Efficient Management of Environmental Control Within Electrical Substations for Decarbonisation Purposes

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Contents

List of Figures

List of Tables

List of Equations

Abstract

Decarbonisation of building operations is identified as a key component of national decarbonisation strategies. Reducing the energy demand of buildings is to be achieved through more stringent regulation for new construction and the retrofitting of existing stock. These are applicable to both domestic and most non-domestic building types, although no such efforts have been made to decarbonise electrical substations.

Electrical substations are critical infrastructure assets that house distribution equipment enabling electricity to reach customers' homes and business premises. To reduce the risk of damage to distribution equipment environmental, control is required to maintain specific levels of temperature and relative humidity. This research explores how these assets can be decarbonised whilst maintaining the required internal environmental conditions.

Using a longitudinal case study method, three archetypal substations were subject to remote monitoring of energy consumption and environmental conditions, performance testing and energy modelling. This revealed that non-compliant humidity levels were occurring, as well as over-conditioning of temperature as a result of ineffective control systems. Consequently there was a significant performance gap detected between the measured and modelled energy consumption.

Observing the monitoring results and the unique constraints of substations, a bespoke approach to retrofitting the substations was developed. Differing from more established retrofit hierarchies, this prioritised enhancement of control systems over the performance of building fabric. This ensured that the compliance of environmental conditions was guaranteed along with further decarbonisation benefits.

Interventions were delivered across the three case study substations with benefits established through further monitoring of energy and environmental conditions. An overall decrease in energy consumption and payback periods between 2 and 18 years across the three sites were coupled with considerably improved environmental conditions in two sites. This study shows that the application of retrofit is applicable to substations and can result in substantial co-benefits for their operators. Whilst many of the interventions to decarbonise are not dissimilar to those applied to more established building types consideration is necessary to ensure maintaining the required environmental conditions is addressed.

Chapter 1 Introduction

1.1 Introduction

Electrical substations are critical infrastructure assets that enable the distribution of electricity to homes and business premises. The assets consist of buildings that house electrical distribution equipment. Environmental control within these buildings is essential to maintain specified humidity and temperature levels necessary to prevent damage to the distribution equipment and associated drastic consequences such as power cuts and serious damage to the electrical network.

Decarbonisation of buildings through energy efficiency measures has become increasingly common as awareness of environmental issues has grown in recent times. This is true of both domestic buildings such as houses and non-domestic buildings such as those for commercial and industrial purposes. Electrical substations however are unique as they have specific energy consuming systems for the purposes of maintaining environmental conditions but are a not a building function where energy efficiency is addressed nor has been researched.

Through an academic industry partnership, this study will look at how these previously unaddressed assets can be decarbonised through improving energy efficiency whilst adhering to the constraints unique to their application.

1.2 Energy in Buildings

Carbon emissions associated with buildings energy use account for approximately 19% of the UK's greenhouse gas emissions (HM Government, 2020). As such, decarbonisation of buildings is seen as a necessary step to reach national and global carbon reduction targets. These reductions can be made through energy efficiency measures such as improved performance of building fabric through enhanced insulating properties, alternative efficient building services and intelligent control systems that minimise unnecessary energy use (Crosbie & Baker, 2010). As awareness of environmental issues has grown in recent history so has the requirement to incorporate such measures in the construction of new build properties as dictated through updates to building regulation (Jones et al., 2013). Additionally, such measures can be retrofitted to existing buildings in the form of an form of an energy efficiency *intervention* (Crosbie & Baker, 2010).

As the demand for efficient building fabric and services has risen so has the awareness of the concept of the *performance gap*. The performance gap is the undesirable difference between expected energy performance and actual energy use and it is well documented that this occurs in non-domestic buildings (van Dronkelaar et al., 2016). The causes of performance gap are various and often difficult to diagnose. Measurement is a necessary step to verify the performance of either building fabric or services and identify any subsequent performance gap. There are a wide range of tools and techniques available for this ranging from testing individual elements at commissioning stage to long term energy monitoring (Fitton, 2013; Johnston et al., 2015).

Decarbonisation of buildings and energy efficiency interventions are well established in domestic buildings and other regulated non-domestic building types such as buildings for commercial and industrial purposes. This is evident in the existence and necessary compliance to part L of the building regulations (conservation of fuel and power) (HM Government, 2016), large scale retrofit programmes to improve the energy performance of housing (Jones et al., 2013) and schemes such as the Public Sector Decarbonisation Scheme (HM Government, 2021). In this study an opportunity is presented to apply these concepts to a unique building use case that has not previously been explored from an energy efficiency perspective.

1.3 Electricity North West Limited and Electrical Substations

Electricity North West Limited (ENWL) are one of fourteen Distribution Network Operators (DNO) in the UK that are responsible for maintaining and operating the distribution electricity network. Where electricity is produced at points of generation and transported through transmission networks throughout the country, the distribution network takes electricity directly to customers' homes and business premises for utilisation. Electrical substations are a critical asset within the distribution network, they house equipment that enables the transformation of voltage to the appropriate level (transformers) and allows for the switching of circuits (switchgear) (Ofgem, 2015).

ENWL operate the following categories of substations: Distribution, Primary and Grid (Bulk supply point) listed in ascending order of the quantity of customers supplied from the asset. These are differentiated by the voltage levels at which they operate. Within primary and grid assets there is a requirement for maintaining specific environmental conditions of temperature and humidity. This is for the purposes of preventing damage to equipment housed within the substations through partial discharge (PD). PD is the when electrical discharges occur inside or on the surface of electrical insulation materials when equipment is energised (Byrne, 2014). The effects of PD can be significant including network failure resulting in power cuts for customers and regulatory financial penalties for DNO's (Ofgem, 2017). Furthermore, extreme instances could present severe danger to staff or members of the public within the proximity of substations due to explosions, fires or release of gases. It is well established that PD is more likely to occur in high moisture environments (Byrne, 2014; Meng et al., 2013), hence the need for management of environmental control within these assets.

There are over 5000 grid and primary substations within the UK (Energy Networks Association, 2015), 558 of these are owned and operated by ENWL. ENWL deploy an environmental control policy within these assets to maintain the required low moisture environment, this consists of condensate dehumidification systems and electric heaters to maintain the minimum parameters of 50% relative humidity and 10°C (Electricity North West Limited, 2007). The total energy demand and carbon emissions associated with ENWL's grid and primary substation estate is 10.5million kWh/year and 2,400 Tonnes of CO_2e/year respectively, these figures are based on meter readings held by ENWL and current electricity conversion factors (BEIS, 2021c). It is expected that the environmental control systems account for significant contributions to this consumption.

To better understand the operation and management of the environmental control systems within substations and how their efficiency can be improved for the purposes of decarbonisation, ENWL have engaged in a HEIF (Higher Education Innovation Fund), knowledge exchange partnership with the University of Salford. In this partnership the researcher is seconded into the property team of ENWL enabling access to substation buildings to conduct the research. There are several desirable outcomes and benefits of this research for ENWL. Firstly, ENWL wish to reduce their energy consumption along with associated carbon emissions and cost. The organisation have an ambitious decarbonisation plan which includes addressing carbon emissions associated with substations (Electricity North West Limited, 2019), such efficiencies will benefit the organisation commercially through reduced operational cost and also improve reputations through demonstrating their commitment to lowering carbon emissions. Furthermore, whilst improved efficiency can be associated with reduced energy demand it can also result in improved effectiveness. As such, improving the effectiveness of environmental control would bring with it more compliant environmental conditions within substations and a reduced risk of damage to the asset, the distribution equipment stored within as well as the associated negative consequences such as power cuts, damage, and financial penalties.

There is no known research into energy use within substations making this research unique and an original contribution to knowledge. Whilst energy use in buildings, decarbonisation and building performance are well researched and established disciplines the application of these concepts to substation buildings will require a unique approach. Such distinguishing features of substations from more conventional building types include the following:

1. Occupancy – substation buildings are generally not occupied, and it can be weeks or months between occupancies.
2. Environmental conditions required – The minimum temperature of 10°C is lower than what would be expected in an occupied building (BEIS, 2021a) and the requirement of humidity control is not routine in other building types.

3. Accessibility – Authorisation to substations must be granted to individuals by their operator, this requires completion of dedicated training and certification. When they are operational, there is a limit on what work can be completed inside to modify and enhance the buildings efficiency.

Consideration of these unique factors along with any more arising are to be considered in the design and execution of this research.

1.4 Justification

Within this chapter a research gap has been identified. Decarbonisation through improving energy efficiency of buildings, both domestic and non-domestic is essential to meet national carbon reduction targets. However, there is no known research into the decarbonisation of electrical substations. These are a building function that serve a significant purpose within society through distribution of electricity. There is a large quantity (5000+) in the UK, of which 558 are operated by ENWL with an associated carbon footprint of 2400 Tonnes of CO_2e/year. This illustrates the significant scale of the issue indicating the impact that could be achieved through the study findings.

There are unique aspects of electrical substation operation such as their specific humidity and temperature requirements, occupancy and access constraints that are not found in other building functions. As these are not frequently seen in other building use types, a specific study is warranted to identify the impact that these have on their building performance including any performance gap and the approach required for decarbonisation.

1.5 Research Direction

In consideration of the context of this research relating to the unique nature of substation buildings, the following aim and objectives have been derived to provide direction and focus to the study.

1.5.1 Aim:

Aim: Decarbonise the operation of electrical substations whilst maintaining the required internal environmental conditions.

1.5.2 Objectives:

O1: Investigate the use of energy in electrical substations from a building performance perspective.

O2: Identify the unique constraints of substation buildings and their operation and how this impacts the approach to decarbonisation.

O3: Develop a method to evaluate the current building performance of electrical substations and improvements made after the application of energy efficiency interventions.

O4: Derive a method to select and evaluate the effectiveness of fabric and systems upgrades to decarbonise substations.

O5: Make recommendations for frameworks to decarbonise electrical substations for the wider electricity network.

The work undertaken to reach these aims and objectives will be detailed within this MPhil thesis which has the following structure:

1.6 Chapter Outline

Chapter 1 of this thesis is this introduction. It commences with introducing the concepts of low energy buildings and interventions to improve energy efficiency in buildings. Then, the unique building use case of electrical substations is introduced along with the context of research partner organisation ENWL. The research justification is outlined along with aims and objectives and then subsequently this chapter outline.

Chapter 2 is a literature review addressing the question: "Why is it Important to Maintain Environmental Conditions Within Electrical Substations?" In answering this question, the role of substations within the distribution network is addressed as well as their distinguishing features and those that make a typical substation. Then the need for environmental control and the current approaches for achieving this within substations is detailed.

Chapter 3 is a further literature review chapter addressing:- How Buildings Gain and Lose Energy Through Their Fabric and How is This Evaluated? This chapter starts by identifying the physical phenomena that enable heat transfer to occur and identifying and how and where these occur within the context of buildings and those that are applicable to substations. Whilst this chapter focuses on energy as heat, it is also necessary to address moisture to understand humidity control within substations, as such, an overview of psychrometrics – the study of moist air is included and how this is applicable in substation environmental control systems. Following this an overview of the methods available to evaluate energy loss from buildings is included with a particular focus on those that could be applied to substations.

Chapter 4 Methodology, details the relevant research philosophies, strategies, and methods applicable and to be implemented in this study. The research onion analogy is used to aid selection of these attributes. These items are then used to form a method capable of meeting the aims of the study including the selection of substations as case studies and the data collection techniques to be deployed.

Chapter 5 Results, includes the presentation of data acquired through the methods detailed in the previous chapter. This includes the interventions identified, pre & post-intervention environmental conditions and energy consumption allowing for the identification of the measured improvements in efficiency due to intervention.

Chapter 6 is the Discussion. Within this chapter the key findings and emerging themes from the results are reviewed along with why they have occurred and the implications outside of the study for substation operators and other industries. These themes include the pre-intervention environmental conditions, success of interventions, the hierarchical application of interventions and how this differs to other building types.

Chapter 7 is the final chapter and provides conclusions on the findings identified throughout and relates these against the study aim highlighting where an original contribution to knowledge is made. Furthermore, the areas where future research can build on the findings of this study are identified.

Chapter 2 Why is it Important to Maintain Environmental Conditions Within Electrical Substations?

2.1 Introduction

Electrical substations are infrastructure assets critical to the transmission and distribution of electricity. Those who operate and maintain substations must maintain specific levels of humidity and temperature inside the assets to protect the equipment housed within. These conditions are obtained through specific environmental control systems.

This section covers the purpose of a substation within the electrical transmission and distribution networks, the equipment that is typically found within as well as the building attributes that are archetypical of the substation population.

The concepts of partial discharge, corrosion and the significant impact of these occurring in substations are explored. The current known approaches to environmental control within substations through electrical and mechanical means as well as through building fabric controls are reviewed.

This chapter will address objectives O2 & O3 identified in the introduction chapter.

2.2 Electricity Generation, Transmission & Distribution

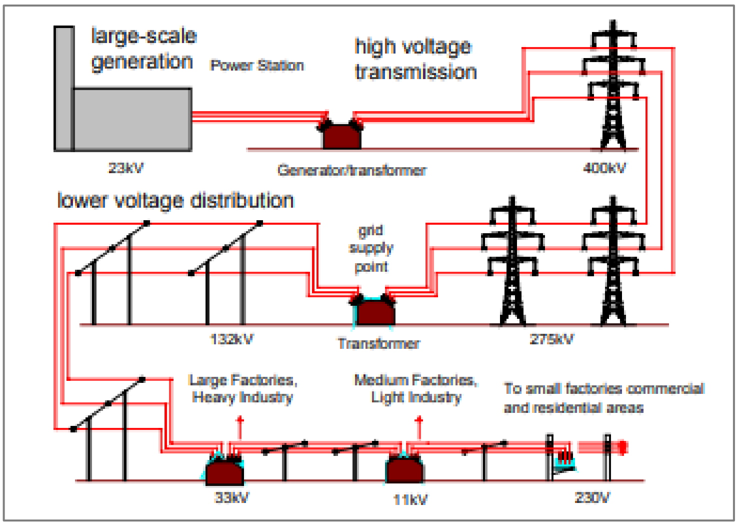
In the UK, electricity is a vital source of energy. In 2020 it accounted for 19.9% of all energy use across industry, transport, domestic and services sectors. The energy source with the largest consumption was natural gas at 34%. However, electricity is unique as it has a consistent presence in each sector of use – Industry 29.9%, domestic 38.6%, transport 1.7% and services 29.9% (BEIS, 2021b). Electricity, unlike natural gas is not a primary source of energy, an energy source that is embodied within natural resources. It is a secondary energy source, meaning it is converted from natural resources to a usable form. This process of conversion to a usable form is undergone through generation.

Furthermore, electricity is expected to play a larger role in the future of energy consumption as technologies shift from fossil fuels to electricity to enable decarbonisation. Two examples of this are heat and transport (Madeddu et al., 2020; Zhang & Fujimori, 2020). Currently the most popular source of space heating in homes is gas boilers (BEIS, 2021a), the UK governments energy strategy is targeting the installation of 600,000 electric heat pumps a year by 2028 to decarbonise the national provision of domestic space heating (HM Government, 2020). The sale of fossil fuel (petrol and diesel) vehicles is to be banned in the UK in 2030 making electric vehicles the default option for road users (HM Government, 2020) this will create increased demand for the purposes of electric vehicle charging increasing the contribution of electricity within the transport sector.

