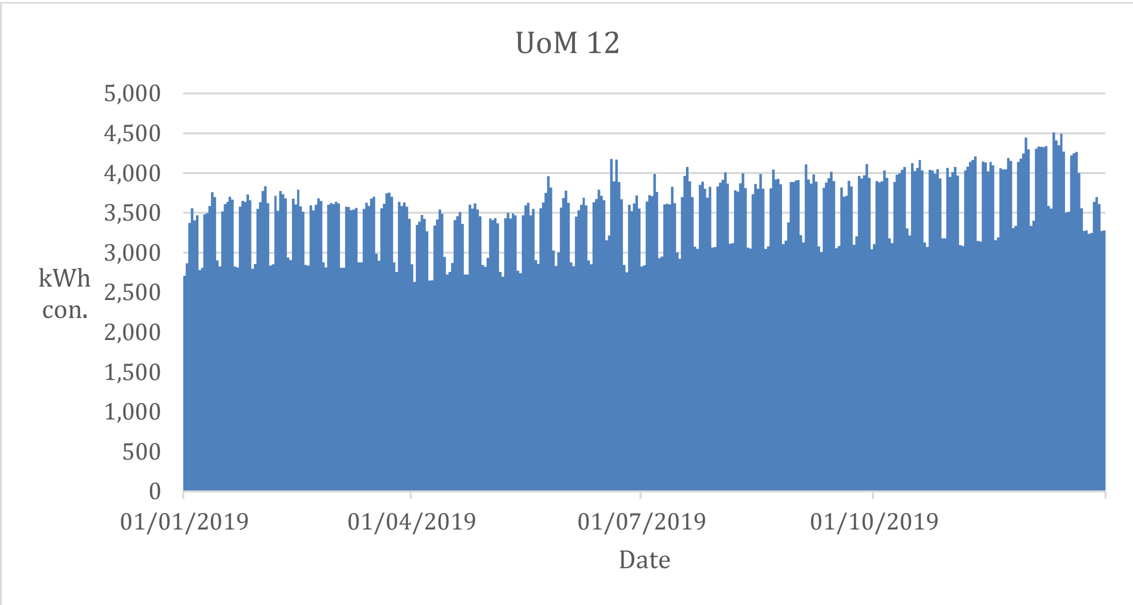

Figure 5-3: Annual electrical consumption in UoM 12, using 2019 data. Building codes can be found in Table 4-4.

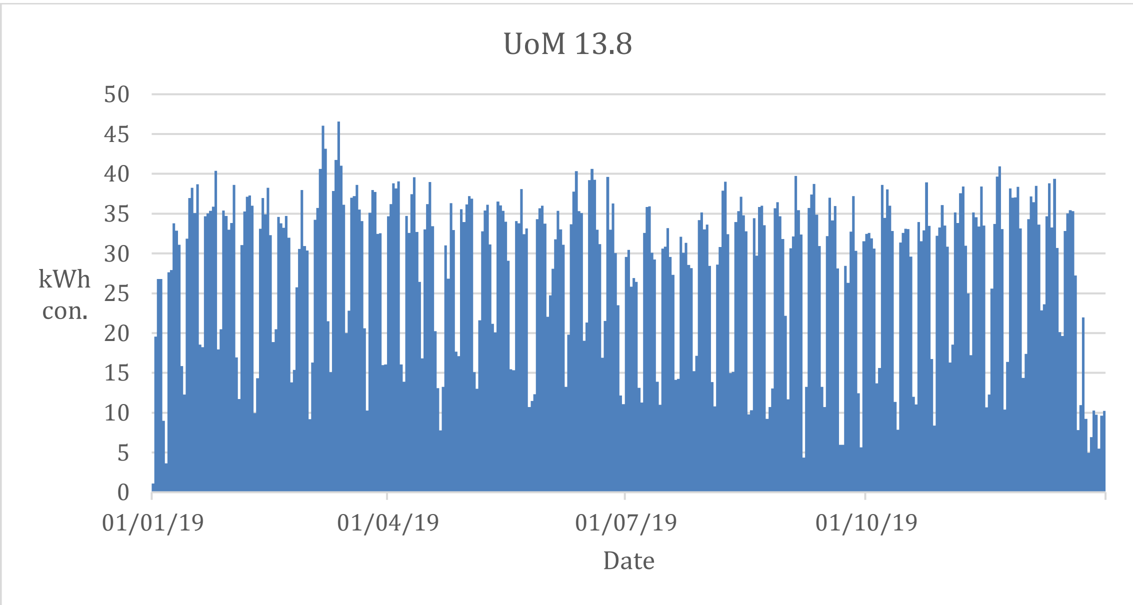

Figure 5-4: Annual electrical consumption in room UoM 13.8, in UoM 13, using 2019 data. Room codes can be found in Table 7-1, whilst building codes can be found in Table 4-4.

It was initially hypothesised that electrical consumption, on a building-wide scale, would remain relatively consistent across the datasets. This was assumed due to several factors: consistent staff and student numbers, lack of major retrofits and constant equipment usage within the buildings. On a granular unregulated room-level scale, it was also hypothesised that the annual electrical consumption would be much more variable. Patterns amongst the data, such as daily and monthly trends, was assumed to be visually apparent.

Understanding how out-of-hours consumption varied against in-hours consumption was imperative. As such, days were categorised into in-hours periods (08:00-18:00) and then into out-of-hours periods, on a building-wide and room-wide level. These operational hours assumptions were based on the literature review, on official operational hours listed in different university documents, and based on discussions with various interviewees. Average weekday and weekend days were also compared, to help further understanding on how the buildings and rooms were being used across the week. Theoretically, the rooms across most of the buildings should have been empty during weekends, according to contextual data provided by the universities. For example, at the University of Manchester, most case study buildings are closed during weekends (Saturdays and Sundays). The external universities also indicated a similar idea, where most of the buildings should be empty and primarily unoccupied.

Peak consumption trends and baseload consumption also had to be assessed, in order to understand how the different buildings performed. To calculate peak consumption, data across the universities were assessed to identify any peak hourly and daily trends. This analysis method would include visual graphical analysis and tabular analysis. Peak hourly consumption would primarily occur throughout a typical workday (such as 10:00-11:00) whilst peak week consumption would frequently occur on weekdays, normally on Mondays, Tuesdays, and Thursdays. Wednesdays and Fridays typically indicated lower consumption overall and would typically not demonstrate peak consuming days.

Finally, different potential external factors were also considered regarding whether they would impact room-level unregulated energy power consumption. For example, Heating Degree Days (HDD) and Cooling Degree Days (CDD) were initially considered and were calculated. However, for the available data, it was decided that calculating HDD and CDD were not an important external factor, primarily as both relate to a building's thermal properties.

Therefore, compared to room-level power consumption, both HDD and CDD were deemed not to affect the results obtained within the study significantly. Some of this analysis is displayed within Chapter 7, however.

5.5.2 Incorporation of Contextual Datasets

Finally, once the data had been treated and assessed accordingly, the research incorporated available contextual information from the case study universities. Contextual data were categorised as anything relating to non-electrical readings, such as floorplan designs, room measurements, equipment lists, operational hours, ages of buildings, the purpose of the buildings. This information was deemed necessary to calculate a series of measurements and to calculate how several factors affected hourly, daily, monthly, and annual consumption.

Floorplan measurements provided information on what the different rooms were being used for across the buildings and information such as maximum occupancy numbers. Room sizes meant that $kWhm^{-2}$ and $kWhm^{-2}$ per annum measurements could be calculated. Where room measurements were not available, the kWh consumption was still considered and assessed as a part of this work. The exact process for analysing the data were still conducted across all the universities, where there was still a superior level of available data (such as occupancy numbers and room purposes).

Equipment lists meant that different types of equipment could be categorised and correlated to any changes within electrical consumption. Operational hours also acted as a potentially imperative factor in understanding room-level electrical consumption. By looking at the operating hours of the buildings, different outlying datasets (such as rooms that acted outside of expectations during out-of-hours periods) could be further explored.

Building age was captured during the work, in order to identify whether building age mattered in assessing total electrical consumption or whether it may not have much impact. The purpose of the buildings was also integral to this work. The research also aimed to assess how different buildings (and rooms) significantly impacted total unregulated energy consumption. It was also intended that building age be compared to building purpose to see whether there was a significant difference in results.

Gathering this contextual information was a complex process for all the universities. Some simple contextual information was provided (such as floorplan measurements and room purposes). However, other contextual information had to be researched in-depth (such as building age, operational hours, and room sizes). The most detailed contextual information was gathered from the University of Manchester due to the access to direct databases (like Coherent and Archibus) and the number of informative contacts. These factors were also compared to the CIBSE Guide F Higher Education benchmarks (2012), which represent the most up-to-date widely used university benchmarks for the Higher Education sector.

Trends and insights obtained from the interview process were also used in comparison to the sub-metering data. Specific information on rooms, such as types of equipment or changes in occupancy, were compared to the unregulated energy and electrical datasets. Further analyses were noted for rooms with this detailed interview information, in order to explore whether there was a correlation between user-activities and unregulated energy consumption.

5.6 Validation of the Data

The selection of data was based on several factors. Each factor was decided in advance of the data selection, and the aim was to ensure this approach would be applied to each university. Some variations of this approach were made for different buildings for several reasons, each listed here. The primary method is described in further detail here.

- **Factor 1:** At least one years' worth of data must be available on a sub-meter level.
- **Factor 2:** The sub-meter must be working for at least 90% of each per annum dataset.
- **Factor 3:** Outlying data must be removed from the dataset, but a record of this removal must be kept.

Based on the order of importance, Factor 1 was deemed the most critical factor overall, as a suitable amount of data were required to sufficiently assess and quantify levels of unregulated energy. Factor 1 was quickly applied to the University of Manchester dataset, as the EMS was accessible to the research team. However, only historical datasets, sent in .csv files, were available for the other case study universities. Hence sometimes, these datasets only included one years' worth of data. Typically, they varied from one to three years' worth of data. Based on this, it was concluded that they would be deemed suitable if the datasets were of a minimum of one year.

Factor 2 required the sub-meters to be working for most of the year or for most of the dataset (assuming the dataset was longer than one year). 90% was selected as a suitable percentage; it was noted that many sub-meters would occasionally indicate they were not working for a brief period (2-3 days per annum). So, a 100% working rate was unlikely for most sub-meters. Any sub-meters that indicated a period where they were no longer working for substantial periods, such as one month, were excluded from this work. This factor was applied across all the universities and buildings studied.

Factor 3 describes a slightly more subjective criterion; however, the basis of this factor is further explained here. Any dataset that indicated a reading over ten times the regular average reading for the same period, such as 15:00, would be excluded from the dataset. This factor did not have to be frequently applied to the research, as Factor 1 and 2 ensured the datasets were consistent and reliable. However, this step did have to be used occasionally on a building-wide level and a sub-metering level. This is Factor concept is demonstrated below in Figure 5-5, using the University of Manchester data.

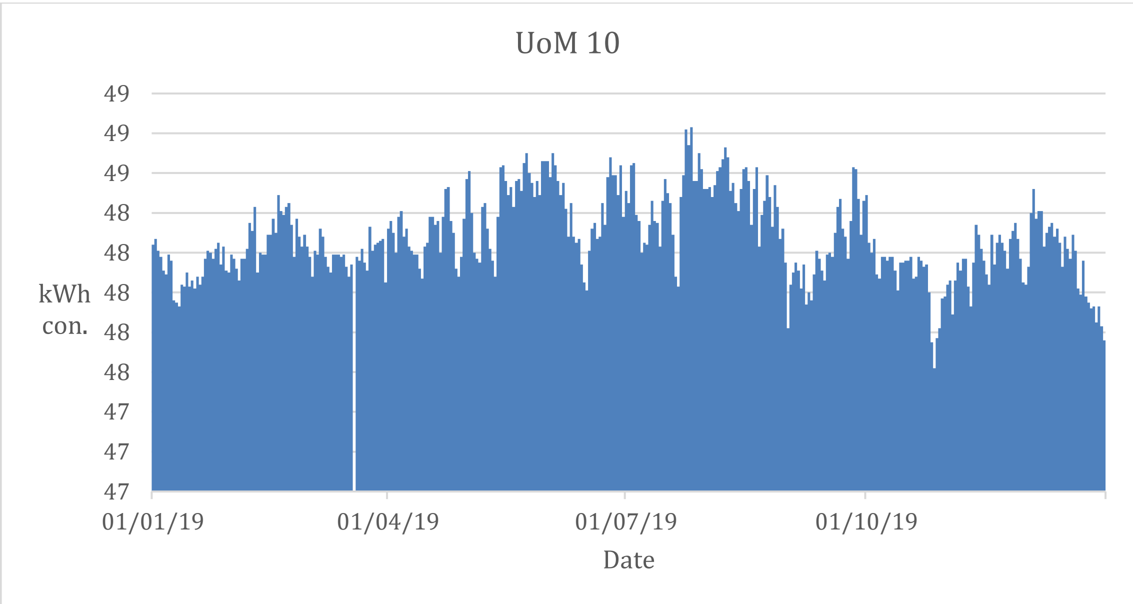

Figure 5-5: Total annual (2019) electrical consumption within the UoM 10 building.

A note was made if Factor 3 had to be applied to any dataset, so the removed figure was always still available. Frequent outlying data were removed from a series of dates at the Manchester Metropolitan University. Across various sub-meters, outlying data were identified as taking place on the same days and at the exact time, such as with Manchester Metropolitan University. The reasoning for the series of outlying data on these dates was unknown. However, the issue was hypothesised that the Estates were running a test on the sub-metering at this time. This would explain why so many datasets indicated a problem with the sub-metering during these times. Alternatively, there was potentially an issue with the building's sub-metering.

Some more variable factors were also considered before the Factor creation. Accordingly, the first step included assessing how the data had been collected. For this stage, the accuracy of the data had to be examined. For example, "Was the data from a sub-meter that frequently breaks down?" "Did the overall building metering indicate some sub-meters might be broken?" If the answer was yes to either of these questions, the dataset would then not be assessed further. Secondly, the data's validity had to be checked. For example, questions such as "Does the room m^2 measurement seem reasonable?" or "Do the electrical readings seem reasonable? How do they compare to the literature review?" were all considered. If there were unregulated power consumption readings of over 1000 $kWhm^{-2}$ per annum for specific rooms, the dataset was initially highlighted as incorrect until further information from that sub-meter could be obtained (as some laboratories did reach this amount; hence this step was conditional based on the data available).

Chapter 6 - University Practices, Policies and Energy Demand

6.1 Introduction

The previous chapters have set up the need to discuss, assess and develop a further understanding of the topic of unregulated energy consumption. This understanding has been a particular oversight within the Higher Education sector; in order to improve this oversight, this thesis work now broadens to assess unregulated energy consumption within the case study universities.

Chapters 6 and 7 detail the results of this thesis. Chapter 6 presents insights from seven semi-structured interviews conducted with building managers, technical and operational managers, Estates facility managers and building users. Throughout the interviews, a series of trends were identified by manually identifying common themes throughout the interviews. Frequent trends within the interviews typically related to heating, highlighting annual and variable building usage patterns, COVID-19 pandemic concerns, and sustainability not typically considered a personal responsibility.

These interviews were conducted, following the collection and analysis of sub-metering data, to understand better the university working practices which affect unregulated energy consumption and to gather detailed room and equipment information. Both further our understanding of energy consumption in different spaces. Finally, this chapter presents a thematic analysis, which highlights differing perceptions towards personal responsibilities to implement initiatives and underlines the importance of the user regarding energy consumption.

Comparatively, Chapter 7 compares sub-metering data provided by each university and assesses levels of unregulated energy consumption for various university rooms and buildings. Chapter 7 is primarily focused on quantitative data and consequentially answers the questions outlined in Section 1.3, thereby answering lingering questions from Chapter 6, such as determining whether “the user” impacts unregulated energy consumption.

6.2 Interview Overview

Seven interviews were conducted with building users undertaking different roles, as summarised in Table 6-1. In order to protect the interviewees' identities, some of the roles referred to within the table have been generalised.

Table 6-1: A list of the anonymised interviewee information for the University of Manchester.

Interviewee code	Role	Any energy responsibilities?	Building-related to	Interview-focus
Interviewee 1	Building and laboratory user	No	UoM 6	Personal research; the role of the user
Interviewee 2	Technical Operations Manager	Responsible for running the building, with energy partially linked to this	UoM 10	Building management responsibilities; the role of the user; room information
Interviewee 3	Engineering Director	Responsible for running the building, with energy partially linked to this	UoM 8	Building management responsibilities; the role of the user; room information
Interviewee 4	Head of Operations	Responsible for running the building, with energy partially linked to this	UoM 8	Building management responsibilities; the role of the user; room information
Interviewee 5	Professor linked to Climate and Energy Policy	Responsible for planning carbon policies, with energy partially linked to this	None	Academic responsibilities; the role of the user; sustainability
Interviewee 6	Senior Technical Operations Manager	Responsible for running the building, with energy partially linked to this	UoM 12	Building management responsibilities; the role of the user; room information
Interviewee 7	Principal Energy Engineer	Responsible for university energy management	None	Estates responsibilities; the role of the user; sustainability

The list of interview questions can also be found in Appendix B and Appendix C. The questions listed in the Appendices were used as a guide; the intention for the interviews was that they would be semi-structured, and depending on the interviewee, certain question sections were less relevant. For example, Estates-focused interviewees were not asked room-specific or building-specific information. Instead, they were asked additional questions about sustainability and energy initiatives, both current and planned future initiatives.

The interviews were analysed from two different viewpoints. Firstly, it was important to understand different buildings' functions and usage patterns. This required collecting room usage and contextual equipment data during the interviews and then analysing the responses to these two categories. Secondly, a thematic analysis needed to be conducted to identify factors that shape and influence energy consumption, both regulated and unregulated. Specific codes were used to identify various trends in these interviews. For example, the following words would have fallen within the “regulated energy” category:

- Heat; heating; hot; cold; temperature; radiators; light; lighting; bright; dark; dim; air conditioning.

6.3 Overview of the Case Study Buildings

The literature in Chapter 3 highlights how unregulated energy demand is dependent on building function and equipment used to carry out that function. This is a dynamic process, where there might not be detailed records kept of equipment, or this may change over time, depending on organisational or academic needs. To overcome this information oversight, a detailed inventory of equipment is presented here for some case study rooms that have been co-developed with different users and university staff. These inventory lists are listed here within Table 6-2 to Table 6-5. This information is combination of previously found historical equipment lists and interviewee data.

Table 6-2: A breakdown of equipment and room information gathered from Interviewee 1, focusing on UoM 6, in the University of Manchester.

Building	**Room number**	**Room function**	**Equipment within the room**	**Changes to use**	**Typical occupancy**
UoM 6 Used for electrical engineering	UoM 6.3	Electrical engineering; server room	An SSF six system; A Lemke LDS 6; DayCor UV camera; 800kV AC Test Set; 600kV DC Test Set; RIV3 with three-channel RIV Meter and 500kV PD free Coupling Capacitor; 200kVA, 11000 / 433V no load, 3 phase, 50Hz, ONAN transformer; Supply of replacement air cushion system for 2MV impulse generator.	Big impulse generators changed within last five years; building is now unoccupied due to the MECD move	Heavily used

Table 6-3: A breakdown of equipment and room information gathered from Interviewee 2, focusing on UoM 10, in the University of Manchester.

Building	Room	Room function	Equipment within the room	General experiments being run in the room
UoM 10 Used for robotics and machine learning. No major building changes since 2018.	No relevant sub-meter code	Machine learning and optimisation lab	28-30 computers	AI-based work; a postgraduate research space
	No relevant sub-meter code	General lab	14 computers	A lot of user interfaces and human computer interaction stuff are conducted in the room. It is a PGR space so "they do tend to accrue computers".
	UoM 10.2	Server room	143 servers 2 AC units Numerous networking switches	Initially a comms room, the room was adapted into a server room. Some equipment was moved into a separate machine room in Jan/Feb 2020.
	UoM 10.1	Computer cluster	100 desktop computers; 100 single watching monitors	Initially a comms room, the room was adapted into a computer cluster.
	No relevant sub-meter code	Computer cluster	96 desktop computers; 96 monitors	/
	No relevant sub-meter code	Computer cluster	60 computers	/
	No relevant sub-meter code	Teaching area	106 computers	Initially the room was "a series of meeting rooms and quiet labs" which was "knocked together to make one large teaching area where "the use of that [room] has changed significantly"; this room

				change was completed in 2020.
	No relevant sub-meter code	General lab	A Spinnaker system, with a dedicated 100 kilo kW supply; 2 chillers	/

Table 6-4: breakdown of equipment and room information gathered from Interviewees 3 and 4, focusing on UoM 8, in the University of Manchester.

Building	Room number	Room function	Equipment within the room	Changes to use	Typical occupancy
UoM 8 Used mainly for chemical engineering research.	UoM 8.17	Terra Hertz lab	All old research equipment moved to Room 2.013	Initially it was a Digitcal lab but was transformed into a Terra Hertz laboratory in 2022; 3D printer removed from room	
	UoM 8.11	Nano infrared suite	Numerous small power instrumentation Numerous high-powered laser systems	Previously was the old Terra Hertz lab, which has been moved to Room 1.007	
	No relevant sub-meter code	Composites lab	Small quantities of low power equipment 2 fume cupboards		
	UoM 8.3	Chemical and energy lab	3 fume cupboards	Changed from a composite lab to an energy lab in August 2017	2-10
	UoM 8.4	Industrial chemical partner lab	Mbraun glove boxes Numerous low-consuming desktop instruments Several fume cupboards		2-10
	UoM 8.15	Chemical lab	Numerous low-consuming desktop instruments 1 cryostat		2-20
	UoM 8.12	Chemical lab	Numerous benchtop 13A atom force microscopes 1 cryostat		2-20

	UoM 8.13 + UoM 8.14	Chemical lab	5 high-powered lasers A 32A compressor A 32A supply for the cryostat unit 1 cryostat		
	UoM 8.22		Plasma deposition systems and metal depositions 1 E-beam spotter	An E-beam spotter was installed Christmas 2019	Highly used bay
	UoM 8.24	Chemical lab	2 microscopes, multiple surface mount equipment, 2 wet benches, 2 fume cupboards		
	UoM 8.10	Electromagnetic control room	1 Closed-loop magnetic cryostat (only equipment within the room)		

Table 6-5: A breakdown of equipment and room information gathered from Interviewee 6, focusing on UoM 12, in the University of Manchester.

Building	Room number	Room purpose	Equipment within the room
UoM 12 Used primarily for cell and medical research.	UoM 12.8, UoM 12.9, UoM 12.11	General experiments	Same types of equipment in each room: Small benchtop equipment running off 13-amp supplies (micro centrifuges, small benchtop apparatus, benchtop centrifuges, under bench -20°C fridges)
	No relevant sub-meter code	Instrument room	Heated incubators (running at 37°C), multiple ice machine
	UoM 12.14	Freezer room	Six -80°C freezers
	No relevant sub-meter code (6 rooms in all)	General labs	Four Class-2 microbiological safety cabinets in each room, eight CO_2 incubators in each room
	No relevant sub-meter code	Cold room	Chillers
	UoM 12.18	Glass wash	Two large autoclaves, three autoclaves overall Drying oven (running at approx. 50°C)
	No relevant sub-meter code	General lab	One x-ray irradiator, Two liquid-coiled 10,000-volt transformers
	UoM 12.15	-80°C freezer room	Six -80°C freezers
	UoM 12.16	-80°C freezer room	Four -80°C freezers

6.4 Effects of Academic and Research Practices on Unregulated Energy Consumption

This section outlines and discusses various academic and research practices and their effects on unregulated energy consumption. Firstly, this section assesses how building occupancy affects energy demand. Secondly, it assesses the types of equipment required for particular types of research – such as an electrical engineering building uses different equipment to a chemical engineering building.

6.4.1 Operational Hours and Building Usage in University Buildings

One question that consistently arose during the literature review stage of the research was, "Do operational hours have an impact upon unregulated energy and what are the true operational hours for typical Higher Education buildings?" As previously discussed in both Section 2.3 and Section 3.3.4.2, operational hours can be defined as the main period where a building will be predominantly occupied. The literature review suggested in Section 3.3.4.2 that Higher Education buildings have largely variable operational periods, depending on the type of building. A laboratory building may be used on weekends, for example, in order for samples to be continuously checked and analysed, whereas a humanities building may not be open on weekends.

One of the goals of the interviews was to understand how building usage changed over a year, a month, a week, and a day. Many universities are closed over the Christmas period, and usage drops during other holiday periods, for example, Chinese New Year and the summer. Interviewees reported that holiday periods, such as the summer holidays, Christmas, and Chinese New Year, were the major cause for a reduction in staff and students across the case study buildings which were primarily used for research (including UoM 6, UoM 7 and UoM 12. UoM 10 acts as the exemption here as it is a predominantly teaching building). Interviewee 1 noted that the UoM 6 building was less occupied during January and February due to staff and students returning home for the Chinese New Year.

In contrast, the usage patterns of a building primarily used for teaching (the UoM 10 Building) differed from the research-orientated buildings, as outlined by Interviewee 2:

> *"Christina Birch: Okay. So that, that gives an idea. Would you say there's any kind of a major changes in usage across the year apart from that? Or is it pretty consistent?*
>
> *Interviewee 2: I mean, the glib answer to that is the huge spikes in use just before deadlines.*

Christina Birch: Yes. Well, it's an honest, you know, yeah. […]

Interviewee 2: Not really the, there are dips in use around the exam periods because- a lot of our clusters get grabbed for the exams."

For UoM 10, the rest of the year saw little to no change in usage patterns or major reductions in staff or student numbers, however the pre-exam periods saw an increase in building usage.

When assessing typical electrical consumption profiles across the case study buildings, there was typically a clear building-wide reduction in consumption during holiday periods, with Christmas in-particular. This is unsurprising as, across all of the case study universities, there are consistent reductions in electrical consumption during the Christmas holiday period. Accordingly, this is due to reductions in staff and student numbers on campuses, and due to the buildings themselves often being shut down, where only essential staff members are allowed to use the buildings during this period. Similarly, a connection can be made between the Christmas shutdown periods and the COVID-19 pandemic shutdowns. The pandemic itself acts as an example of a substantial change in occupancy levels across all of the case study buildings and universities. When the pandemic was mentioned, it was more often to explain a change in the usage of rooms and laboratories, such as in Interview 2, where teaching laboratories within UoM 10 were almost completely unused. Similarly, Interview 6 noted a large change in working patterns within the building, denoting that since COVID, there had been a large uptick in hybrid working (working from home more frequently, for example). The exception for this allowance would be Research Technicians, as Interviewee 6 highlighted the need for them to be working at laboratory benches to conduct research. Generally, though, across all the interviews, whilst the COVID-19 pandemic did have a substantial effect on the usage of the buildings and on the numbers of staff and students allowed on campus, these changes have since reduced back to an almost pre-pandemic level.

Whilst changes in annual and monthly building usage patterns were expected, it was vital to further understand changes across more granular datasets, such as on a daily or weekly basis. The findings from the interviews suggest that the university buildings are typically used across weekends, particularly laboratory or research-focused buildings, where staff members require access to their research on a 24/7 basis, for example to check samples or ensure equipment is up and running. The interviews also highlight that most computers across the university can be accessed remotely, allowing for staff and students to work from home or from other offsite locations. These two findings potentially explain why out-of-hours consumption does not substantially decrease, where literature on the topic does suggest that out-of-hours consumption typically does not reduce substantially due to equipment being left on (Soares et al., 2015).

For the building-specific interviewees, with knowledge of UoM 8, UoM 6, UoM 10 and UoM 12, the participants were asked the questions, "What are the typical open hours for the room/building? What are the actual in-use hours like?" This question was asked in order to identify two things: firstly, did the building's official operational hours, used by the Estates, match actual usage of the building? And secondly, did the unregulated energy consumption data show any correlation to the true operational hours of the building?

The official core operational hours for the buildings were found to typically be 09:00-18:00 for weekdays, whilst weekend usage of the buildings varied accordingly. For UoM 6, the building was normally used during core operational hours, including for experiments. Interviewee 1 stated:

> *"Experiments largely would only be done 09:00 till 17:00 or maybe 9:00 till 18:00, depending on how long, but you wouldn't tend to get much in the way of high voltage experimentation going on."*

Outside of core hours, the interviewee did point out people would come in to do sample preps, such as on weekends although this was not officially allowed.

For UoM 10, operational hours of the building typically matched the expectations of the Estates, though Interviewee 2 did point out the flexible nature of working within the building, and discussed the actual hours where the building is in use:

> *"So yeah, 09:00 till 18:00 is the main opening hours. Yeah. And during that period, it's pretty much constantly used during the week […] There are extended opening hours for the students that go until 09:00 o'clock. I believe it used to be later […] that they used, that used to be 11:00. And theoretically, the building is open for use from 08:00 in the morning. However, one of the things that you will run into here is that a lot of the, certainly the researchers won't physically be present in the building […] but will be using their computers."*

Similarly, for UoM 8, the usage hours followed a similar pattern to those of UoM 6 and UoM 10, though as it is classed as a 24-hour facility there was more flexibility in the usage of the building. Interviewee 4 stated typical usage hours for the staff within the building:

> *"08:00-19:00. But realistically we'll probably start seeing an increase in the number of people coming in about 11:00 AM- till about midnight. But we're a 24-hour facility, so there could be someone here in here at 03:00 in the morning."*

When prompted, Interviewee 3 declared that, whilst not promoted by management, staff members would frequently enter the building outside of core hours, though the numbers of staff within the building would be severely reduced during weekends. This occurrence was similarly mentioned as taking place in UoM 6 as well by Interviewee 1. In terms of people using the building at the weekends, Interviewee 3 mentioned:

> *"And [at] weekends we're probably, you probably have, I know, five, 10% occupancy."*

Interview 1 highlights that occupancy levels remain considerably much lower at weekends, though officially, the buildings should be unoccupied, according to management. Finally, UoM 12 matched similar operational hours to that of UoM 6 and UoM 8, with Interviewee 7 stating:

> *"You, you're pretty much a 9:00 till 17:00 or a 09:00- course pretty much general office hours […] I think but most people are 09:00 till 17:00. The building is open all the time. And people will come in and do, if, if you've got cell lines growing, for example, […] or doing time, time course experiments, but they're, you know, that'll be weekends and, and evenings. Holidays, but nothing major.*

Access to the UoM 12 building was also monitored by Interviewee 6, where building users could only access the building out-of-hours with permission being granted from their research group leader, with Interviewee 6 stating:

> *"I control the access for the building, so- we, we have human tissue authority regulations, so we have a secondary security for all the lab areas […] As part of that agreement, so people only get access to the labs once they've been fully inducted to the building. And also for out-of-hours access we have to seek permission from their, their group leader."*

Each of the interviews discussed in this section highlight the flexible nature of working within a university. Using the data from the interviewees, it is apparent that whilst weekday operational hours remained relatively consistent, weekend occupancy of the buildings was much more variable. Though the user demand for the building was lower across all the buildings on weekends, they remained consistently used in some way or another.