Electricity generation is the process of producing electric energy by transforming other forms of energy such as mechanical, chemical or nuclear. Electricity generation typically takes place at large scale power stations such as fossil fuels (coal, gas and oil) or nuclear (Breeze, 2017). Such power stations generate electricity at a voltage of 23kV, the voltage is then "stepped up" through transformers to 275kV or 400kV for the purposes of transmission. This is done to reduce the current of the electricity under transmission as electrical losses are proportional to current (Grigsby, 2012). This is the first of several transformations' electricity will undergo. Electricity generation also occurs at renewable sites such as solar or wind but follows a different transformation cycle to transmission.

Electricity transmission is the bulk and often long distance movement of electricity from the point of generation to the distribution networks and a small number large industrial customers (Grigsby, 2012). Distribution is electricity provision to the majority of customers through lower voltage, more localised networks operating from 132kV to 230V. This interconnected system of generation, transmission and distribution is visualised in Figure 1 (Parliamentary Office of Science and Technology, 2001).

Figure 1: UK Electricity Network



Electricity distribution is done through either underground electricity cables or overhead lines. Underground cables are typically used in built up urban areas, whereas overhead lines are usually found in rural areas (UK Power Networks, 2019).

The system presented in Figure 1 represents what is a traditional view of the electricity network. In line with decarbonisation efforts, electrification of heating and transportation and other advances in technology the concept of a *smart grid* is becoming increasingly prevalent. Smart grids are upgraded electricity networks which are enhanced with two-way digital communication between supplier and consumer, intelligent metering and monitoring systems (EC, 2021). A distinguishing feature of smart grids is that the role of the consumer is developed, rather than simply consuming electricity the consumer can store energy in dedicated battery systems or within electric vehicles and be sold back to suppliers from either energy storage or renewable systems (Lunde et al., 2016). The applications of smart grids include reduced electricity prices, reduced carbon intensity and increased energy security (Dileep, 2020). Whilst these developments to the electricity grid are significant, it is not expected that it will impact on the subject of this research.

The transformation of electricity, between points of generation, transmission, and distribution networks, occurs at electrical substations.

2.3 Electrical Substations

An electrical substation is a subsidiary station of a distribution system where voltage is transformed from high to low or the reverse using transformers and/or where circuit switching takes place (Ofgem, 2015). The following equipment is typically found within a substation (Chambers, 1999):

- **Transformers**: The equipment used to change the voltage from high transmission levels to lower transmission levels, they are cooled with oil and fans to prevent heat build-up that would decrease their capacity.
- **Switchgear:** The purpose of switchgear is to interrupt circuits while current is still running through them. This done by contacts that open in air, oil or gas to interrupt the circuits.
- **Switchboards:** Substations will have a switchboard consisting of meters, relays, controls and indicators that oversee the control of the Transformers and switchgear.
- **Control Systems and Cubicles:** These systems house the control and instrumentation equipment used in association with the transformers and switchboard. The devices can provide the operator with network parameters such as feeder current and busbar voltage that describe the operation of the substation.

There are multiple categories of substations defined by the voltage levels at which they operate. These are broadly outlined in Table 1 below adapted from (Energy Networks Association, 2015).

Table 1: Types of Substation

Substation Category	Typical Voltage Transformation Levels	Approximate number nationally	Typical Size (m^2)	Typical Number of Customers Supplied
Grid (Grid supply point)	400kV to 132kV	380	250	200,000 - 500,000
Grid (Bulk supply point)	132kV to 33kV	1,000	75	50,000 - 125,000
Primary	33kV to 11kV	4,800	25	5,000 - 30,000
Distribution	11kV to 400/230V	230,000	5	1 - 500

This research is sponsored by Electricity North West Limited (ENWL), one of fourteen DNO's (Distribution Network Operators) in the UK. DNOs are organisations that maintain and operate the regional grids that branch from the national grids to deliver power to industrial, commercial and domestic users (Energy Networks Association, 2019). As a result, the focus of this research will be solely on grid (bulk supply point) and primary substations. These are the relevant asset category operated by ENWL along with distribution substations which do not have the same environmental control requirements. For the purposes of this report use of the word "substation" refers to grid (bulk supply point) and primary assets unless stated otherwise.

To understand the nature of environmental control within substations it is necessary to explore the buildings that house the internal environment of a substation. Table 2 contains analysis performed on asset management data held by ENWL (Electricity North West Limited, 2018a) detailing various building criteria and the most popular criterion for the substation population.

Table 2: Substation Building Population Analysis

Building Aspect	Most Popular Criterion	Percentage of the Substation Population that this applies (%)
Building type	Standalone	96
Building Construction	Stone/Brick	95
Roof Type	Flat	72
Roof Construction	Asphalt	67
Substation Commissioned	1960's	41

A substation that embodies the criteria described is Pendleton Primary located within Salford, Greater Manchester. An aerial image of this substation is shown in Figure 2.

Figure 2: Aerial View of Pendleton Primary Substation

Whilst substations are commonly single storey, they often have a subterranean cable trench that contains the incoming and outgoing electrical cables.

Figure 3: Pendleton Primary Cable Trenches

They can be covered by wooden, or steel trench covers. The cable trenches at Pendleton primary are pictured in Figure 3 with covers on (left) and covers lifted (right).

2.4 Partial Discharge and the Effects of Moisture

Partial discharge (PD) is when electrical discharges occur inside or on the surface of electrical insulation materials caused by high voltage electrical stressing of the insulation system when equipment is energised. When PD occurs it emits energy in forms such as light, heat, sound and gaseous discharge such as ozone and nitrous oxides (Byrne, 2014). Air with high moisture content and direct water ingress is known to promote development of PD and is demonstrated in research completed by EA technology (Byrne, 2014) and Chongqing university (Meng et al., 2013). Consequently, within substations there is a requirement to maintain a low moisture environment to prevent PD from occurring.

PD leads to progressive deterioration and significant failures of all distribution assets including switchgear, transformers and cables. Figure 4 shows examples of where PD has occurred on electrical assets – circuit breaker (left) and cables (right)(Byrne, 2014). The consequences of PD include equipment failure, danger and incursion of costs.

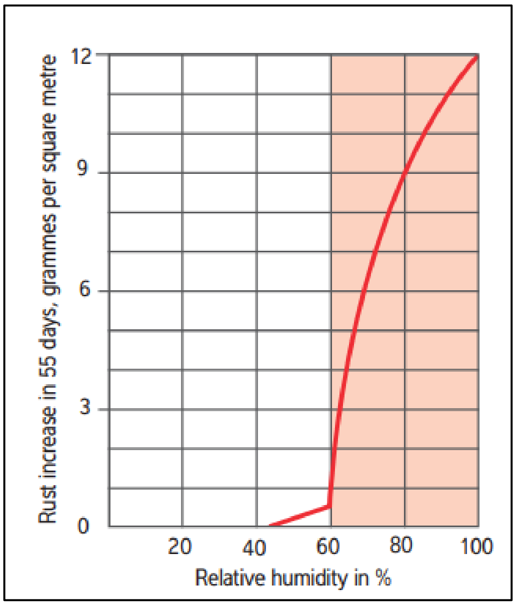
Figure 4: Evidence of PD on Electrical Assets

Equipment failure can have severe consequences. A network failure / powercut will result in a loss of electricity to thousands of customers such as homes or businesses that are supplied from the substation. Additionally, DNO's will receive significant financial penalties from industry regulatory body Ofgem for the quantity of CIs (Customer interruptions) and CMLs (customer minutes lost) occurring within their distribution network (Ofgem, 2017).

Extreme instances of PD could present severe danger to both public in the proximity of, and any staff working within the substation. This could be due to explosions, subsequent collapse of structures, fires and noxious or toxic gas in the environment. In the event of PD occurring costs will be incurred by the asset owner in several forms such as the immediate costs to make the site safe, replacement / repair of affected electrical equipment and the financial penalties for power outages occurring.

As well as the specific risk of PD occurring, high humidity is known to cause corrosion of metals. Figure 5 shows the increase in corrosion in terms if grams of rust per square meter of steel against increasing Relative Humidity levels (Calorex, 2019). Relative Humidity (RH) is a measure of moisture contained within air, expressed as a percentage of what would be the point of saturation of moisture.

Figure 5: Steel Corrosion Curve



Environmental control strategies to control moisture through maintaining specific humidity levels and reduce the risk of PD occurring can be utilised by substation operators.

2.5 Environmental Control Strategies within Substations

2.5.1 Mechanical and Electrical Systems

To prevent partial discharge from occurring, DNO's employ use of an environmental control strategy to maintain minimum parameters of temperature and relative humidity for prevention of partial discharge. These policy's also state a temperature to be maintained when the substation is occupied for the thermal comfort of those working within and a minimum temperature for WC areas to prevent freezing of utilities. Furthermore, an environmental alarm will be raised if the target parameters are exceeded considerably. The environmental control policy of ENWL and Western Power Distribution detailing these environmental conditions are summarised in Table 3.

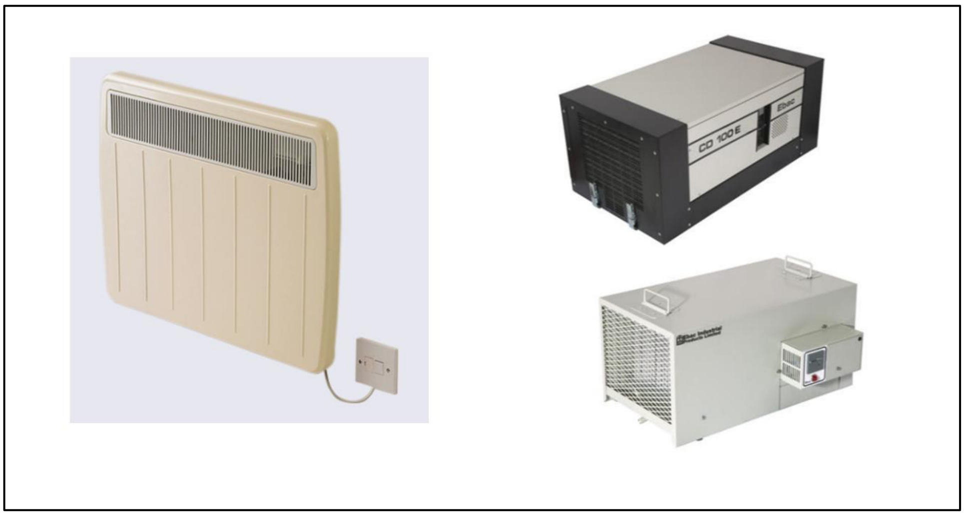
Table 3: DNO Required Environmental Control Parameters

Company	Minimum Operating Temperature (°C)	Operating Relative Humidity (%)	Comfort (Boost) Temperature (°C)	WC Temperature (°C)	Alarm Temperature (°C)	Alarm Humidity (%)
Electricity North West (Electricity North West Limited, 2007)	10	50	15	5	7	70
Western Power Distribution (Western Power Distribution, 2013)	10	55	20	Unknown	Unknown	Unknown

The environmental control policies of other DNOs are not known due to lack of public availability of the relevant documents. It is assumed similar parameters are specified due to the significance of preventing partial discharge. Whilst an operating RH of 50% is stated by ENWL, documentation produced on their behalf by appointed contractor United Utilities Electricity Services states that RH should not exceed 60% at all times (Fisher, 2010). As such 50% RH should be viewed as a target, with the band of between 50 and 60% RH viewed as acceptable, acknowledging that some deviation in RH levels is likely to occur with natural building ventilation and use of openings. These RH targets are only applicable in switchrooms and control rooms within substations, these are referred to as operational areas. The RH targets do not apply in areas such as WC's, entrance/lobby areas and transformer enclosures that are often situated in outdoor compounds or separate buildings.

ENWL use a combination of heating and dehumidification to achieve the required conditions within substations. The systems used are EBAC CD30e or CD100e dehumidification units and electric convector heaters such as the Dimplex PLCNX (Electricity North West Limited, 2007). These are pictured in Figure 6 below.

Figure 6: Dimplex PLCNX (Left) and EBAC CD100e & CD30e (Right)



The Dimplex heaters are controlled though the following thermostat combination. A Sunvic TLM thermostat that provides the necessary background heating and a Sangamo power saver unit that provides a boost temperature where required. This combination is pictured in Figure 7 the sunvic thermostat is fitted with an anti-tamper cover that covers the thermostatic dial. The EBAC dehumidification units are controlled through in-built humidistats.

Figure 7: Sunvic Thermostat (Above) and Sangamo Power Saver (Below)

The minimum temperature of 10 °C is necessary for effective operation of the dehumidification units. The reasoning for this will be reviewed along with the operation and functionalities of dehumidification systems in Section 3.6.

2.5.2 Trenches

As well as moisture in air, direct water ingress into the substation must be prevented. Cable ducts are the point of entry/exit of subterranean cables in trenches; these must be sealed to prevent water ingress into the cable trench. Systems such as the Rayflate or Nofirno duct sealing, pictured below in Figure 8 are utilised in substations (Electricity North West Limited, 2018b).

Figure 8: Rayflate (Right) and Nofirno (Left) Cable Duct Sealing Systems

Moisture barriers are installed between the trenches and conditioned areas of a substation to prevent rising humidity entering conditioned spaces. This can be done by two methods depending on the suitability of the site: a sand and concrete skim or a trench splitter system.

A sand and concrete skim is obtained by filling the trench with a fine grain of sand. A weak concrete skim (approximately 50mm) is then installed to the level of the switch room floor. A trench splitter system consists of wooden batons supporting a moisture barrier of thermal insulating board cut to fit around the cables (Electricity North West Limited, 2018b). A trench splitter system is demonstrated in Figure 9.

Figure 9: Trench Splitter System

These trench management systems are deployed within new and refurbished substations as specified within ENWL's relevant code of practice. However, this is a relatively new requirement and, as such, substations that have not been recently commissioned or refurbished will only have the wooden or steel trench covers as detailed in section 2.3.

2.5.3 Building Fabric

Building fabric serves as a means of modifying natural / external environmental conditions to produce a satisfactory internal environment (Foster & Greeno, 2007). The environmental condition of target 50% RH is not solely achieved by the building fabric and hence the mechanical and electrical systems, detailed within section 2.5.1, are required. However, the fabric serves as an envelope to house the environmental conditions and can impact on the effectiveness of operation and overall requirement for the electrical and mechanical systems. There are several areas for consideration in building fabric that effect environmental conditions within a substation. These include air permeability and thermal transmittance.

Infiltration is the flow of air into a building through cracks and other unintentional openings in the building envelope (Men et al., 2020), Air permeability is the quantification of this infiltration. This is a key consideration in the requirement for environmental control systems of heating and dehumidification. Specifying, targeting and measuring an air permeability rate is a requirement for most commercial buildings (ATTMA, 2010). However, as substations are not occupied buildings, they do not have to conform to this requirement hence it is not a current consideration in their design. How air permeability can be used to analyse environmental control systems and the impact of this not being included within substation design is to be reviewed within Chapter 3 .

U-Values are a measure of the thermal transmittance and insulating properties of building fabric. The lower the U-value the less heat will be lost, proportional to the inside / exterior temperature difference. Limiting U-values within substations through design is beneficial for the efficiency of heating and dehumidification systems. U-Values of 0.45 $Wm^{-2}k^{-1}$ for walls and 0.25 $Wm^{-2}k^{-1}$ for roof's are specified in the design for substations (Electricity North West Limited, 2007). In comparison for building regulation there is no limiting U-Value for fabric elements of the floor or doors specified in their design. As these are large areas of the building fabric and following the absence of an air permeability target, it is evident that building performance is not a primary concern within substation design. U-values and their impact on environmental control are to be explored further within Chapter 3 .

2.6 Summary

The electricity network in the UK is critical to all industries and domestic energy use. For electrical energy to reach the end users it is transported from its point of generation through transmission and distribution networks. Throughout these networks the voltage is transformed at various points, this transformation occurs at electrical substations.

There are multiple classes of substation, categorised by the voltage levels at which they operate. The relevant classes of substation to this research are grid (bulk supply point) and primary substations as they are owned and operated by the DNO Electricity North West Limited (ENWL). An analysis of asset management data for these classes of substation has identified that the archetypal substation was commissioned in the 1960's, has a flat asphalt roof, is of stone/brick construction and is a standalone building.

Partial discharges are electrical discharges occurring inside or on the surface of electrical insulation materials. When this occurs, energy is emitted in forms of light, heat and sound. The impact of partial discharge can be significant and can cause damage to the electrical assets themselves as well as the substations in which they are housed, creating a hazardous environment for operatives working in the substation and members of the public in near proximity. Further impact can be through power outages and subsequent regulatory fines for those that own and operate substations. It is well established in research and in industry that high levels of moisture promote partial discharge and consequently the operators of substations employ environmental control policies.

To ensure a substation environment minimises the risk of partial discharge occurring DNO's have a target of 50% relative humidity and 10°C in operational areas. The following temperatures are also to be maintained throughout: 15°C when occupied for operative thermal comfort and 5°C in WC areas to prevent freezing. These conditions are maintained by a combination of heating and dehumidification systems.

Control of environmental conditions is also contributed to by the building fabric. Cable entry points are to be sealed to prevent moisture ingress at a subterranean level and moisture barriers are installed in cable trenches to prevent rising humidity. The building fabric also affects the environmental control through its air permeability and U-Values. Whilst limiting U-values for walls and roof elements are specified within current substation design, air permeability rates are not. The impact of these specified and absent design criterion on environmental control are to be discussed further within the following chapter.

Chapter 3 will investigate the ways in which energy is gained or lost from building fabric and how this can be evaluated. This will enable the characteristics of building fabric relevant to efficiently maintaining specified levels of temperature and humidity to be identified as well as techniques that could be used for evaluating the characteristics of substation building fabric. This will establish a knowledge base necessary to analyse the building fabric of substations and identify how improvements could be delivered and measured.

Chapter 3 - How Buildings Gain and Lose Energy Through Their Fabric and How is This Evaluated?

3.1 Introduction

Electrical substations are critical infrastructure assets that enable the distribution of electricity to domestic and commercial customers. Within these assets it is essential to maintain specified conditions of temperature and humidity for the protection of distribution equipment housed within, preventing damage through occurrence of partial discharge. The effects of such damage can be catastrophic resulting in power outages, damage to equipment and serious injury, as well as resulting in significant regulatory financial penalties for those that operate substations.

This research has been initiated with electrical distribution network operator Electricity North West Limited (ENWL). ENWL wish to better understand how to efficiently maintain the required environmental conditions within their substation estate, not only to prevent damage to their assets, but also for the purposes of decarbonisation, reducing the energy consumption and associated carbon emissions of the environmental control systems necessary to maintain the specified temperature and humidity levels.

The aim of this research is to “Decarbonise the operation of electrical substations whilst maintaining the required internal environmental conditions”. To reach this aim, an understanding is required of how buildings gain and lose energy through their fabric and how this is evaluated, both generally and applied in the specific context of maintaining the required environmental conditions within substations.

To acquire such understanding this section will explore the concepts of heat, energy, building fabric and their interactions. Additionally, to understand the implications of moisture levels, an overview of psychrometrics - the study of moist air, is undertaken. Additionally, the methods used to evaluate and measure such energy gains and losses are detailed and the outline methodology and suitable applications for each defined. An initial broad review of these topics is undertaken to create a base of understanding and where necessary the application in the context of substations is investigated. This chapter will build on Chapter 1 to further the knowledge necessary to meet objectives O1 and O2.

3.2 Building Fabric, Heat and Energy

The fabric of a building can be defined as the roof, walls, windows, floors and doors of a building (The Carbon Trust, 2018). Buildings are designed to provide conditions appropriate to the activities that take place within them considering the comfort and safety of the building occupants, weather and noise exclusion, provision of adequate heat, light and air. The building fabric must be designed to ensure that requirements relating to these factors are met, consequently building fabric is a means of modifying natural / external environmental conditions to produce a satisfactory internal environment (Foster & Greeno, 2007). In the context of substations, building fabric serves to maintain the minimum environmental parameters of temperature and relative humidity required as well as protecting assets from weather to safely house the distribution equipment within. Damage to the equipment can result in significant negative consequences including power outages and regulatory fines for substation operators.

This section will largely consider the application on heat, a major consideration in building energy gains and losses. To understand how heat within buildings is affected by building fabric it is necessary to define the following key terms (Cleveland & Morris, 2015).

- **Energy** - the ability to do work.
- **Heat** - a measure of the amount of energy transferred from one body to another because of temperature difference between those two bodies.
- **Temperature** - a measure of the average kinetic energy of the molecules in a gas, liquid, or solid.

These items and their interlinked relationships will be explored within this section how they relate to maintaining the required environmental conditions within substations.

3.3 Heat Transfer

Heat transfer can be defined as the transfer of energy that results in a heat loss (Hall, 2010). In the application of buildings this heat transfer can be desirable such as cooling a building on a hot day by opening a door or window, likewise it can also be undesirable, such as heat loss through walls of a building being heated. When controlling the temperature within a building it is necessary to understand the mechanisms in which heat is gained and lost. These are conduction, convection and radiation.

3.3.1 Conduction

Thermal conduction is the transfer of energy (as heat), which occurs between neighbouring molecules of materials in close contact without bulk movement of the materials (Hall, 2010). A consequence of the 2nd law of thermodynamics is "Heat transfer does not independently occur from a body of lower to a body of higher temperature"(Antonsson & Grote, 2012). Conversely, it can be said that heat will always transfer from a body of higher temperature to one of a lower temperature. This can be observed in conductive heat loss where heat is lost though the building fabric where the outside temperature is lower than that inside. Heat transfer is proportional to the difference in temperature either side of the material and the conductivity of the material, this is demonstrated in Equation 1.

$$q = \lambda \frac{\delta T}{\delta x}$$ *Equation 1*

Where q is rate of heat transfer per unit of area (Wm^{-2}), λ is the materials thermal conductivity ($Wm^{-1}k^{-1}$), δT is the temperature difference either side of the material and δx is the thickness of the material (Hall, 2010).

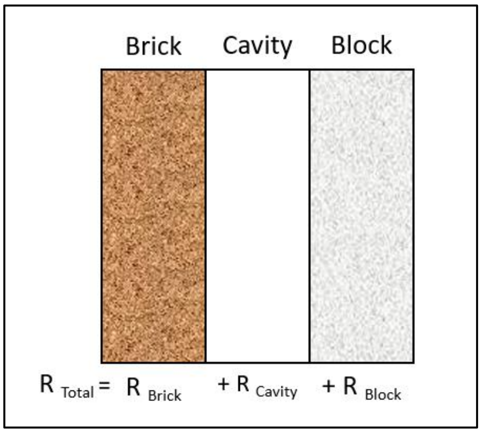
The property of thermal conductivity is a measure of a materials ability to conduct heat, it is fixed for any single material and does not vary with the thickness. For instance, a construction material such as concrete will have a thermal conductivity value that will not vary with the quantity used in construction. A further useful property when evaluating building fabric is *Thermal Resistance* or *R Value*. The R value is the resistance to heat transfer for an element of building fabric of defined thickness. This is shown in Equation 2.

$$R = \frac{d}{\lambda}$$ *Equation 2*

Where R is the thermal resistance (m^2KW^{-1}), d is thickness (m) and λ is the materials thermal conductivity ($Wm^{-1}k^{-1}$).

In a building's fabric, elements are often made from multiple layers for example cavity walling. In these instances, the total R value is cumulative. This is demonstrated in Figure 10 below.

Figure 10: Cumulative R Value



Within substations conduction occurs through the building fabric that is typically a brickwork - cavity - blockwork wall construction for walls and concrete slab for roof construction. The heat transfer is driven through temperature difference between the ambient external temperature and the temperature within the substation.

3.3.2 Convection

Convection occurs when there is conduction of heat molecules of a fluid and the motion of that fluid carries those molecules away from the heat source (Hall, 2010). In relation to a building fabric, it typically relates to the movement of air across the outer surface. This can be characterised as forced or natural convection.

Natural convection occurs when a difference in temperature produces a variation in terms of the fluid density from area to area that produces the movement itself. Forced convection occurs where velocity of the fluid is determined from another energy source such as the wind or mechanical means (Annaratone, 2010).

Quantification of heat transfer by convection can be evaluated by using Equation 3.

$$q_{conv} = h_c(T_1 - T_2)$$ *Equation 3*

Where q_{conv} is the rate of heat transfer per unit of area (Wm^{-2}), h_c is the convection coefficient ($Wm^{-2}k^{-1}$) and T_1- T_2 is the temperature difference over which the convection is occurring (k). The value of the convention coefficient depends on multiple factors including the material geometry, surface material properties such as roughness, fluid properties such as viscosity and flow properties such as whether the flow is laminar; when the flow is of uniform direction and velocity or turbulent, when the flow is chaotic and without uniform direction and velocity. Consequently, the coefficient is not easily calculated and there exists a number of empirical correlations for various situations that are used to estimate the coefficient (CIBSE, 2007). Such examples in buildings include convection occurring in air passing through cavities in walls or double-glazing window enclosures.

Convection is applicable in substations in the form of wind passing over the building fabric, removing heat from the assets.

3.3.3 Radiation

Thermal radiation is electromagnetic radiation that is emitted by a body as a result of its temperature. All objects with a temperature above absolute zero emit thermal radiation through a spectrum of wave lengths (Hall, 2010). Such examples include a heated building radiating heat to its surroundings, or a radiator heating the interior of a building. The amount of heat transfer from radiation can be quantified by Equation 4.

$$q_{rad} = \varepsilon\sigma S T^4$$ *Equation 4*

Where q_{rad} is the heat transfer by radiation(W), ε is emissivity - the ratio of energy radiated from a materials surface to that of a perfect emitter (often known as a black body), σ is the Stefan-Boltzmann constant 5.669 x 10^{-8} Wm^{-2} k^{-4}, S is the area (m^2) and T is the absolute temperature of the body (k) (Annaratone, 2010). The value of emissivity varies with multiple material properties including their colour; hence the term black body as darker colours have more radiation emitting qualities. Within building fabric, and indeed specifically substations there is little application, of radiative heat transfer in the building fabric. Applications of radiative heat transfer typically involve higher temperatures to be of importance such as heating a space with an open fire or the heating of earth by the sun. Algebraically these high temperatures can be seen as overcoming the minute value of the Stefan-Boltzmann constant used in Equation 4.

3.3.4 Overall Heat Transfer Coefficient U-Value

The most common metric used in relation to heat transfer in building fabric is the *U value.* The U value can be defined as thermal transmission in unit time through unit area for a given element of construction (Burberry, 1983) and is the inverse of the R value resulting in the units Wm^{-2} k^{-1}. Both U value and R value can be used to quantify thermal losses, however U values appear to be used more regularly in relevant research literature and resources including the relevant UK building regulations document (HM Government, 2016). U values can also incorporate convective heat transfer processes such as air passing over the exterior wall of a building (Annaratone, 2010). ENWL currently specify a maximum U-Value for walls of 0.45 $Wm^{-2}k^{-1}$ within construction of substation buildings (Electricity North West Limited, 2007). Comparatively, the current maximum U value for walls as specified in current building regulations is 0.3 $Wm^{-2}k^{-1}$ (HM Government, 2016). By specifying a U-value for building fabric the quantity of heat lost is limited which in turn will limit the heating demand of the building.

3.4 Heat Transfer Within Building Fabric

Through section 3.3 the mechanisms of heat transfer are described. The application of these within the context of building fabric are described in section 3.4.

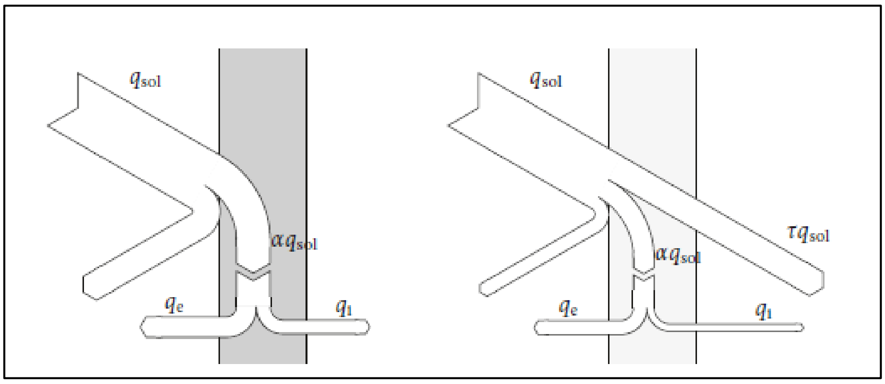
3.4.1 Specific Heat Capacity and Thermal Storage

A key metric of building fabric materials is their specific heat capacity. This can be defined as the thermal capacity per unit mass or volume and unit temperature difference. This has the units Jkg^{-1} k^{-1} (expressed per unit mass) and Jm^{-3} k^{-1} (expressed per unit volume) (Burberry, 1983). Dependent on the function of the building a space heating system will be installed to ensure satisfactory thermal conditions are met (Foster & Greeno, 2007). The selection of building material considering its specific heat capacity can affect heat gains and losses in the building supplementary to those provided by the heating system. Masonry walling materials (e.g., Brick and block) have high specific heat capacities. Where a heating system is active the fabric will build up a reservoir of heat, then when the system is inactive the stored heat will slowly be gained by the interior space of the building (Greeno & Osbourn, 2013). This process demonstrates heat transfer occurring through conduction and convection as heat is released to the building and radiation when the fabric is gaining heat in the day via solar means as well as through any heating system. This phenomenon is referred to as sensible heat storage (Sarbu & Sebarchievici, 2018).

3.4.2 Solar Gain

Solar radiation on earth can on average be measured at 1000Wm^{-2} this figure will fluctuate with time of day, geographical location and time of year (Pinterić, 2017). This solar radiation is transmitted through transparent materials much more effectively than non-transparent materials as illustrated in Figure 11 below, originally from Building Physics (Pinterić, 2017).

Figure 11: Solar Gain for Transparent (Right) and Non-Transparent(left) Materials



Where q_{sol} is the solar heat flow, αq_{sol} is the solar radiation absorbed by the fabric, τq_{sol} is the solar radiation transmitted through the building fabric and q_e and q_1 are heat leaving the fabric to both the exterior and interior.

Building fabric can be designed to control the absorption of this radiation for maximum benefit. Such factors to consider include the amount of glazed areas, type of glass used in windows and properties of building fabric besides windows (Greeno & Osbourn, 2013).