For UoM 10, whilst users may not be in the building itself outside of core hours, they will typically use their remote-controlled computers for work and research purposes. As a computational mathematical building, this means a series of high-powered computers must be frequently left on in order to make this remote access possible. Similarly, other interviewees mentioned a similar occurrence, where staff and students may not necessarily be present in the building out-of-hours but will require computer usage. This could explain, on a wider scale across the university, an increase in buildings baseloads, in order to make this computer access accommodation. To see whether this was the case, an in-hours vs out-of-hours analysis was conducted for different computer clusters across the case study universities. This can be found in Section 7.4.2. These flexible working patterns does potentially mean an increase in unregulated electrical consumption but also allows for 24/7 research to be conducted.

The definition of in-hours and out-of-hours has been previously discussed in Section 3.3.4.1 and Section 3.3.4.2. Each of the interviews show that, the buildings were predominantly used between 09:00-18:00. However, this does not capture cleaning staff coming into the buildings early in the morning or security staff working later in the evening. So, whilst the buildings may be predominantly empty, they cannot be classified as completely empty, hence the building as still being used, even outside of core hours. Both cleaning staff and security staff do not have a major impact upon unregulated energy consumption as both groups do not require access to high-powered equipment. According to the interviews, four of the buildings frequently saw small members of staff working in the buildings on weekends, so were actively in-use during these periods, though occupancy numbers tended to be much lower.

In order to define usage of buildings and actually define what out-of-hours can mean, whilst these case study buildings are used outside of core working hours, due to the small percentage of staff working inside of them, for these case study buildings, the in-use hours are defined as 09:00-18:00, and out-of-hours consumption are defined as 18:00-09:00 on weekdays, all-day for weekends. These hours are not representative for all Higher Education buildings but do act as a guide for laboratory-focused buildings.

6.4.2 Equipment and Small Power Loads

During the interviews, equipment was often discussed, particularly where the interviewees would provide contextual information on types of equipment in different rooms. This section breaks down this topic further, firstly by discussing different research practices that can affect unregulated energy consumption, such as changing room use, which in turn impacts consumption. Secondly, this section also discusses that in many cases, records/inventories are poor, both historical lists (needed to understand changes going back in time) and records of small power loads. The need for up-to-date information is best provided not from historical lists or records but from building users and various operational managers based within the buildings themselves.

This research revealed that, for many rooms and buildings, there were no inventories of equipment, including larger three-phase pieces of equipment and small power loads. A lack of inventories not only presented challenges to this research in understanding how the use and purpose of particular rooms or buildings affected unregulated energy consumption. This also consequentially makes it harder for building managers to do the same. Due to oversights in the historical equipment datasets, it was decided that the interview process would be used to obtain more up-to-date equipment information.

Where interviewees were able to go into depth, discussing the types of equipment used across the buildings, the specific equipment and small power loads were detailed in Table 6-2 to Table 6-5. The combination of historical equipment lists with the information obtained from the interviewees was a vital step into understanding unregulated electrical consumption in different room. For example, the data in Table 6-4 captures some but not all the small power equipment listed within two rooms UoM 8, as shown below in Figure 6-1, which was captured during a preliminary visual analysis approach in February 2020:

Figure 6-1: A sample layout of two rooms within UoM 8.

During both the historical equipment list analysis and interview process, small power load equipment was often not mentioned. Instead, larger pieces of equipment, such as three-phase equipment, were mentioned instead. Hence, in order to collect all pieces of small power load equipment, it is recommended that the university conducts a series of equipment audits, which could then be easily updated by building users once new equipment is placed in a room or old equipment is taken away from a room. The lack of detailed equipment inventories offers an opportunity for the university to make use of the local knowledge of building managers to provide accurate equipment lists accessible to relevant staff within the appropriate building, such as for staff members that monitor energy usage or manage the building overall, or an open-access database for all staff members.

The data from the case study rooms suggested that a change in equipment can result in a change in energy consumption. Likewise, a change in a room's overall purpose and number of occupants can also result in a change in energy consumption. This is further explored in detail in Chapter 7, Section 7.4.2.

6.5 University Initiatives

Leading onto the topic of sustainability at the University of Manchester, Table 3-3 previously provided a deeper insight into the various initiatives taking place across each of the case study universities. The key information is, however, summarised here:

- The university aims to be zero carbon by 2038.
- Using 2007/08 as a baseline, the university has achieved a 37% absolute carbon reduction (using 2018/19 data).
- From 2007/08 up to 2019/20, the university has reduced electrical emissions by 46.35% (from 53,496 tCO_2 to 24,796 tCO_2).
- The 10,000 Actions campaign is the university's primary campaign, encouraging staff to take personal actions in and out of the workplace.

6.5.1 Managing Building Challenges

It was noted throughout the interviews that regulated energy remained a consistent concern for several of the interviewees, most notably heating and lighting. The interviews appeared to have a more direct relationship with regulated energy as opposed to unregulated energy, in the sense that regulated energy challenges were mentioned much more consistently than unregulated energy challenges.

Heating was a concern mentioned by multiple interviewees and with a common level of exasperation in relation to heating which different users explained did not work as required to meet their needs or the needs of other building users, which is partly demonstrated here with Interviewee 2. The UoM 10 building was built in 1972, meaning it is classed as an older building with an older heating system:

"The heating and cooling in [UoM 10] has been a multi-decade train wreck. And has been a constant source of problems with Estates because the- it really is not actually fit for purpose. The control of temperature in different zones around the building is- if they make one area colder, it makes another area warmer and vice versa. And it- it's terrible. It really is and there have been many conversations to try and get it improved, whether or not it ever will, I don't know.

I've heard it said that it would actually be easier to knock the building down and build a new one to fix the heating problems. Whether that's true, I don't know. But it wouldn't surprise me at this point."

Interviewee 6 had a similar reaction, and discussed the UoM 12 building, which was built in 2014. This building would be classed as a modern building, meaning the issue here was that the heating, and building, were not working as it should. Interviewee 6 mentioned that:

"Well, you've got people in that, in, in what would be cooking in the, in the summer and freezing in the winter."

The heating in the building remained a consistent issue and had to be quickly rectified, where in 2017-2018 radiators were added across the building to resolve the issue.

"Interviewee 6: Yeah. Yeah. And the, there's all sorts of problems with the snagging and eventually when [redacted] was Head of Estates. And we kept going, saying, listen, "it's 18 degrees in, in the building at best".

Christina Birch: Yeah.

Interviewee 6: Although that's technically, you know- "legally"- it's absolutely miserable."

On a topic that received a less emotive response from the interviewees, the issue of lighting was mentioned throughout several interviews, particularly for UoM 10, UoM 8 and UoM 6. There was a desire from several interviewees for automated lighting to be rolled out across various buildings. For example, Interviewee 2 mentioned, in order to make the building more sustainable, an increase in the amount of automated lighting would be beneficial, as at present there was automated lighting only within retrofitted areas in the building. Similarly, for UoM 8 and UoM 12, both building managers did encourage sustainable activities focusing primarily on lights and computers being turned off. This focus on lighting and computing suggests a focus on "easy wins" perhaps, or a focus on easily visible ways to reduce energy consumption. Only two interviewees mentioned other initiatives that could be implemented within laboratories, such as through automated fume cupboard sashes, which were in place within UoM 8.

Across other buildings within the University of Manchester, after speaking to different staff members, it was found that manual lighting existed in several spaces on campus. Where manual lighting did exist, users felt like they could have direct control over their lighting. In UoM 7.1, in the building's computer cluster, lighting could be turned on in specific areas, removing the need to light up the room in its entirety. This is displayed in Figure 6-2 below. As this one room contained approximately 149 double lights with an additional 40 in the room's annex and 6 in the adjoining corridor, being able to control and at least partially turn off lighting could thereby cause a substantial reduction in the overall lighting consumption. This lighting set-up was found to be a consistent one across other clusters at the university.

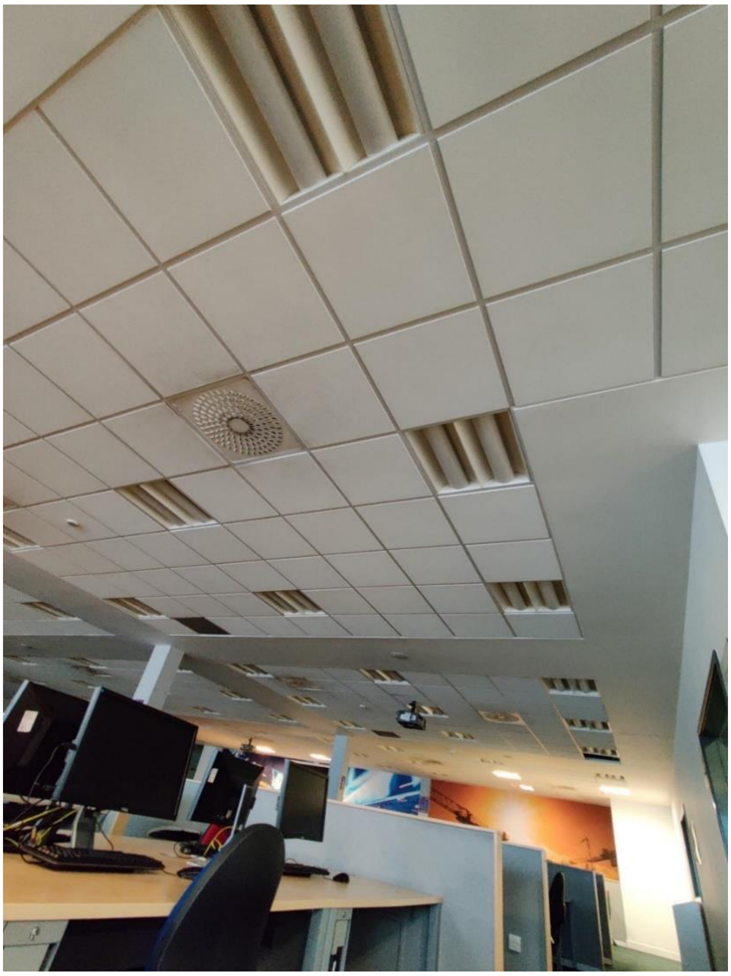

Figure 6-2: A demonstration of the lighting within UoM 7, in the computer cluster.

There was an ongoing concern amongst some of the interviewees about what the future could hold, focusing mainly on the possibility of rolling blackouts. The worry for these interviewees was more so on a financial side, focusing on financial implications of the energy crisis. For context, during the interview-process in December 2022, the UK was going through a period of energy uncertainty and substantially high energy costs (Department for Business, Energy & Industrial Strategy, 2022a). Organisations had been forewarned about potential energy blackouts, and this was felt as a major concern among building managers particularly, such as Interviewees 3 and 4:

> *"Interviewee 4: We've been told to prepare for rolling blackouts. So, if the government decide that they're gonna have an eight-hour power blackout, what do we do?" […]*
>
> *"Interviewee 3: But, if the electricity went off in the [different lab building], the impact is, you know, just, just disruption. The impact for the, the- is- sorry for the [UoM 8] is significantly more than- what is clean space will suddenly become very dirty space. That- and that could be a several hundred-thousand-pound clean down.*
>
> *Interviewee 4: And we could have potentially millions [of] pounds of damage to the kit as well."*

Comparatively, Interviewee 5 noted the need to have a long-term Estates strategy focus in order to reduce potential financial crises whilst also considering decarbonisation concerns:

> *" Interviewee 5: You know, we [the Estates], we did a thing years ago where we did some work on aligning the long-term maintenance strategy and decarbonisation, and it just got, it just got rejected, but without any like, bring it back or- and you know, it was just like, and so it, it just kinda withered. Yeah.*
>
> *Christina Birch: Yeah.*
>
> *Interviewee 5: But by goodness we wished we'd done it once the energy prices fired up in any way!"*
>
> *[…]*
>
> *Interviewee 5: If your energy price doubles, your payback time halves. So, all these things that people thought were too expensive you know, it's, it's kind of the ally of some, it, it's the ally of decarbonisation, the energy price increase. As long as people are strategic enough in their thinking, one of the problems is sometimes they get pitted against each other. It's like, "Well,*

we can't do that because we've got these energy price rises". And it's like, well, yeah, but surely that's only going one way in the long run. So, we need to invest on getting the demand."

Overall, there was a clear understanding from the interviewees of various challenges within their buildings, typically linked to heating. However, as will now be discussed, there was less awareness in terms of various initiatives in place, to reduce energy consumption.

6.5.2 Sustainability and Energy-specific Initiatives in Higher Education

Moving onto the issue of sustainability, whilst the interviews predominantly focused on understanding the case study buildings better, there was also a focus on understanding the importance of sustainability in the university. Two interviewees in particular spoke in length about different initiatives being held in the university, whilst the other interviewees mentioned the topic to a lesser extent.

Interviewees 5 and 7 both indicated large sustainability-focused changes have been occurring within recent years in particular, and sustainability seemed to have a much larger role to play within management and the Estates, though initially there was a reluctance and general lack of initiative, from a university-level, to declare a climate emergency. According to Interviewee 5, who began to speak about the university's Zero Carbon Management plan and carbon reduction target (which aims for the university to become zero carbon by 2038):

"We announced the target with no plan of how to deliver against it. Now that's not that unusual in climate emergency type framings although we, although we actually didn't declare the climate emergency. […] We made a, we made an announcement where we said that we supported the UK Parliament- the UK Government, in declaring a climate emergency, which they actually hadn't done. It was the UK Parliament, and it was a very strangely worded press release in my opinion.

And […] slightly demonstrates us not quite knowing at that time what our position was. We didn't want to declare a climate emergency. We only wanted to do it if someone else was doing it. And then we didn't actually bother to check that we were getting the right people to do it."

The Zero Carbon Management plan itself was hailed as being integral to both interviewees, which lays out the university's future goals and plans to become a Net Zero carbon university by 2038. The plan itself, as explained by Interviewee 7, focuses on various pathways, however the first three years of work are heavily focused on energy efficiency works. So, the Estates-based interviewees focused primarily on future goals, which were clearly laid out in various policy documents and in the Zero Carbon Management plan.

However, most of the interviewees were unaware of sustainability initiatives being run in their buildings and felt like the responsibility lay else in the university, such as the Estates. For example, Interviewee 1 had not heard of Green Impact, one of the university's previous sustainability campaigns, and mentioned that:

> *"Interviewee 1: I'm just trying to think if we've [even] been told to turn lights off!*
>
> *Christina Birch: Oh, okay. Is that, is that the same for your new building as well, or-*
>
> *Interviewee 1: Yeah. It's like, it's not a high consideration. It's got to be said. Yeah, I can't think of anything off the top of my head where we've been told or asked to […] to do anything really."*

Interviewee 1 concluded that it was an issue not being particularly considered, or if there were things going on, they were not being filtered through to PhD researchers and Research Associates. From a building user perspective, dissemination of top-down information seemed to be an issue, where there was a lack of clear communication or university-strategy, In terms of sustainability.

However, for interviewees that were responsible for Building Management, some felt able to have direct control over their building environments; for example, Interviewees 3 and 4 showed that both building managers, whilst not having energy management responsibilities as part of their jobs, did have other sustainability responsibilities:

> *"Interviewee 3: We do obviously from our financial responsibilities […] -we, we're obviously encouraged as a part of the green agenda and sustainability agenda through, through the Management team of the university to reduce power where possible. You know, so we do encourage things like lights to be turned off and computers to, you know, so through, through university policies, but we, both of our roles are really aligned to, to university policies."*

If the building-based interviewees (and excluding the Estates-based interviewees) felt able to make a change or where they recommended changes, these changes were always attributed to turning off the lights, switching off computers and occasionally turning off laboratory equipment. This sentiment is likely replicated across other buildings as, thorough visual analysis, sustainability-focused posters typically related to heating and lighting. A snapshot of this has been captured from Building 12 and is shown in Figure 6-3 and Figure 6-4.

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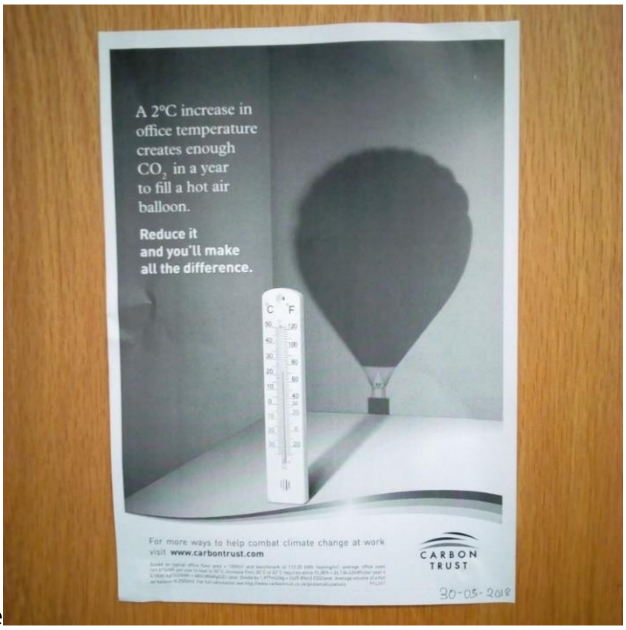

Figure 6-3: A sustainability-focused poster, observed across various buildings across Manchester. This photo was taken from Building 13.

Figure 6-4: Another sustainability-focused poster, observed across various buildings across Manchester. This photo was taken from Building 13.

Certain buildings, such as UoM 8, have auto sashes on several fume cupboards, where both Interviewees 3 and 4 agreed this would be beneficial if this could be rolled out across the building, in order to reduce unnecessary energy consumption. They also agreed that more auto lighting would be beneficial across the campus. Interviewees 1 and 2 felt like targeting computer-usage would be feasible within their buildings, where in UoM 10 for example, the monitors on desktop PCs within the building never automatically go to sleep. The knowledge given by these interviewees are incredibly helpful, as they help give the university an insight into ways to reduce both regulated and unregulated energy consumption in different campus buildings.

6.6 The Impact of Building Users

The role of the user is an integral one to understand, partly in order to add context to variable unregulated energy levels, but also to understand how university buildings are used. For example, the interviews suggested flexible building usage patterns across the case study buildings, thereby making actual operational hours often different to the official operational hours (defined by the university's Estates teams), as discussed in Pages 111-116. Whilst weekday building occupancy numbers did typically match the official operational hours, buildings were often partially occupied on weekends, which did not match the official operational schedule, as noted by the Estates.

The focus of the interviews often also went back to "getting the job done", primarily concentrating on research outputs instead of taking the "responsibility" of integrating different sustainability initiatives. In terms of energy, most of the interviewees focused on "switching off", primarily for lighting and desktop computers. For the Estates-focused interviewees, their focus remained more so on the Zero Carbon Management plan and future work on what the university can do. There is a need to merge these two separate focuses in order for the University of Manchester to enact various research and user practices, particularly in relation to different occupant and research needs, whilst also reducing unnecessary energy consumption across the Estates.

The interviewees displayed various insights and observations relevant to the discussion of energy consumption, such as offering equipment information or personal opinions related to energy-specific initiatives. Overall, the context and understanding provided by these interviewees help lead into a further discussion on the topic of unregulated energy consumption, as will be discussed further in Chapter 7.

Chapter 7 - Unregulated Energy Consumption in UK Universities

7.1 Overview

The previous chapters have set up the need to discuss, assess and develop a further understanding of the topic of unregulated energy consumption. This understanding has been undeveloped within the Higher Education sector; in order to improve this oversight, this thesis work now broadens to assess unregulated energy consumption within the case study universities.

Within Chapter 6, unregulated energy profiles have been created for a series of different academic spaces. Various energy consumption profiles were created using total Gross Internal Area (GIA) or Net Internal Area (NIA). Unregulated energy-specific sub-metering data were rare within older buildings and were more prevalent in newer buildings, particularly laboratory buildings.

Through the analysis, it was noted that unregulated energy typically consisted of under half of a building's total electrical consumption on a building-wide level, which goes against what the literature suggests. As mentioned within Chapter 3, the notion that a building consumes approximately 50% regulated and 50% unregulated energy is mentioned in the literature, though one that often has little backing added to it. Within the University of Manchester, the data suggests that on average 24.74% of a building's electricity is due to unregulated loads. In contrast, approximately 75.26% was due to regulated energy and generic distribution boards (which contain both regulated and unregulated energy). These findings suggest that the sub-meters capturing unregulated energy on the campuses are typically room-level sub-meters. The buildings with the highest unregulated energy consumption were all linked to laboratory rooms and other research-intensive rooms.

Both operational hours and occupancy levels were found to significantly impact unregulated electrical consumption. This was particularly apparent during the COVID-19 pandemic where, across three universities, (the University of Reading, Aston University, and the University of Manchester), overall baseload electricity consumption reduced by 30-50%; however electrical consumption remained consistently high during evenings, weekends and other out-of-hour periods. On a room-specific level, a correlation can be made between zero occupancy periods, such as the COVID-19 pandemic and Christmas shutdown periods, and lower unregulated energy consumption. Using this information, it can be considered that there are two types of out-of-hours consumption: “soft” out-of-hours periods, where consumption does not drop significantly, such as evenings and weekends, and “hard” out-of-hours periods, such as over Christmas and COVID, where consumption drops with low occupancy. Thereby there was found to be an intricate connection between unregulated energy consumption and occupancy numbers.

Across all the case study universities, operational hours indicated that equipment was consistently left on out-of-hours during weekends, causing a higher baseload than initially anticipated. As a recommendation, building managers could successfully reduce unregulated energy during out-of-hours periods by focusing turning off equipment out-of-hours.

7.2 Energy Demand and Consumption in Higher Education Buildings

Overall building electrical consumption measurements were collected using Energy Management System (EMS) sub-meters, at a frequency of 30-minute intervals, for the University of Manchester. Electrical consumption figures for the other universities were collected through .csv files, varying from 15-minute intervals up to hourly intervals. For Nottingham Trent University only monthly electrical and gas figures were available.

This section focuses on how unregulated energy was categorised and broken down across the case study buildings.

7.2.1 Room Codes

Further assessing the unregulated consumption within the case study rooms, a thorough breakdown of the rooms, their sub-meters, and annual electrical consumption values are listed in Tables 7-1 to 7-6, listed for each of the case study universities. These tables will be referenced throughout this chapter, in order to identify building and room codes.

Table 7-1: Unregulated sub-metering, room types, and annual electrical consumption at the University of Manchester.

Building and room code	Sub-meter/room type	kWhm^{-2} per annum				
		2017	2018	2019	2020	2021
UoM 1.1	Catering	341	312	302	110	201
UoM 3.1	Catering	247	230	200	79	88
UoM 3.2	Comms	639	631	629	827	674
UoM 3.3	Comms	584	578			597
UoM 5.1	Comms			221	224	224
UoM 6.1	Admin		439	364	255	218
UoM 6.2	Admin					
UoM 6.3	Laboratory		89	67	43	54
UoM 6.4	Switch room	767				
UoM 6.5	Switch room		27	21	18	20
UoM 7.1	Computing	102	70	60	65	66
UoM 8.1	Laboratory	359	329	346	143	356
UoM 8.2	Laboratory	203	177	127	112	168
UoM 8.3	Laboratory	231	323	319	261	197
UoM 8.4	Laboratory	403	521	237	94	501
UoM 8.5	Laboratory	1,368	1,800	1,684	1,338	494
UoM 8.6	Laboratory	41	33	27	25	25
UoM 8.7	Laboratory	81	116	118	133	21
UoM 8.8	Laboratory	73	75	93	55	146
UoM 8.9	Laboratory	99	92	94	48	104
UoM 8.10	Laboratory	145	310	1,388	1,031	1,436
UoM 8.11	Laboratory	118	80	163	146	184
UoM 8.12	Laboratory	66	66	71	33	
UoM 8.13	Laboratory	93	148	137	117	
UoM 8.14	Laboratory	981	1,255	1,063	784	1,119
UoM 8.15	Laboratory	391	404	379	268	458
UoM 8.16	Laboratory	79	91	103	73	92
UoM 8.17	Laboratory	314	303	362	260	282
UoM 8.18	Laboratory	192	161	108	33	18
UoM 8.19	Comms	449	330	319	342	343
UoM 8.20	Comms	493	488	491	513	516
UoM 8.21	Laboratory	350	305	215	166	310
UoM 8.22	Laboratory	179	44	98	115	161
UoM 8.23	Laboratory	21	23	42	35	42
UoM 8.24	Laboratory	137	276	220	136	293

UoM 8.25	Laboratory	397	399	390	298	434
UoM 8.26	Laboratory	976	950	901	928	934
UoM 8.27	Laboratory	341	381	411	474	977
UoM 8.28	Cleanroom	85	85	85	86	86
UoM 8.29	Cleanroom	105	104	103	102	102
UoM 8.30	Laboratory	1,653	1,657	1,779	1,112	2,060
UoM 8.31	Laboratory	520	481	502	403	510
UoM 10.1	Computing		190	207	203	166
UoM 10.2	Computing		70	64	49	56
UoM 11.1	Comms			67	74	74
UoM 11.2	Laboratory		33	33	25	39
UoM 11.3	Storage				87	85
UoM 11.4	Switch room				1,378	1,247
UoM 12.1	Admin	126	123	128	119	105
UoM 12.2	Catering	756	603	667	240	206
UoM 12.3	Catering	130	129	122	98	96
UoM 12.4	Computing	615	620	704	705	725
UoM 12.5	Computing	781	946	924	724	701
UoM 12.6	Computing	709	710	696	696	706
UoM 12.7	Computing	1,276	1,376	1,320	1,362	1,361
UoM 12.8	Laboratory	66	60	59	46	61
UoM 12.9	Laboratory	42	35	38	32	39
UoM 12.10	Laboratory	253	293	286	189	229
UoM 12.11	Laboratory	25	30	27	15	21
UoM 12.12	Lecture theatre	35	32	33	25	28
UoM 12.13	Computing	1,047	1,383	1,419	1,407	997
UoM 12.14	Laboratory	1,780	1,821	2,047	2,105	2,047
UoM 12.15	Laboratory	876	888	1,049	1,049	1,121
UoM 12.16	Laboratory	2,510	2,493	2,511	2,616	2,540
UoM 12.17	Laboratory	1,006	1,079	1,660	1,359	1,797
UoM 12.18	Laboratory	85	199	282	141	223
UoM 13.1	Workshop	65	75	74	43	
UoM 13.2	Workshop	66	57	11		
UoM 13.3	Workshop	390	197	374	257	279
UoM 14.1	Computing			88	109	170
UoM 14.2	Catering			43	11	11
UoM 15.1	Catering	92	126	132	37	31
UoM 15.2	Computing			68	51	80
UoM 16.1	Catering			487		

UoM 16.2	Workshop	722	767	579	240	47
UoM 17.1	Catering	255	242	177		73
UoM 17.2	Computing	76	109	83	72	100
UoM 17.3	Lecture theatre	90	104	101		
UoM 18.1	Storage	27	36	38	29	14
UoM 18.2	Storage	877	868	744	697	685
UoM 18.3	Lecture theatre	192	167	157	137	135
UoM 18.4	Lecture theatre	190	176	171	156	160
UoM 18.5	Lecture theatre	86	81	75	73	65
UoM 18.6	Lecture theatre	49	45	49	32	43
UoM 19.1	Catering	0	70	79	57	50
UoM 19.2	Catering	0	43	49	36	41

Table 7-2: Annual kWh consumption for the Aston University building's sub-meters.

Sub-meter code	Sub-meter name	Room definition	2019/20 data (kWh per annum)
AU 1	Catalysis lab	Laboratory	83,894
AU 2	IT Server Room	Server room	9,329
AU 3	1st Floor Lab 3&4 P+L	Laboratory	20,527
AU 4	1st Floor Lab1	Laboratory	27,521
AU 5	1st Floor Lab2	Laboratory	24,848
AU 6	1st Floor Lab3 – Algae Lab	Laboratory	26,177
AU 7	1st Floor Lab4	Laboratory	20,693
AU 8	Gasifier compound P+L	Laboratory	3,348
AU 9	Gasifier	Equipment	22,322
AU 10	Ground lab 1	Laboratory	19,127
AU 11	Ground lab 2 power	Laboratory	5,406
AU 12	Lift	Lift	2,156

Table 7-3: Annual kWh consumption for the Manchester Metropolitan University buildings' sub-meters.

Sub-meter code	Sub-meter name	2016/17 (kWh per annum)
MMU 1	Car Park Lighting	73,362
MMU 2	Data Centre Cooling	32,500
MMU 3	LV Room Power	3,526
MMU 4	Server Room	598
MMU 5	Emergency Lighting	22,983
MMU 6	Energy Centre MCC3	600
MMU 7	External Lighting Plaza	6,695
MMU 8	External Lighting Plaza	3,486
MMU 9	Café Power	20,894
MMU 10	Kitchen electricity	N/A
MMU 11	Loading Bay	N/A
MMU 12	Kitchen supply	44,987

Table 7-4: Annual $kWhm^{-2}$ calculations for the Nottingham Trent buildings.

Sub-meter code	Type of building	$kWhm^{-2}$ per annum	
		2015/16	2016/17
NT 1	Offices	63	64
NT 2	Teaching hub (art/design)	679	586
NT 3	Conference centre	76	76
NT 4	Exhibitions/education (art/design)	82	76
NT 5	Library	148	157
NT 6	Admin/offices	72	85
NT 7	Admin/offices	78	80
NT 8	Medical office	50	46
NT 9	Study/workshops/laboratories	90	93
NT 10	Lecture/teaching/admin	89	94
NT 11	Shared space	201	198
NT 12	Laboratories (physics)	69	54
NT 13	Offices	23	31
NT 14	Teaching (art/design)	40	40

Table 7-5: Annual kWh consumption for the University of Reading building's sub-meters.

Sub-meter code	**Sub-meter name**	**Sub-meter/ Room definition**	**kWh per annum**	
			2017/2018	**2018/2019**
UoR 1	Sockets, autoclave, washing machine	General equipment + sockets	11,771	12,907
UoR 2	Cold stores 3.15; 3.16; 3.19; 3.14	Cold stores	19,234	17,627
UoR 3	1st floor	Floor power	95,403	88,541
UoR 4	Power in corridor, laboratories, offices	Floor power	22,299	12,907
UoR 7	Power sockets in research laboratories	General equipment + sockets	51,975	62,137
UoR 10	Power sockets, controls, and alarms	General equipment	41,643	42,830
UoR 11	Research lab; Digestion room	Laboratory	7,933	12,624
UoR 12	EVLDB 1117; 1116; 2807	Lighting	16,817	17,444
UoR 13	3.30-3.42	Same definition and room as UoR 12		
UoR 14	Constant temp rm 3.08	Laboratory	11,744	15,532
UoR 15	Constant temp rm 3.09	Laboratory	1,487	2,723
UoR 16	Constant temp rm 3.10	Laboratory	5,311	6,858
UoR 17	Constant temp rm 3.07	Laboratory	6,832	2,849

Table 7-6: Annual kWh consumption for the University of Sheffield building's sub-meters.