To limit this effect techniques such as solar shading, increasing the thermal capacity of the building fabric and adopting reflective outer surfaces can be deployed (Lomas & Porritt, 2017).

High performance and low emissivity glass provide a reflective surface that inhibits heat entering the space from the exterior limiting this type of heat gain. Shading prevents unwanted heat from penetrating the glazing. Increasing the thermal capacity of the fabric maximises the radiation absorbed by the fabric (αq_{sol} in figure 2 above) and minimises the radiation transmitted through the building fabric (τq_{sol} in figure 2 above) (The Carbon Trust, 2018). The amount of energy absorbed by the fabric is applicable to sensible energy storage as detailed in section 3.1.

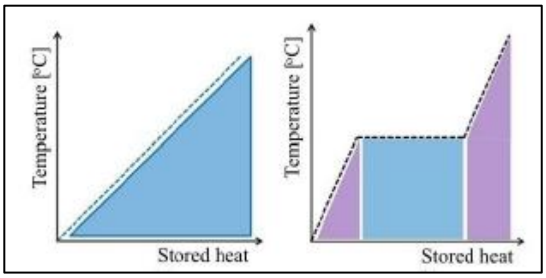
Part L of UK building regulations restricts the amount of glazing that can be used in buildings to limit solar gains however the gains can be beneficial in winter months and colder climates (HM Government, 2016).

Substations typically do not have any glazed areas as they would pose a security risk and are not required for the building function, hence the application of solar gain is minimal within this context.

3.4.3 Latent Heat and Phase Change Materials

Latent heat refers to the amount of heat energy required to undergo a change of phase without a change of temperature (Pinterić, 2017). Materials where latent heat can be applied for the purposes of energy storage are known as Phase Change Materials (PCM's) due to their property of releasing energy with a change in physical state (Sarbu & Sebarchievici, 2018). Comparing PCM's to sensible storage (explored in section 3.4.1), PCM's can store heat at an almost constant temperature when undergoing the phase change whereas sensible heat storage materials have a direct positive correlation between temperature and the quantity of stored heat. This is demonstrated in Figure 12 below that shows the profile of temperature against stored heat for both sensible heat (left) and latent heat (right) originally from, Comprehensive Review of Energy Thermal Storage (Sarbu & Sebarchievici, 2018).

Figure 12:Typical Stored Heat Against Temperature Profiles



PCM's can be applied in both daily and seasonal energy storage with a wide variety of techniques and materials. Most applicable in this literature review is the embedding into the building fabric. This can be done by the following methods (Ostry & Charvat, 2013) :

- Impregnation of porous building materials with a PCM.
- Microencapsulation – PCMs are enclosed in a polymer capsule (micrometre to millimetres in size) and dispersed into a gypsum or other material matrix.

- Incorporation of PCM's in containers such as panels and pouches that are fixed to the building fabric.

Examples of phase change materials include paraffin compounds, salt hydrate and gallium (Sarbu & Sebarchievici, 2018). The researcher is not aware of any instances of PCM materials being incorporated within the building fabric of electrical substations. Research has suggested that within the UK climate PCM can be used to reduce and manage overheating in buildings (Auzeby et al., 2017). It is not expected that overheating will be an issue within the environmental control of substations as there is no maximum temperature only the minimum of 10 °C. Hence, it is not expected that the utilisation of PCM is applicable in substation buildings.

3.4.4 Thermal Bridges

When analysing the mechanisms of heat transfer such as conduction and convection building fabric elements are considered as homogeneous in respect of their thermal properties as detailed in sections 3.3.1 - 3.3.3, in practice heat flows in various directions and properties can change along single building components (Pinterić, 2017). The heterogeneous nature of building materials can result in thermal bridges occurring. Thermal bridges are discontinuities in any thermal barrier of building fabric resulting in increased heat transfer (Totten et al., 2018). An example of this occurring is in the edges and corners of buildings as demonstrated in the thermographic analysis pictured in Figure 13, originally from Building Physics (Pinterić, 2017).

Figure 13: Thermographic Analysis of Room Edges

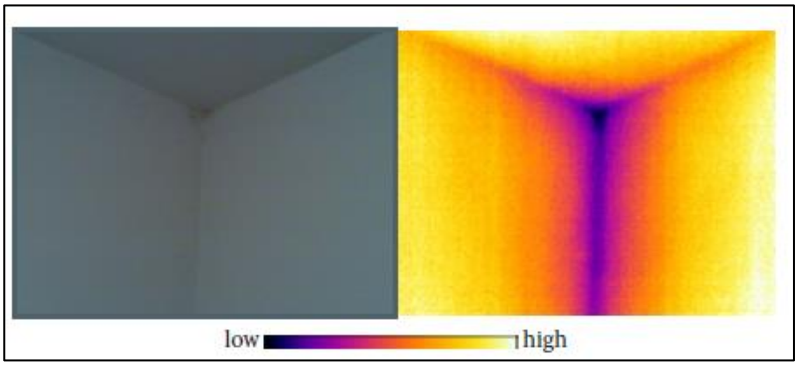


Figure 13 shows the lower temperatures occurring in the edges and corner of the room, demonstrating a thermal bridge. The lower temperatures can also promote damp and mould growth (Pinterić, 2017) (slightly visible in the left hand picture) that can have undesirable effect on heat transfer. As the damp or mould areas contain a concentration of water the overall thermal conductivity of this section of the building fabric will increase as a result of water having a high thermal conductivity compared to some insulating materials (Pinterić, 2017).

Thermal bridges can also occur where a conductive element passes through or bypasses a thermal barrier providing a path of less resistance through insulation and the building fabric (Totten et al., 2018). Examples of thermal bridges of this form are wall framing, projecting concrete balcony slabs, parapets and window frames (Totten et al., 2018). Thermal bridging can also occur due to discontinuities in insulation caused by poor workmanship and quality of installation (Burberry, 1983).

Figure 14: Dehumidifier Drainage Hose Within Substation

Thermal bridges in substations can occur with entrance doors as well as through any services that penetrate the building fabric such as electrical cables or a dehumidifier drainage hose as pictured in

Figure 14 above.

3.4.4.1 Natural Ventilation & Infiltration

Natural ventilation uses the natural forces of wind and buoyancy to introduce fresh air and distribute it in buildings for the benefit of the occupants, ensuring a comfortable, fresh and healthy indoor environment (Yang & Clements-Croome, 2012). Principally there are two mechanisms that enable natural ventilation, they are Wind Driven Ventilation and Buoyancy-Driven (Stack) ventilation.

When a building is in the presence of wind, an energy conversion takes place. On the windward side air pressure is increased, on the leeward side an under-pressure is formed. The pressure differential arising across the building cause infiltration of air through openings such as louvers in the building fabric (Everett et al., 1985; Yang & Clements-Croome, 2012).

Buoyancy driven (stack) ventilation occurs as warm air in a room will rise due to its lower density, this is replaced by cooler denser air from the outside. This phenomenon is increased by the presence of wind creating a pressure differential at the exterior of the building further driving the ventilation (Everett et al., 1985; Yang & Clements-Croome, 2012).

In addition to creating a healthy and clean environment natural ventilation can be used for cooling, removing heat from internal spaces; this is dependent on the incoming air from the surroundings being cooler than the indoor temperature. A lower temperature can be ensured by a shaded or landscaped space, sourcing air from over a body of water or from underground (Yang & Clements-Croome, 2012).

Ventilation rates within buildings can be quantified in terms of air changes per hour (ACH) which can form the basis of design targets such as those stated within the relevant building regulations documentation (HM Government, 2013). From this ventilation rate it is possible to calculate the rate that heat loss occurs through ventilation as detailed in Equation 5. Adapted from (Najjar et al., 2019) to ensure consistency in nomenclature.

$$q_{vent} = 0.34\, n\, V\, \Delta T$$ *Equation 5*

Where q_{vent} is the heat loss occurring through ventilation (W), 0.34 is a constant derived from the specific heat of air, n is the number of air changes occurring ($hour^{-1}$), V is the internal building volume and ΔT is the internal / external temperature difference.

As well as through intentional means, air can also enter a building by the process of air infiltration. This is the uncontrolled flow of air into a space through unintentional gaps and cracks in the building envelope, the corresponding loss of air from an enclosed space is called exfiltration and often referred to as air leakage (Bhatia, 2012). This, often undesirable, phenomenon contributes to the overall ventilation rate, increasing the heat loss that occurs as defined in Equation 5. Inversely, it is possible for a building with insufficient ventilation, either by design or construction, to become too warm and uncomfortable for occupants (The Carbon Trust, 2018).

Air infiltration is difficult to determine though analytical means although it can be quantified through an air permeability test. This test procedure is to be discussed within measurement under section 3.5.3.

Within substations there is no specification for required ventilation rates. It is desirable for ventilation and air infiltration to be minimised as to reduce internal conditioned air exiting the substation increasing heat loss through the building fabric.

3.5 Measurement and Evaluation

Measuring and evaluating the heat loss and gain through building fabric is important to understand a buildings performance and determine the energy demand required to maintain the necessary internal conditions. This can also relate to a measure of the environmental impact associated with operating a building. From here within, the methods available of evaluating and measuring energy loss are reviewed.

3.5.1 U-Value Measurement

3.5.1.2 Analytical Calculation

As discussed in section 3.3.4 the U value is a commonly used metric used in relation to the performance of building fabric elements. Commonly used structures and building fabric elements have U values listed with standard values, such as in CIBSE guide A (CIBSE, 2019a). Equally, for constituent elements of building fabric of known thermal resistance, R value, the U value for a composite building envelope can be evaluated by use of the Equation 6.

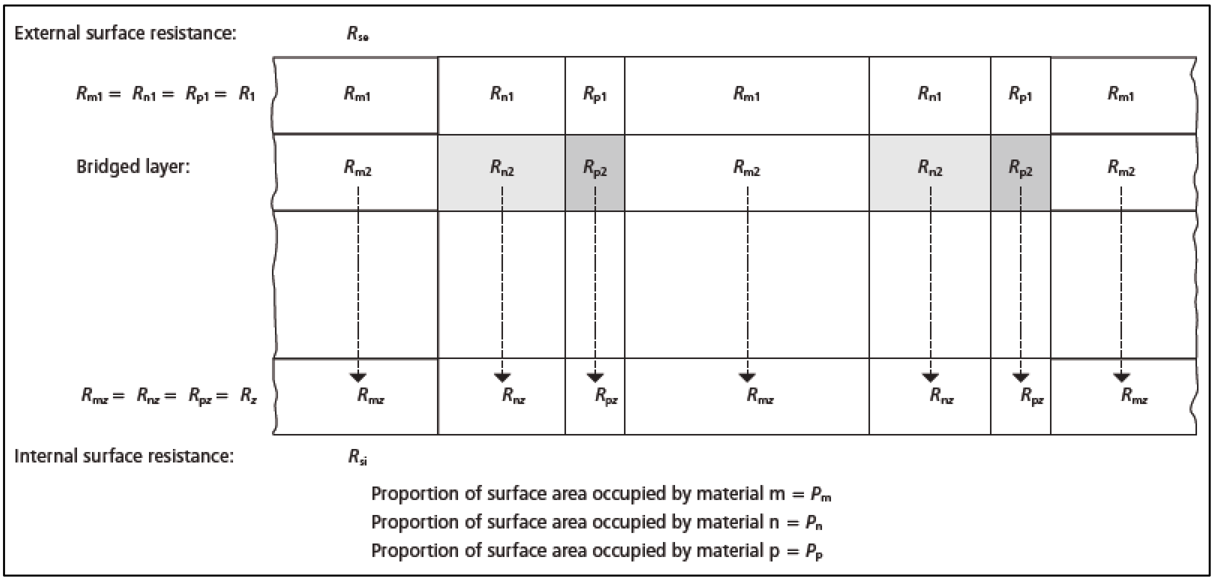
$$U = \frac{1}{R_{si} + R_1 + R_2 + \cdots + R_a + R_{se}}$$

Equation 6

Where U is the thermal transmittance ($Wm^{-2}\,K^{-1}$), R_{si} is the internal surface resistance ($m^2K\,W^{-1}$) R_1 and R_2 are the thermal resistances of components 1 and 2 ($m^2K\,W^{-1}$), R_a is the thermal resistance of the airspaces ($m^2K^{-1}\,W^{-1}$) and R_{se} is the external surface resistance ($m^2K\,W^{-1}$) (CIBSE, 2019). This straightforward calculation can be used for determining if composite wall constructions adhere to standards such as building regulations or, in regards to a substation, the relevant design policy.

Equation 6 assumes the heat transfer is perpendicular to the building fabric. This is true if the building element is homogeneous with consistent materials, conductivity and thickness throughout. Analytical methods of calculating the U value of thermal bridged elements are possible by utilisation of Equation 7 and Equation 8 to calculate the lower and upper limits of thermal resistance. This is demonstrated in the scenario detailed in Figure 15 below of a single bridged layer, bridged repetitively by two elements composed of different materials originally from CIBSE Guide A (CIBSE, 2019).

Figure 15: Thermal Bridge Example



$$R_L = R_{se} + R_1 + \frac{A_m + A_n + A_p}{\left(\frac{A_m}{R_{m2}}\right) + \left(\frac{A_n}{R_{n2}}\right) + (A_p/R_{p2})} + R_3 \ldots . + R_2 + R_{SI}$$

Equation 7

Where R_L is the lower limit of the thermal resistance ($m^2K\ W^{-1}$) R_1 to R_2 are the thermal resistances of unbridged layers ($m^2K\ W^{-1}$), A_m, A_n and A_p are the areas of elements composed of materials m, n and p (m^2), R_{m2}, R_{n2} and R_{p2} are the thermal resistances of elements composed of materials m, n and p for (bridged) layer, R_{se} is the external surface resistance and R_{si} is the internal surface resistance (m^2KW^{-1}).

$$R_U = (A_m + A_n + A_p)\left(\frac{A_m}{R_{se} + R_{m2} + (R_1 \ldots . + R_z) + R_{si}} + \frac{A_n}{R_{se} + R_{m2} + (R_1 \ldots . + R_z) + R_{si}} + \frac{A_p}{R_{se} + R_{m2} +}\right)^{-1}$$

Equation 8

Where R_u is the upper limit of thermal resistance ($m^2K\ W^{-1}$) R_1 to R_z are the thermal resistances of (unbridged) layers 1…z ($m^2K\ W^{-1}$). A_m, A_n and A_p are the areas of elements composed of materials m, n and p (m^2) R_{m2}, R_{n2} and R_{p2} are the thermal resistances of elements composed of materials m, n, and p for layer 2 ($m^2K\ W^{-1}$) R_{se} is the external surface resistance ($m^2K\ W^{-1}$) and R_{si} is the internal surface resistance ($m^2K\ W^{-1}$). The resultant U-Value can be calculated by Equation 9 (CIBSE, 2019).

$$U = \frac{1}{1/2(R_L + R_U)}$$

Equation 9

Further, more complex analytical methods exist for calculating the U-value of building elements with more complex thermal bridges that those depicted in Figure 15, however these can be evaluated by other methods such as in-situ measurement.

3.5.1.3 In-Situ Measurement

U-Values can be calculated by measuring the heat flow through an element with a heat flow meter or calorimeter together with temperatures either side of the element under steady state conditions of constant temperature. In building construction and maintenance these conditions do not exist. However, it is possible to measure U-Values in situ in “real world” conditions. This is done by application of one of the following methods outlined in the British Standard BS ISO 9869-1:2014 (BSI, 2014).

1. Imposing steady-state conditions using a hot and a cold box. This method is commonly used in a laboratory environment, but is cumbersome in the field.
2. Assuming that the mean values of the heat flow rate and temperatures over a sufficiently long period of time give a good estimate of the steady-state. This is valid if:
    a. The thermal properties of the materials and the heat transfer coefficients are constant over the range of temperature fluctuations occurring during the test.
    b. The change of amount of heat stored in the element is negligible when compared to the amount of heat going through the element.
3. Using dynamic theory to consider the fluctuations of the heat flow rate and temperatures in the analysis of the recorded data.

Of these three methods, method 2 is most applicable to this research. Use of hot and cold boxes would not be practical for use in substation environments and the two conditions stated in method 2 can be applied practically in most substation environments.

There are two main apparatus for use with this method. Heat flow meter (HFM) and temperature sensors.

A HFM is a transducer that gives an electrical signal which is a direct function of the heat flow transmitted through it. These are thin, thermally resistive plates with temperature sensors arranged in such a way that the electrical signal given by the sensors directly relates to the heat flow through the plate. Temperature sensors are transducers giving an electrical signal as a function of its temperature (BSI, 2014). Figure 16 shows heat flow meters (red disks) deployed for measuring various points on an external wall (Meulemans et al., 2016).

Figure 16: HFM in Use

The electrical data from the HFM should be collected continuously or at fixed intervals of between 10 and 30 minutes. The measurement of conditions of heavy elements such as masonry walls should continue until one of the following three conditions are met.

1. The duration of the test exceeds 72 hours
2. The R-Value obtained at the end of the test does not deviate by more than +/- 5% from the value obtained 24 hours before.
3. The R value obtained by analysing the data from the first time period does not deviate by more than +/-5% from the values obtained from the data of the last time period.

The U-Value for the element subject to the measurement can be calculated by Equation 10.

$$U = \frac{\sum_{j=1}^{n} q}{\sum_{j=1}^{n}(T_i - T_e)}$$

Equation 10

Where q is the recorded heat flux (Wm^{-2}) T_i and T_e are the internal and external temperature (k) and J is the index of the individual measurements.

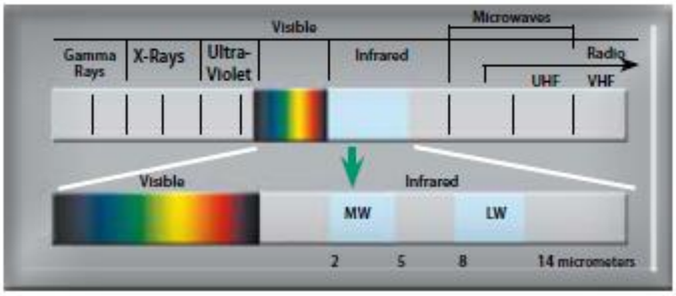
One limitation of this method is that only the U-Values at which the HFM are placed are measured, this will not be representative of the entire building fabric element if there are thermal bridges present, causing areas of enhanced heat loss. Inversely if an HFM is positioned unknowingly on a thermal bridge it will record a higher rate of heat loss than what is representative of the entire building fabric (Marshall et al., 2018; Pelsmakers et al., 2017).

3.5.2 Thermography

Thermography is the use of infrared cameras where a target can be measured remotely without contact. This is done by measuring the infrared energy radiating from the surface of the target and converting this into an equivalent surface temperature (CIBSE, 2019b).

Within the electromagnetic spectrum infrared radiation lies between the visible and microwave portions. As stated in section 3.3.3, any object with a temperature above absolute zero emits some infrared radiation. Figure 17, (FLIR, 2019) shows the infrared region highlighted within the wider electromagnetic spectrum.

Figure 17: Infrared Section Highlighted within Electromagnetic Spectrum

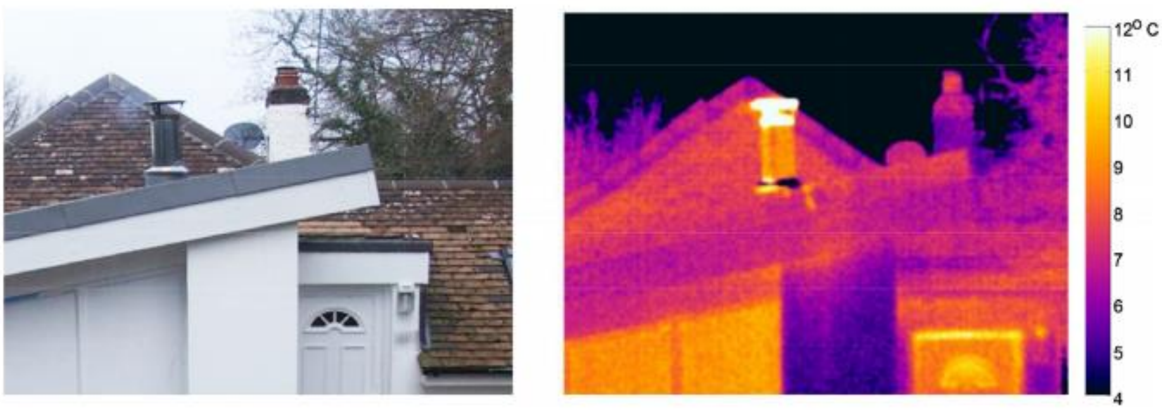


Different temperatures will display as different colours in the thermographic image. A benefit of thermography is that it is non-invasive but still can detect issues that lie within building fabric.

3.5.2.1 Qualitative Thermography

The applications of Thermography can be both qualitative and quantitative. The qualitative analysis aims at determining the presence of thermal anomalies in the building surface (Lucchi, 2018). Examples of these anomalies are thermal bridges and passages of air. An example of thermography identifying such issues is shown in Figure 18 (Al-Habaibeh et al., 2020) where an enhanced rate of heat loss occurring through the chimney is identified through the thermographic image.

Figure 18: Thermographic Images Identifying Thermal Defects in Buildings



3.5.2.2 Quantitative Thermography

The quantitative applications of thermography include U-value measurement and determining the moisture content of walls (Lucchi, 2018; Marshall et al., 2018).

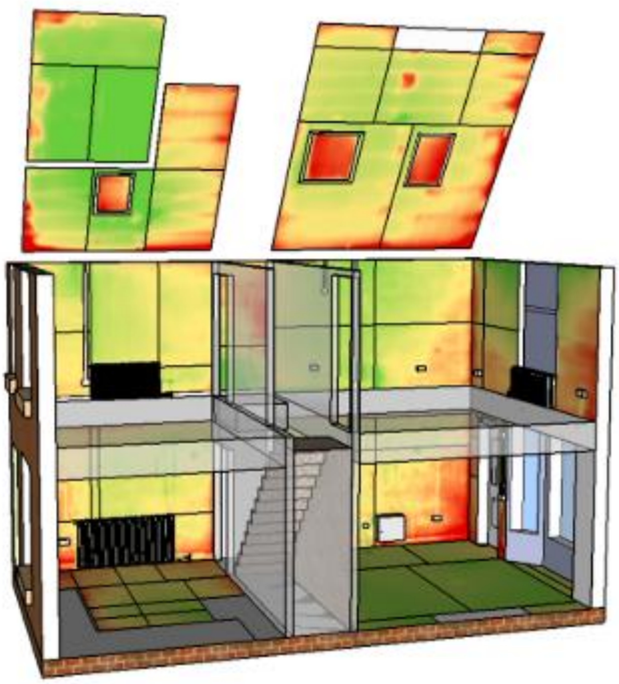
The first instance of thermography in U-value measurement occurred in 2008 completed by Robert Madding. Madding identified a procedure for determining the R value (inverse of U Value) of an exterior wall by thermography. This is done by use of Equation 11, arranged for U-value calculation.

$$U = \frac{4\epsilon\sigma T_s^3 \left(T_s - T_{refl}\right) + h_{in}(T_s - T_{in})}{T_{in} - T_{out}}$$ *Equation 11*

Where ε is the wall emissivity, $\sigma$is the Stephan boltzmans constanst, T_s is the wall surface temperature (K), T_{refl} is the reflected temperature (K), T_{in} is the indoor air temperature(K), T_{out} is the outdoor air temperature (K) and h_{in} is the convective coefficient ($Wm^{-2}k^{-1}$) (Nardi et al., 2016). The procedure assumes a steady state condition of heat transfer with the convective coefficient being calculated in line with ISO9869 (BSI, 2014). R_{refl} is required to eliminate the reflected radiation contribution from the thermal image and obtain the true temperature of the wall in question (Nardi, 2016). This can be obtained by placing aluminium foil on the element prior to measurement and allowing to equilibrate with the surroundings. The foil has an emissivity of 1 and is therefore equal to the reflective temperature, R_{refl}. The procedure is based on steady state conditions although Madding applied the procedure in real world transient conditions and was able to measure over a period of 24 hours and analysis data where conditions close to steady state existed (Madding, 2008).

In comparison to in situ measurement with HFM, quantitative thermography is also not disruptive however has the advantage of measuring the transmittance of an entire building element when compared to HFM that will measure the transmittance at specific points in the building. Such variation in U-value is shown Figure 19 (Marshall et al., 2018) where a visualisation, produced through quantitative thermography identifies higher U-Values in the red areas of the building fabric. Potential drawbacks include dependence on the climatic conditions and pollution and smoke affecting the emissivity captured and influencing the data recorded (Soares et al., 2019).

Figure 19: Variation in U-Value of Building Fabric Measured through Quantitative Thermography



3.5.3 Air Permeability Testing

As stated in section 3.4.4.1 air infiltration can occur in the form of gaps and cracks within the building fabric. These items can be difficult to locate by visual inspection and can be obscured by finishing's (ATTMA, 2010). Air infiltration can be quantified to a buildings air permeability (often referred to as air tightness), the approved method for measuring a buildings air permeability in line with building regulations document part L1A is given in the Air Tightness Testing and Measurement Association (ATTMA) document, Measuring Air Permeability of Building Envelopes (non-dwellings) (ATTMA, 2010). The process detailed in this document can be summarised as follows:

- Within the building to be tested, all HVAC systems are switched off and temporarily sealed along with any other ventilation/ external doors and windows are also sealed prior to the test.
- A variable flow portable fan is temporarily installed in a doorway or suitable opening.
- The test fans are activated and the flow through them increased until a pressure of 50-100Pa is achieved. The total air flow through the fan and the building pressure differential between the interior and exterior is recorded.
- The fan speed is then adjusted to produce steps of approximately 10Pa pressure differential with the fan flow and pressure difference recorded at each step.
- A relationship between the fan flow rate and the building pressure differential can be derived in the form of Equation 12.

$$Q = C(\Delta p)^n$$ *Equation 12*

Where Q is the recorded fan flow (m^3h^{-1}), Δp is the pressure difference (Pa) and C&n are dimensionless constants specific to the building in question. The fan flow required to achieve the reference pressure differential of 50Pa can then be derived from Equation 12. This value can them be divided by the internal building envelope area to determine the air permeability in $m^3h^{-1}m^{-2}$ to confirm compliance with building regulations.

Air permeability is a mandatory test for new dwellings and commercial buildings, the maximum air permeability as per current building regulations is 10 $m^3h^{-1}m^{-2}$ (HM Government, 2016). As substations are not occupied buildings, they do not need to adhere to building regulations and hence air permeability testing does not form part of the commissioning process nor is there an applicable target air permeability rate.

During the air permeability test procedure, when the building is pressurised an air leakage audit can be completed. The increased pressure differential makes passages of air leakage more identifiable as the rate of infiltration is increased. Such areas of leakage can be identified by simply feeling the draught occurring or by using a smoke emitting pencil. The draughts entering the building are clearly visible in the movement of the smoke (Fitton, 2013). Furthermore, thermography can also be incorporated in an air leakage audit. The pressure differential applied to the building exaggerates the air infiltration through any defects in the building fabric (Gil-Valverde et al., 2021) making them more pronounced on a thermographic image. This process of air leakage auditing is not formalised in a standard but is common practice by those undertaking air permeability testing.

The air flow rate recorded in air permeability testing is a result of a pressure differential much higher than what would occur under natural conditions and is therefore not representative of the air change rate under normal conditions. The ventilation rate, under normal conditions is a key factor in determining the ventilation heat loss as per Equation 5. It is possible to use analytical means to estimate the air change rate under normal conditions from the fan flow rate Q, obtained through the air permeability test procedure. To do so a naturally occurring pressure difference must be assumed. Research has estimated 4pa to be a reasonable value although this will vary with conditions such as temperature difference, wind speed and wind direction. The air change rate n under natural conditions can be calculated through Equation 13 (Sherman & Grimsrud, 1980).

$$n = \frac{Q_{50}}{(\frac{50}{4})^c * V}$$ *Equation 13*

Where n is the is air change rate (h^{-1}), Q_{50} is the flow rate at 50 pa (m^3h^{-1}), c is the pressure exponent (obtained from the air permeability test) and V is the internal volume of the building (m^3). There is much debate about the suitability of this method and alternative techniques that measure air permeability at lower pressures giving a more accurate representation of the air change rate under normal conditions are emerging although yet to become established to a point comparable to the blower door method (Pasos et al., 2019; X. Zheng et al., 2019).

Air permeability testing through the blower door method is an established and standardised method of quantifying heat loss from a building, and it can also be used to estimate moisture ingress occurring which will be discussed within section 3.6. Limitations of the method include that the flow rate measured is not representative of the ventilation rate under normal conditions. Furthermore, the accuracy of measurements are known to be impacted by wind speed (X. Zheng et al., 2020). Despite these drawbacks of the method, it is well established and a useful test procedure in relation to the environmental control within substations and is suitable to be utilised in this research.

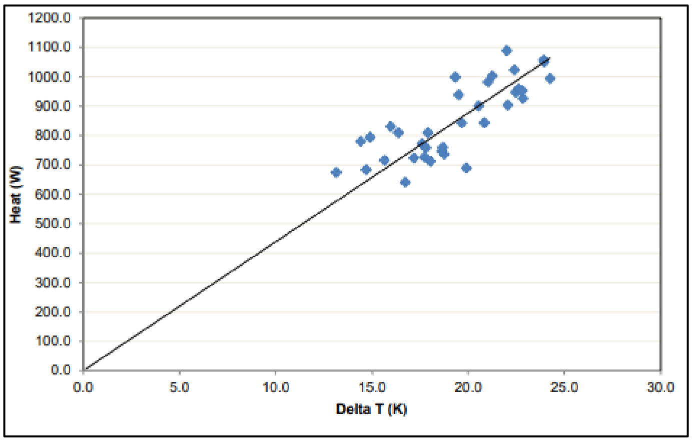
3.5.4 Co-heating and HLC

Whilst a U value is determined for a single building fabric element such as a window or door, a co-heating test is a method of evaluating whole building fabric performance. The output of the co-heating test is the total heat loss coefficient (HLC) in Wk^{-1} which represents the total building thermal characteristics accounting for losses from both transmission and ventilation losses (Bauwens & Roels, 2014). The outline co-heating test procedure is as follows (Bauwens & Roels, 2014):

- The indoor air of an unoccupied dwelling is heated to a steady state temperature using electric heaters and fans.
- Data loggers and measurement equipment is used to measure the electrical energy use necessary to maintain the elevated temperature, indoor and outdoor air temperatures, indoor and outdoor relative humidity, wind speed, precipitation and solar radiation.
- During the test internal doors are opened to facilitate homogenous temperature distribution

Plotting the results of Q_h (W) the electrical heating energy consumption against ΔT (k) the average internal / external temperature difference for time intervals of 1 day will produce a straight-line graph, an example is shown in Figure 20 (Wingfield et al., 2012).