Sub-meter code	Sub-meter name	2017/18 data (kWh per annum)
UoS 1	125A Commando Socket	54,567
UoS 2	Chiller	255,590
UoS 3	Distribution Board DBA5	11,038
UoS 4	Distribution Board DBEQ1E	265,548
UoS 5	Distribution Board DBEQ1N	60,989
UoS 6	Distribution Board DBEQ2E	100,188
UoS 7	Distribution Board DBEQ2N	108,932
UoS 8	Distribution Board DBEQ3E	52,886
UoS 9	Distribution Board DBEQ3N	53,476
UoS 10	Distribution Board DBEQ4E	64,025
UoS 11	Distribution Board DBEQ4N	60,521
UoS 12	Distribution Board DBFFLPN	122,958
UoS 13	Distribution Board DBGF1E	6,848
UoS 14	Distribution Board DBGF1N	56,325
UoS 15	Distribution Board DBRN	323
UoS 16	GAN Reactor	28,436
UoS 17	Humidifier	54,567
UoS 18	Mechanical Control	135,516
UoS 19	Rapid Thermal Annealer	57,836
UoS 20	RM106, 63A Commando Socket	66,859
UoS 21	Miscellaneous	76,479

Summarising the main information listed within Tables 7-1 to 7-6, most of the universities had granular sub-metering within specific areas, such as for particular rooms or linked to specific pieces of equipment. For most of the universities (the University of Manchester, Manchester Metropolitan University, the University of Reading, the University of Sheffield, and Aston University), there were several generically named sub-meters, such as "Power in corridor, laboratories, offices". This generic sub-meter naming issue was prevalent across all the universities, with the exception of Nottingham Trent University, which only offered building-wide monthly energy consumption values. In other instances, particularly within the University of Manchester and the University of Sheffield, a wide number of sub-meters would be linked to generic distribution boards, meaning detailed analysis could not be conducted for these sub-meters. To resolve this issue, a detailed analysis was conducted on sub-meters with clear definitions (where they could be clearly defined as either regulated or unregulated sub-meters) or linked to specific rooms.

7.2.2 Annual and Monthly Consumption Trends

Across the case study universities, overall annual consumption values were calculated. Monthly and annual trends were compared, where this is demonstrated below using data from the University of Sheffield (showing monthly consumption in the building's unregulated sub-meters), Aston University (showing monthly consumption across laboratories), and Nottingham Trent University (showing general building trends), in Tables 7-7 to 7-9. The room codes for these universities can be found in Table 7-6, Table 7-2 and Table 7-4 respectively. Colour codes refer to each column separately, in order to identify trends across each sub-meter (rather than a singular colour code being applied to the entire table).

Table 7-7: Monthly unregulated electrical consumption in the University of Sheffield, using 2017/18 data. Green highlighting indicates lower monthly consumption for each specific unregulated energy sub-meter. Red highlighting indicates higher consumption levels, for each specific unregulated energy sub-meter.

Month	kWh per month			
	UoS 1	UoS 16	UoS 19	UoS 20
Apr-17	2,053	2,233	4,753	3,205
May-17		2,323	4,865	2,277
Jun-17		2,179	4,393	7,470
Jul-17		2,469	4,868	8,186
Aug-17		2,503	4,494	5,293
Sep-17		2,320	4,951	6,982
Oct-17		2,742	4,998	5,657
Nov-17	2,947	2,749	4,982	5,442
Dec-17	4,195	2,729	5,200	5,709
Jan-18	14,257	2,708	5,214	5,739
Feb-18	24,021	1,328	4,174	5,167
Mar-18	6,487	2,153	4,943	5,733

Table 7-8: Monthly unregulated electrical consumption, across different laboratory rooms, in Aston University, using 2019/20 data. Green highlighting indicates lower monthly consumption for each specific sub-meter. Red highlighting indicates higher consumption levels, for each specific sub-meter.

Month	kWh per month						
	AU 3	AU 4	AU 5	AU 6	AU 7	AU 10	AU 11
May-19	1,961	2,737	3,379	2,914	2,403	7,419	
Jun-19	1,969	2,691	3,138	2,756	1,962	8,112	
Jul-19	1,571	3,069	2,030	2,735	1,041	9,579	
Aug-19	1,928	3,046	2,235	2,783	1,585	8,622	
Sep-19	1,791	2,611	2,216	2,722	2,533	6,169	
Oct-19	2,146	2,260	2,727	3,162	2,709	6,803	
Nov-19	2,003	2,154	2,608	2,953	2,375	6,451	306
Dec-19	1,630	2,050	1,740	1,912	1,788	5,100	510
Jan-20	1,699	1,958	1,099	1,171	1,077	4,903	608
Feb-20	1,679	2,207	2,017	1,708	1,634	4,341	562
Mar-20	1,433	1,513	1,417	1,140	1,306	4,726	425
Apr-20	717	1,212	191	179	257	3,062	936

Table 7-9: Monthly building-wide electrical consumption for Nottingham Trent University, using 2015/17 data. Green highlighting indicates lower monthly consumption for each building. Red highlighting indicates higher consumption levels, for each building.

Month	kWh per month													
	NT 1	NT 2	NT 3	NT 4	NT 5	NT 6	NT 7	NT 8	NT 9	NT 10	NT 11	NT 12	NT 13	NT 14
Aug-15	7,274	121,057	18,700	62,227	112,703	56,658	26,527	1,172	52,698	271,761	93,731	4,735	3,905	11,527
Sep-15	7,587	122,320	21,270	62,144	100,438	80,959	28,080	1,004	53,537	244,797	100,619	6,285	5,167	13,178
Oct-15	8,048	117,583	22,149	103,687	121,953	84,214	29,278	1,476	58,362	242,002	109,359	6,994	6,227	18,913
Nov-15	8,458	126,632	20,722	109,563	127,357	95,428	30,158	1,322	64,013	258,356	110,455	7,305	5,465	20,677
Dec-15	6,915	127,057	19,186	74,793	91,738	88,653	23,401	1,218	43,897	187,660	89,005	7,962	4,469	13,529
Jan-16	8,263	116,433	24,964	102,439	114,213	87,169	30,244	1,425	60,578	226,381	105,241	9,390	5,437	20,200
Feb-16	7,840	110,558	24,210	102,409	115,843	93,917	29,342	1,441	63,503	239,692	106,390	9,794	5,175	18,897
Mar-16	7,691	119,281	24,328	100,718	120,872	89,494	27,957	1,352	61,415	236,284	105,697	9,829	4,996	19,328
Apr-16	7,620	109,289	24,328	102,950	132,586	86,418	27,853	1,331	64,725	239,545	102,883	8,430	5,377	19,608
May-16	7,281	106,520	23,538	107,704	155,220	83,036	28,057	1,415	69,384	270,446	112,028	6,158	4,802	19,317
Jun-16	6,869	99,360	22,949	83,892	125,203	72,055	26,996	1,029	54,888	263,333	97,715	3,399	3,886	15,995
Jul-16	7,115	95,679	22,084	76,173	126,727	72,617	29,334	1,012	54,812	308,553	93,486	1,806	3,684	13,665
Aug-16	7,023	91,991	17,908	55,943	117,213	68,760	29,404	613	49,490	285,703	89,669		3,534	11,010
Sep-16	7,170	103,960	19,796	64,927	108,328	76,593	28,899	924	52,772	279,780	102,561		4,325	13,710
Oct-16	8,119	104,116	22,845	88,286	117,993	92,552	31,235	1,378	61,840	273,623	115,534	6,989	6,050	19,403
Nov-16	8,524	103,063	24,931	100,702	117,656	95,218	29,985	1,438	66,887	270,743	108,280	9,079	7,862	21,353
Dec-16	7,818	96,306	18,807	74,368	102,132	96,027	25,814	1,068	54,310	232,976	94,489	3,543	7,715	16,372
Jan-17	8,787	93,393	25,321	99,334	113,430	129,350	32,804	1,365	68,252	255,725	106,791	13,922	9,391	19,627
Feb-17	8,054	83,435	24,723	89,665	103,205	117,077	29,331	1,279	62,743	236,782	99,136	9,696	7,915	18,270
Mar-17	8,064	93,353	25,856	96,576	141,831	121,882	28,604	1,342	70,966	267,450	107,190	8,347	7,718	19,137
Apr-17	6,809	93,888	21,837	82,809	148,871	99,979	25,640	1,160	56,021	208,276	95,024	7,132	6,299	15,677

Across these representative samples, when assessing both unregulated energy and overall building-wide energy consumption, there was no strong correlation between the time of year and energy consumption. For example, most buildings in Nottingham Trent observed a reduction in August (potentially related to the absence of students at this time of year), however no such reduction was observed in other universities. There were however some small apparent trends across the universities, including a large reduction in electrical consumption in April 2020 in Table 7-8, which correlates with the start of the building closures, due to the COVID-19 pandemic in the UK.

Initially a reduction during Christmas breaks was initially anticipated, based on the literature and discussions with different staff members, however, this was not observable within the datasets presented across the universities, on a building-wide or room-wide level. Focusing on other times of the year, on a room-level and a building-wide level across each university, there were no clear electrical reductions during the Christmas break period for laboratory buildings across the obtained data. Using the University of Manchester, the only types of rooms that demonstrated a clear reduction over the Christmas breaks were lecture theatres, workshops, and catering facilities. Laboratories, computing rooms, and comms rooms represent some of the types of rooms that did not demonstrate this clear Christmas-time reduction.

Using the same case study rooms and buildings listed in Tables 7-7 to 7-9, differences in electrical consumption have been calculated in Tables 7-10 to 7-12. These tables demonstrate a series of variable reductions in electrical consumption during Christmas periods, which disproved the initial anticipation that electrical consumption would be consistently reduced across all of the datasets during the Christmas break.

Table 7-10: Differences in electrical consumption at the University of Sheffield, colour-coded separately for each separate sub-meter.

Month	Changes in kWh consumption			
	UoS 1	UoS 16	UoS 19	UoS 20
Apr-17				
May-17		90	112	-928
Jun-17		-144	-472	5,193
Jul-17		290	475	716
Aug-17		34	-374	-2,893
Sep-17		-183	457	1,689
Oct-17		422	47	-1,325
Nov-17		7	-16	-215
Dec-17	1,248	-20	218	267
Jan-18	10,062	-21	14	30
Feb-18	9,764	-1,380	-1,040	-572
Mar-18	-17,534	825	769	566

Table 7-11: Changes in electrical consumption at Aston University, colour-coded separately for each separate sub-meter.

Month	Changes in kWh consumption						
	AU 3	AU 4	AU 5	AU 6	AU 7	AU 10	AU 11
May-19							
Jun-19	8	-46	-241	-158	-441	693	
Jul-19	-398	378	-1,108	-21	-921	1,467	
Aug-19	357	-23	205	48	544	-957	
Sep-19	-137	-435	-19	-61	948	-2,453	
Oct-19	355	-351	511	440	176	634	
Nov-19	-143	-106	-119	-209	-334	-352	
Dec-19	-373	-104	-868	-1,041	-587	-1,351	204
Jan-20	69	-92	-641	-741	-711	-197	98
Feb-20	-20	249	918	537	557	-562	-46
Mar-20	-246	-694	-600	-568	-328	385	-137
Apr-20	-716	-301	-1,226	-961	-1,049	-1,664	511

Table 7-12: Changes in electrical consumption at Nottingham Trent University, colour-coded separately for each separate sub-meter.

Month	Changes in kWh consumption													
	NT 1	NT 2	NT 3	NT 4	NT 5	NT 6	NT 7	NT 8	NT 9	NT 10	NT 11	NT 12	NT 13	NT 14
Aug-15														
Sep-15	313	1,263	2,570	-83	-12,265	24,301	1,553	-168	839	-26,964	6,888	1,550	1,262	1,651
Oct-15	461	-4,737	879	41,543	21,515	3,255	1,198	472	4,825	-2,795	8,740	709	1,060	5,735
Nov-15	410	9,049	-1,427	5,876	5,404	11,214	880	-154	5,651	16,354	1,096	311	-762	1,764
Dec-15	-1,543	425	-1,536	-34,770	-35,619	-6,775	-6,757	-104	-20,116	-70,696	-21,450	657	-996	-7,148
Jan-16	1,348	-10,624	5,778	27,646	22,475	-1,484	6,843	207	16,681	38,721	16,236	1,428	968	6,671
Feb-16	-423	-5,875	-754	-30	1,630	6,748	-902	16	2,925	13,311	1,149	404	-262	-1,303
Mar-16	-149	8,723	118	-1,691	5,029	-4,423	-1,385	-89	-2,088	-3,408	-693	35	-179	431
Apr-16	-71	-9,992	0	2,232	11,714	-3,076	-104	-21	3,310	3,261	-2,814	-1,399	381	280
May-16	-339	-2,769	-790	4,754	22,634	-3,382	204	84	4,659	30,901	9,145	-2,272	-575	-291
Jun-16	-412	-7,160	-589	-23,812	-30,017	-10,981	-1,061	-386	-14,496	-7,113	-14,313	-2,759	-916	-3,322
Jul-16	246	-3,681	-865	-7,719	1,524	562	2,338	-17	-76	45,220	-4,229	-1,593	-202	-2,330
Aug-16	-92	-3,688	-4,176	-20,230	-9,514	-3,857	70	-399	-5,322	-22,850	-3,817	-1,806	-150	-2,655
Sep-16	147	11,969	1,888	8,984	-8,885	7,833	-505	311	3,282	-5,923	12,892	0	791	2,700
Oct-16	949	156	3,049	23,359	9,665	15,959	2,336	454	9,068	-6,157	12,973	6,989	1,725	5,693
Nov-16	405	-1,053	2,086	12,416	-337	2,666	-1,250	60	5,047	-2,880	-7,254	2,090	1,812	1,950
Dec-16	-706	-6,757	-6,124	-26,334	-15,524	809	-4,171	-370	-12,577	-37,767	-13,791	-5,536	-147	-4,981
Jan-17	969	-2,913	6,514	24,966	11,298	33,323	6,990	297	13,942	22,749	12,302	10,379	1,676	3,255
Feb-17	-733	-9,958	-598	-9,669	-10,225	-12,273	-3,473	-86	-5,509	-18,943	-7,655	-4,226	-1,476	-1,357
Mar-17	10	9,918	1,133	6,911	38,626	4,805	-727	63	8,223	30,668	8,054	-1,349	-197	867
Apr-17	-1,255	535	-4,019	-13,767	7,040	-21,903	-2,964	-182	-14,945	-59,174	-12,166	-1,215	-1,419	-3,460

Further investigating these changes, in Figures 7-1 to 7-3, Aston University, the University of Sheffield and the University of Manchester are used as representative samples here, to show the changes across annual consumption, focusing particularly on the Christmas shutdown period. For each, there were clearly no major reductions in total unregulated consumption over the Christmas period. This lack of a reduction occurred across most of the laboratories across each university (that contained a case study laboratory room, meaning Manchester Metropolitan University was thereby excluded from this observation). This lack of major electrical consumption reductions in the laboratories can be explained, after speaking to staff members across the universities, as being due to laboratory equipment being required to be left on, even when buildings are unoccupied. This was highlighted as being necessary, so that equipment and research samples were not damaged by turning off equipment.

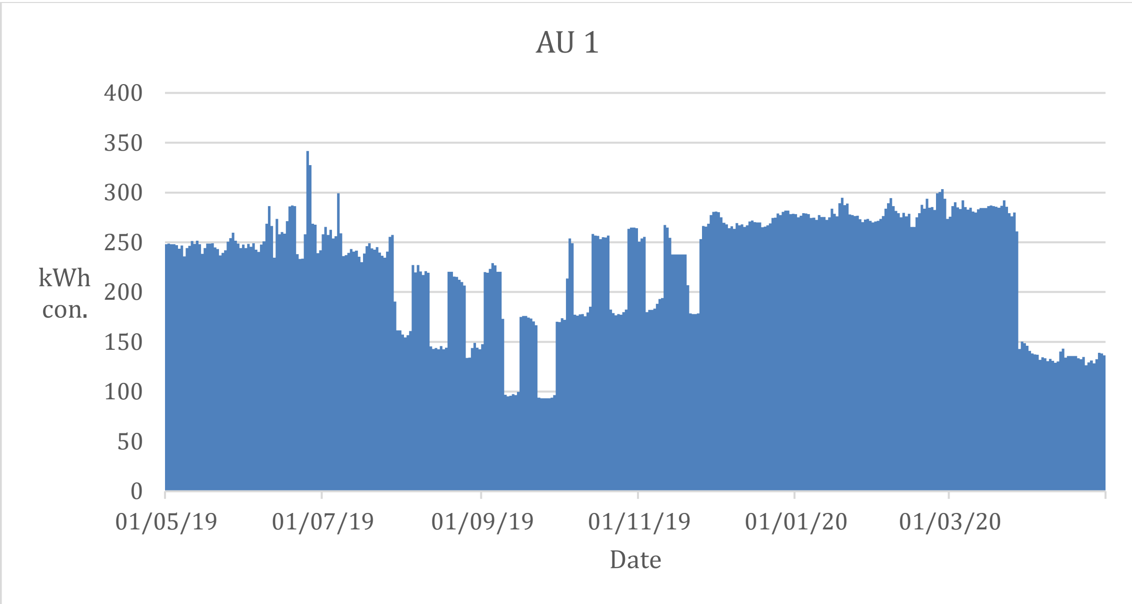

Figure 7-1: Daily kWh consumption, for the AU 1 room at Aston University, on a room-wide level.

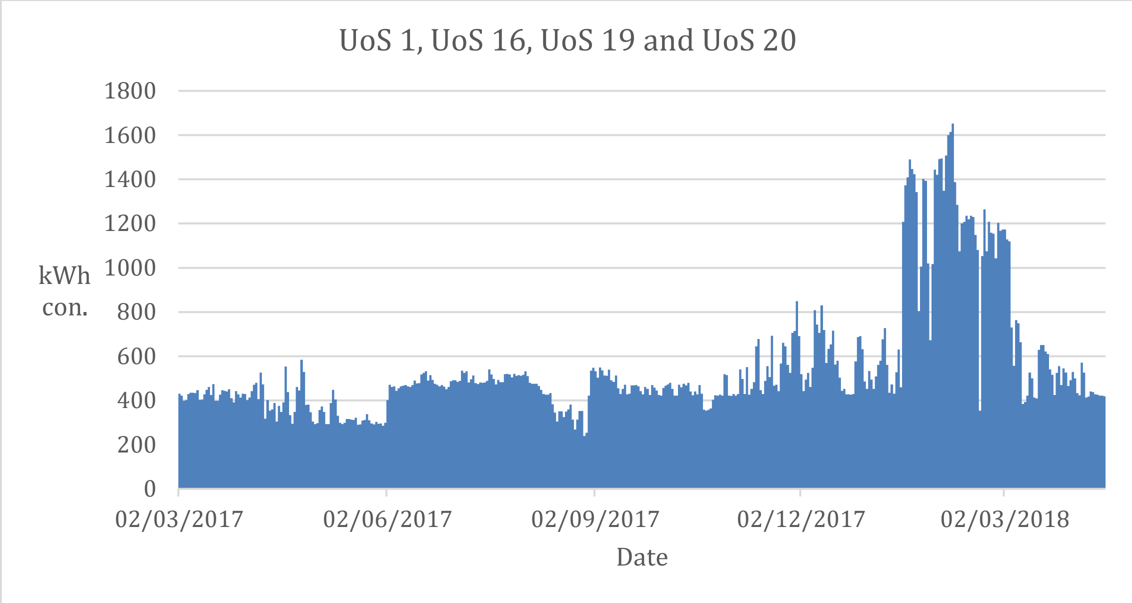

Figure 7-2: Daily kWh consumption, for the University of Sheffield, assessing all the unregulated energy sub-meters in the building.

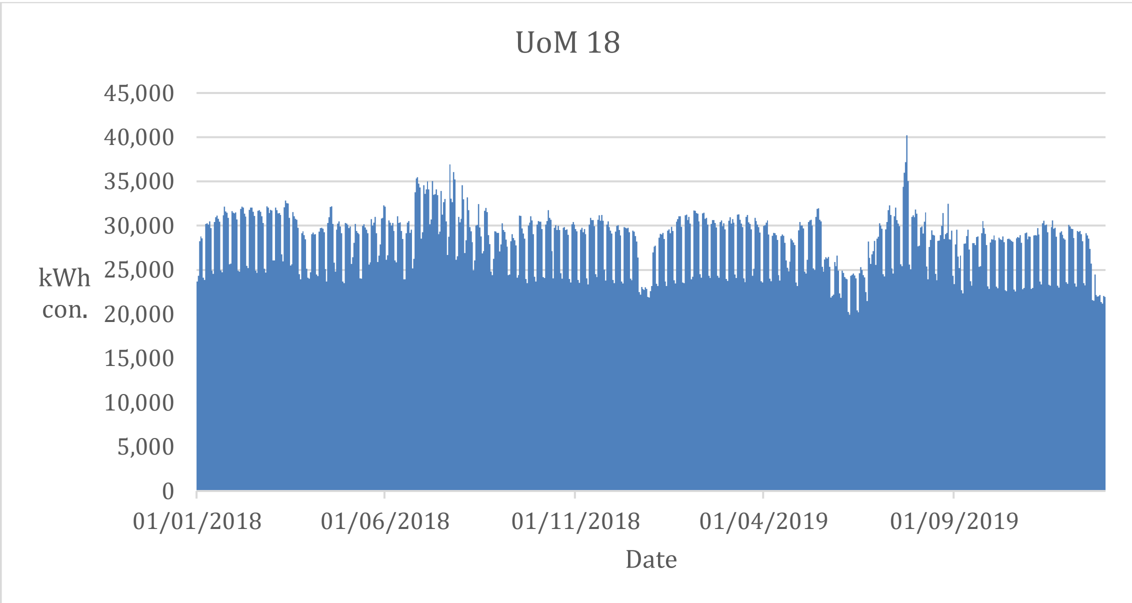

Figure 7-3: Daily kWh consumption, for the UoM 18 building at the University of Manchester, on a building-wide level.

For non-laboratory buildings, there was a slightly larger reduction in unregulated and overall electrical consumption, however again these reductions were focused on peak consumption across the Christmas periods, and the baseloads for different rooms remained consistent, and comparable to the rest of the year. Hence, through using building-wide and room-wide data, there was not a clear discernible correlation between time of year and electrical (and unregulated energy) consumption.

7.2.3 Benchmark Comparisons

This section displays how different rooms perform compared to benchmarking schemes. In Figures 7-4 to 7-6, the benchmark electrical consumption reading has been taken from CIBSE (2012) and compared to the calculated kWhm^{-2} per annum readings for the University of Manchester building stock. Catering facilities, science-based lecture rooms and laboratories have been selected here as the sample selections, as they represent three of the most common types of rooms across Higher Education buildings.

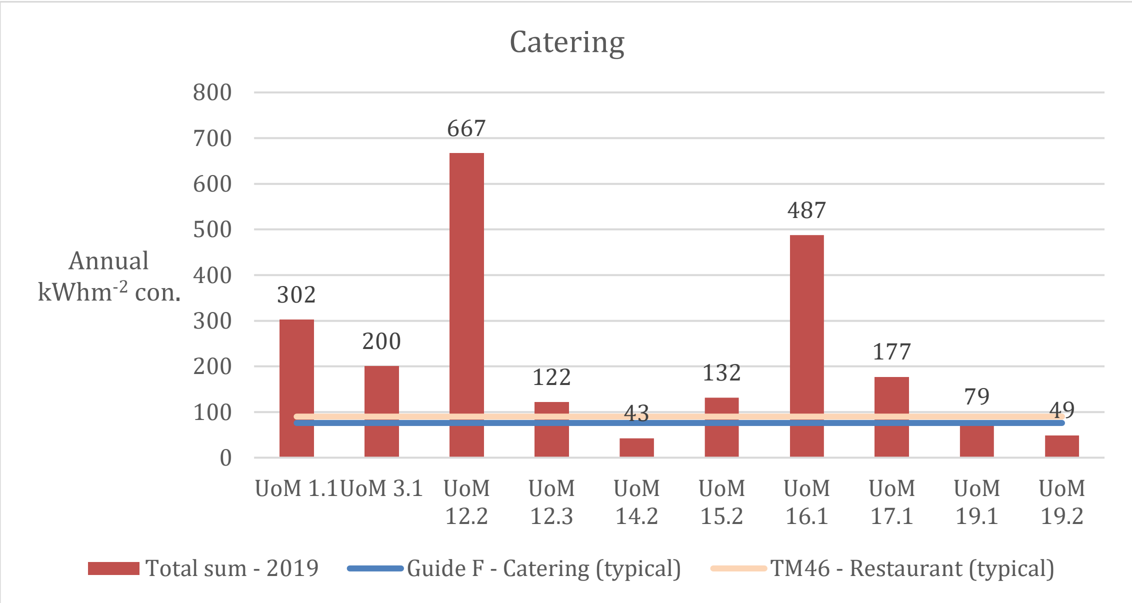

Figure 7-4: Annual kWhm^{-2} electrical consumption ranges in catering facilities at the University of Manchester.

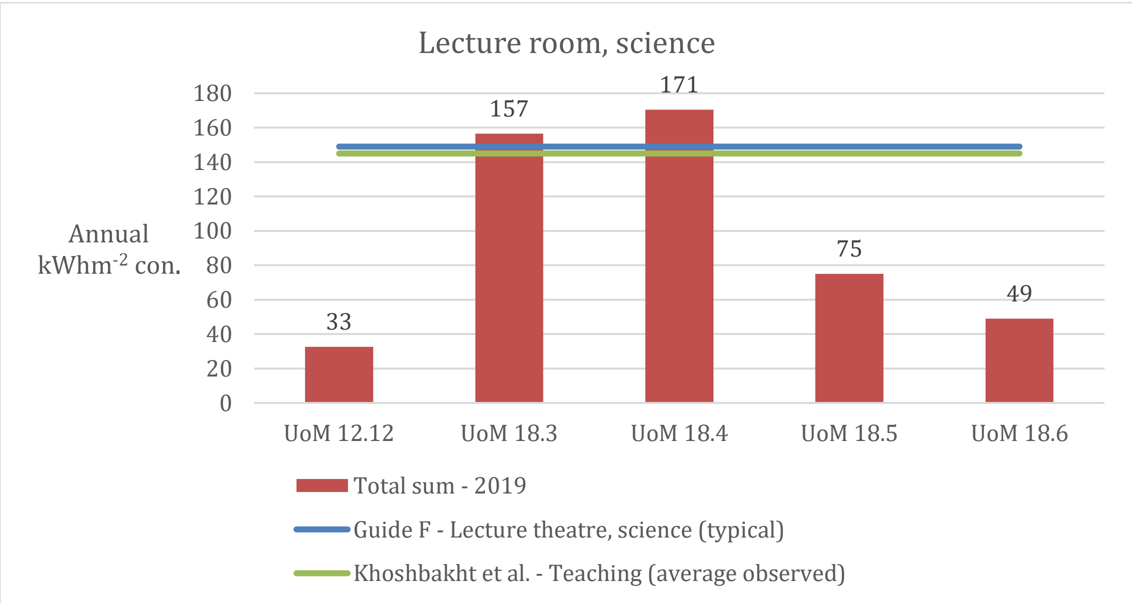

Figure 7-5: Annual kWhm^{-2} electrical consumption ranges in science lecture rooms at the University of Manchester

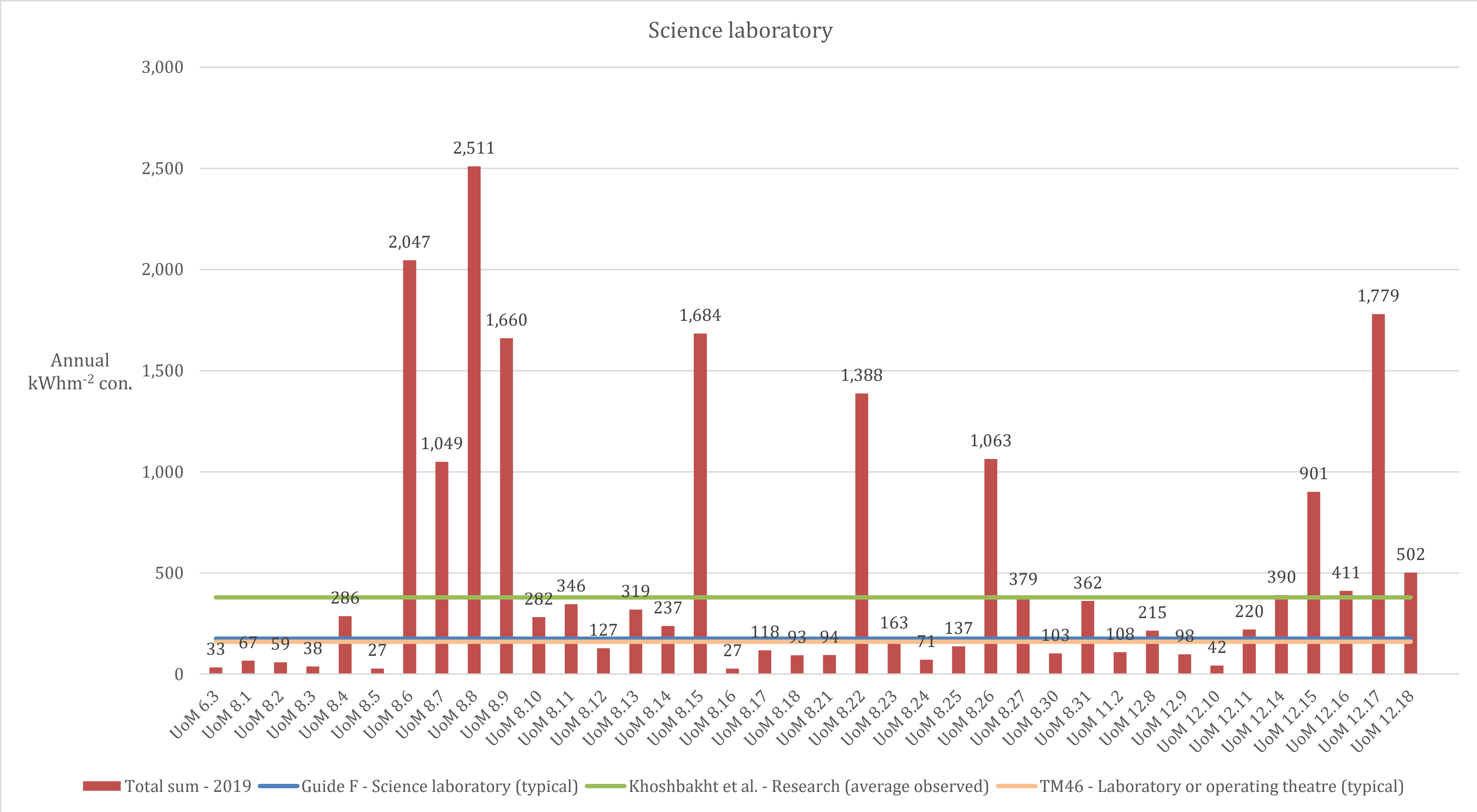

Figure 7-6: Annual kWhm-2 electrical consumption ranges in laboratories at the University of Manchester.