Figure 20: Example Co-heating Graph



The gradient of the line of best fit will give the HLC coefficient for the building, this is defined in Equation 14 (Bauwens & Roels, 2014).

$$HLC = \frac{Q_h}{\Delta T}$$

Equation 14

In this form the impact of solar energy is not accounted for. Further analysis can be undertaken to account for solar gain by the building as well as splitting the heat loss between transmittance and ventilation by applying methods that determine either heat loss through transmittance or ventilation such as in-situ U-Value measurement or air permeability testing respectively (Johnston et al., 2015).

The co-heating test procedure is extensive and is not readily applied to buildings that are occupied or fulfilling a function such as substations. Whilst its outputs give a robust measure of the entire building fabric performance (Jack et al., 2018), to complete within a live substation would require the building to be vacated for an elongated period and for distribution equipment such as switchgear to be isolated to stop internal heat gains occurring. Such constraints make conducting a co-heating test in a live substation unfeasible.

3.5.5 Building Energy Modelling

Building Energy Modelling or Thermal modelling is the process of using computational simulations or analytical calculations for predicting the energy consumption of buildings or associated metrics such as energy cost, greenhouse gas emissions or renewable generation (Harish & Kumar, 2016). Such calculations have various applications such as for sizing mechanical and electrical systems, assessing the benefits of building retrofit enhancements and for the purposes of compliance to demonstrate adherence to policy such as building regulations. The different types of modelling can be broadly categorised as either dynamic or steady state. Steady state models are modelled with averaged conditions that do not change with time whereas dynamic modelling is iterative, with variables and conditions changing with multiple timesteps (Raslan & Davies, 2010).

3.5.5.1 Steady State Modelling

The Standard Assessment Procedure (SAP) and Simplified Building Energy Model (SBEM) are quasi-steady state modelling methods based on monthly average calculations. They are used for assessing the energy performance of domestic and non-domestic buildings respectfully. Both methods consist of tabulated non-graphical user inputs whereby the characteristics of the building such as its construction, air permeability rate, U-values and geometry are inputted along with details of relevant mechanical and electrical systems (Department for Communities and Local Government, 2008). The software will output, among other metrics the monthly energy use and carbon emissions that can be used to demonstrate compliance with building regulations. One limitation of these calculation methods is that they are unable to model complex HVAC systems and strategies (Raslan & Davies, 2010). DSM (dynamic simulation modelling) can accommodate such systems and has several other beneficial functionalities compared to the steady state modelling.

3.5.5.2 Dynamic Thermal Modelling

Dynamic thermal modelling of buildings is a computational method used by design, construction and maintenance teams to determine the energy use of a building (Tudor, 2013). Software constructs a 3D model of a building and uses algorithms to complete iterative simulations of the building's thermal behaviour (Energy Plus, 2019).

In comparison to SBEM modelling, DSM (dynamic simulation modelling) is a more advanced tool and as well as being used to demonstrate compliance with building regulations has a more diverse functionality to that of SBEM. This functionality includes (Raslan & Davies, 2010):

- 3D CAD interface capable of incorporating geometry from CAD files.
- More detailed input options for systems, controls and materials.
- Hourly calculations.
- Outputs including load calculations, thermal comfort, and energy performance analysis.

The versatility of dynamic thermal modelling makes it an appropriate software tool within this study to model the energy use within substations and the benefits of interventions in line with the research objectives. Steady state methodologies such as SAP and SBEM are not appropriate as they are principally for demonstrating compliance with building regulations which is not applicable to substations.

3.5.5.3 Performance Gap

There is often a difference between modelled energy performance and actual energy use, this phenomenon is known as a performance gap and is well known to occur in non-domestic buildings (van Dronkelaar et al., 2016). Causes of the performance gap can occur within the design, construction and operational stages of the building life cycle with a key contributing factor being the difference between measured and predicted performance of building fabric (Johnston et al., 2015).

During the design process of buildings actions can occur that later manifest into differences in energy performance from predicted. This includes poor design practice such as the over specification / oversizing of M&E systems or a lack of detail on finishing or consideration to constructability within the design. This lack of sufficient design can develop into lower-than-expected levels of thermal performance during the construction phase when unspecified detail is then defined by those constructing the building rather than in the designer. Furthermore, poor thermal performance can be contributed to by substandard quality of materials and levels of workmanship such as discontinuities of insulation. Some such problems may not be easily identifiable during construction due to fabric consisting of multiple layers e.g. cavity walls (De Wilde, 2014).

To quantify the size of performance gap or indeed its presence in respect of building fabric, measurement of building performance can be undertaken (Johnston et al., 2015). Comparing the results of the methods reviewed in this section such as co-heating, U-Value measurement and air permeability testing against design targets will identify such gaps. Inputting measured values into computational models will make for more accurate modelled energy performance.

During the operational phase of the building there are variables that whilst accounted for in building models are inherently difficult to determine in the design phase and will likely vary in the built and occupied building. These include, occupancy schedules, thermostat settings / accuracy, heat gains from equipment, operation of plug-in appliances and external weather conditions all of which can impact the energy demand of a building (Elnabawi & Hamza, 2019). Determining accurate use profiles from engagement with occupants is possible but can require occupants to be already living in the property to understand and articulate their routines (Hamza et al., 2015), this is not plausible for all building modelling applications.

Of the variables listed in the operational phase that can influence energy use and in turn the performance gap, several are applicable to substation buildings. The occupancy patterns are irregular and not predictable, equipment within will be emitting undefined heat gains and thermostat settings whilst specified to accommodate minimum required temperatures are liable to change with occupant intervention and accuracy of the control instrumentation.

3.5.6 Energy Monitoring

Energy monitoring can be defined as the regular collection and analysis of data concerning energy use, as well as the various contributory factors that influence energy consumption (Fitton, 2013). Within the application of buildings and indeed that of substation buildings monitoring the energy consumed by heating and other environmental control systems as well as the internal and external climates can allow for evaluation and analysis of heat loss through the building fabric.

Energy provided to a building can be measured in a number of ways. The most basic is though monthly billing or reading of supply meters. However, in recent years the UK government has been progressing a roll out of smart meters for gas and electricity metering that monitor consumption in real time, communicate with the energy supplier and allow occupants to monitor data in half hourly intervals through an in home display (Department for Business Energy and Industrial Strategy, 2018). Where energy supplies exist that are not metered there exists methods and solutions for monitoring. Electricity supplies can be measured indirectly through use of a current transformer (CT), typically consisting of a ring of magnetic material that is penetrated by the live cable to be monitored, this then induces a voltage in the secondary magnetic winding that is measured to determine that passing through the live cable. This indirect connection is advantageous as it means cables can be monitored from a discrete location and allows for multiple devices to be used to determine the consumption of different circuits to differentiate demand from various systems (Vesma, 2017). This functionality of CT sensors makes them a suitable system for monitoring energy consumption within electrical substations. Whilst methods exist for measuring common forms of energy other than electricity such as gas, these are not to be reviewed as gas supplies are not present in substation buildings.

As heat loss through building fabric is proportional to the internal / external temperature difference, monitoring and analysing internal temperature can provide context to monitored energy demand. Furthermore, internal temperature can be a key indicator in determining if a building is fit for its intended purpose, in the case of occupied buildings this can be if levels of sufficient thermal comfort are being achieved. Monitoring internal temperature or “Testing by Measurement” (CIBSE, 2019a) can determine if the required levels of thermal comfort are being obtained. Within substations, thermal comfort is not of great concern as they are generally unoccupied. However, this can be likened to the minimum temperature required as part of substation environmental control. As such, monitoring internal temperature will be required to fulfil the research aims of evaluating environmental control by determining if the minimum temperatures are being maintained within the substation buildings. The same can be said of monitoring internal relative humidity levels although this is not a major contributor to heat loss through building fabric.

By monitoring and analysing external climate, insights into building performance and heat loss can be sought. A common energy management concept, *Degree Days,* quantifies the duration and severity of external temperature. Here temperature difference is measured from external temperature against a base temperature: the external temperature at which the building heating (or cooling) systems need to run to maintain comfortable conditions (CIBSE, 2006). Degree days can be used to determine statistical relationships between external climate and heating demand, from which energy consumption or associated budgets can be estimated. This can also be used to normalise the effect of external temperature when comparing energy demand from two different periods, ensuring a meaningful comparison (D'Amico et al., 2019; The Carbon Trust, 2012). The relationship between degree days and energy demand can also be used to determine the HLC of a property by using regression analysis (Fels, 1986). A further benefit of monitoring external climate data is that it is possible to import data sets into DSM software for utilisation in simulations, making the computational model reflective of the building modelled and its actual external climate rather compared to when a generic climate data set is used (D'Amico et al., 2019).

Conducting monitoring of the three metrics discussed, internal climate, external climate and environmental control energy demand will all be necessary for fulfilling the research aim. Recent advances in technology have resulted in affordable remote monitoring solutions for the parameters detailed being widely available (De Wilde, 2014) making deployment of such monitoring achievable for the research.

3.6 Moisture & Psychrometrics

This section has so far reviewed the application of heat gains and losses through building fabric. Such items are relevant to heating demand and maintaining specified temperatures within buildings. Within substations there is also the requirement to maintain a low moisture environment for the prevention of partial discharge and associated damage. To understand how such an environment is maintained and the role of building fabric in doing so, it is necessary to review the relevant principles of psychrometry, with a particular focus on dehumidification.

3.6.1 Psychrometrics Overview

Psychrometrics is the study of the moist air, a mixture of air and water vapour (Struchtrup, 1988). Psychrometrics is critical when designing air conditioning systems for buildings where air cannot be too dry or moist and condensation must not occur. In substations it is key to ensuring desired humidity levels are obtained. Key concepts within psychrometry are humidity, dew point and condensation.

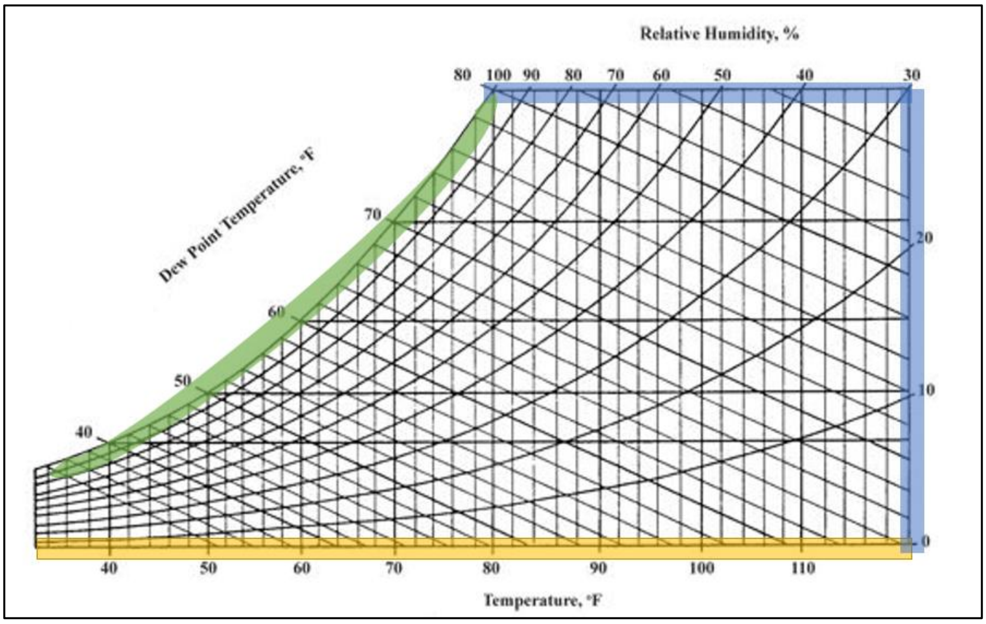
Humidity can be measured in terms of relative humidity and humidity ratio. Relative humidity (RH) is the ratio between the actual mole fraction of vapour in the sample, and the vapour mole in the saturated state (Struchtrup, 1988). Alternatively, it can be defined as a percentage of water vapour held in a given volume relative to the amount of water the air can hold at saturation (Dehum, 2017). This is to say that at 100% RH, the air in a room would be saturated and condensation will occur on surfaces in this space.

Humidity Ratio, commonly given the symbol ω is the mass ratio of vapour to air in a volume of moist air this is expressed in terms of grams of moisture per kilogram of dry air (Struchtrup, 1988). In relation to substation environments humidity is measured in terms of RH.

Condensation is the formation of water droplets from air that is cooled beyond its dewpoint temperature (Ikenberry & Schnell, 2015). Dewpoint temperature, T_d is the temperature at which vapor starts to condense when moist air is cooled and can no longer hold the moisture at a specified humidity level (Dehum, 2017).

These metrics, as well as temperature all interact and vary as one or more changes and are best viewed on a psychrometric chart. A simplified chart is shown in Figure 21, the axis highlighted in yellow is the temperature of moist air, in blue is the RH and green the dewpoint temperature.

Figure 21: Simplified Psychrometric Chart



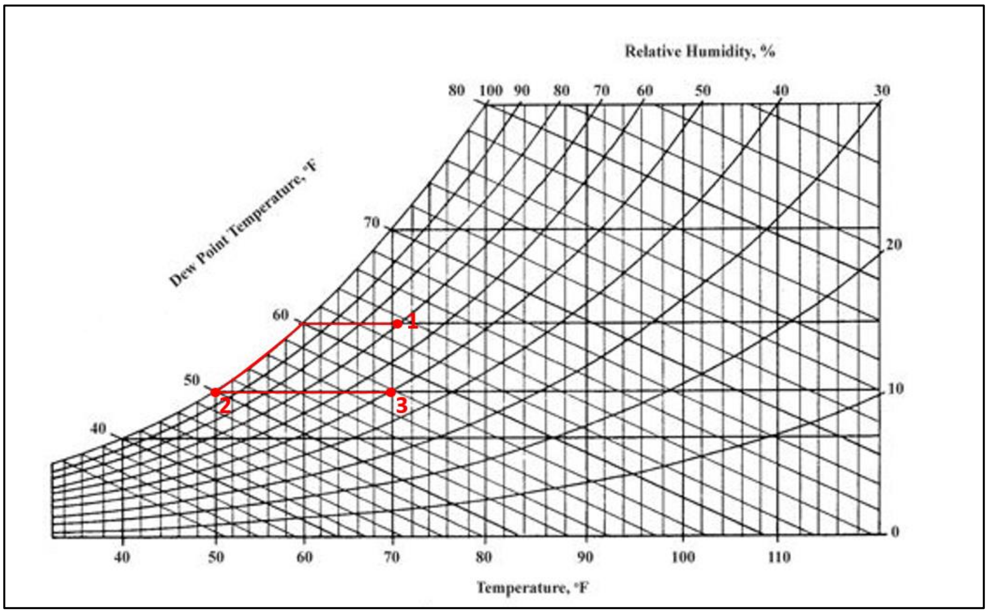
There are various configurations of such a chart available incorporating different metrics, each chart is unique to a given atmospheric pressure as relationships between variables will differ with pressure.