The data indicated variable results within the University of Manchester, particularly for the laboratory rooms. Compared to other Higher Education benchmarks, the University of Manchester data depicts higher catering electrical consumption, whereas CIBSE benchmarks suggest readings between 76-90 $kWhm^{-2}$ are typical. Additionally, for laboratories, there remain several outlying laboratories within the data listed in Figure 7-6. However, information from the building managers validated the room measurements and energy consumption data. Hence it was determined that the outlying readings were not anomalies, and instead represented energy-intensive rooms. For a further breakdown of the information within the figures, refer to Table 7-1.

The initial benchmarking definitions are also broad spanning. For example, the catering category referred to staff kitchens, cafes, and restaurants, hence the potential variability in the results. A typical staff kitchen would have a microwave, kettle, and sink, whereas a café or restaurant would contain ovens and other higher-powered small power loads. For the catering facilities listed in Figure 7-4, each facility remained open during the same hours on weekdays, whilst most of the facilities were closed on weekends. UoM 1.1 is the only exception to this. Hence, the differences in unregulated energy consumption must be attributed to the types of equipment used, left on and catering activities performed within these spaces instead. The CIBSE values need to be specific to the use case, as the process of combining data under a single category is not helpful nor applicable in reality, such as demonstrated for the catering information in Figure 7-4. This is also likely true for other rooms as well, where additional contextual and specific information (such as equipment lists and operational hours) are required for a detailed analysis.

Using data from the University of Manchester, an unregulated energy consumption graph was generated to understand how consumption varied across diverse types of rooms. For these data, $kWhm^{-2}$ measurements were generated to better compare the data. Some room categories had small sample sizes (for example, only two storage rooms were compared). In contrast, other categories had a much larger sample size (for example, laboratories had a sample size of 25). This would explain why specific categories a large performance range, as their sample sizes are not entirely representative. A building stock profile graph was generated based on these categories, as shown in Figure 7-7.

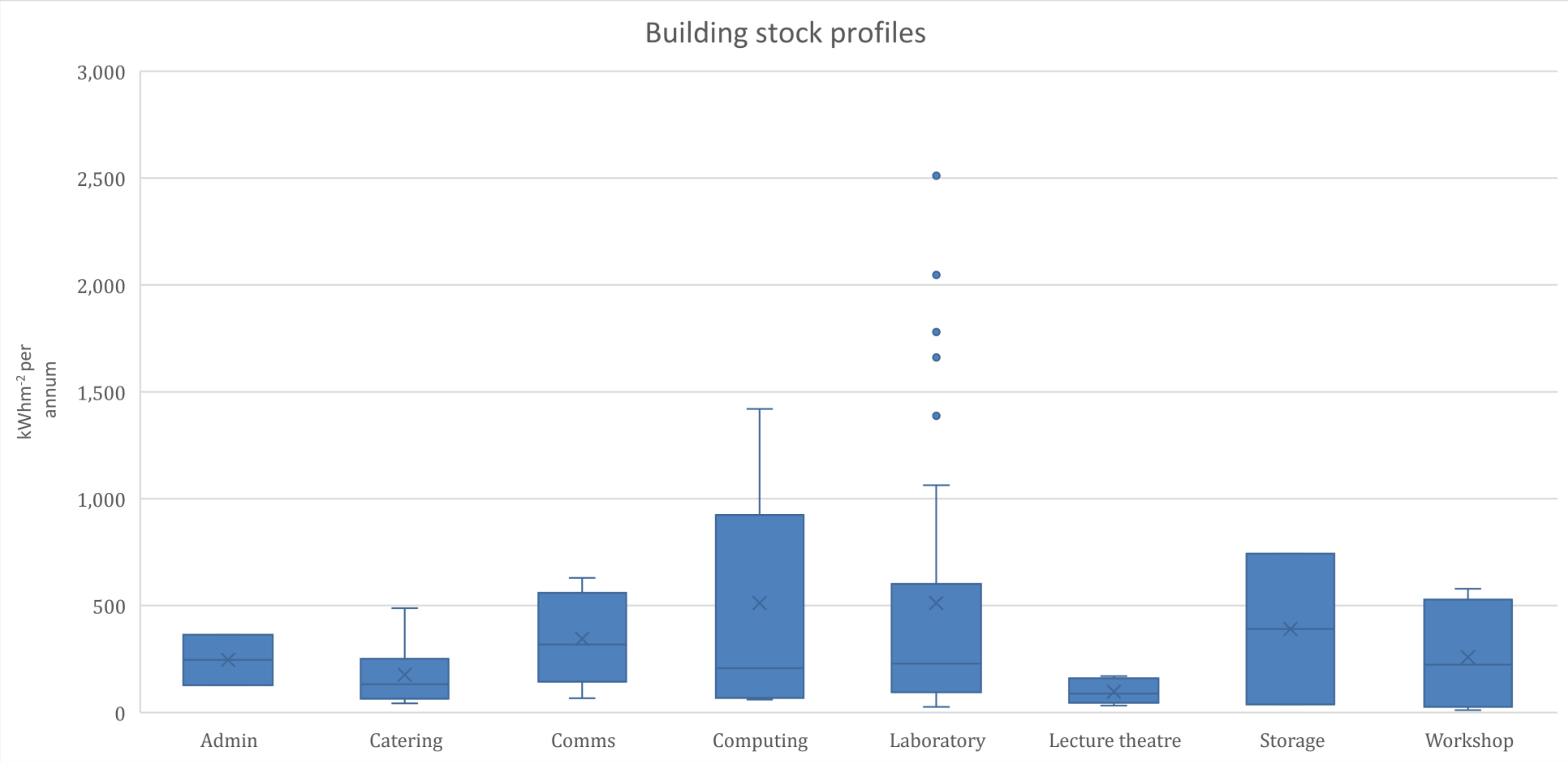

Figure 7-7: Unregulated electrical consumption in different University of Manchester buildings. The midline in each box represents the median, whilst the x in each box represents the mean. Outliers here have been defined as data points that exist outside the outer fences of the boxes.

Referring to Figure 7-7, it is apparent that specific laboratories contain outlying information, as outlined within the laboratory dataset. It was assumed that the initial m^2 measurements could have been incorrect or that the sub-meter readings may have referred to a floor (or linked to a larger room). However, discussions with the relevant building manager concluded that the measurement data were correct and that instead, the outlying information was due to particularly energy-intensive activities. Generally, many of the room types consumed much more than initially anticipated, or in the least, they suggest wide performance ranges. Whilst small sample sizes limit the confidence with which typical performance ranges can be applied to the energy usage in some rooms type. In some cases, very highly energy-intensive rooms particularly appear to distort the statistical distributions of more standard behaviour rooms. This complicates attempts to provide simple, standard performance ranges and necessitates more careful consideration of the room type, purpose, and equipment before attempting to categorise the. All these rooms measure power consumption (except the one workshop category); hence, it is suggested that unregulated energy varies depending on the room type and the equipment used.

Most room types had a relativity wide performance range, except for lecture theatres. The performance ranges do not match previous benchmarks, such as the CIBSE Guide F benchmarks. This is due to the CIBSE benchmarking data being comprised of older data. The CIBSE benchmarks focus on total building consumption per m^2, whilst this work primarily focuses on room-level consumption per m^2. Hence, based on the university's building definition, the CIBSE data would include higher/lower consumption areas than initially anticipated. For example, the CIBSE's "library" category includes catering spaces, social spaces, computer clusters and other types of spaces. Comparatively, this information has been separated and analysed independently within the thesis work. Hence this may cause some disparity between these results and the Guide F benchmarks.

7.3 Unregulated Energy in Different Rooms

7.3.1 Unregulated Energy Across the Case Study Rooms

Within this section, data are examined from the University of Manchester, Aston University, the University of Sheffield, and the University of Reading. This section examines how daytime consumption varies against evening consumption and assesses weekday consumption against weekends. For most universities and across most room types, the out-of-hours baseload consumption was typically much lower than the in-hours consumption. Not all rooms see a large reduction in weekend consumption however, particularly in lower-consuming room types. For example, lecture and teaching spaces. The baseload and peak consumption difference is rather limited, as demonstrated below in Figure 7-8 and Figure 7-9.

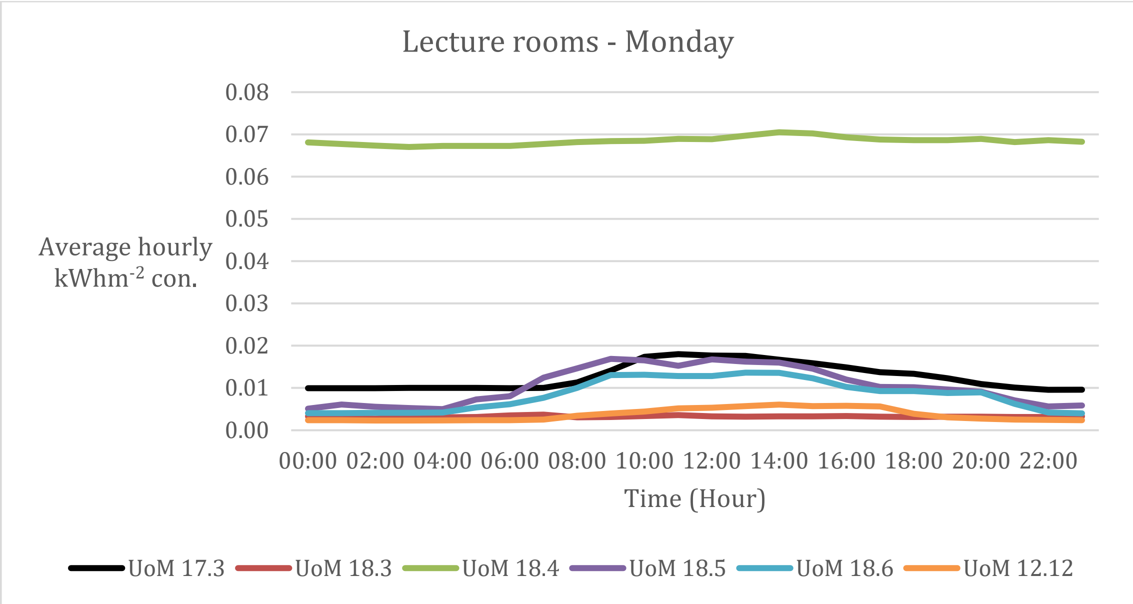

Figure 7-8: Average weekday 2019 consumption patterns for different University of Manchester lecture rooms.

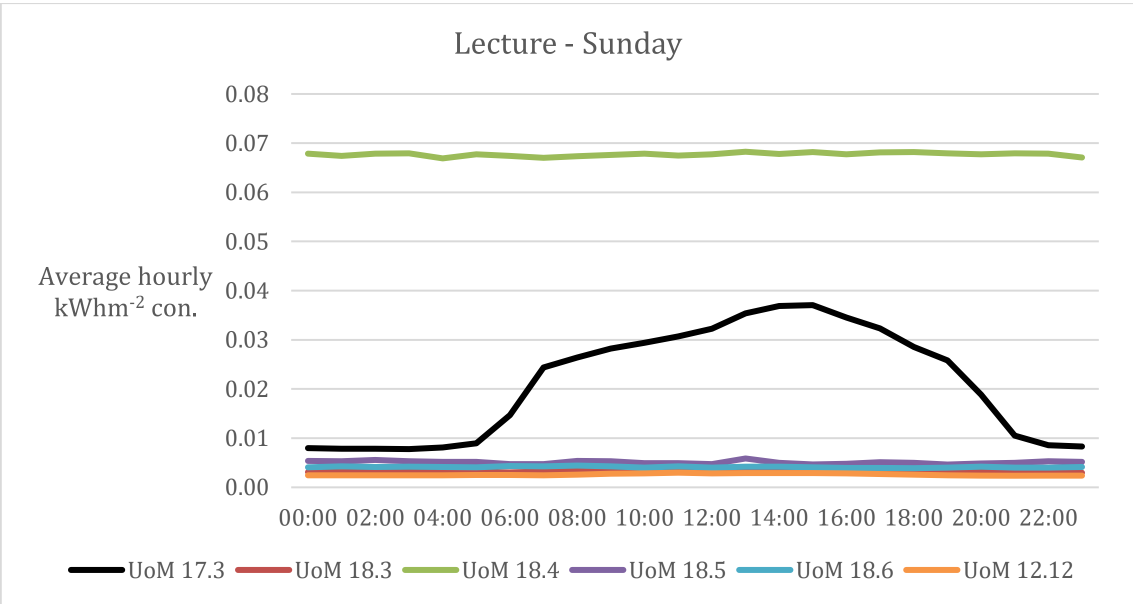

Figure 7-9: Average weekend 2019 consumption patterns for different University of Manchester lecture rooms.

For lecture rooms, there is a drop in some lecture theatres over the weekend, particularly in UoM 18.5 and UoM 18.6 but this is offset by increases in UoM 17.3 at the weekend leading to an overall consumption level that does not significantly from weekday to weekend.

Interestingly, the baseload for UoM 18.4 did not vary across weekdays and weekends, in fact UoM 18.4 had a consistently high baseload, across the dataset. This suggests that focusing on making individual high-use rooms efficient could be a more effective focus in reducing power usage rather than focusing efforts more broadly. UoM 17.3 also sees an increase in weekend consumption when compared to weekday consumption. After further investigation, it was found that this space is frequently used over weekends, for external seminars and all-day lectures. Hence, whilst the $kWhm^{-2}$ difference is still low, this is the primary reason attributed to the weekend increase in consumption.

When assessing typical usage profiles across different university buildings, particularly focusing again on the room categories used in Figures 7-1 to 7-3, the following room profiles have been created from the University of Manchester data sets, to show typical daily patterns for the same room types. These are shown in Figures 7-10 to 7-15.

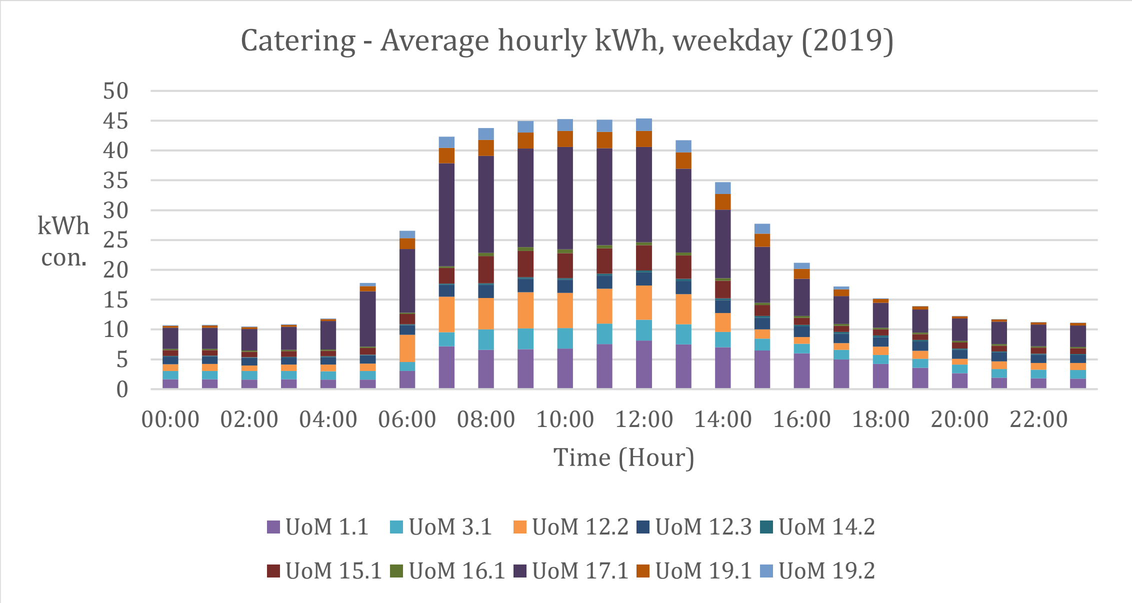

Figure 7-10: Typical weekday daily consumption, calculated using 2019 data, for different catering facilities at the University of Manchester.

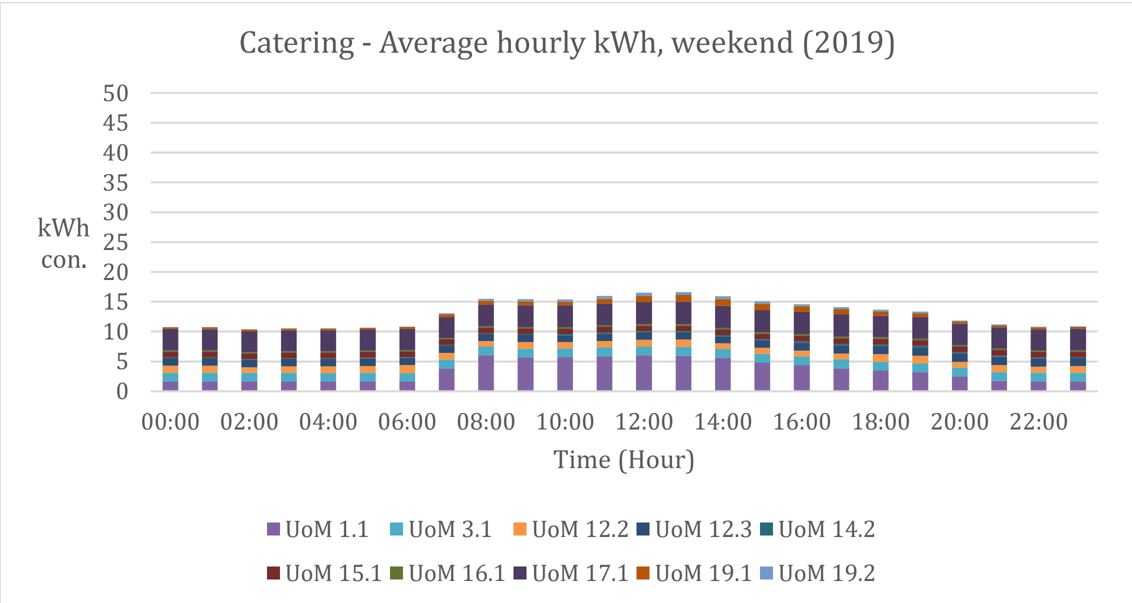

Figure 7-11: Typical weekend daily consumption, calculated using 2019 data, for different catering facilities at the University of Manchester.

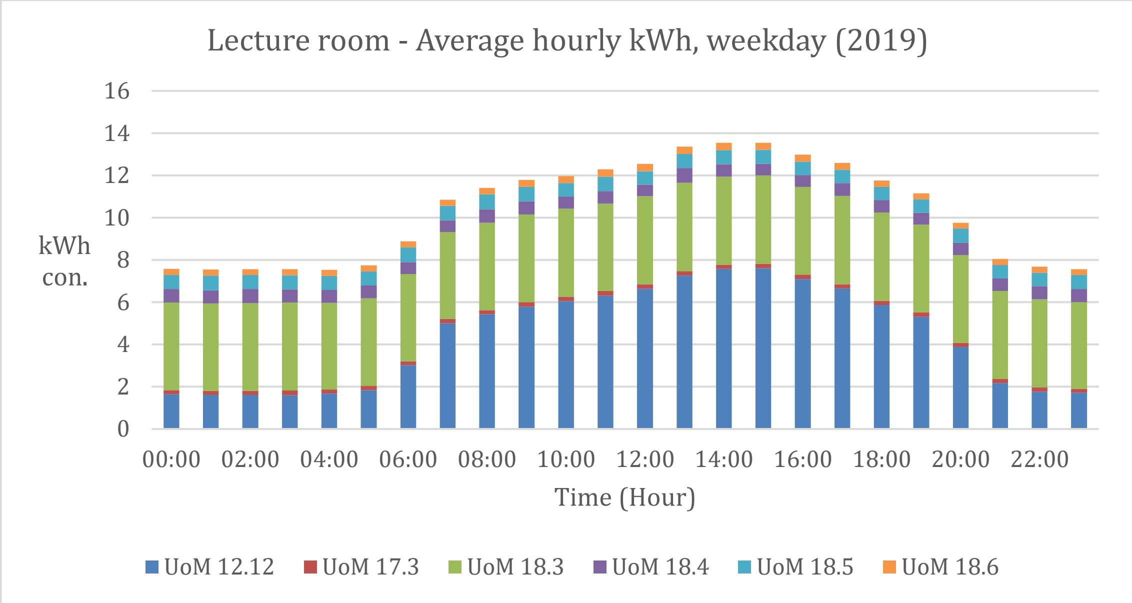

Figure 7-12: Typical weekday daily consumption, calculated using 2019 data, for different lecture rooms at the University of Manchester.

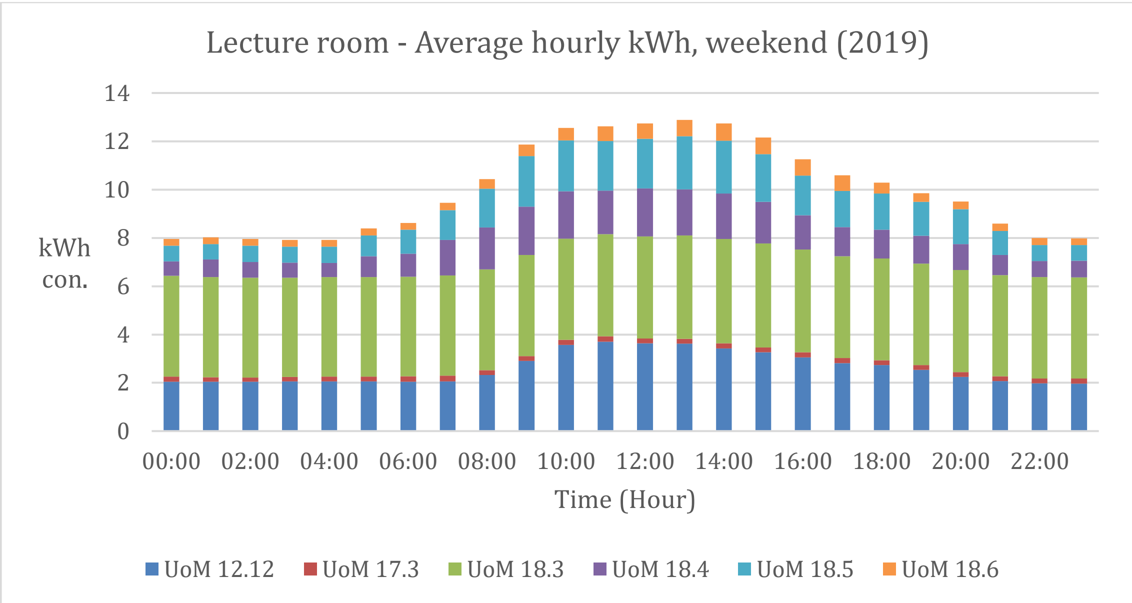

Figure 7-13: Typical weekend daily consumption, calculated using 2019 data, for different lecture rooms at the University of Manchester.

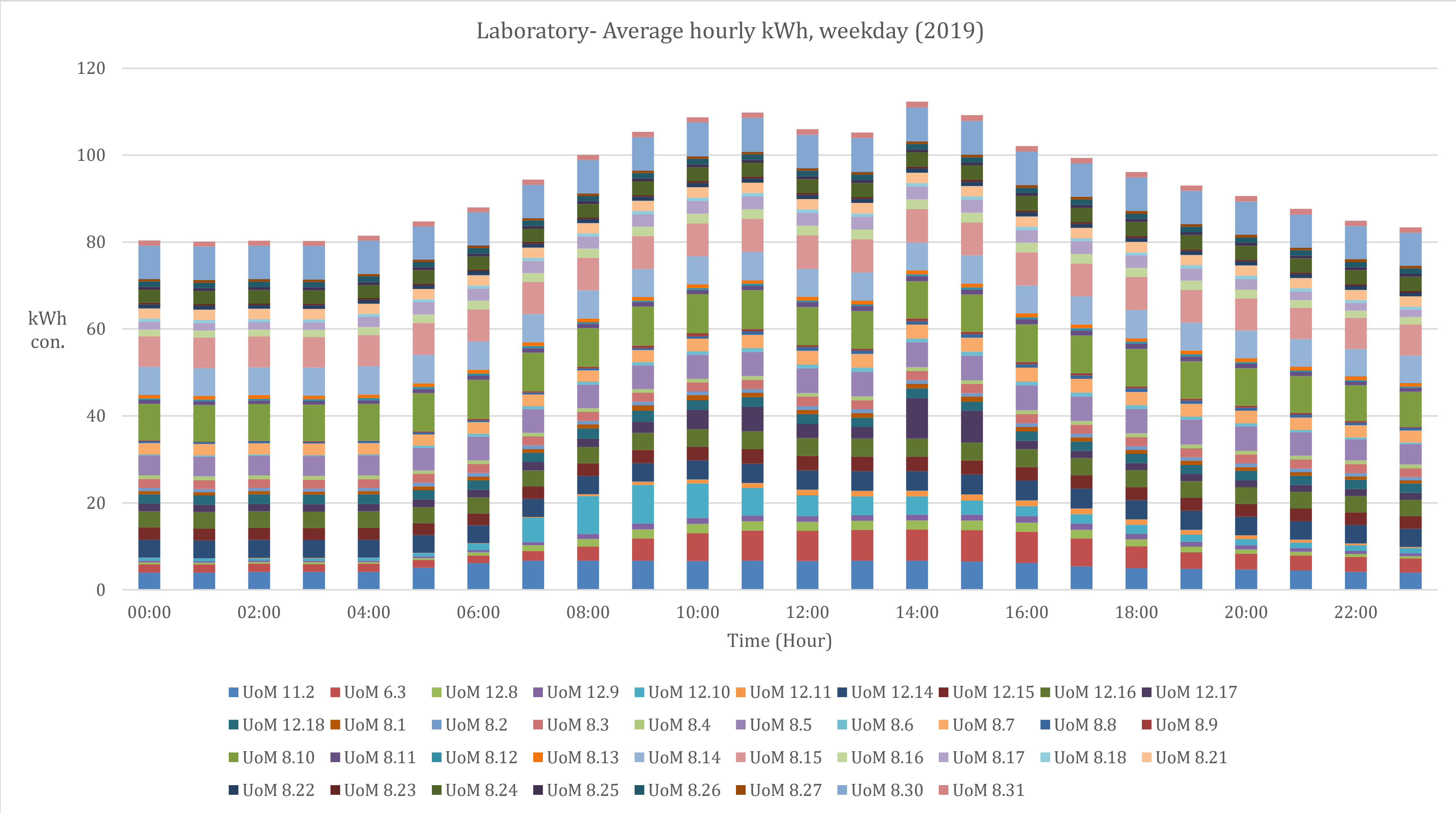

Figure 7-14: Typical weekday daily consumption, calculated using 2019 data, for different laboratories at the University of Manchester.

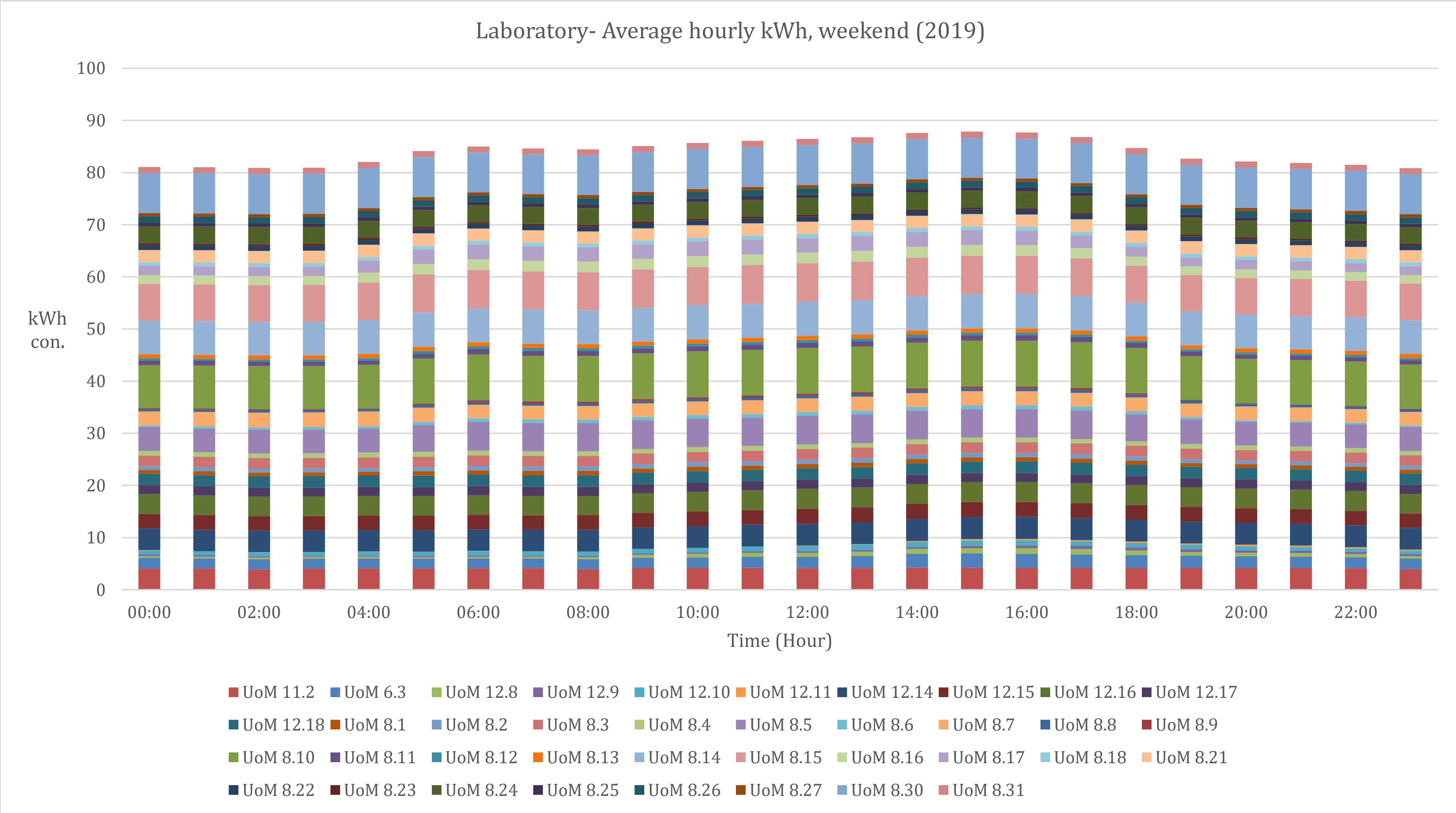

Figure 7-15: Typical weekend daily consumption, calculated using 2019 data, for different laboratories at the University of Manchester.

Using these room types, there is an apparent difference between weekdays and weekends for the majority of catering rooms in Manchester, except for the catering spaces open across weekends. Differences in electrical consumption for each of the catering spaces in Manchester are displayed below, comparing Mondays and Sundays, as shown in Table 7-13. The data in Table 7-13 shows consistent reductions on the weekends for the difference catering spaces.

Table 7-13: Average drops in consumption between weekends and weekdays at the University of Manchester, across different catering spaces. Green represents the largest percentage reductions whilst red represents smallest percentage reductions.

Catering space	**Percentage reduction in electrical consumption, comparing weekends to weekdays (kWh)**		
	2017	**2018**	**2019**
UoM 1.1	31.02%	21.52%	19.27%
UoM 3.1	36.13%	39.88%	30.04%
UoM 12.2	61.87%	65.18%	59.27%
UoM 12.3	26.74%	26.26%	25.15%
UoM 15.2	52.38%	53.52%	53.33%
UoM 16.1	34.65%	43.93%	28.40%
UoM 17.1	73.12%	67.54%	58.20%
UoM 14.2	30.79%	31.96%	27.61%
UoM 19.1	75.30%	68.27%	57.24%
UoM 19.2	83.38%	73.48%	75.81%

Finally, laboratory spaces within Manchester show a small reduction in total unregulated energy consumption during weekends, compared to weekdays. Figure 7-14 and Figure 7-15 shows a consistently high baseload for all the University of Manchester laboratories, suggesting that equipment is left on during out-of-hours periods. Using the data, this 31.96 kWh reading means a 28.45% drop from peak consumption to baseload consumption for weekdays, whereas for weekends this translates as a 7.02 kWh difference, or a 7.99% drop between peak consumption to baseload consumption.

7.3.2 Laboratory Comparisons Between the Case Study Universities

Using data obtained from each of the case study universities, analysis has been conducted in order to identify trends within unregulated energy patterns in different types of rooms. For example, when assessing typical usage profiles across different university buildings, particularly focusing on different types of laboratory rooms, the following room profiles have been created from data provided by the University of Sheffield, Aston University, and the University of Reading, and can be found in Figures 7-16 to 7-18. For the University of Sheffield, the data points refer to different types of laboratory equipment, as opposed to separate rooms.

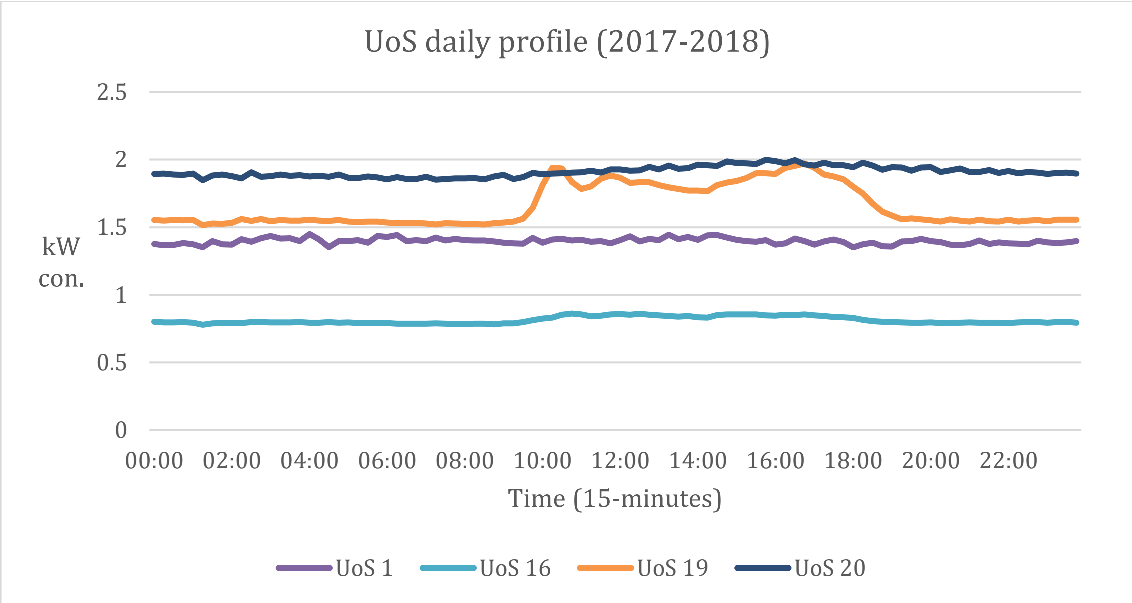

Figure 7-16: Average daily laboratory equipment consumption for the University of Sheffield, using data from 2017-2018.

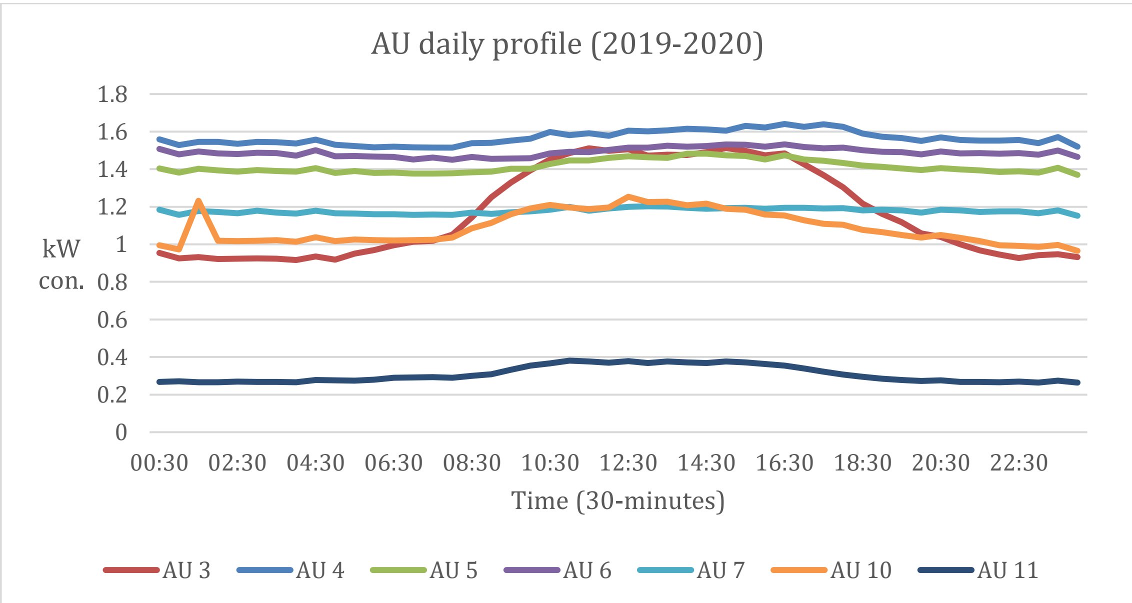

Figure 7-17: Average daily laboratory consumption for Aston University, using data from 2019-2020.

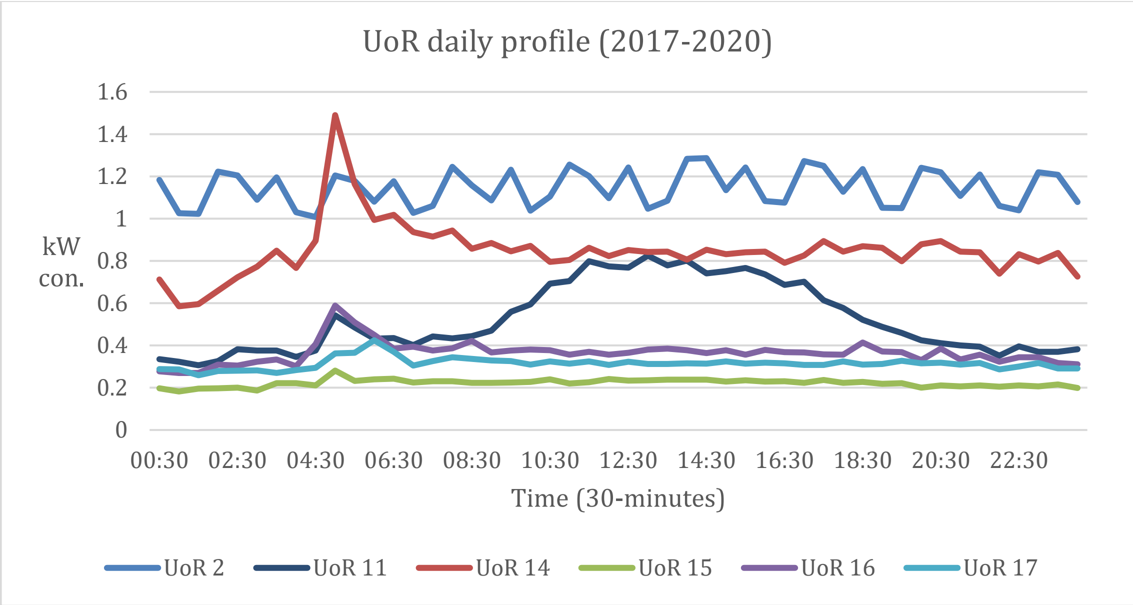

Figure 7-18: Average daily laboratory consumption for the University of Reading, using data from 2017-2020.

In terms of electrical consumption, the actual figures for the laboratories are low. Nonetheless, the data from each university suggests a consistently high baseload outside of the buildings' core operational hours (for these case study buildings, this would be approximately between 09:00-18:00).

Using Aston University as an example here, equipment being left on out-of-hours was a primary contributor to the often-high unregulated energy baseload. For example, the AU 1 room was the highest-consuming room within the building. In-hours and out-of-hours consumption remained the same, and thereby, it was assumed that equipment is left on consistently. The same issue was prevalent within AU 4, where a consistent, prevalent baseload was noticed – in fact, comparing the peak consumption period (13:00 for Aston) against the lowest baseload period (00:00 for Aston), there is only a range of -1.20 to 1.00 kWh, displaying a small difference between the two, suggesting little variation at all between the baseload period and peak consumption period. Only AU 5 demonstrated a baseload which would vary significantly across different months. On a day-by-day level, however, when comparing peak consumption periods (13:00) against the baseload period (00:00) the range is only -1.90 to

To further assess differences between the laboratory data across the universities, a statistical analysis has been conducted. Statistical analysis, focusing on changes between daily weekday and weekend patterns, has been conducted on all the unregulated energy datasets obtained from the case study universities, in order to assess potential trends within laboratory rooms. This analysis can be found in Table 7-14.

Table 7-14: Laboratory room performance ranges across different years, using data from Aston University and the University of Manchester.

Building and lab code	kWh per day - 2017			kWh per day - 2018			kWh per day - 2019		
	Min day	Average	Max day	Min day	Average	Max day	Min day	Average	Max day
AU 1							93	229	342
AU 3							104	502	764
AU 4							5	36	43
AU 5							17	56	93
AU 6							38	75	125
AU 7							6	68	132
AU 10							12	206	488
AU 11							7	19	58
UoM 8.1	2	22	39	0	20	42	0	21	39
UoM 8.2	6	30	61	13	27	41	6	19	31
UoM 8.3	16	36	58	28	50	67	41	50	61
UoM 8.4	0	35	69	10	46	59	8	21	62
UoM 8.5	0	103	181	16	135	200	11	127	195
UoM 8.6	14	24	46	9	19	28	12	16	20
UoM 8.7	6	47	74	19	68	85	33	69	108
UoM 8.8	5	12	29	3	12	33	3	16	50
UoM 8.9	0	9	40	3	8	37	2	8	34
UoM 8.10	0	21	180	17	46	257	16	205	256
UoM 8.11	15	17	56	0	12	22	7	24	41
UoM 8.12	7	10	17	5	10	19	2	11	163
UoM 8.13	5	14	123	12	22	34	9	20	31
UoM 8.14	6	143	246	6	183	249	5	155	237
UoM 8.15	18	182	233	32	188	227	39	176	240
UoM 8.16	7	37	84	12	42	63	29	48	67
UoM 8.17	36	52	73	29	50	83	35	60	80
UoM 8.18	22	32	47	21	27	37	3	18	33
UoM 8.21	5	92	104	5	80	100	4	57	78
UoM 8.22	2	41	46	2	10	42	2	23	35
UoM 8.23	0	5	18	0	5	20	2	9	395
UoM 8.24	0	49	127	43	98	127	20	78	104

UoM 8.25	0	16	17	0	16	17	0	15	17
UoM 8.26	0	33	33	0	32	34	0	30	32
UoM 8.27	5	11	22	6	13	22	6	14	19
UoM 8.30	136	172	197	34	173	208	15	186	209
UoM 8.31	26	30	35	5	27	37	19	29	35
UoM 12.8	6	31	46	2	28	47	1	27	47
UoM 12.9	1	21	46	1	18	45	0	19	44
UoM 12.10	10	52	110	15	61	111	15	59	121
UoM 12.11	0	13	28	0	15	28	0	14	28
UoM 12.14	80	90	110	56	92	109	95	103	140
UoM 12.15	50	59	78	5	60	75	61	70	95
UoM 12.16	73	93	117	0	92	110	83	93	131
UoM 12.17	0	34	125	0	36	122	0	56	131
UoM 12.18	0	18	127	0	41	127	0	58	146

Using the data listed within Table 7-14, it can be ascertained that, whilst there is a large variability in minimum and maximum consumption per day, for each laboratory, there is often little difference between the annual minimum and maximum figures. There is often a broad spread for minimum consuming days, though minimum consuming days often occur during winter/springtime months. Year after year, most of the laboratories suggest little to no changes between 2017 to 2019 (in the minimum and maximum performance ranges).

7.4 Matching Contextual Data with the Sub-metered Data

Prior to the interview process, various trends were noticed across the dataset however, to fully comprehend the information presented, it was imperative to mix contextual information with the sub-metering information. As such, the following section assesses relevant contextual data, in combination with the sub-metering data.

7.4.1 Occupant Numbers and Operational Hours

There are correlations between occupancy and operational hours, however, in certain types of rooms across all of the universities. Lecture theatres, catering facilities (refer to Table 7-13) and computer clusters frequently demonstrate a drop off in electrical consumption. Figures 7-10 to 7-17 have also previously demonstrated some of these typical daily consumption range variances.

The data from the universities suggested a clear correlation between unregulated energy consumption, occupancy levels and operational hours. Unregulated energy consumption was typically highest during in-use periods of the day, such as 08:00-19:00, where the buildings themselves would assumedly have the highest occupancy levels, across all the case study universities. Referring to the occupancy hours listed in Table 4-4, for example, most of the University of Manchester buildings are officially open from 08:00-18:00. Using data from three of the case study universities, Manchester Metropolitan University, the University of Reading and the University of Sheffield, the electrical consumption differences between daytime (in this case 08:00-18:00) to out-of-hours periods (18:00-08:00) has been calculated. Tables 7-15 to 7-17 break down the differences between in-hours and out-of-hours periods. When these data were compared to electrical consumption data, there was typically a noticeable increase in consumption during work hours (compared to mornings) and a noticeable reduction out-of-hours (compared to work hours data).

Table 7-15: A heat map of kWh consumption for 00:00 – 23:00 data, for each sub-meter, at Manchester Metropolitan University. Data has been totalled across the dataset for each hour of the day. Red = highest monthly consumption, Green = lowest monthly consumption.

Sub-meter	**Hour of the day**																							
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***
MMU 1	5,854	5,839	5,849	5,869	6,038	6,446	7,602	8,898	9,747	9,982	10,110	10,373	10,158	10,132	10,167	10,501	10,504	10,047	9,058	8,197	7,787	7,680	6,811	5,931
MMU 2	5,700	6,100	5,600	5,900	5,400	5,700	6,800	5,900	5,200	5,700	7,800	4,900	5,600	6,500	7,400	5,900	6,300	5,900	6,600	5,200	5,300	6,500	6,600	5,100
MMU 3	393	392	394	394	393	394	395	397	400	406	407	407	404	406	403	399	398	396	394	393	393	394	394	394
MMU 4	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
MMU 5	3,250	3,251	3,268	3,262	3,233	3,170	3,139	3,115	3,057	3,017	3,001	3,026	3,023	3,029	3,044	3,083	3,153	3,183	3,204	3,254	3,267	3,304	3,306	3,285
MMU 6	78	76	73	71	70	71	73	76	81	84	84	84	83	82	82	81	81	82	82	83	83	83	83	81
MMU 7	1,257	1,255	1,262	1,256	1,142	895	672	499	329	169	115	105	105	106	120	215	398	559	743	975	1,195	1,256	1,257	1,257
MMU 8	669	669	672	667	595	454	333	238	144	59	34	35	31	32	43	103	205	295	398	527	643	670	670	670
MMU 9	1,395	1,371	1,365	1,348	1,336	1,326	2,456	3,402	3,846	3,920	3,908	3,787	3,685	3,561	3,268	2,723	2,369	2,217	2,096	1,855	1,597	1,523	1,483	1,434
MMU 12	5,180	5,180	5,206	5,231	5,328	6,035	12,981	22,877	27,967	29,583	30,138	30,181	30,776	29,269	24,350	17,311	11,065	7,847	7,241	6,728	5,989	5,476	5,233	5,209
MMU 13	75,764	75,589	75,683	75,679	75,727	75,727	75,730	75,716	75,757	75,830	75,868	75,955	75,969	76,093	76,062	76,075	76,006	75,911	75,910	75,846	75,846	75,710	75,926	75,855

Table 7-16: A heat map of kWh consumption for 00:00 – 23:00 data, for each sub-meter, at the University of Reading. Data has been totalled across the dataset for each hour of the day. Red = highest monthly consumption, Green = lowest monthly consumption.

Sub-meter	**Hour of the day**																							
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***
UoR 1	1,264	1,264	1,257	1,254	1,249	1,232	1,256	1,275	1,539	1,987	2,087	1,938	1,799	1,987	2,244	1,934	1,532	1,400	1,356	1,327	1,315	1,299	1,289	1,274
UoR 2	2,359	2,399	2,450	2,377	2,362	2,413	2,354	2,462	2,396	2,423	2,521	2,455	2,445	2,529	2,586	2,483	2,507	2,540	2,442	2,447	2,487	2,425	2,413	2,441
UoR 3	10,518	10,454	10,471	10,409	10,357	10,297	10,424	12,027	12,601	12,853	12,998	13,078	13,101	13,171	13,272	13,241	13,054	11,248	10,891	10,837	10,737	10,693	10,635	10,553
UoR 4	1,703	1,674	1,737	1,827	1,933	1,816	1,720	1,884	2,059	2,327	2,524	2,406	2,258	2,447	2,748	2,503	2,079	1,961	1,890	1,838	1,789	1,749	1,794	1,789
UoR 5	188	188	188	188	188	193	208	231	261	309	333	333	328	322	326	305	261	225	202	190	188	189	188	187
UoR 6	106	110	121	126	149	166	192	241	289	329	363	367	356	376	376	344	285	213	176	152	146	130	132	124
UoR 7	6,456	6,433	6,416	6,389	6,340	6,334	6,357	6,416	6,508	6,744	6,919	7,005	7,053	7,078	7,112	7,093	7,015	6,907	6,807	6,711	6,619	6,578	6,531	6,490
UoR 8	105	103	117	111	147	140	127	137	146	134	140	142	141	134	144	137	126	132	124	123	120	117	120	115
UoR 9	391	381	422	423	524	502	495	498	534	503	528	517	526	514	536	515	529	516	516	498	489	431	445	383
UoR 10	4,438	4,429	4,432	4,429	4,446	4,458	4,463	4,598	4,810	5,073	5,229	5,324	5,357	5,372	5,385	5,335	5,165	4,923	4,683	4,552	4,476	4,467	4,450	4,436
UoR 11	703	676	810	770	981	980	894	935	975	1,231	1,492	1,680	1,700	1,686	1,594	1,605	1,481	1,272	1,078	944	866	797	817	779
UoR 12&13	1,828	1,824	1,818	1,821	1,797	1,806	1,803	2,166	2,227	2,314	2,380	2,404	2,412	2,411	2,418	2,395	2,362	2,321	1,951	1,887	1,865	1,865	1,845	1,837
UoR 14	1,385	1,340	1,597	1,725	2,548	2,304	2,089	1,986	1,860	1,832	1,709	1,800	1,809	1,761	1,799	1,799	1,727	1,855	1,849	1,792	1,855	1,688	1,740	1,671
UoR 15	406	421	413	473	525	505	500	494	477	483	491	498	501	508	500	494	486	492	477	451	445	443	445	442
UoR 16	584	620	671	679	1,062	1,025	833	814	842	807	783	776	797	815	791	785	785	764	840	746	769	724	736	670
UoR 17	614	574	602	592	701	843	722	716	710	679	682	675	679	670	681	675	666	676	665	686	671	646	659	622

Table 7-17: A heat map of kWh consumption for 00:00 – 23:00 data, for each sub-meter, at the University of Sheffield. Data has been totalled across the dataset for each hour of the day. Red = highest monthly consumption, Green = lowest monthly consumption.

Sub-meter	**Hour of the day**																							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
UoS 1	2,252	2,253	2,293	2,324	2,300	2,306	2,325	2,311	2,298	2,282	2,300	2,287	2,315	2,332	2,342	2,296	2,282	2,282	2,242	2,281	2,265	2,272	2,268	2,278
UoS 2	10,245	9,941	9,784	9,683	9,558	9,318	9,361	9,523	10,156	11,025	12,018	12,878	13,479	13,983	14,436	14,515	14,299	13,762	13,165	12,570	12,049	11,505	10,996	10,582
UoS 3	277	276	276	278	276	276	276	273	272	415	1,151	1,267	1,094	934	724	799	793	706	442	280	274	275	276	277
UoS 4	12,261	12,142	12,239	12,230	12,222	12,188	12,150	12,105	12,095	12,163	12,351	12,397	12,513	12,601	12,676	12,794	12,777	12,681	12,530	12,391	12,350	12,286	12,275	12,296
UoS 5	2,849	2,811	2,840	2,848	2,841	2,828	2,810	2,798	2,810	2,873	2,931	2,996	3,032	3,051	3,058	3,043	2,991	2,936	2,876	2,838	2,829	2,825	2,834	2,842
UoS 6	4,157	4,135	4,154	4,162	4,153	4,187	4,280	4,460	4,616	4,883	5,035	5,092	5,203	5,249	5,318	5,300	5,201	5,094	4,913	4,724	4,548	4,350	4,248	4,196
UoS 7	4,880	4,833	4,867	4,870	4,840	4,823	4,776	4,770	4,814	5,139	5,446	5,545	5,607	5,633	5,665	5,693	5,664	5,624	5,325	5,068	4,946	4,885	4,885	4,886
UoS 8	2,421	2,396	2,422	2,425	2,420	2,413	2,415	2,451	2,459	2,517	2,638	2,668	2,693	2,715	2,724	2,717	2,661	2,623	2,518	2,473	2,470	2,456	2,419	2,424
UoS 9	2,533	2,502	2,532	2,537	2,534	2,519	2,494	2,481	2,499	2,547	2,613	2,634	2,647	2,649	2,694	2,725	2,700	2,626	2,546	2,514	2,507	2,514	2,516	2,533
UoS 10	2,774	2,725	2,762	2,769	2,756	2,745	2,722	2,712	2,777	3,325	3,524	3,621	3,671	3,666	3,686	3,699	3,642	3,378	2,897	2,775	2,775	2,767	2,767	2,773
UoS 11	2,513	2,484	2,511	2,516	2,513	2,494	2,469	2,461	2,494	3,327	3,569	3,648	3,675	3,702	3,728	3,752	3,655	3,143	2,541	2,489	2,486	2,488	2,496	2,514
UoS 12	5,756	5,693	5,759	5,759	5,759	5,741	5,711	5,702	5,723	5,792	5,805	5,763	5,807	5,797	5,816	5,848	5,835	5,831	5,812	5,771	5,760	5,747	5,757	5,766
UoS 13	264	262	265	265	265	264	263	265	291	395	403	399	398	398	398	401	401	398	382	340	300	279	272	268
UoS 14	2,430	2,410	2,430	2,432	2,431	2,421	2,404	2,406	2,472	2,565	2,740	2,850	2,889	2,963	2,951	2,982	2,885	2,757	2,545	2,444	2,441	2,438	2,442	2,438
UoS 15	15	16	17	17	18	19	21	20	20	18	13	10	9	7	7	8	8	9	9	11	12	13	14	15
UoS 16	1,309	1,293	1,305	1,307	1,305	1,299	1,293	1,291	1,288	1,307	1,383	1,392	1,404	1,384	1,383	1,399	1,397	1,380	1,334	1,305	1,303	1,303	1,307	1,306
UoS 17	2,252	2,253	2,293	2,324	2,300	2,306	2,325	2,311	2,298	2,282	2,300	2,287	2,315	2,332	2,342	2,296	2,282	2,282	2,242	2,281	2,265	2,272	2,268	2,278
UoS 18	6,351	6,320	6,362	6,372	6,372	6,354	6,336	6,339	6,330	6,342	6,334	6,307	6,310	6,286	6,333	6,346	6,336	6,351	6,351	6,348	6,363	6,354	6,370	6,367
UoS 19	2,545	2,509	2,542	2,541	2,543	2,529	2,511	2,504	2,500	2,576	3,085	3,004	3,018	2,937	2,944	3,076	3,180	3,098	2,804	2,570	2,542	2,536	2,542	2,547
UoS 20	3,102	3,083	3,082	3,088	3,082	3,064	3,049	3,052	3,056	3,082	3,112	3,138	3,162	3,178	3,223	3,245	3,249	3,218	3,198	3,175	3,160	3,134	3,127	3,115
UoS 21	3,502	3,465	3,493	3,489	3,495	3,471	3,459	3,451	3,445	3,509	3,834	3,949	3,891	3,818	3,820	3,864	3,683	3,516	3,499	3,490	3,492	3,497	3,496	3,516

One example of combining the equipment data with operational hours and occupancy data would be UoM 8.10 (an electromagnetic control room), which contains only a three-phase cage that takes up 60% of the room; the cage was similar to a faraday cage, which had a magnet in a cryostat. Whilst the room had a capacity for two three-phase sockets and two single-phase sockets, the kit only used the three-phase socket. For this example, a typical weekday against a typical weekend day is compared in Figure 7-19. The very small variations from operational hours in the week to evenings and weekends suggest that the equipment baseload (and not increases in consumption during usage) are the main contributors to the room's overall regulated consumption. This is supported following interviews with the building manager.

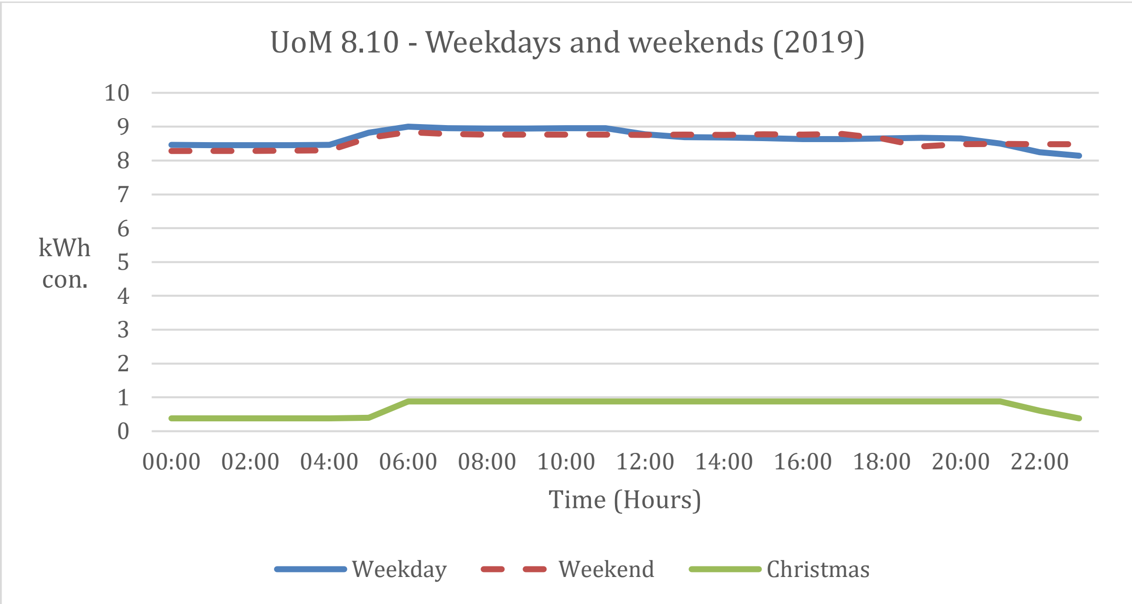

Figure 7-19: Average weekday, average weekend, and total Christmas day electrical consumption for UoM 8.10, in the University of Manchester.

As seen in Figure 7-19, there is no difference between weekdays and weekends, nor any changes in the room's consumption profile. According to the building manager, the reasoning for this is that frequently turning on and off this equipment would be unfeasible (and could damage the machine). Hence, the constant baseload is consistent; however, the equipment is occasionally turned off. This can be seen replicated during the Christmas-time data line, represented in Figure 7-19, indicating that over substantial periods, the equipment can be turned off. Over shorter holiday periods, such as Easter, this reduction was not noticeable within this room.

By comparing weekday, weekend, and holiday-time unregulated consumption, it becomes evident that reducing baseload consumption within laboratories is possible, though it is tricky. The UoM 8.10 room example is not an exemplary example for the data across the different universities, though its daily electrical consumption is higher than for other types of laboratories. However, it does represent a consistent trend, where the baseload of a laboratory room far exceeds an ideal performance range. Ideally, a room's baseload should be minimal or, at the very least, reduced whenever possible. For cases where this is not possible improved and realistic understanding of energy consumption within laboratories should be sought to enable the identification of underperforming areas for improvement.

7.4.2 Combining Equipment Data with Electrical Consumption Data

Due to oversights in the historical equipment datasets, it was decided that the interview process would be used to obtain more up-to-date equipment information. Using the information provided by various interviewees, contextual information was compared to sub-metering information, in order to ascertain whether small changes in room occupancy figures/room equipment types/general research being conducted in different spaces, would have an impact on unregulated energy consumption.