3.6.2 Dehumidification Process

As reviewed in section 2.5.1 temperature and humidity levels are maintained within substations by use of electric convector heaters and condensate dehumidification units such as the EBAC CD30e or CD100e.

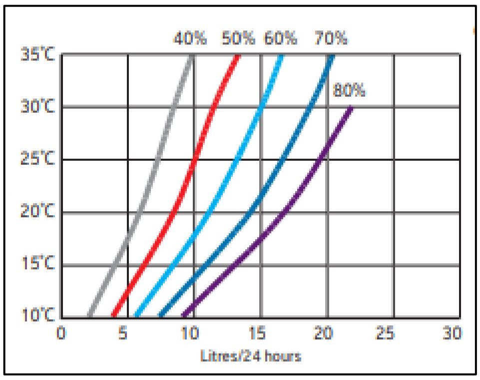
The EBAC dehumidification units operate in a condensing cycle to remove moisture from the air. In this process moist air is passed over cooling coils to lower its temperature past its dewpoint, at this stage the water content in the air is condensed and it is drained away from the process. The cooled air is then heated to lower the humidity ratio, ω and the RH to the desired level (Struchtrup, 1988). This process is visualised in the psychrometric chart shown in Figure 22 below.

Figure 22: Condensate Dehumidification Process



At point 1 ambient air at 70% RH is chilled beyond its dewpoint removing moisture from the air. At point 2 the air is then heated, lowering the RH to a target of 50% where at point 3 the air is returned to the room. The process uses a refrigeration cycle to cool the air, the effectiveness of this cycle largely depends on the temperature of the air. The warmer the air, the more significant quantity of cooling can occur and hence the more effective removal of moisture can occur, this dictates the requirement for a minimum temperature of 10°C within substations. Whilst no data on the effect of temperature is available for the EBAC units utilised in substations Figure 23 shows performance graphs for a similar condensate dehumidifier, the Calorex OTW15 at various RH levels (Calorex, 2019).

Figure 23: Extract Rates of Calorex OTW15 Condensate Dehumidifier



The electric heaters deployed in substations serve to maintain a temperature that allows the condensate dehumidification units to effectively remove moisture from the air. When a space is heated the RH within will decrease regardless of the presence of humidity control systems. This is as the mass of moisture that can be held within a given volume before saturation occurs will increase with temperature, whilst the humidity ratio remains the constant, resulting in a lower RH. It is noted that dehumidification systems that are less impacted by temperature exist such as desiccant systems that operate by passing air through a moisture absorbing material (Dehum, 2017), such systems can operate at sub-zero temperatures negating the need for a minimum temperature.

3.6.3 Dehumidification Demand

Dehumidification demand is directly proportional to the total air change rate from both infiltration and ventilation of a given building. The introduction of unconditioned ambient air will displace the conditioned air and introduce moisture into the building. Quantification of this dehumidification demand in grams of water per hour can be calculated by use of Equation 15 (Narayan et al., 2019).

$$D = \rho V n (\omega_1 - \omega_2) \qquad \textit{Equation 15}$$

Where D is dehumidification demand (gh^{-1}), ρ is air density (kgm^{-3}), V is volume of space requiring conditioning (m^3) n is air change rate (h^{-1}), $\omega_1$is the specific humidity of the ambient unconditioned air and $\omega_2$is the specific humidity of the required air ($g_{water}\, kg_{air}^{-1}$). As such, decreasing the conditioned volume and/or the air change rate within a building will decrease the dehumidification demand. The same could be said of reducing the volume that specifically requires conditioning. The value of n, can be calculated through use of Equation 13 following completion of an air permeability test or through determining the air change rate through dynamic thermal modelling software.

Notably, within the ENWL design specification for substations there is no specification for a defined air permeability rate. This is likely a consequence of substations being defined as unoccupied buildings and therefore do not need to comply with building regulations. As a result, the above method of calculating dehumidification demand is not currently applied in the selection of dehumidification systems. The selection of dehumidifiers is by the manufacturers stated effective dehumidification volume (Electricity North West Limited, 2007). These volumes are stated at specific conditions of 30°C, 80% RH a condition that does not routinely occur in the UK climate. As dehumidifier effectiveness is reduced at lower temperatures, it is expected that the effective volumes observed are less than those stated by the manufacturer.

There are no specified ventilation rates for design of substations however several existing substations have been recorded as having ventilation installed within the fabric. It is thought that this ventilation was historically installed as way of providing conditioning of buildings prior to the specification of dehumidification systems. Since the installation of dehumidifiers, the ventilation is redundant and counterproductive to environmental control as it is increasing the air change rate within substation buildings and increasing the dehumidification load.

3.7 Summary

This chapter has covered the interaction of energy and building fabric focusing on heat but also covering the application of moisture. The key physical mechanisms of heat transfer are conduction, convection and radiation all of which have an application in building fabric. The U-value is a key metric in the areas of building fabric and energy loss / gain and in the research area of environmental control within all buildings including substations.

These mechanisms of heat transfer are relevant to the specific applications in which building fabric can gain and lose energy. These include: Thermal storage, solar gain, latent heat, thermal bridges and ventilation/infiltration. All have some relevance in the field of substations as they are phenomena that can be found within substation buildings. The exception to this is solar gain as glazing is not typically found within substation buildings.

The evaluation of U-values can be done by analytical calculation, in-situ measurement with HFM or quantitative thermography. Analytical calculations provide a straightforward method for evaluating U-values based on the materials that make up a building fabric. However, this assumes all heat transfer is perpendicular to the building fabric and all materials are homogenous. Use of HFM measure heat flux through a proportion of the building fabric area and can take account of thermal bridges if located accordingly. Use of HFM is applicable for the substation environment as they do not require controlled conditions and can be deployed within the operational building.

Thermography can be applied for the evaluation of heat loss. Qualitative thermography can be used for determining the presence of thermal bridges and other anomalies in building fabric that contribute to heat loss. Quantitate thermography can be used as a further method of U-value measurement that can be applied on site in a non-disruptive manor although as this would involve equipment left outside buildings for elongated periods of time it is not suitable for application in substations.

Air permeability testing evaluates the level of infiltration within a building by determining the total air permeability of a building. When undertaking an air permeability test it is common practice to undertake an air tightness audit to identify areas of infiltration within the fabric that are contributing to the overall air permeability. This is a mandatory assessment for new domestic and commercial buildings. This is not required for substations as they are not occupied buildings however it is an area that shall be explored further in this research as is key to heat loss and the results of testing can be used to estimate the air change rate of the building. This is a key metric in not only heat loss but in environmental control.

There are methods for evaluating the whole fabric performance, HLC, of a building that is the summation of losses through transmission (U-Values) and infiltration. Whilst this would give a comprehensive measure of a building fabric efficiency, it is unfeasible to conduct in an operational substation building hence cannot be completed to evaluate heat loss in this study.

Building Energy Modelling can be used for calculating the energy use of buildings. Steady state modelling methods such as SAP and SBEM use analytical spreadsheet calculations to predict a buildings energy use and associated environmental impact. Dynamic thermal modelling can be used for a range of outputs relating to energy consumption, thermal conditions and mechanical and electrical systems. The versatility of dynamic thermal modelling makes it an appropriate tool for evaluating energy and heat loss in substations. The performance gap, the difference between modelled and observed energy use can be caused through design, construction and operation of buildings. Conducting measurement of building fabric performance can enable understanding of performance gap and refine computational models. As substation buildings are already in the operation phase there are a number of variables that could contribute to the performance gap including heat gains from internal equipment, occupancy schedule and thermostat set points and accuracy.

The practice of energy monitoring can be advantageous for analysing energy demand and heat loss through buildings. Energy demand can be monitored through metering or dedicated remote monitoring to quantify the heating demand in a building. CT sensors can be used for electrical supplies with multiple units deployed to capture electrical demand for different systems. Additionally, through monitoring the internal and external climate evaluation of heat loss, building performance, and associated environmental control can be made. For instance, by monitoring internal temperature, it can be determined if actual temperatures are in line with the requirements for environmental control within electrical substations or if over / under conditioning is required. Such practice will be advantageous for this study to gain an understanding of the demand of the heating and dehumidification systems as well as the conditions they are providing in substations, identifying any performance gap. Furthermore, monitoring external conditions enables the quantification of the degree days occurring in a given period, a measure of duration and severity of external temperature. This can be used to draw relationships between heat loss and external temperature from which heating demand can be estimated and like for like comparisons for heating demand between two different periods carried out. The availability of affordable, remote monitoring solutions makes it a suitable and necessary process for fulfilling the research aim.

Maintaining a specified humidity level in substations is done so through deployment of condensate dehumidification systems that remove moisture by cooling air beyond its dewpoint temperature to condense the moisture, then heating the air to lower its RH level. The extraction rates of these systems are known to be dependent on temperature hence the requirement for a minimum 10°C temperature being required within substations. The demand of dehumidification systems is proportional to the total air change rate within a building and its volume. The total air change rate can be estimated through undertaking an air permeability test although interestingly there is not a design requirement for air change rates or a target air permeability for newly build constructions.

This chapter has identified the mechanisms in which heat can be lost from a building and moisture levels controlled. There are numerous methods available to evaluate how a building performs in respect of retaining heat and conditioned air however only a selection of these that are feasible to conduct on substation buildings. Those identified in this chapter as feasible will be incorporated in a method to evaluate the current building performance of electrical substations and improvements made after the application of energy efficiency interventions in line with objective O3. This will form part of the following chapter, Methodology.

Chapter 4 Methodology

4.1 Introduction

In the inception of this project a unique building use case of substations is presented with the aim of decarbonisation of this building type. Chapter 2 provided an in-depth review of these buildings identifying the unique operational requirements and constraints they are subject to that may influence the approach to decarbonisation. The key findings can be summarised as follows:

- Within the internal substation environment there is a need to maintain the environmental conditions of 50% RH and a minimum of 10°C. The current approach to do so by operators is through condensate dehumidifiers and electric heaters.
- This low moisture environment is necessary to limit the risk of damage through partial discharge to electrical distribution equipment.
- Building performance and energy efficiency is not a priority in current substation design specification.

Chapter 3 then explored energy loss through buildings and its evaluation, identifying suitable methods for evaluation of energy loss of substation buildings. Key points from this chapter are:

- The relevant ways energy loss occurs in substation buildings is heat loss through transmittance (building fabric) and heat and conditioned air escaping the building through infiltration. The most appropriate way of evaluating these is through in-situ heat flux measurement and air permeability testing, respectively.
- Modelling the heating demand of substations can be done through dynamic thermal modelling software as this can account for non-standard variables such as occupancy and setpoints. Dehumidification energy demand is best modelled through analytical moisture balance calculations.

The knowledge gained from these literature review chapters positions the study suitably for creation of a method to reach the research aim as specified in objectives O2 & O3. However, to further define the scope the following boundaries are to be applied to the study:

<u>Boundary 1 - Substation Category</u>

This study will focus only on Grid and Primary Substations, that is substations that operate voltage transformation levels of 132kV to 33kV and 33kV to 11kV/6.6kV. Whilst there are other categories of substation, these either do not have such requirement for specific environmental control or are not an asset class owned and operated by industry partner, ENWL.

Boundary 2 – Exclusion of Behavioural Aspects

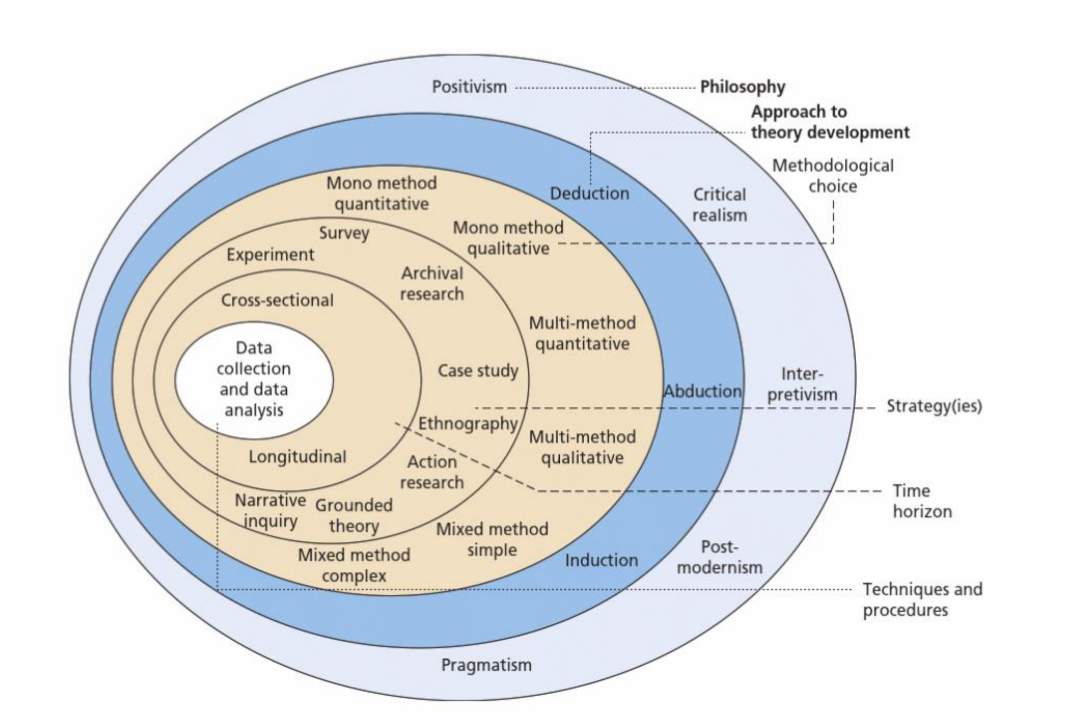
The energy consumption within buildings is affected by the building fabric and electrical / mechanical systems that are covered in detail within the literature review chapters of this research. The behaviours of those occupying the substations can also influence the efficiency of environmental control within buildings including substations. This can be through actions such as thermostat operation and adjustment to suit individuals' thermal comfort. Thermal comfort defined as the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation (Carlucci, 2013). This research, whilst acknowledging the significant affect that these behavioural aspects can have on energy efficiency (Carroll & Berger, 2008; Dietz et al., 2009), does not aim to address the root cause of these actions, and understand why and how they occur. The research will focus on substation's building fabric and electrical mechanical systems whilst limiting the effect of individual behaviours where possible.

This chapter will describe the research philosophies, strategies, and methods applicable and to be implemented in this study. To justify this, a review of widely used research approaches is conducted using the research onion analogy and those that are not appropriate with the aim, objective's, boundaries, and the subject matter in question are to be discounted with the most suitable selected to be incorporated within the research.

4.2 Research Onion Model

The metaphor of a research onion is used to illustrate the decisions and selections on research strategy, data collection techniques and analysis procedures. Each layer of the onion acts as a gateway where decisions are made on the various elements of the research leading to the selection of the data collection methods, the final decisions made in the centre of the onion. This concept, originally from R*esearch Methods for Business Students* (Saunders et al., 2016) is visualised in Figure 24.

Figure 24: Research Onion Model



This metaphor will be utilised as a guide in the selection and justification of the methodologies of this research. With each layer covering a different decision point in the development of the method, the available options will be detailed and where relevant discounted or selected as appropriate for use within this research. The result of which will be a method capable of satisfying the research aim.