Information provided by the interviewees did help answer various lingering questions surrounding unregulated energy consumption in various rooms. Additionally, much of the equipment data obtained from the interviewees also offered insight into why there were changes in electrical consumption within certain rooms. For example, the interviewees suggested that from July-August 2017 there was a change in room usage in UoM 8.3 in the UoM 8 building, which saw the lab change from a composite lab to an energy lab in August 2017. In this research laboratory, all the equipment from the room was removed and instead the fume cupboards were installed into the room. Using sub-metering data, Figure 7-20 demonstrates an increase in unregulated energy consumption from this period onwards, and across future datasets.

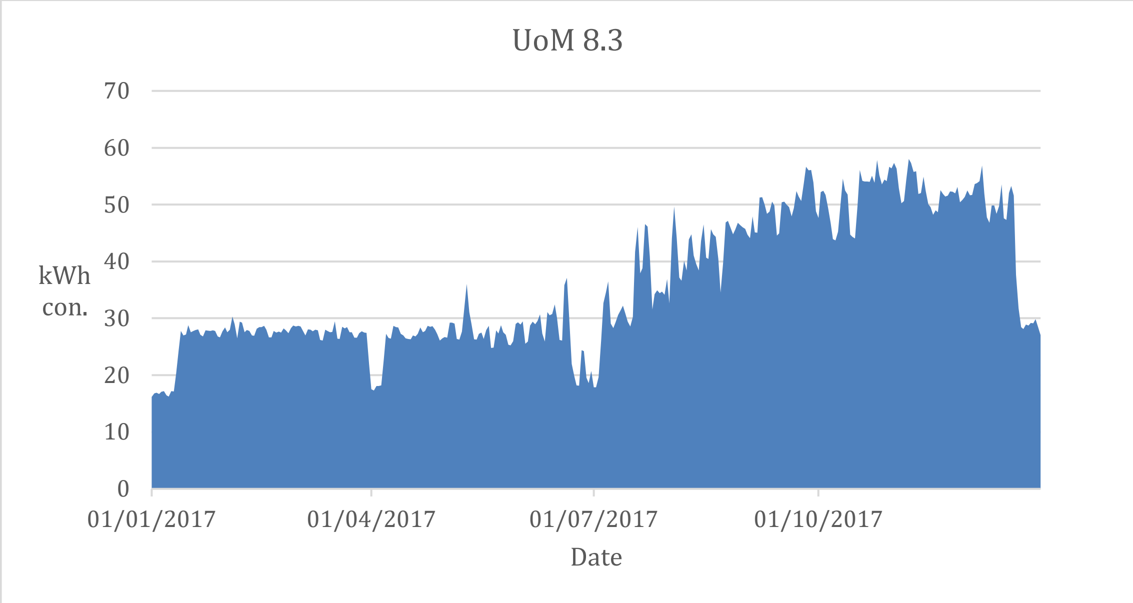

Figure 7-20: An increase in electrical consumption, once UoM 8.3's room purpose changed.

As another example, UoM 8.22, a deposition and dry lab, in UoM 8 once again, according to the building managers, saw a new E-beam spotter installed Christmas 2019. The data suggests a small kWh increase directly after this installation, as shown in Figure 7-21, however, the installation of the equipment does not cause a prolonged change in overall unregulated energy consumption.

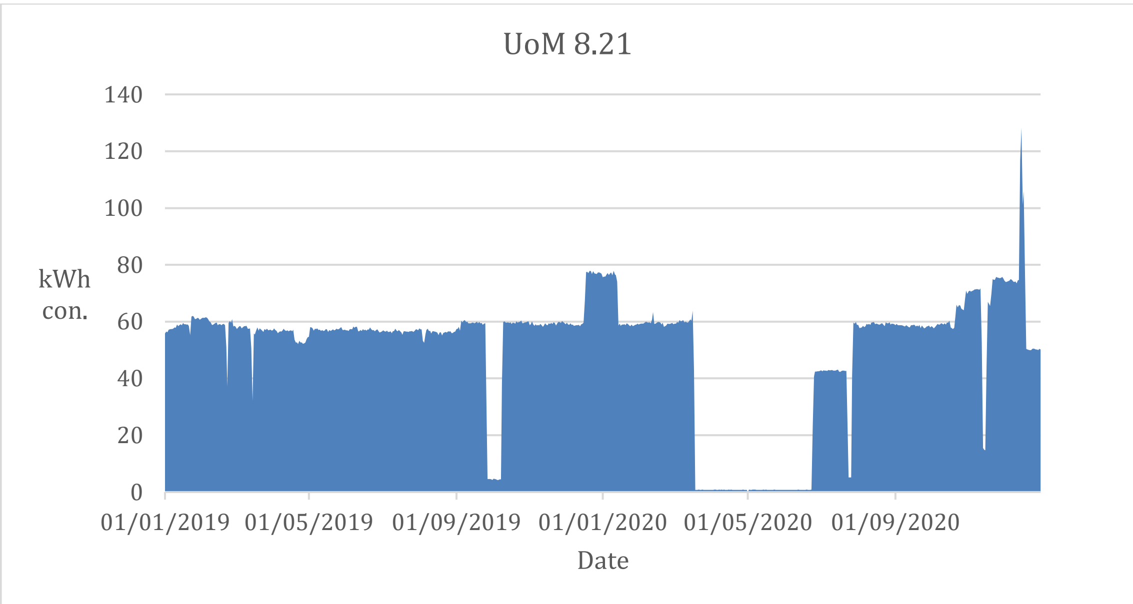

Figure 7-21: A demonstration for a change in electrical consumption in UoM 8.22, once the E-beam spotter was installed during "Christmas 2019".

Figure 7-20 and Figure 7-21 show some of this combination between electrical consumption and contextual information, where changes in the room's research purposes and installation of new equipment saw a change in total electrical consumption. The overall changes to rooms, changes to equipment and overall occupancy figures for the case study rooms can be found in Table 6-2 to Table 6-5. For UoM 8.4, the changing of the room's purpose caused a steady increase in long-term unregulated energy consumption, whilst the installation of a new E-beam spotter in UoM 8.22 showed no clear changed in long-term unregulated energy consumption, meaning installation of new equipment does not always have a significant impact on energy consumption.

Using data listed in Tables 6-2 to 6-5, there is a strong suggestion that users can impact unregulated energy consumption. UoM 8.17 was transformed from a general laboratory to a Terra Hertz laboratory "in the last year" according to Interviewee 3 and Interviewee 4, meaning that, based on the time of the interview, this occurred at the beginning of 2021 at the earliest. 2021 data suggests a total kWh consumption of 1067 kWh, whereas 2022 kWh consumption for UoM 8.17 increased to 3797, suggesting the change in room purpose had a substantial impact on the overall unregulated energy consumption.

As another specific case study, in UoM 6.3, new equipment was commissioned across a series of dates; for this focus, the focus remains primarily on the 2017-2020 datasets. For example, a replacement air cushion system for the 2 MV impulse generator was commissioned in June 2017, and an 800 kV AC Test Set and a 600kV DC Test Set were commissioned in July 2018. However, a massive reduction in electricity consumption was noticed on 11th November 2017; prior to this date, readings averaged at 449 kWh per day. From this point onwards, readings averaged at 111 kWh per day for the rest of the dataset. Between the 10th and 11th November, there was an electrical kWh reduction of 78.56%. The room continued to consume much lower amounts of electricity across the dataset up until 2020, shown in Figure 7-22 below. The commissioning of this equipment seems to have caused a reduction in electrical consumption in the room, as it is likely that older, less-efficient equipment was removed in order to commission the newer equipment.

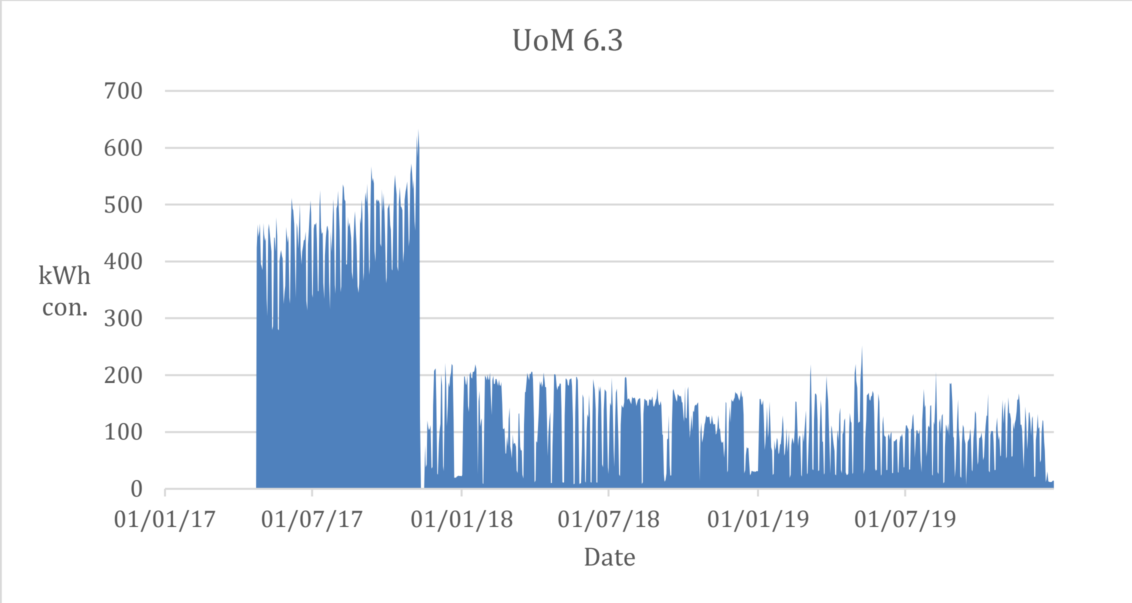

Figure 7-22: Daily electrical consumption in UoM 6.3, at the University of Manchester.

Focusing on computing power now, during the interview process, it was hypothesised in Chapter 6 that computing facilities are continuously left on out-of-hours, in order to allow staff and students to remotely login to their desktop computers. Using sub-metering data and server room data from Manchester Metropolitan University, Aston University and the University of Manchester, differences between server room electrical consumption vary across the universities. For the server rooms, there are major kWh difference across the four universities between in-hours consumption and out-of-hours consumption (often only varying from 1-15% for the different server rooms across the day), with the exception of UoM 10, which does demonstrate a small change between in-hours and out-of-hours periods (varying up to 32% per day). The little to no differences between the in-hours and out-of-hours suggest that computer facilities may be used out-of-hours, or in the very least that computing facilities remain constantly available (and hence the server rooms are left on consistently, on a 24/7 basis, in order to allow constant access to university systems).

7.4.3 Insights Obtained from the COVID-19 Pandemic

In March 2020, the UK began to shut down public institutions and private businesses due to the COVID-19 crisis. Universities were part of this shutdown, although their specific shutdown dates varied across each university. The official governmental shutdown was declared on the 26th of March, although many organisations closed their doors before this date. For example, the University of Manchester closed all its campuses and suspended all non-essential activities on the 17th of March (The University of Manchester, 2020b). Only essential staff, such as security staff, could continue working on-site if necessary. In all, this shutdown period has caused a massive reduction in energy consumption across various universities, and its effect on unregulated energy consumption is of interest to this research. When compared to other shutdown periods, such as Christmas shutdowns, the COVID-19 shutdown caused an abrupt reduction in electrical consumption across multiple countries (IEA, 2021). Similar findings have been replicated within other buildings, such as Aston University, which saw an average electrical consumption decrease of approximately 50-60%.

Across universities, the building occupancy levels remained close to zero. Still, due to the nature of the buildings, they must remain habitable for occupants to reoccupy them with sometimes little notice. Issues such as legionella, mould and corrosion of materials are all possible unless the building remains habitable; for example, heating must stay on, but ventilation and fan coil maintenance can be reduced as fewer contaminants are being emitted within the building (CIBSE Journal, 2020). Hence electrical consumption will have reduced in specific areas, and there is an assumption that unregulated energy would overall reduce during this time.

With the potential fiscal impact of the crisis, on a positive note, there was also a noticeable reduction in total energy consumption across university buildings. Birch et al. (2020), however, noted that this expectation and relationship between occupancy reductions and energy consumption was not as anticipated. There had been an assumption across different energy management teams within the case study universities that energy consumption should substantially reduce as occupancy numbers dropped to near zero. As unregulated energy is typically user-related, the occupants did not directly use many devices during the shutdown, such as laboratory and office equipment, catering facilities, supplementary heating, and lifts. Hence, in theory, these should all be turned off, as hypothesised in the Birch et al. study (2020). However, the Birch et al. research found that unregulated electricity consumption reduced by approximately 46.61% (using the week before and the week during lockdown). The reason for this smaller than anticipated reduction was primarily due to equipment being left on. The case study university's baseload remained higher than expected for zero occupancy buildings. Birch et al. noted that the baseload remained high primarily due to the equipment being left on across various; several regulated systems (such as hot water and heating) were also left on consistently. Other devices such as emergency and external lighting and server rooms were hypothesised to consume as normal. There was also an assumption for server rooms to potentially start consuming more than the initial shutdown period, as the demand for IT and remote access was determined to be high. Although the reduction in baseload electricity consumption was not as significant as anticipated during the pandemic, the COVID-19 crisis provided insight into how baseload consumption across universities is highly tied to occupancy levels, as would be expected.

Referring back to the thesis research, and comparing data from all the universities, there was a consensus that when occupancy was at its lowest, such as during Christmas shutdown periods, unregulated electrical consumption would typically also be at its lowest. This was consistent across the universities, where most buildings would be closed during Christmas time (or, if not completely closed, would be running with only a skeleton staff). This concept ties in with the third research question, which considers the specific effects of both operational hours and occupancy levels.

On the 17th-18th March 2020, many buildings at the University of Manchester indicated a significant reduction in electrical consumption and saw a sustained reduction in the following months. Not every building achieved such a reduction, however; for example, using February-March data, the UoM 4 building consumed on average 6,312 kWh per day. Using April-May data, the UoM 4 building consumed on average 5,456 kWh per day. Thus, the baseload for the building remained large, even when occupancy of the building reduced to near-zero.

To better understand the effects of zero occupancy (or minimal occupancy) the 2020-2021 COVID-19 pandemic is an exemplary period for evaluating how much unregulated electrical consumption different buildings would consume during a typical day (as it was assumed all buildings would remain operational yet empty, except for a skeleton staff).

For this example, UoM 8.2 compares unregulated power consumption from previous years. For Manchester, the university officially closed on the 16th-17th of March 2020. Hence, this room’s immediate reduction in occupancy and power consumption correlates (as across many others on campus). Figure 7-23 shows this immediate reduction in electrical consumption on these dates.

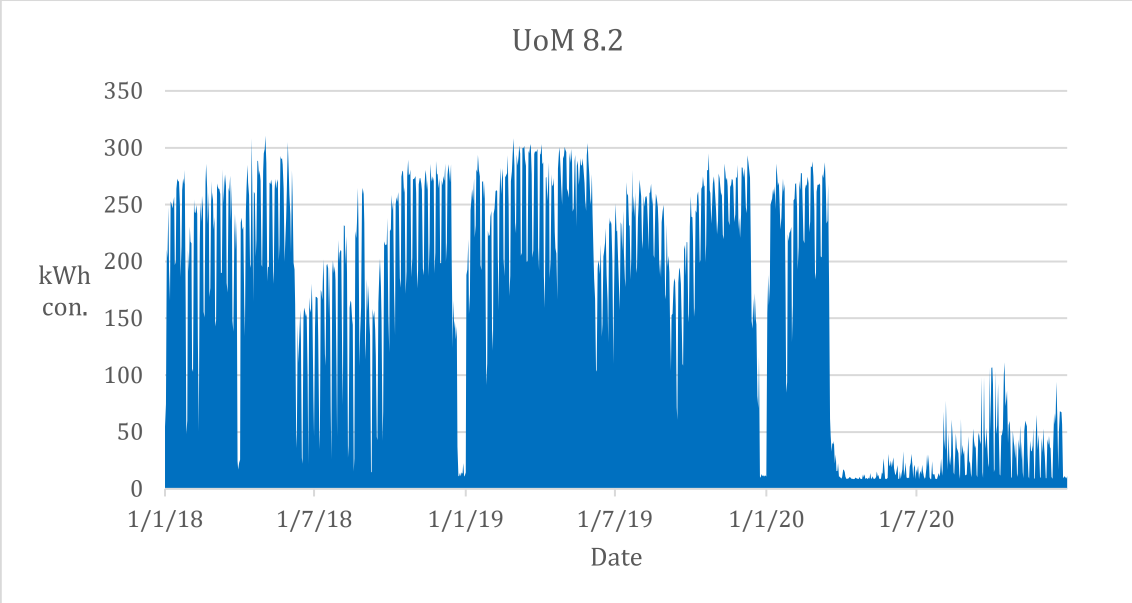

Figure 7-23: Annual electrical consumption in UoM 8.5, at the University of Manchester.

Most of the case study campus buildings assessed within this work were open on weekdays and closed on weekends, hence consumption should be much lower across the weekends. The weekday operational hour profiles typically run from a typical 08:00-18:00 timeframe, though certain buildings remained open until 19:00-21:00. For Aston University, data were provided for a series of rooms within the case study building. Requested information included baseload information to understand how the university performed pre-pandemic and during the pandemic. Based on this discussion, the energy manager confirmed that overall consumption dropped 50-60% during lockdown compared to pre-COVID figures on average**.** At the time of this contextual discussion, which took place in May 2020, heating was running only 2-3 hours per day; equipment was turned off and different rooms, such as catering facilities and general laboratories, were closed. On the 23rd of March, the university officially closed**.** However, facilities such as the children's hospital and the eye laser surgery clinic remained open, and a skeleton staff (approximately 20 staff members) were actively on campus.

In general, within the AU building, there was a noticeable relationship between the laboratory data and the time of year. AU 5, AU 6, AU 7, and AU 10 (for building code definitions, refer to Table 7-2) demonstrated similar patterns, where high-consuming equipment appears to be turned off during the Christmas shutdown period and the COVID-19 period, particularly for the latter two rooms. However, AU 11 did not fit this pattern as it was the only room that did not display a noticeable decrease in consumption during the COVID-19 shutdown period, during the dataset period (May 2019-April 2020). The data from the building suggests that zero occupancy and low-occupancy periods correlate with lower energy consumption, such as during the Christmas break and during the COVID-19 pandemic.

Continuing the analysis of power consumption during the COVID-19 crisis, the University of Reading closed in April 2020. On the 17th of April 2020, it was announced that the university would be shutting the campus. By the end of April, it was determined that electricity use was down by 40%, compared to pre-shutdown consumption. Heating within the buildings remained on until the end of April. This reduction replicated other shutdown periods as during their Christmas shutdowns, the University of Reading typically reduced energy consumption by approximately 33% (on a campus level, including heating and electricity). The reduction in consumption during the COVID-19 pandemic was 40%, so a similar amount to their typical Christmas shutdowns. Hence the COVID-19 shutdown matched closely with previous shutdowns. They noted what equipment was switched off every day, in order to keep a track record of the devices left on at the university. In all, ventilation consumption across the university accounted for a substantial proportion of consumption.

Generally, several things were noticed from the Reading data concerning their baseload consumption and the COVID-19 crisis. For UoR 7 (refer to Table 7-5 for a breakdown of building codes), small power load equipment, such as power sockets, suggested a moderate baseload and minor out-of-hours differences, suggesting equipment was left on consistently. At the end of March 2020, there is an apparent reduction in consumption until just after the beginning of July 2020, where certain staff members were allowed back in the building to conduct research. Consumption then massively increases again from this point, back to pre-COVID levels.

Certain rooms were expected to have a high baseload, such as UoR 2. These cold rooms were not dependent on occupancy, as consumption remains constant across 2020 (even during COVID-19). The baseload was around 43 kWh per day. They also indicated no weekday vs weekend variability or daytime vs night-time variability. Laboratory rooms with lower consumption, such as UoR 11, indicate similar patterns with little to no out-of-hours electrical reductions. However, the 2020 shutdown suggested that even low-consuming rooms still made hefty reductions of in-hours electrical consumption. For the two lab rooms in the

University of Reading, the average daily January-March vs April-July readings going from 35.58 to 13.01 kWh per day. For all the universities assessed in this section, there was a clear correlation between zero occupancy and low-occupancy periods and a reduction in energy consumption. There is therefore a clear relationship between occupancy levels and unregulated (as well as regulated) consumption. This relationship is distinct from, and stronger, than that of out-of-hours (evening and weekend) reductions from the electricity consumed in hours. This however is not true for every room type and the equipment operating must be carefully considered.

7.5 Breakdown of Unregulated Energy Vs Regulated Energy

Breaking down the total unregulated and regulated energy across the universities was a complex endeavour. The main issue was that, when assessing the building's total electrical consumption reading, and then totalling up the entire sub-meters within the building, there was often a difference between the two sum totals. Essentially, there was a difference in data collected from the top-down vs the bottom-up approach. This could be for several reasons; for example, many buildings contained generic distribution boards (DBs) and individual sub-meters. Occasionally, the individual readings could also be captured under the distribution boards. Thereby, the readings could theoretically be counted twice when using the bottom-up approach.

Certain sub-meters were also weighted; for example, Heating, Ventilation, and Air Conditioning (HVAC) sub-meters typically had a 0.1 multiplication applied. This is due to the readings likely being captured under multiple distribution boards and individual sub-meters; hence, the multiplication is applied to correct these readings. However, even after the weighting was applied, the two totals often did not align. One additional reason for this could be that frequently, sub-meter data linked to generic DBs, which in this case would be classified as including both unregulated and regulated energy consumption. These DBs are also likely responsible for the misalignment between the other building's total electrical reading and the totalled sub-meter readings. These DBs also link to individual sub-meters occasionally, meaning sometimes the totalled sub-meter readings may accidentally count a reading twice rather than just once.

Hence, to resolve this issue, only buildings where the two totals equalled (or had minor kWh differences, such as a difference of under 100 kWh) were included to understand the breakdown of unregulated and regulated consumption within the buildings. Looking at data from the University of Manchester, Figure 7-24 details the different regulated and unregulated consumption categories, whilst Figure 7-25 highlights the differences between the two categories, using the same data. A further thorough breakdown of the data listed in these two figures can be found in Appendix D.

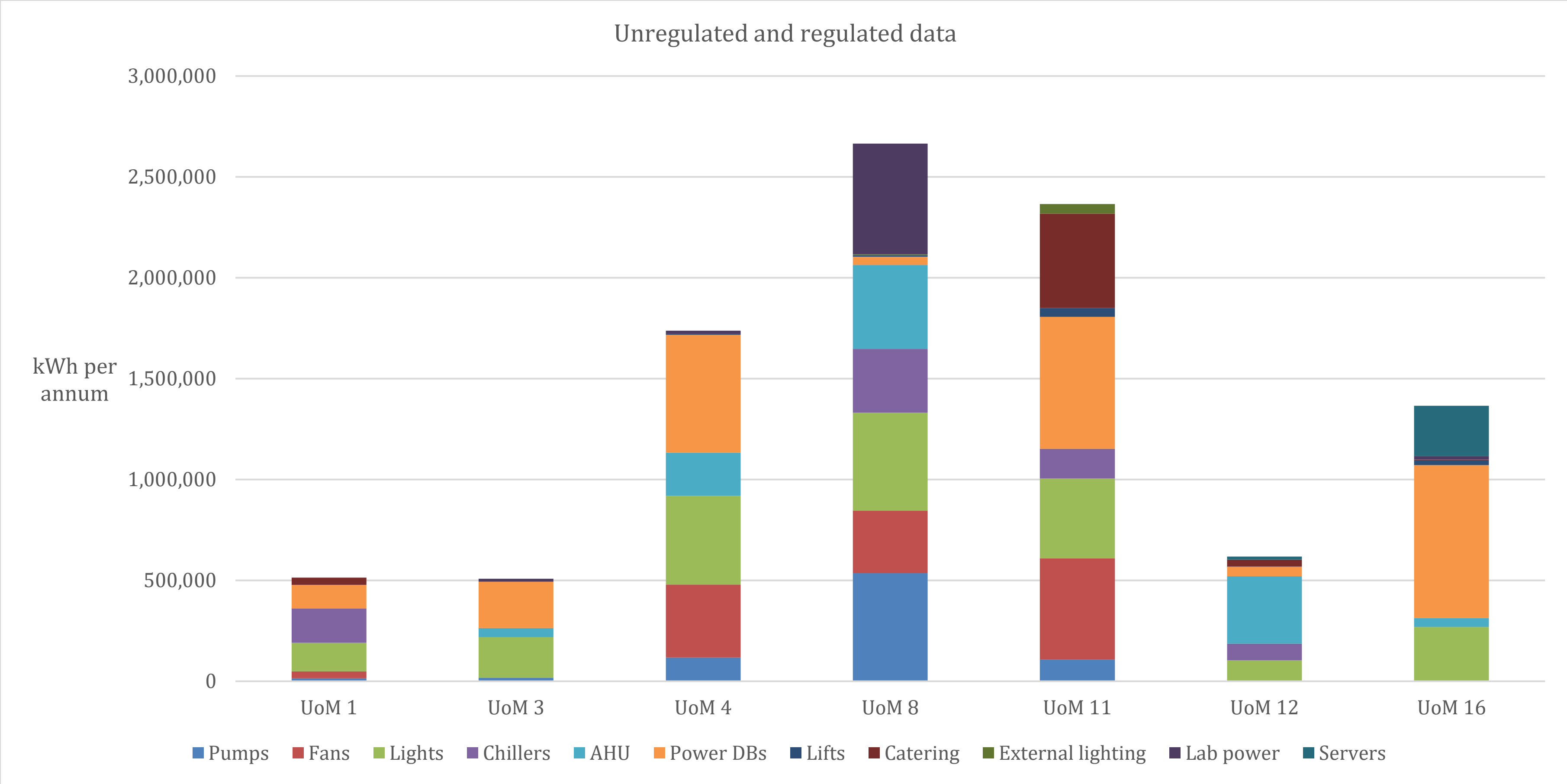

Figure 7-24: kWh electrical consumption for different regulated and unregulated energy types across different University of Manchester buildings.

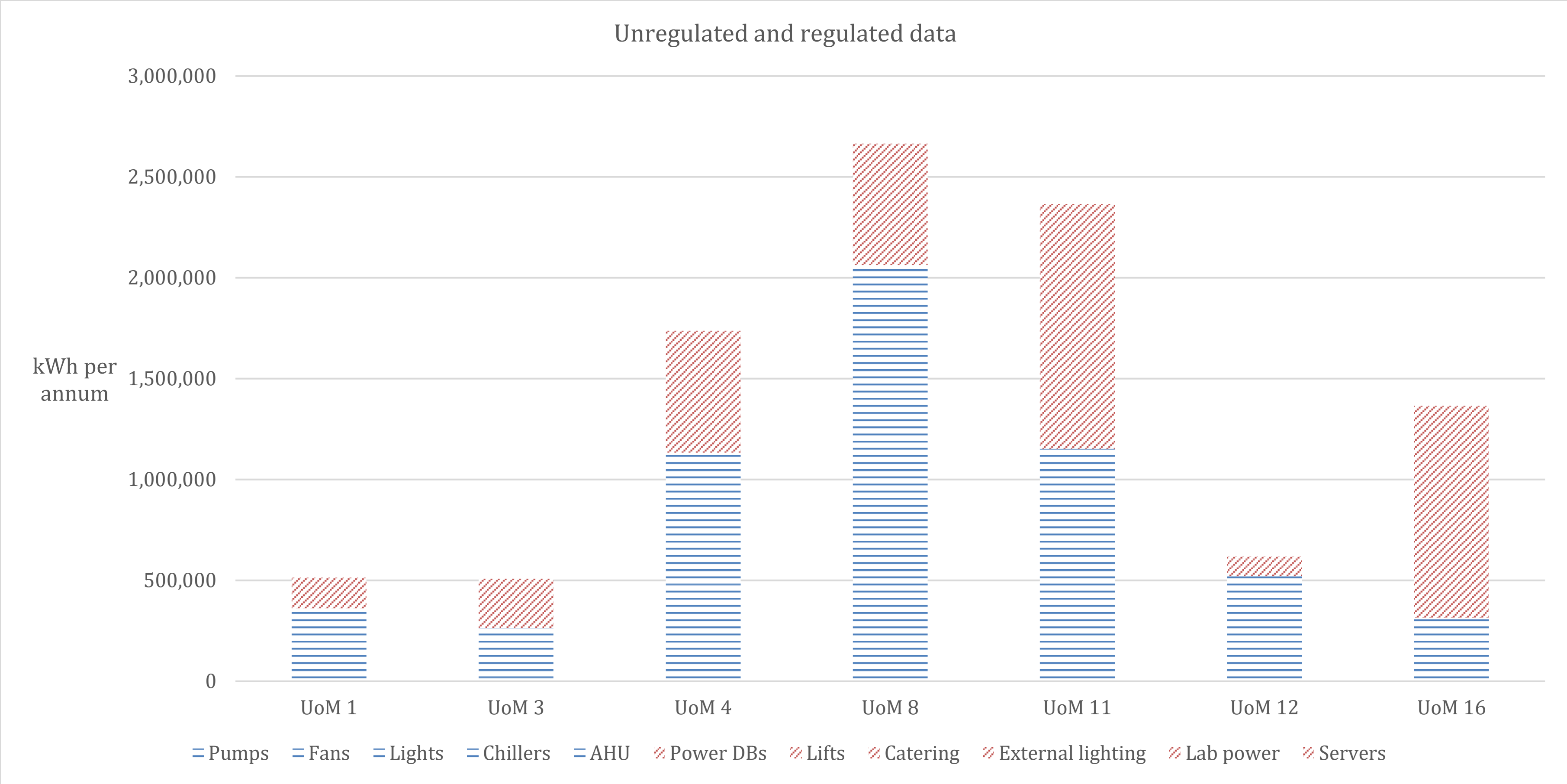

Figure 7-25: kWh electrical consumption for different regulated and unregulated energy types across different University of Manchester buildings. Blue refers to regulated energy, whilst red refers to unregulated energy.

The building's overall sub-meters indicate that unregulated energy consumption was typically lower than regulated energy consumption for the selected buildings. As a note, these figures only account for electrical consumption and not heating consumption. The levels of unregulated energy differed immensely depending on the type of building and demonstrate the variable areas of both regulated and unregulated consumption.

Comparatively, using sub-metering data, a comparison between the total amounts of unregulated vs regulated energy (or distribution board information) was also calculated for each of the other case study universities. These findings are represented in Figures 7-26 to 7-28.

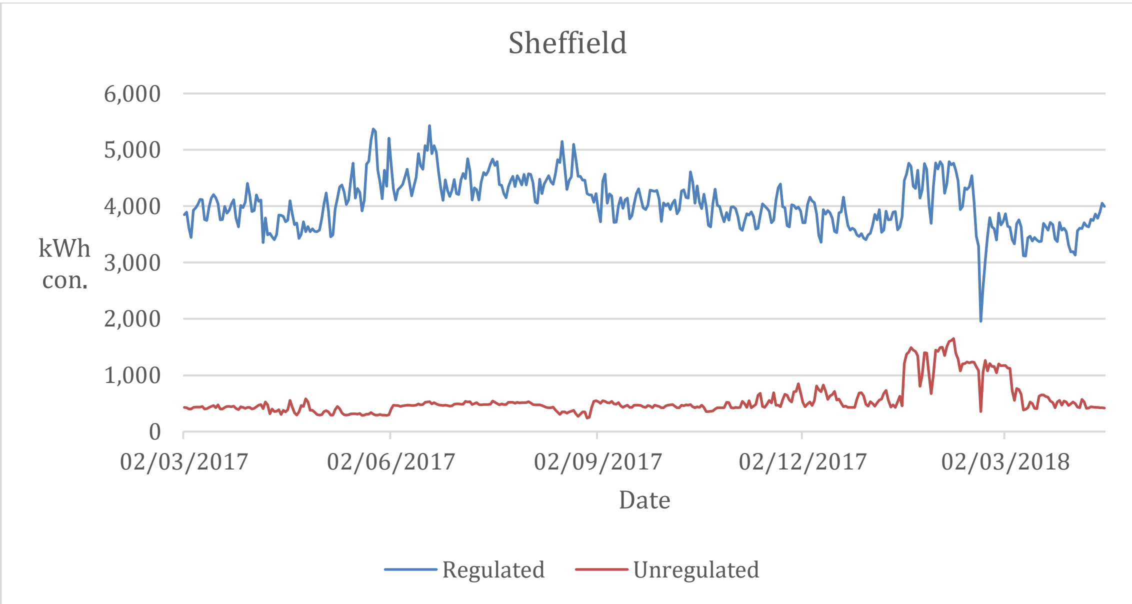

Figure 7-26: Daily unregulated and regulated energy consumption within the case study building at the University of Sheffield.

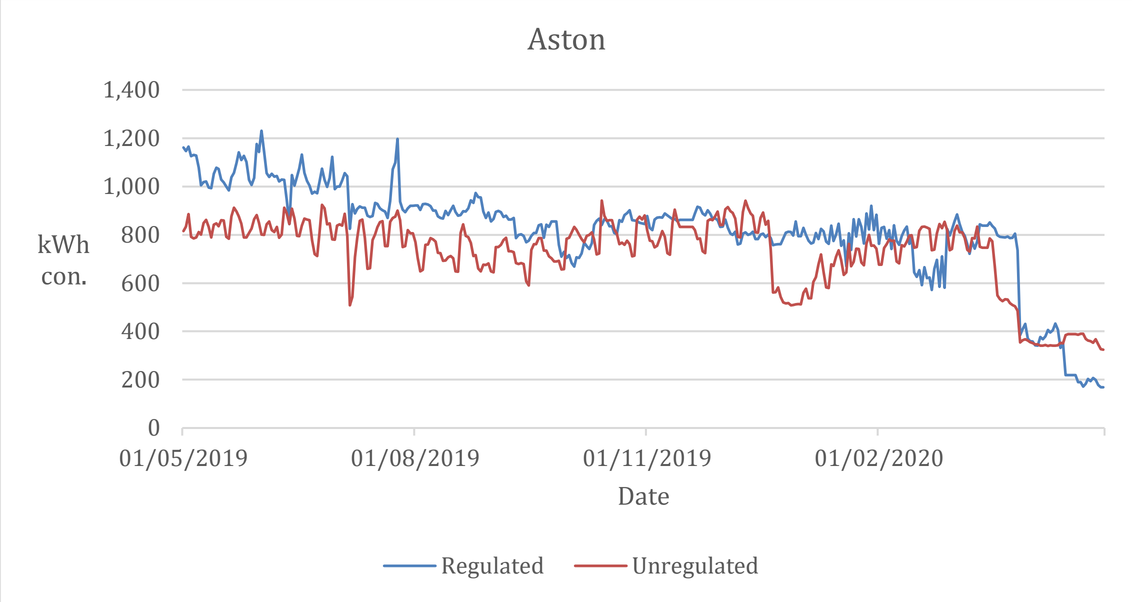

Figure 7-27: Daily unregulated and regulated energy consumption within the case study building at Aston University.

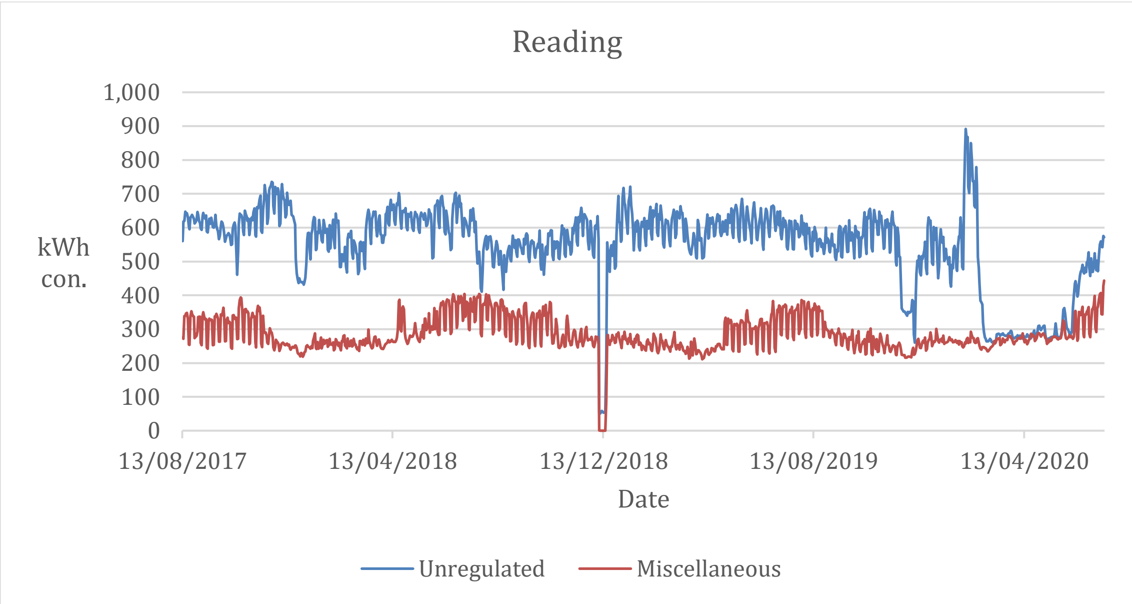

Figure 7-28: Daily unregulated and miscellaneous energy consumption within the case study building at the University of Reading. Miscellaneous refers to generic distribution board information which lack clear definitive information, and which could be broken down into either unregulated or regulated energy.

The initial concept, ascertained earlier throughout the literature that unregulated energy represented approximately 50% of a building's total consumption, is shown here to be highly dependent on the building. In the respective order for each of the case study universities listed here, the overall breakdown of unregulated energy percentage is as such:

- The University of Sheffield: 12.04%
- Aston University: 46.94%

- The University of Reading: 65.82%

Manchester Metropolitan University data has been excluded from these percentages and this breakdown of unregulated energy consumption, as the building lacks regulated sub-meters or distribution boards required for comparison. Additionally, it is worth noting here that the University of Reading's comparison is set against other miscellaneous sub-meters, as opposed to regulated sub-meters. Comparatively, using the University of Manchester data, it was found that on average (and using 2019 data), unregulated energy typically represented 22.49% of a building's total electrical consumption. For a more detailed breakdown of the case study buildings, Table 7-18 breaks down the data further.

Table 7-18: A breakdown of Unregulated vs Regulated + Distribution Boards sub-metering across the case study buildings at the University of Manchester.

Building code	kWh			Percentage breakdown	
	Unregulated	Regulated + DBs	Total	Unregulated	Regulated + DBs
UoM 1	167,587	763,348	930,935	18.00%	82.00%
UoM 2	672,598	769,196	1,441,794	46.65%	53.35%
UoM 3	250,191	703,440	953,631	26.24%	73.76%
UoM 4	674,694	1,788,248	2,462,942	27.39%	72.61%
UoM 5	15,516	140,315	155,831	9.96%	90.04%
UoM 6	81,560	331,095	412,655	19.76%	80.24%
UoM 7	55,775	582,595	638,370	8.74%	91.26%
UoM 8	857,518	3,379,266	4,236,784	20.24%	79.76%
UoM 10	145,454	2,446,485	2,591,939	5.61%	94.39%
UoM 11	459,149	2,567,869	3,027,018	15.17%	84.83%
UoM 12	406,858	900,317	1,307,175	31.12%	68.88%
UoM 13	455,118	628,495	1,083,613	42.00%	58.00%
UoM 14	N/A	N/A	N/A	N/A	N/A
UoM 15	136,220	537,906	674,126	20.21%	79.79%
UoM 16	1,162,057	1,498,361	2,660,418	43.68%	56.32%
UoM 17	164,768	907,244	1,072,012	15.37%	84.63%
UoM 18	75,691	9,951,160	10,026,851	0.75%	99.25%
UoM 19	188,241	1,322,725	1,510,966	12.46%	87.54%
UoM 20	2,261,579	3,185,322	5,446,901	41.52%	58.48%

7.6 Do Different Building Factors Affect Unregulated Energy?

Overall, it was found that building-related factors, such as building size, age, and external conditions, such as temperature, had little to no impact on unregulated-energy consumption specifically. Regarding building age, data were taken from the University of Manchester, in order to identify if there could be any correlation between building age and unregulated energy consumption.

Data from the University of Manchester illustrated that newer builds tended to consume more energy. However, this was primarily due to these newer buildings being research-focused buildings, containing high proportions of laboratory equipment. Figure 7-29 indicates a spread in energy consumption across buildings of various ages, with post-1970s buildings having a higher span in electrical consumption ranges. It also becomes apparent that there is a tendency for modern buildings to consume more than historical and pre-1970s builds. First, this is due to a trend in obtaining more energy-intensive equipment; as technology advances, so too does research capabilities. And secondly, a substantial proportion of the more modern campus buildings tend to be laboratory or research buildings, which typically have higher energy consumption.

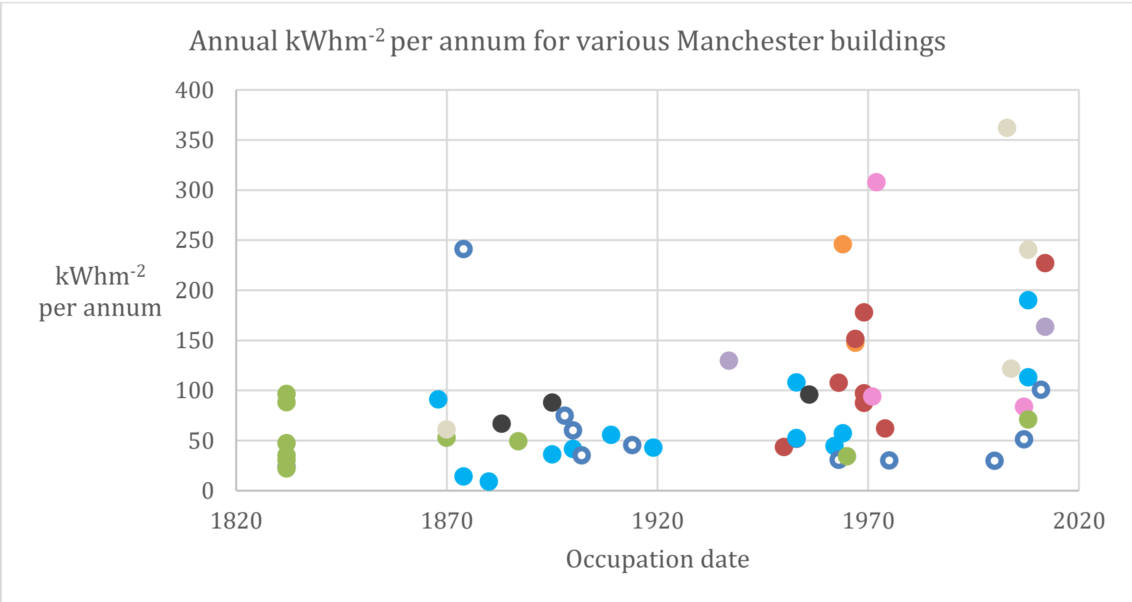

Figure 7-29: kWhm^{-2} per annum electrical consumption, calculated using 2019 data, for different buildings at the University of Manchester. Green = Admin/support, Turquoise = Teaching, White = Mixed mode building (mixed amount of teaching and research spaces), Grey = Medical and bioscience laboratories, Black = Social space/student dominated space, Purple = Library, Red = Engineering laboratories, Orange = Chemical laboratories, and Pink = Maths and computing.

The building data indicates how much electricity different laboratory buildings can consume, representing a potentially substantial amount of regulated and unregulated energy consumption.

In terms of potential correlations between unregulated energy and external temperatures, or weather conditions, this work assessed Cooling Degree Days (CDD) and Heating Degree Day (HDD) information and compared these data to the unregulated consumption within the case study rooms. Data from 2017-2019 suggests the total amount of HDD were 1889, 1992 and 1984 respectively (Department for Business, Energy & Industrial Strategy, 2022b). Based on this information, it was weather correcting was considered, however once HDD changes were applied to overall kWh consumption figures, only a small difference was made to the total consumption. As this work does not focus on heating and HVAC as part of this work, and as the focus of this work is on a granular room-level, as opposed to building-level, it was decided that weather-correcting the data would not be beneficial for the energy consumption analysis. The same decision was also made for CDD. Finally, some literature suggests that weather has less of an impact on energy consumption, compared to other factors, such as occupancy (Guan et al., 2016).

7.7 Insights Obtained from Sub-metering Data

The key findings of this chapter are briefly summarised in this section. Relating to the initial concept that unregulated energy consumes approximately 50% of a building's consumption, the data suggested a much wider span, with an average reading coming to 22.49% across the University of Manchester building stock, as indicted in Table 7-18. However, in practical terms it is essential to understand that, as expected, there are a range of performances, and the actual value will depend on the types of buildings assessed. This is also with the caveat that many buildings contained a high proportion of generic DBs, which could monitor both unregulated and regulated energy, meaning these percentages will change, if these generic DBs can be further investigated.

The unregulated consumption within university buildings is typically captured primarily by room-level power consumption sub-meters, and the highest unregulated energy-consuming rooms typically relate to engineering and chemical laboratory rooms. This can be attributed to sub-meters typically being used to measure equipment consumption and small power loads. They do not capture lighting or heating consumption.

The typical regulated vs unregulated breakdowns for different buildings varied less, in terms of daily consumption profiles and overall quantities of unregulated energy consumption, than initially anticipated. However, this could be because different regulated and unregulated consumption types were frequently captured under generic distribution boards and would not be classified separately, making it harder to accurately calculate regulated vs unregulated as proportions of total consumption.

Across the case study universities, there was often a clear difference between in-hours and out-of-hours periods, which were defined in this research through both the literature review and through the interviews with different building users. Out-of-hours periods frequently demonstrated lower unregulated energy consumption levels, compared to in-hour periods. However, as was noted to be the case for laboratories and research spaces in particular, the difference between peak consumption periods and baseload consumption periods was often quite minimal, suggesting a high baseload for many laboratories, workshops, and computing spaces.

Chapter 8 - Conclusions

8.1 The Research Problem

As previously ascertained, building regulatory standards are currently primarily only applied to regulated energy, and most building-specific studies focus on internal Heating, Ventilation, and Air Conditioning (HVAC), hot water, and lighting. This singular viewpoint is insufficient, and it is stated here that the inclusion of unregulated energy within building regulatory standards and building designs is crucial. Both regulated and unregulated energy are required for a building to perform and function, and the research has shown an interlinked relationship between the two. Therefore, if both forms of energy are required, including unregulated energy within regulatory standards is also vital.

From a Higher Education perspective, to reduce CO_2 emissions and reduce overall consumption, decreasing overall unregulated energy consumption provides a potentially majorly impactful opportunity. The literature review on the topic of unregulated energy suggested that was a general knowledge gap. Most of the existing literature primarily related to privately owned office buildings, and typically focused on specific areas of unregulated energy, such as small power loads. Due to these gaps existing in the Higher Education sector, this research work aims to begin to fill a gap in the knowledge base.

8.2 Summarising the Research Questions

Regarding the initial research questions, this thesis has aimed to answer each. Referring to the initial questions, this section briefly summarises the results for each question.

What are the unregulated energy profiles for different types of building stock?

The unregulated energy profiles for different buildings suggested that unregulated energy is typically under half of a building's total energy consumption. This concept differs from what the current literature suggested, where it was assumed approximately 50% of a building's total energy consumption was due to unregulated energy. Using the University of Manchester building stock, the average building consumed 22.49% of unregulated energy, with the remaining energy being comprised of regulated energy and generic distribution boards. This research concludes, instead, that a lower range is much more typical across Higher Education buildings.

What factors influence unregulated energy consumption in different types of buildings?

This research concludes that human factors, such as equipment usage, occupancy levels, and operational hours, were the main factors that affected unregulated energy. These three categories heavily impacted electrical consumption, and unregulated energy consumption, across all the case study universities. As unregulated energy is typically defined as "user-related" within the literature, the idea that human factors affect unregulated energy is not a particularly surprising conclusion. However, this research highlights the importance of the building user, and how unregulated energy can be directly affected by the user. It was also concluded that user activities had a much more significant effect on unregulated energy consumption than building-related factors. Factors such as Cooling Degree Days (CDD) and Heating Degree Days (HDD) were also found to have little to no impact on the results. Building age only had a minor impact on unregulated energy consumption values compared to user-related factors. For example, factors such as occupancy levels, operational hours, and types of equipment affect unregulated energy consumption. Heavily used single-phase laboratories would consume more, per m^2, than sporadically used single-phase laboratories, for example.

As the current literature suggests, do occupancy and operational hours impact unregulated energy?

It was found that occupancy levels and operational hours significantly impact unregulated energy. During zero occupancy or near zero occupancy periods, unregulated energy consumption would typically reduce substantially; however, in laboratories particularly, a constant electrical baseload was still heavily present. Across all the universities, high-level baseload electrical consumption was consistent across all the universities. During the COVID-19 crisis, baseload consumption typically reduced between 30-50% across the universities, a much lower reduction than initially anticipated (by some building managers). Before the pandemic, baseload consumption was substantial, particularly within research laboratories, computer clusters, and catering facilities. By assessing room-level sub-metering, it was determined that many campus rooms were left "on" throughout the day and frequently left "on" during weekends and non-term periods. Baseload consumption was typically much lower for academic offices, teaching rooms and other non-research focused rooms. This research underlines the importance of occupancy levels and operational hours, and how integrated the two factors are with unregulated energy.

Do building users have a direct impact on unregulated energy?

Finally, it is concluded here that building users do have a direct impact on unregulated energy consumption. Data combined from Chapter 6 and Chapter 7 show that changes in room usage, changes in types of equipment, and changes in room occupants do have an impact on unregulated energy. The results from the interviews also show that building users typically have both academic and research flexibility in their work schedules, which does have an impact on unregulated energy consumption. Additionally, whilst the official operational hours of the buildings typically matched the actual operational hours on weekdays, buildings which should be unoccupied on weekends typically were semi-occupied.

The interviews also suggest that unregulated energy concerns were often less obvious to building users, and instead regulated energy concerns, such as heating and lighting, were much more obvious and apparent to them.

8.3 Broader Implications of the Results

A wider definition of unregulated energy has been created here, based on the findings of this research, based partially on previous literature definitions, and based on the observation that unregulated energy is typically user-related. This definition, as previously mentioned in Section 1.2.5, is as follows:

Unregulated energy represents energy consumption within a building, which building regulations do not mandate a specific requirement upon. For most types of unregulated energy consumption, it can also be defined as energy consumption, within a building, that is linked directly to a building user, or in the control of the user.

The literature on unregulated energy, at present, is particularly limited for the Higher Education sector and indeed for other public institutions. Most information relates to private institutions, such as privately owned offices. Hence there was a severe lack of available data. By quantifying the amounts of unregulated energy in different university buildings, the research has allowed for further understanding of the topic. The literature has now been expanded upon, and further information is now known about how unregulated energy varies across different UK universities.

This research also provides insight into essential factors affecting unregulated energy by furthering understanding of the topic. This insight also allows building managers and university Estates to target unnecessary unregulated energy consumption areas by discovering the critical factors.

This work has also discussed the need for further investigations into the breakdowns of sub-metering, on a granular level. Reflecting on the sub-metering upon which this thesis is based, the need to understand unregulated energy consumption is frequently overlooked by building designers, when initially designing the sub-metering needs of the building. From a sub-metering observation, unregulated energy remained a frequent oversight. The buildings frequently contained a high proportion of generic distribution boards (DB). DBs typically separate into numerous specific sub-meters. So, one DB may measure a floor's total electrical consumption. 10 sub-meters then branch off this primary DB, measuring different parts of the floor. However, if only DB information is available, then both regulated and unregulated energy information would be combined, making detailed analysis impossible. In addition, both power and lighting would occasionally be combined for sub-metered rooms, making their breakdown impossible. For the unregulated sub-metering, different categories of unregulated energy were frequently overlooked.

Under each category, data varied based on the building type, as unregulated energy sub-metering was much more frequent in laboratory buildings. It is concluded here that the lack of sub-metering of unregulated energy is a barrier to understanding different rooms' baseload, peak and overall consumption profiles. Understanding these consumption profiles would also potentially allow the universities to reduce any potentially unnecessary unregulated energy consumption, such as during out-of-hours periods. As such, this work highlights and suggests for sub-metering to be placed on a detailed and granular level, in order to monitor and manage different building areas, for both regulated and unregulated energy.

By targeting unregulated energy consumption, this research has presented a method to reduce overall building consumption, by identifying key areas of considerable unregulated energy consumption. Targeting unregulated energy specifically allows the Estates to affect user-related consumption. Changing behaviours remain one key method of affecting user-related energy consumption, so the Estates could establish different approaches to assist in changing these behaviours.

Consequently, by reducing unnecessary energy consumption (whether regulated or unregulated), the universities themselves could easily create cost savings. In a hypothetical situation, if a reduction of around 10% of total electricity consumption were achieved, for the University of Manchester alone, this could be a potential reduction of 3,778,253 kWh (using HESA 2019/2020 data). In likelihood, reducing by such an amount is a monumental task; this work therefore suggests a series of recommendations on reducing unnecessary unregulated energy.

8.4 Key Observations and Recommendations

Based on the analysis performed on the unregulated energy data from the case study universities, performance guidance for modern and redbrick universities have been created and suggested within Section 8.4. This simple guidance allows building managers and facility management teams to understand how unregulated energy varies across different universities.

Key outputs and suggestions are made here, considering the conclusions ascertained from this research and a series of observations made. Rather than being framed as recommendations, this section suggests key areas where unregulated energy could be further assessed. Additionally, these key areas can be used as a guideline for building managers to help further understanding of what unregulated energy is and how it impacts different buildings.

- Unregulated energy consumption is most prevalent in laboratory and research-focused buildings. Both building types typically indicate high in-use and out-of-hours baseload consumption, thereby suggesting different pieces of unregulated energy are left on unnecessarily and that staff members may be using equipment out-of-hours.
- Occupancy levels and operational hours have a significant impact on unregulated energy. During the COVID-19 crisis, most rooms saw a substantial decrease in regulated and unregulated energy consumption.
- Unregulated energy is user-related, meaning that staff members have direct or indirect control of their rooms' unregulated energy consumption.

- Integrating different top-down approaches is a beneficial approach. For example, the case study universities all have detailed policies and sustainability goals, as outlined within Chapter 4 (which provides insight into how the universities aim to reduce consumption and would be considered a top-down approach). Combined with their multiple bottom-up approaches, they assist the universities in achieving their overall building performance goals. These approaches must be adequately communicated to staff members, as several of the interviewees were unaware of different initiatives taking place, across the University of Manchester.
- For many rooms and floor-by-floor consumption sub-meters, weekdays and weekends consume a similar amount. Hence, equipment seems to be left on consistently across all universities.

8.5 Future Work

For future work, it is recommended that datalogging equipment be applied across several case studies to assess the actual effects of equipment consumption. Studies should focus on well sub-metered buildings, as the better the sub-metering, the easier it is to break down critical unregulated energy consuming areas. Additionally, detailed sub-metering allows for a more accurate portrayal of total regulated vs unregulated consumption breakdowns.

It is recommended here that further interviews and discussions with interviewees, across a wide array of building and universities, would be insightful, and allow for further factors, which impact on unregulated energy consumption, to be identified.

Future work should also aim to break down laboratory consumption in as much detail as possible. These areas remained the highest-consuming areas on campus and typically had high baseloads, which could be reduced depending on the room.

8.6 Concluding Remarks

In conclusion to this thesis, unregulated energy is an integral type of energy that requires further investigation, particularly in the Higher Education sector. Sub-metering can be used to ascertain quantities of unregulated energy consumption and can thereby be used to compare these data to other buildings. While regulated energy is well-understood and documented, this thesis has demonstrated the need for further analysis of unregulated energy within the Higher Education sector.

To understand the link between users and unregulated energy consumption, this work has combined both a quantitative and qualitative approach, by combining insights obtain from sub-metering data and insights obtained through a series of informal discussions and semi-structured interviews. This thesis has also quantified unregulated energy consumption across the Higher Education sector. The main objective of the initial research problem was to assess and quantify unregulated energy consumption within the Higher Education sector. The thesis focus on unregulated energy was intended to help reduce unnecessary electrical consumption and help reduce CO_2 emissions across different universities.

Based on the thesis results, unregulated energy consumes a moderate proportion of a building's total electrical consumption, as highlighted in Chapter 7. Unregulated energy consumption is typically highest in research-focused buildings, and baseload consumption remained an issue across most of the case study research-focused buildings. Using the data available, it is concluded here that equipment usage remains an integral area to target. Additionally, as unregulated energy is highly user-related, it requires a human-centric approach to reduce this consumption. It is imperative from a sustainability focus to reduce this unnecessary consumption for the case study universities to achieve their CO_2 emissions reduction targets.

References

1E and The Alliance to Save Energy. (2009). *PC energy report 2009 – United States, United Kingdom, Germany*. [Online]. Available at: https://www.twosides.info/wp-content/uploads/2018/05/The_Power_to_Save_Money.pdf (Accessed: 19 September 2020).

Aston University. (2019). *Carbon Management Plan*. [Online]. Available at: https://www2.aston.ac.uk/environment/Documents/Carbon%20Managment%20Plan%20-%202019.pdf (Accessed: 29 March 2020).

Aston University. (2021). *Carbon Neutral Roadmap.* Available at: https://www.aston.ac.uk/sites/default/files/2022-04/Carbon%20RoadMap.pdf (Accessed 4 March 2023).

Agarwal, Y., Balaji, B., Gupta, R., Lyles, J., Wei, M., & Weng, T. (2010). Occupancy-driven energy management for smart building automation. *BuildSys'10 – Proceedings of the 2nd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*. 2nd November 2010. New York: ACM, pp. 1-6.

Altan, H. (2010). Energy efficiency interventions in UK higher education institutions, *Energy Policy*, 38(12), pp. 7722-7731.

Aljabr, N., Chamakiotis, P., Petrakaki, D. & Newell, S. (2021). After-hours connectivity management strategies in academic work. *New Technology, Work and Employment*, 37(2), pp. 185-205.

Bennett, M., Hopkinson, P. & James, P. (2006). Benchmarking Environmental Performance in the English University Sector: The Experience of the Higher Education Environmental Performance Improvement (HEEPI) Project, in Schaltegger, S., Bennett, M. and Burritt, R. (eds.) *Sustainability Accounting and Reporting.* Dordrecht: Springer, pp. 409-430.

Berg, F., Flyen, A. C., Godbolt, Å. L., & Broström, T. (2017). User-driven energy efficiency in historic buildings: A review. *Journal of Cultural Heritage*, 28, pp. 188-195.

Birch, C., Edwards, R., Mander, S., & Sheppard, A. (2020). Electrical consumption in the Higher Education sector, during the COVID-19 shutdown. *2020 IEEE PES/IAS PowerAfrica,* 25-28 Aug. 2020. IEEE. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9219901 (Accessed: 15 November 2020).

Blok, V., Wesselink, R., Studynka, O. & Kemp, R. (2015). Encouraging sustainability in the workplace: a survey on the pro-environmental behaviour of university employees. *Journal of Cleaner Production*, 106, pp. 55-67.

Bolton, P. & Hubble, S. (2021). *Coronavirus: Financial impact on higher education* (House of Common Library Number 8954). The House of Commons Library.

Brady, L., & Abdellatif, M. (2017). Assessment of energy consumption in existing buildings. *Energy and Buildings*, 149, pp. 142–150.

BREEAM. (2011). Ene 01 Reduction of emissions. [Online]. Available at: http://www.breeam.com/BREEAM2011SchemeDocument/content/06_energy/ene01_general.htm (Accessed: 18 April 2018).

Britegreen. (2014). *University Carbon Reduction League Table: Performance to date by HEFCE funded institutions April 2014.* [Online]. Available at: http://docplayer.net/amp/45797869-University-carbon-reduction-analysis-and-league-table.html (Accessed 15 December 2017).

Britegreen. (2016). *Carbon Emissions in Higher Education: 2020 Carbon Target Progress Report for the Academic Year 2014/15*. [Online]. Available at: https://www.sustainabilityexchange.ac.uk/files/brite_green_-_university_sector_carbon_reduction_progress_report_2005-2015.pdf (Accessed 7 March 2023).

Brown, N., Bull, R., Faruk, F. & Ekwevugbe, T. (2012). Novel instrumentation for monitoring after-hours electricity consumption of electrical equipment, and some potential savings from a switch-off campaign. *Energy and Buildings*, 47, pp. 74-83.

BSRIA. (2001). Rules of Thumb (UK 3rd Edition): Guidelines for assessing building services. In *Technical Note TN-15/2001 BSRIA* (ed. Martin Boushear).

Carbon Trust. (2011). *Closing the Gap -Lessons learned on realising the potential of low carbon building design*. CTG047, July 2011. London: Carbon Trust.

Christiansen, N., Kaltschmitt, M., Dzukowski, F., & Isensee, F. (2015). Electricity consumption of medical plug loads in hospital laboratories: Identification, evaluation, prediction and verification. *Energy and Buildings*, 107, pp. 392-406.

Chung, H.M. & Rhee, K.E. (2014). Potential opportunities for energy conservation in existing buildings on university campus: a field survey in Korea. *Energy and Buildings*, 78, pp. 176-182.

CIBSE. (2008). *TM46 – Energy Benchmarks*. *CIBSE Knowledge Series: KS6*. London: CIBSE.

CIBSE. (2009). *CIBSE TM39: Building energy metering*. London: CIBSE.

CIBSE. (2010). *CIBSE TM50: Energy efficiency in commercial kitchens (includes corrigenda 1 June 2010).* London: CIBSE.

CIBSE. (2012). Energy efficiency in buildings – CIBSE Guide F. In *Energy efficiency in buildings (3rd ed.)*. London: CIBSE.

CIBSE. (2013). *CIBSE TM54: Evaluating Operational Energy Performance of Buildings at the Design Stage*. London: CIBSE.

CIBSE. (2014). *CIBSE Guide G: Public health and plumbing engineering*. London: CIBSE.

CIBSE Journal. (2020). *Preventing Covid-19 spreading in buildings*. [Online]. Available at: https://www.cibsejournal.com/technical/preventing-covid-19-spreading-in-buildings/ (Accessed 8 June 2020).

CIE. (2017). *TR 150/2017 Guide on the limitation of the effects of obtrusive light from outdoor lighting installations* (2nd ed). Austria: CIE-UK.

Cohen, R. (2013). *The Performance Gap in Non-Domestic Buildings*, presented at Ecobuild 2013. London/Swindon: Verco/Technology Strategy Board.

Cornell University. (2023). *Dashboard List.* [Online]. Available at: https://portal.emcs.cornell.edu/d/2/dashboard-list?orgId=2 (Accessed 19 January 2023).

Costa, Nuno & Matos, Inês. (2016). Inferring Daily Routines from Electricity Meter Data, *Energy and Buildings*, 104, pp. 294-301.

Darby, S. (2006). *The Effectiveness of Feedback on Energy Consumption: A Review of the Literature on Metering, Billing and Direct Displays*. Oxford: Environmental Change Institute, University of Oxford.

Dasgupta, A., Prodromou, A., & Mumovic, D. (2012). Operational versus designed performance of low carbon schools in England: Bridging a credibility gap. In *HVAC and R Research*, 18, pp. 37-50.

Davis, J. A., & Nutter, D. W. (2010). Occupancy diversity factors for common university building types. *Energy and Buildings*, 42(9), pp. 1543-1551.

Demanuele, C., Tweddell, T., & Davies, M. (2010). Bridging the gap between predicted and actual energy performance in schools. *World Renewable Energy Congress XI*, *September*, pp. 1-6.

Department for Business, Energy & Industrial Strategy. (2016). *Building energy efficiency survey, 2014–15: overarching report*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565748/BEES_overarching_report_FINAL.pdf (Accessed 4 April 2021).

Department for Business, Energy & Industrial Strategy. (2020). *Non-domestic National Energy Efficiency Data-Framework (ND-NEED), 2020.* Available at: https://www.gov.uk/government/statistics/non-domestic-national-energy-efficiency-data-framework-nd-need-2020 (Accessed 5 May 2021).

Department for Business, Energy & Industrial Strategy. (2021a). *UK enshrines new target in law to slash emissions by 78% by 2035*. [Online]. Available at: https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035 (Accessed 8 September 2021).

Department for Business, Energy & Industrial Strategy. (2021b). *2021 UK Greenhouse Gas Emissions*. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1134663/emissions-statistics-summary-2021.pdf (Accessed 8 April 2023).

Department for Business, Energy & Industrial Strategy. (2022a). *Quarterly Energy Prices: UK July to September 2022 and estimates for 2022*. [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1126144/quarterly-energy-prices-december-2022.pdf (Accessed 7 March 2023).

Department for Business, Energy & Industrial Strategy. (2022b). *Mean heating degree days 2002 to 2021 (DUKES 1.1.9)*. [Online]. Available at: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fgovernment%2Fuploads%2Fsystem%2Fuploads%2Fattachment_data%2Ffile%2F1094200%2FDUKES_1.1.9.xlsx&wdOrigin=BROWSELINK (Accessed 9 March 2023).

Department for Communities and Local Government. (2008). The Government's methodology for the production of Operational Ratings, Display Energy Certificates and Advisory Reports. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7806/998942.pdf (Accessed 19 October 2021).

Department of Energy and Climate Change. (2011). The Carbon Plan: Delivering our low carbon future. Executive Summary. In *New directions for youth development*.

Department of Energy and Climate Change. (2014). The Government's Standard Assessment Procedure for Energy Rating of Dwellings. BRE; Watford. Available at: https://studylib.net/doc/18584610/sap-2012-the-government-s-standard-assessment-procedure (Accessed 4 May 2021).

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.

Dougherty, K., (2018). Unregulated energy – why we should care. CIBSE Journal. Available at: https://www.cibsejournal.com/opinion/unregulated-energy-why-we-should-care/ (Accessed 16 November 2018).

ECON 19. (2000). Energy use in offices. In *Energy Efficiency Best Practice Programme Energy Consumption Guide ECG19*. Watford: Building Research Energy Conservation Support Unit.

Ekwevugbe, T., Brown, N., Pakka, V. & Fan, D. (2017). Improved occupancy monitoring in non-domestic buildings. *Sustainable Cities and Society*, 30, pp. 97-107.

Entwisle, M. (2016). Technical Performance, in Taylor, I. (ed). *Future Campus: Design Quality in University Buildings*. Newcastle upon Tyne: RIBA Publishing, pp. 129-133.

Escobedo, A., Briceño, S., Juárez, H., Castillo, D., Imaz, M., & Sheinbaum, C. (2014). Energy consumption and GHG emission scenarios of a university campus in Mexico. *Energy for Sustainable Development,* 18, pp. 49-57.

European Parliament. (2019). *Climate Change.* [Online]. Available at: https://www.europarl.europa.eu/doceo/document/TA-8-2019-0217_EN.html (Accessed 8 April 2021).

Foster, D., Lawson, S., Wardman, J., Blythe, M., & Linehan, C. (2012). 'Watts in it for me?' Design Implications for Implementing Effective Energy Interventions in Organisations. *Conference on Human Factors in Computing Systems – Proceedings*.

Frimpong, E., & Twumasi, E. (2021). Prediction of unregulated energy usage in office buildings, *International Journal of Building Pathology and Adaptation*.

Gaetani, I., Hoes, P. J., & Hensen, J. L. M. (2016). Occupant behavior in building energy simulation: Towards a fit-for-purpose modelling strategy. *Energy and Buildings*, pp. 121.

Greenhouse Gas Protocol. (2013). Technical Guidance for Calculating Scope 3 Emissions (version 1): Supplement to the Corporate Value Chain (Scope 3). Available at: https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf (Accessed 1 May 2023).

Gormally, A.M., O'Neill, K., Hazas, M.D., Bates, O.E.G. & Friday, A.J. (2019). 'Doing good science': The impact of invisible energy policies on laboratory energy demand in higher education, *Energy Research & Social Science*, 52, pp. 123-131.

Goulden, M. & Spence, A. (2015). Caught in the middle: The role of the Facilities Manager in organisational energy use, *Energy Policy*, 85, pp. 280-287.

Guan, J., Nord, N., & Chen, S. (2016). Energy planning of university campus building complex: Energy usage and coincidental analysis of individual buildings with a case study. *Energy and Buildings*, 124, pp. 99-111.

Gul, M. S., & Patidar, S. (2015). Understanding the energy consumption and occupancy of a multi-purpose academic building. *Energy and Buildings*, 87, pp. 155-165.

Haas, R., Auer, H. & Biermayr, P. (1998). The impact of consumer behaviour on residential energy demand for space heating, *Energy and Buildings*, 27(2), pp. 195-205.

Hafer, M. (2017). Quantity and electricity consumption of plug load equipment on a university campus. *Energy Efficiency*, 10(4), pp. 1013-1039.

Hargreaves, T. (2018). Beyond energy feedback. *Building Research & Information*, 46(3), pp. 332-342.

Hargreaves, T. & Middlemiss, L. (2020). The importance of social relations in shaping energy demand. *Nature Energy*, 5, pp. 195-201.

Hasanuzzaman, M., Islam, M.A., Rahim, N.A. & Yanping, Y. (2020). Chapter 3 – Energy demand, Hasanuzzaman, M.D> & Rahim, N.A. (eds.) *Energy for Sustainable Development: Demand, Supply, Conversion and Management*. Academic Press, pp. 41-87.

HEEPI. (2006). *Results of the HEEPI HE Building Energy Benchmarking Initiative 2003-4*.

HEFCE. (1996). *Energy management study in the higher education sector Management Review Guide*. Bristol: Higher Education Funding Council.

HESA. (2021a). *HE Provider Data: Estates Management*. Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/estates/environmental (Accessed 22 January 2021).

HESA. (2021b). *Higher Education Providers.* Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/support/providers (Accessed 14 May 2021).

HESA. (2021c). *Higher Education in Numbers.* Higher Education Statistics Agency. [Online]. Available at: https://www.universitiesuk.ac.uk/facts-and-stats/Pages/higher-education-data.aspx (Accessed 14 May 2021).

HESA. (2021d). *Who's studying in HE?* Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/students/whos-in-he (Accessed 8 April 2021).

HESA. (2021e). *What is the income of HE providers?* Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/finances/income (Accessed 13 May 2021).

HESA. (2022a). *Table 2 – Energy.* Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/estates/table-2 (Accessed 7 September 2022).

HESA. (2022b). *Table 3 – Emissions and Waste.* Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/estates/table-2 (Accessed 12 January 2023).

HESA. (2023). *Table 4 – Transport and environment*. Higher Education Statistics Agency. [Online]. Available at: https://www.hesa.ac.uk/data-and-analysis/estates/table-4 (Accessed 2 May 2023).

Historic England. (2017*). Energy Efficiency and Historic Buildings: Application of Part L of the Building Regulations to Historic and Traditionally Constructed Buildings*. Historical England. Available at: https://historicengland.org.uk/advice/technical-advice/energy-efficiency-and-historic-buildings/building-regulations-and-energy-efficiency/ (Accessed 25 January 2018).

Hoolohan, C., McLachlan, C., Jones, C., Larkin, A., Birch, C., Mander, S., & Broderick, J. (2021). Responding to the climate emergency: How are UK universities establishing sustainable workplace routines for flying and food? *Climate Policy, 21*(7), pp. 853-867.

IEA. (2021). *Covid-19 impact on electricity* [Online]. Available at: https://www.iea.org/reports/covid-19-impact-on-electricity (Accessed 18 March 2021).

Jafary, M., Wright, M., Shephard, L., Gomez, J., & Nair, R. U. (2016). Understanding Campus Energy Consumption – People, Buildings and Technology. *IEEE Green Technologies Conference*, *2016-April*.

Janda, K.B., Bottrill, C. & Layberry, R. (2014). Learning from the "data poor": energy management in understudied organizations. *Property Investment and Finance*, 32(4), pp. 424-442.

Junnila, S. (2007). The potential effect of end-users on energy conservation in office buildings. *Facilities*, 25(7/8), pp. 329-339.

Kamilaris, A., Kalluri, B., Kondepudi, S., & Kwok Wai, T. (2014). A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings. *Renewable and Sustainable Energy Reviews*, 34(C), pp. 536-550.

Kamilaris, A., Ngan, D. T. H., Pantazaras, A., Kalluri, B., Kondepudi, S., & Wai, T. K. (2015). Good practices in the use of ICT equipment for electricity savings at a university campus. *2014 International Green Computing Conference, IGCC 2014*, pp. 1-11.

Kampelis, N., Gobakis, K., Vagias, V., Kolokotsa, D., Standardi, L., Isidori, D., Cristalli, C., Montagnino, F. M., Paredes, F., Muratore, P., Venezia, L., Dracou, M. K., Montenon, A., Pyrgou, A., Theoni, K., & Santamouris, M. (2017). Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings. *Energy and Buildings*, 148, pp. 58-73.

Kawamoto, K., Shimoda, Y., & Mizuno, M. (2004). Energy saving potential of office equipment power management. *Energy and Buildings*, 36(9), pp. 915-923.

Kazandjieva, M., Heller, B., Gnawali, O., Hofer, O., Levis, P., & Kozyrakis, C. (2011). Software or hardware: The future of green enterprise computing. *Tech. Rep. CSTR 2011-02*, Stanford University, Stanford, Calif, USA, 2011.

Khoshbakht, M., Gou, Z., & Dupre, K. (2018). Energy use characteristics and benchmarking for higher education buildings. *Energy and Buildings*, 164, pp. 61-76.

Lawrence, R., & Keime, C. (2016). Bridging the gap between energy and comfort: post-occupancy evaluation of two higher-education buildings in Sheffield. *Energy and Buildings*, 130, pp. 651-666.

Leaman, A., Stevenson, F. & Bordass, B. (2010). Building evaluation: practice and principles. *Building Research and Information*, 38(5), pp. 564-577.

Lyons, S. (1992a). Emergency lighting luminaires. In *Emergency Lighting*.

Lyons, S. (1992b). Illuminances for emergency lighting. In *Emergency Lighting*.

Manchester Metropolitan University. (2020). *Our Sustainable University.* [Online]. Available at: https://www.mmu.ac.uk/sustainability/our-strategy/our-sustainable-university/ (Accessed: 16 March 2021).

Marszal, A. J., Heiselberg, P., Bourrelle, J. S., Musall, E., Voss, K., Sartori, I., & Napolitano, A. (2011). Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings*, *43*(4), pp. 971-979.

McDowall, R. (2007). Fundamentals of HVAC Systems. In *Fundamentals of HVAC Systems*.

Menezes, A. C., Cripps, A., Bouchlaghem, D., & Buswell, R. (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.

Menezes, A. C., Cripps, A., Buswell, R. A., & Bouchlaghem, D. (2013). Benchmarking small power energy consumption in office buildings in the United Kingdom: A review of data published in CIBSE Guide F. *Building Services Engineering Research and Technology,* 34(1), pp. 73-86.

Menezes, A.C., Cripps, A., Buswell, R.A., Wright, J. & Bouchlaghem, D. (2014). 'Estimating the energy consumption and power demand of small power equipment in office buildings', *Energy and Buildings*, 75, pp. 199-209.

Ministry of Housing, Communities & Local Government. (2016a). *Approved Document L2B: Conservation of fuel and power in existing buildings other than dwellings, 2010 edition (incorporating 2010, 2011, 2013 and 2016 amendments)*. London: NBS.

Ministry of Housing, Communities & Local Government. (2016b). *Approved Document L2A: Conservation of fuel and power in existing buildings other than dwellings (incorporating 2010, 2011, 2013 and 2016 amendments)*. London: NBS.

Ministry of Housing, Communities & Local Government. (2016c). *Approved Document G: Sanitation, hot water safety and water efficiency.* London: NBS.

Ministry of Housing, Communities & Local Government. (2020). *Manual to the Building Regulations: A code of practice for use in England*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/901517/Manual_to_building_regs_-_July_2020.pdf (Accessed 16 January 2022).

Ministry of Housing, Communities & Local Government. (2021). *Approved Document F: Volume 2: Buildings other than dwellings. Requirement F1: Means of ventilation. Regulations: 39 and 44.* London: NBS.

Morgenstern, P., Li, M., Raslan, R., Ruyssevelt, P., & Wright, A. (2016). Benchmarking acute hospitals: Composite electricity targets based on departmental consumption intensities? *Energy and Buildings*, 118, pp. 277-290.

Mulville, M., Jones, K., & Huebner, G. (2014). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Architectural Engineering and Design Management*, 10(1-2), pp. 79-90.

New Building Institute. (2012). *Plug Load Best Practices Guide – Managing Your Office Equipment Plug Load, Guide to Energy Savings*. Available at: http://newbuildings.org/sites/default/files/PlugLoadBestPracticesGuide.pdf (Accessed 7 March 2021).

Nottingham Trent University. (2021a). *Sustainability.* [Online]. Available at: https://www.ntu.ac.uk/about-us/sustainability (Accessed 23 March 2021).

Nottingham Trent University. (2021b). Annual Sustainability Report 2018-19. Nottingham Trent University. Available at: https://www.ntu.ac.uk/__data/assets/pdf_file/0027/1060785/Annual-NTU-Sustainability-Report-2018-19.pdf (Accessed 23 March 2021).

Nottingham Trent University. (2021c). *Carbon.* [Online]. Available at: https://www.ntu.ac.uk/about-us/sustainability/sustainability-in-action/carbon (Accessed 23 March 2021).

Nguyen, T.A. & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. *Energy and Buildings*, 56, pp. 244-257.

O'Laughlin, E.M. & Bischoff, L.G. (2005). Balancing parenthood and academia: work/family stress as influenced by gender and tenure status. *Journal of Family Issues*, 26(1), pp. 79-106.

Pegg, I. M., Cripps, A., & Kolokotroni, M. (2007). Post-occupancy performance of five low-energy schools in the UK. *ASHRAE Transactions*, 113 PART 2, pp. 3-13.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), pp. 394-398.

Pritchard, R., & Kelly, S. (2017). Realising operational energy performance in non-domestic buildings: Lessons learnt from initiatives applied in Cambridge. *Sustainability (Switzerland)*, 9(8).

Rafnsdóttir, G. L. & Heijstra, T. M. (2013). Balancing Work–family Life in Academia: The Power of Time, *Gender, Work and Organization*, 20(3), pp. 283-296.

Rodriguez, A., Smith, S. T., Kiff, A. & Potter, B. (2016). Small power load disaggregation in office buildings based on electrical signature classification, 2016 IEEE International Energy Conference (ENERGYCON), 2016.

Royston, S., Selby, J. & Shove, E. (2018). Invisible energy policies: A new agenda for energy demand reduction, *Energy Policy*, 123, pp, 127-135.

Schoofs, A., Ruzzelli, A. G. & O'Hare, G.M.P. (2011). VLAN auditing for preliminary assessment of after hours networked equipment electricity wastage, *Energy*, 36(12), pp. 6910-6921.

Sequeira, H., Carreira, P., Goldschmidt, T., & Vorst, P. (2014). Energy cloud: Real-time cloud-native energy management system to monitor and analyze energy consumption in multiple industrial sites. *Proceedings – 2014 IEEE/ACM 7th International Conference on Utility and Cloud Computing, UCC 2014*.

Srinivasan, R.S., Lakshmanan, J., Santosa, E. & Srivastav, D. (2011). Plug-load densities for energy analysis: K-12 schools. *Energy and Buildings*, 43, pp. 3289-3294.

Soares, N., Pereira, L. D., Ferreira, J., Conceição, P., & da Silva, P. P. (2015). Energy efficiency of higher education buildings: A case study. *International Journal of Sustainability in Higher Education*, 16(5), pp. 669-691.

Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches, *Renewable and Sustainable Energy Reviews,* 47, pp. 74-82.

Steg, L. & Vlek, C. (2009). Encouraging pro-environmental behaviour: An integrative review and research agenda. *Journal of Environmental Psychology*, 29(3), pp. 309-317.

Stern, N. H. (2007). Stern Review: The Economics of Climate Change. *Stern Review: The Economics of Climate Change*, 17, pp. 712.

The University of Manchester. (2019a). *UoM building data.* Unpublished internal company document.

The University of Manchester. (2019b). *Food on Campus Outlet Changes.* Unpublished internal company document.

The University of Manchester. (2021a). *Carbon* [Online]. Available at: http://www.sustainability.manchester.ac.uk/carbon/ (Accessed 2 March 2021).

The University of Manchester. (2021b). *University of Manchester Carbon Data*. Available at: https://documents.manchester.ac.uk/display.aspx?DocID=33439%20 (Accessed 10 May 2021).

The University of Manchester. (2021c). *Energy* [Online]. Available at: http://www.sustainability.manchester.ac.uk/energywater/energy/ (Accessed 10 May 2021).

The University of Manchester. (2023). University of Manchester *Energy Dashboard.* [Online]. Available at: http://www.ems.estates.manchester.ac.uk/dashboard/ (Accessed February 15 2023).

The University of Reading. (2020). *2020-2026 Strategic Plan*. Available at: http://www.reading.ac.uk/web/files/Aboutus/university-strategy.pdf (Accessed 6 April 2021).

The University of Sheffield. (2020). *Strategy and action plan*. Available at: https://www.sheffield.ac.uk/sustainability/strategy (Accessed 1 April 2021).

The University of Sheffield. (2023). *PV-Live.* [Online]. Available at: https://www.solar.sheffield.ac.uk/pvlive/ (Accessed 14 February 2023).

Uddin, M.N., Wei, H.H., Chi, H.L. & Ni, M. (2021). Influence of occupant behavior for building energy conservation: a systematic review study of diverse modeling and simulation approach. *Buildings*, 11(2), 41.

Universities UK. (2017). The economic impact of universities in 2014–15. *Oxford Economics*. [Online]. Available at: https://www.universitiesuk.ac.uk/policy-and-analysis/reports/Pages/economic-impact-universities-2014-15.aspx (Accessed 15 May 2021).

Vadodaria, K. (2014). In-use energy performance evaluation of a student accommodation in the UK. *International Journal of Low-Carbon Technologies*, 9(4), pp. 268-276.

Van Dronkelaar, C., Dowson, M., Spataru, C., & Mumovic, D. (2016). A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings. *Frontiers in Mechanical Engineering*, 1, pp. 1-17.

Van Ruijven, B.J., De Cian, E. & Sue Wing, I. (2019). Amplification of future energy demand growth due to climate change, *Nature Communications*, 10(1), pp. 1-12.

Van Someren, K. L., Beaman, C. P., & Shao, L. (2017). Determining the Difference between Predicted vs. Actual Lighting Use in Higher Education Corridors. *Frontiers in Mechanical Engineering*, 3, pp. 1-15.

Wadud, Z., Royston, S. & Selby, J. (2019). Modelling energy demand from higher education institutions: A case study of the UK, *Applied Energy*, 233-234, pp. 816-826.

Watts, C. (2012). *A Guide to Emergency Lighting (2nd ed.)* London: BSI.

Webber, C.A., Roberson, J.A., McWhinney, M.C., Brown, R.E., Pinckard, M.J. & Busch, J.F. (2006). After-hours power status of office equipment in the USA. *Energy,* 31(14), pp. 2823-2838.

Whittle, C. & Jones, C. (2013). User perceptions of energy consumption in university buildings: A University of Sheffield case study. *The Journal of Sustainability Education* [Online]. Available at: http://www.susted.com/wordpress/content/user-perceptions-of-energy-consumption-in-university-buildings-a-university-of-sheffield-case-study_2013_06/ (Accessed 15 January 2023).

Yan, D., O'Brien, W., Hong, T., Feng, X., Burak Gunay, H., T., F. and Mahdavi, A. (2015). 'Occupant behavior modeling for building performance simulation: Current state and future challenges'. *Energy and Buildings*, 107, pp. 264-278.Yarbrough, I., Sun, Q., Reeves, D.C., Hackman, K., Bennett, R. & Henshel, D.S. (2015). Visualizing building energy demand for building peak energy analysis. *Energy and Buildings*, 91, pp. 10-15.

Zeferina, V., Birch, C., Edwards, R., & Wood, R. (2019). Sensitivity analysis of peak and annual space cooling load at simplified office dynamic building model. *E3S Web of Conferences,* 111.

Appendices

Appendix A: Journal papers, conference papers, conference talks and other contributions

Journal papers

- Birch, C., Edwards, R. Mander, S. and Sheppard, A. (2019). Assessing unregulated electricity consumption in a case study university. BSER&T.
- Hoolohan, C., McLachlan, C., Jones, C., Larkin, A., Birch, C., Mander, S., & Broderick, J. (2021). Responding to the climate emergency: How are UK universities establishing sustainable workplace routines for flying and food? Climate Policy. https://doi.org/10.1080/14693062.2021.1881426.

Conference papers and talks

- IEEE PowerAfrica 2020: Presented a conference paper and gave a talk based on the COVID-19 shutdown and assessing electrical consumption within the Graphene building during the shutdown period.
    - Birch, C., Edwards, R., Mander, S., & Sheppard, A. (2020). Electrical consumption in the Higher Education sector, during the COVID-19 shutdown, *2020 IEEE PES/IAS PowerAfrica*. 10.1109/PowerAfrica49420.2020.9219901.
- CLIMA, May 2019: Presented a co-authored conference paper and gave a talk based on sensitivity analysis to identify important building parameters in heating/cooling within office buildings.
    - Zeferina, V., Birch, C., Edwards, R., & Wood, R. (2019). Sensitivity analysis of peak and annual space cooling load at simplified office dynamic building model. E3S Web of Conferences, 111. https://doi.org/10.1051/e3sconf/201911104038.
- "Investigation of the Impact of Occupant Behavior on Building Performance in the UK and China" workshop, May 2019: Gave a talk on the methodological process of the thesis.
- CIBSE Technical Symposium, April 2019: Presented a conference paper and gave a talk based on testing the unregulated energy methodology within the Schuster building. This conference paper was later adapted into a journal paper, published in BSER&T.
- MACE PGR conference, 2018: An internal conference event presented a poster on the thesis's suggested methodology/preliminary results.

Appendix B: Interview questions for Building Managers, Technical Operational Managers and building users.

The role of different Facility Management teams and energy-saving initiatives

1. What is your current job role title?
2. What do you do within your current job role?

    Probe: What responsibilities do you have for energy management within the building? What does this entail?
3. Who do you report to, in relation to energy-consumption queries e.g., the Estates, the School, specific research groups?

Understanding equipment usage and research areas

1. ***A*****.** What are the main type of experiments being conducted in the building? In the … room? ***(Laboratory buildings only)***

    B**.** What activities are being run in the building/room? ***(For non-laboratory buildings)***
2. Do different research groups/disciplines use this room?
3. What are the main types of equipment being used in the … room?
4. Has equipment usage changed in the building/room during the last five years?

Operational hours and room usage

1. Generally, how frequently is the … room/building used?
2. Is the building predominantly used for research or teaching?
3. Who is using the building/room?

    Probe: staff/postgraduate research or undergraduates etc?
4. What are the typical open hours for the room/building? What are the actual in-use hours like?

    Probe: Is it used on weekends? How do users get access for out of hours use?
5. Have there been any major changes in usage of the building, over the last five years?
6. Do different groups use the room over different periods of the week?
7. We occasionally notice certain energy consumption patterns in the room (e.g., out of hours is higher than expected)? Do you know what the reason behind this could be?
8. Are there any times of year where the room/building is used intensively or infrequently?
9. Does weekly use of the room vary much?
10. Do the main users of the room change across the year, such as students during term-time and then research staff during holiday periods?

Implementing sustainability initiatives

1. Do you get consulted with/been responsible for running different energy-initiatives?
2. Have you noticed any energy initiatives being put in place previously within the building? On a top-down or bottom-up level?

3. If you have previously tried to implement an energy-saving initiative, how did that go?
4. Are there any key areas you would like to see different sustainability initiatives being implemented? E.g., computer clusters using screensavers, heating within the building not matching usage needs etc.
5. In your role, do you feel like you can implement energy-saving initiatives?

Appendix C: Interview questions for Facility Management teams.

The role of different Facility Management teams and energy-saving initiatives

1. What is your current job role title?
2. What do you do within your current job role?

   Probe: What responsibilities do you have for energy management within the building? What does this entail?
3. Who do you report to, in relation to energy-consumption queries e.g., the Estates, the School, specific research groups?

Implementing sustainability initiatives

1. What are some the key energy-saving initiatives currently being implemented within the university?
2. Are you aware of any bottom-up energy-saving initiatives being implemented across the University?
3. In terms of energy-saving initiatives, what kinds of things have previously been done? How has that gone?
4. Are there any key areas you would like to see different energy-saving initiatives being implemented, that have previously worked well or have yet to be implemented across the university? E.g., computer clusters using screensavers, heating within the building not matching usage needs etc.
5. What are the key challenges you've faced when implementing new initiatives (in general, not just energy-saving initiatives)?

Appendix D: Breakdown of regulated and unregulated consumption within five University of Manchester buildings, linked to Table 7-24 and Table 7-25.

Appendix D1: Unregulated and regulated consumption within UoM 8.

UoM 8		
Type of consumption	**kWh consumption**	**Percentage of building consumption**
Pumps	535,403	12%
Air Handling Unit (AHU) supply and extract	415,567	9%
Mechanical plant	1,242,927	28%
Fans	310,735	7%
Lighting	484,533	11%
Busbar riser	116,746	3%
Heat recovery	14,377	0%
Chillers	316,427	7%
Lab switchboard	217,967	5%
Miscellaneous	19,099	0%
Laboratory power	548,796	12%
Small power	41,904	1%
Comms room power	19,251	0%
Lift	7,039	0%
Emergency lighting	4,711	0%
Cleanrooms	216,526	5%

Appendix D2: Unregulated and regulated consumption within UoM 1.

UoM 1		
Type of consumption	**kWh consumption**	**Percentage of building consumption**
Fans	34,400	3.12%
Pumps	14,393	1.31%
Lighting	141,856	12.88%
Small power	116,672	10.60%
Miscellaneous DBs	109,852	9.98%
Equipment	15,517	1.41%
Busbar risers	311,048	28.25%
Chillers	171,190	15.55%
Café	35,398	3.21%
Roof plant room + fans	150,824	13.70%

Appendix D3: Unregulated and regulated consumption within UoM 3.

UoM 3		
Type of consumption	**kWh consumption**	**Percentage of building consumption**
Lighting	201,462	18.92%
Mech. plant room	204,074	19.17%
Pumps	16,123	1.51%
Fans	1,439	0.14%
AHU	44,580	4.19%
Power DBS	229,004	21.51%
Comms room	21,166	1.99%
Lift	1,696	0.16%
Floor P+L	79,138	7.43%
Fume cupboards	13,936	1.31%
Main riser	252,140	23.68%

Appendix D4: Unregulated and regulated consumption within UoM 16.

UoM 16		
Type of consumption	**kWh consumption**	**Percentage of building consumption**
Light – floors	268,673	10.04%
Power – floors	748,173	27.96%
Lab and workshop power	18,165	0.68%
Cleanroom power	102,598	3.83%
Server room power	248,141	9.27%
HTG pump	5,155	0.19%
Mech services + plant	521,821	19.50%
Busbar	293,843	10.98%
AHU plant	44,020	1.65%
Switchboard	241,229	9.02%
Generic DB	10,741	0.40%
Static inverter	42,993	1.61%
Lifts	24,258	0.91%
Kitchen	2,787	0.10%
Security DB	37,042	1.38%
Lecture room supply	64,093	2.40%
Light + power	1,844	0.07%

Appendix D5: Unregulated and regulated consumption within UoM 5.

UoM 5		
Type of consumption	**kWh consumption**	**Percentage of building consumption**
Power DBs	85,883	55.87%
Evacuation lift	199	0.13%
1st F comms room	9,440	6.14%
LG F comms room	5,899	3.84%
Miscellaneous DBs	6,387	4.15%
Mech. Switchroom	22,733	14.79%
Vent plant room	1,968	1.28%
Fans	461	0.30%
Pumps	20,759	13.50%