4.3 Research Philosophy

The outermost layer of the research onion represents research philosophy. Research philosophy is a collection of beliefs and assumptions about the development of knowledge (Saunders et al., 2016). Although this may be viewed as an abstract concept to the unfamiliar, the development of knowledge is exactly what research aims to do. Whether the researcher is aware or not, when carrying out their research, they will make assumptions that categorise the research philosophy. There are three central types of assumptions applicable, they are:

1. **Ontology** – The study of being, that is, the nature of existence and what constitutes reality. Ontological assumptions shape the way research subjects are viewed (Gray, 2018).
2. **Epistemology** - Assumptions about knowledge, what constitutes acceptable, valid, and legitimate knowledge, and how we can communicate knowledge to others. These concern different types of knowledge such as quantitative, textual or visual data and if they are applicable and acceptable to the research (Saunders et al., 2016).

3. **Axiology** – The role of values and ethics within the research process and how the researcher deals with their own values as well as that of any research participants (Gray, 2018).

There are five research philosophies to be considered in this section: positivism, critical realism, interpretivism, postmodernism and pragmatism. These will be assessed in terms of their ontology, epistemology, and axiology to determine what is most appropriate for this research.

4.3.1 Positivism

Positivism relates to the philosophical stance of the natural scientist and entails working with an observable social reality to produce law-like generalisations (Saunders et al., 2016). This philosophy can be likened to a scientist predicting outcomes and identifying cause / effect relationships. The ontology of positivism assumes one true reality, the epistemology is based on scientific observation and the axiology assumes natural and human sciences share common logical and methodological principles dealing with facts and not values (Gray, 2018). These assumptions and the positivist approach align with the nature of this study. It could be viewed that this is a principally a scientific study on how to limit moisture content and control temperature within buildings by using a lower quantity of energy. As such, the ontology of one true reality and epistemology based on observation align with the measurement and interpretation of key metrics that will be required such as energy consumption, U values, and humidity levels. Additionally, as these metrics are to be facts without the influence of values the axiological assumptions of positivism are aligned with the research aims.

4.3.2 Critical Realism

Critical realism focuses on explaining what we see and experience, in terms of the underlying structures of reality that shape the observable events. Moreover, a critical realist approach challenges what is experienced through the senses is then processed subjectively by the mind (Saunders & Tosey, 2012). The ontology of critical realism is layered, the epistemology views facts as social constructions and the axiology accepts and assumes bias in world views, cultural differences and upbringing making this philosophy value-laden research, a direct contrast to positivism. Here the values do not align with the aim and objectives of the research study. The concept of senses being processed subjectively by the mind does not align with the nature of the subject, there is no subjectivity in the measurement and interpretation of the key measurements in this study. Furthermore, the axiology acknowledging bias and cultural differences is not applicable in the context of substation environmental control.

4.3.3 Interpretivism

Interpretivism, like critical realism has direct contrasts to positivism. Interpretivism emphasises that humans are different from physical phenomena because they create meanings (Saunders et al., 2016) and interpretivism is the study of these meanings. It can be seen as the study of social phenomena in their natural environment (Saunders & Tosey, 2012). The ontology of interpretivism is socially constructed and can have multiple meanings and interpretations. The epistemology focuses on narratives, stories and perceptions and the axiology views the researcher interpretation as a significant contribution making this philosophy value bound research. Here the presence of researcher interpretation in axiology and the epistemology are not compatible with the objective nature of the study and the aims and objectives.

4.3.4 Postmodernism

Postmodernism emphasises the role of language and power relations, seeking to question accepted ways of thinking and give voice to alternative views (Saunders et al., 2016). This is often seen as a direct critique of positivism (Gray, 2018). The ontology of postmodernism assumes complex realities some of which are dominated and silenced by others which are constructed through power relations, the epistemology assumes truths and knowledges are decided by dominant ideologies and often challenges the dominant views, the axiology sees some research narratives repressed at the expense of others making this value-constituted research (Gray, 2018). As postmodernism is often viewed as a direct critique of positivism it is understandable that the assumptions within the philosophy clash with those of positivism that fit well. Most notably dominant ideologies deciding truths and knowledges is not aligned with this study and the aim and objectives. Often postmodernism research is found in artistic and social studies as it is not well aligned to scientific or technical studies such as that in question.

4.3.5 Pragmatism

In pragmatism an ideology is true, only if it works and generates practical consequences for society. Pragmatists focus not on whether a proposition fits a particular ontology but whether it suits a purpose and is capable of creating action (Gray, 2018). In the epistemology of pragmatism true theories and knowledge are those that enable successful action, and the focus is on problems, practices, and relevance. The axiology is value-driven research, resulting in the research being initiated and sustained by researchers doubts and beliefs. The elasticity in the assumptions of ontology and epistemology of pragmatism could enable it to be applied to this research. However, pragmatism being value driven research is not aligned with the studies aim and objectives as there is a need for an absence of values in measuring and interpreting the data obtained.

4.3.6 Justification: Research Philosophy

In the application of this research a positivist philosophy is most appropriate to apply. At its core this is a scientific / engineering problem of how to limit moisture content and control temperature within buildings by using a lower quantity of energy. The knowledge established from the research will be through relationships between variables and measurable facts. For example, this substation is at a certain humidity, measured as such and a certain amount of energy has been consumed to do so as recorded through appropriate measurement tools. In this philosophy there is assumed one true reality that is what is observed and measured throughout the research. These measurements are value-free, that is the researcher is neutral when observing them maintaining an objective stance. For example, this intervention has or has not improved the efficiency of environmental control within this substation, and this is demonstrated through the data collected.

If the human behaviours of those who enter and occupy substations were to be considered it would be necessary to incorporate another philosophy such as critical realism to explain why certain behaviours are being observed due to individuals' values, bias and upbringings. However, as this element is not to be addressed a pure positivist approach is appropriate.

4.4 Approach to Theory Development

The second layer of the research onion for discussion is the approach to theory development. Theory can be defined as: A Set of interrelated constructs, definitions, and propositions that present a systematic view of phenomena by specifying relations among variables, with the purpose of explaining and predicting phenomena (Kerlinger & Lee, 2000). Theories are involved all in research projects although they may not be explicitly stated in the design of a project and could only be presented within the findings and conclusions. As such, understanding the role of theory in the research project is an important step in the design of research. This layer will explore the three principal relationships between theory and research: Abduction, Deduction and Abduction.

- **Deduction** is the most common approach. The researcher on the basis of what is known about a particular domain and of theoretical consideration in relation to that domain, deduces a hypothesis that must then be subjected to empirical scrutiny (Bryman & Bell, 2011).
- **Induction** involves the drawing of generalizable inferences from observation. Whereby deduction starts with theory to observations and findings, induction inversely begins with observations and findings to work towards theory (Bryman & Bell, 2011).
- **Abduction** involves repeatably moving between data/observations to theory rather than a single step from one to another. This begins by the observation of a 'surprising fact' ; it then works out a theory of how this could have occurred (Saunders et al., 2016). These 'surprising facts' can occur at any stage in the research process, making it a dynamic approach.

To understand what attributes of these approaches are most applicable to the research in question Table 4 has been reproduced from (Saunders et al., 2016) to allow analysis of what is most fitting to the aims and objectives of this research.

Table 4: Deduction, Induction and Abduction

	Deduction	Induction	Abduction
Logic	In a deductive inference when the premises are true, the conclusion must also be true	In an inductive inference, known premises are used to generate untested conclusions	In an abductive inference, known premises are used to generate testable conclusions
Generalisability	Generalising from the general to the specific	Generalising from the specific to the general	Generalising from the interactions between the specific and the general
Use of Data	Data collection is used to evaluate propositions or hypotheses related to an existing theory	Data collection is used to explore a phenomenon, identify themes and patterns and create a conceptual framework	Data collection is used to explore a phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth
Theory	Theory falsification or verification	Theory generation and building	Theory generation or modification ; incorporation existing theory where appropriate, to build new theory or modify existing theory

The logic of abduction aligns with the research aim; the generation of testable conclusions are conducive to the stated research objective O3 of “Develop a method to evaluate the current building performance of electrical substations and improvements made after the application of energy efficiency interventions”. That of deductive and inductive inferences are not suitable, with deduction incorporating known conclusions to be tested and induction generating untested conclusions both of which would not lead to completion of the research objectives.

The generalisations from this research will be from the specific to the general. Whereby a discrete number of substations are to be investigated to form generalisations to the wider population. Here the generalisability of Induction is preferable to the application.

The use of data within abduction and induction is most suitable to this research study. The data collected acts as a tool to explore the phenomenon of decarbonisation of substations and will identify themes and patterns identifying incumbent inefficiencies and where these can be resolved or where efficiencies can be gained through intervention. These are to then be tested/verified through further data collection. An inductive approach does not allow for further data collection and a deductive approach does not use data as an exploratory tool, more to evaluate the already stated hypothesis. Inductive and deductive approaches are therefore not suitable approaches in respect of data use.

The incorporation of theory is one of generation and modification due to a lack of existing theory or research on the precise subject matter. There is, however, existing theory in existence on the relevant related subjects such as building performance and performance gap that will be used to build new theory based on the findings of the research. As such, the abductive approach is the most applicable incorporation of theory. The more precise applications for theory in deduction and induction are not agreeable with the research in question.

4.4.1 Justification: Approach to Theory Development

The above analysis indicates that an abductive approach to theory development is most applicable to the aim of this research study. As a specific hypothesis or theory is not being set out to be proven / disproven or linked to existing findings or observations; inductive and deductive approaches are discounted. An abductive approach to theory development that allows for collecting data to explore a phenomenon, identify themes and patterns (Saunders et al., 2016) is required to meet the research aim and, hence, will be deployed in this study.

4.5 Methodological Choice

Quantitative and qualitative research can broadly be distinguished as numeric data (numbers) and non-numeric data (words, images, video clips) (Saunders et al., 2016). The selection between quantitative and qualitative, “methodical choice” is the next layer to address when moving towards the centre of the research onion. Quantitative research explores relationships between variables measured numerically and qualitative research studies participants meaning and the relationships between them using a variety of data collection techniques (Rugg & Petre, 2007). Research can be purely quantitative or qualitative and make use of a single data collection technique, known as mono method. Research that utilises more than one data collection technique can be multi-method if all the techniques are of the same categorisation (quantitative / qualitative) or mixed method if these techniques come from both categories (Saunders & Tosey, 2012).

4.5.1 Justification: Methodological Choice

The research objectives align with a quantitative study. Throughout the study variables of temperature, humidity and energy consumption amongst others will be quantified numerically. This is required to determine if substations are compliant within the environmental conditions required and for measuring the effectiveness of interventions installed within substations. Quantitative research aligns with the epistemological assumptions within positivism, which are discussed under research philosophy. A mixed method is to be applied due to the nature of data that will have to be acquired such as monitoring data of the environmental conditions, energy consumption and data from computational modelling. This approach is common in research involving energy performance in buildings and where performance gap will be analysed (Fitton et al., 2017; Jimenez-Bescos & Prewett, 2018; Marshall et al., 2018).

4.6 Research Strategy

The selection of the research strategy should enable the answering of the research question and should be coherent with the research philosophy. Additionally, from a practical point of view the selection of a research strategy should align with the extent of existing knowledge, the amount of time and resources available and the access to or availability of participants (Saunders et al., 2016). Moving through the next layer of the research onion "Strategies", several common research strategies: case study, survey, action research and experiment are discussed and reviewed.

4.6.2 Case Study

A case study is an in-depth inquiry into a specific and complex phenomenon, set within its real world context (Yin, 2013). A case study can explore multiple themes and subjects but are focused on a narrow range of contexts. Because of this, case studies are beneficial in exploring subjects and issues where relationships may be ambiguous or uncertain (Gray, 2018). The relevant engineering concepts linking environmental conditions, building fabric and electrical / mechanical systems are well researched and have been established to the point that they are incorporated within professional and industrial standards. However, the application of these in substations is under researched. Within this application there are variables that are unique to substations and the relationships to environmental conditions are not well documented, these include asset condition, construction, usage, and occupancy. Case studies are therefore a suitable method for this research as they will allow these variables to be established, explored, and understood.

Case studies are also suitable considering the context of the inception of the research with industry partner ENWL. The University of Salford (UoS) are engaged in a Higher Education Innovation Fund (HEIF) Knowledge Exchange with ENWL. In this partnership a UoS employee, the researcher, is seconded to into the ENWL property team who are responsible for the procurement and management of energy for ENWL. The researcher, with assistance from other UoS staff, is tasked with facilitating a better understanding of energy use and energy efficiency throughout ENWL's built estate that includes substations. In this role the researcher is well placed to carry out a case study. By being seconded to ENWL they have authorised access into substations, availability of asset data and can liaise with relevant subject matter experts within ENWL to ensure all works carried out within substations are suitable and safe. The wider team within UoS, Energy House Labs are experienced in carrying out field trials of energy efficiency measures in buildings and completing the required monitoring of environmental conditions that this involves. The involvement of both organisations is such that completing case studies is practical and makes best use of the collaboration between UoS and ENWL.

4.6.3 Survey

A survey is a detailed and quantified description of a population. Surveys involve the systematic collection of data by interview, questionnaire or observation (Gray, 2018). An important aspect of any survey is the selection of the survey sample. As it is not always possible to evaluate an entire population a sample of the population is selected. Put simply, "a good sample is a miniature of the population-just like it, only smaller" (Gray, 2018). Moreover, a sample should be selected on the basis that it is representative of the population. The samples main characteristics are similar or identical to those of the population (Rugg & Petre, 2007).

Surveys are often used to ensure a robust case study design. As the application of substations is new to the researcher and there is no known research into decarbonisation of substations, it is necessary to analysis the population and select sites for case studies that are representative of the substation population, ensuring external validity in the case study. A study that holds external validity will account for phenomena not only in the study but also other settings (Gibbert et al., 2008). In this context this would mean the findings observed in the case study sites being reflective of what is occurring in the wider substation population. Whilst this could be done through new surveys, this exercise has already been completed in the background research presented in Chapter 2 where ENWL asset management data was reviewed to understand the attributes that are typical of a substation building.

4.6.4 Action Research

Action research can be viewed as a family of methodologies, each of which simultaneously pursues action and research. The Action takes the form of change, improvement or implementation in one's workplace consisting of the leaning and understanding (Dick, 2002). Action research projects typically have the following three characteristics (Gray, 2018):

1. Research subjects are themselves researchers involved in a democratic partnership with a researcher.
2. Research is seen as an agent of change.
3. Data is generated from the direct experiences of research participants.

Considering this, it could be tempting to label this research as Action Research as points 2 & 3 in the above list of characteristics could be viewed as applicable in this research and the aim of decarbonising substations could be seen as the "action" in action research. However, this should not exceed the label of case study research as it is often the role of case studies to describe *an intervention,* in the real world context that it occurred (Yin, 2018). Moreover, the identification of interventions is key to the attribute of case studies that is exploring subjects and issues where relationships may be ambiguous or uncertain. Therefore, whilst there may be parallels to action research projects, case study is a more applicable strategy. Furthermore, point 1 in the above list is not applicable as the researcher will not be involved in the research space. Whilst they will be making decisions on the research they will be directed by data.

4.6.5 Experiment

An experiment takes place in an isolated, controlled laboratory environment, where the effects of changing variables are controlled and measured to verify or refute hypothesis on research subjects (Grix, 2010). In the context of this research project, an experimental approach is not appropriate nor possible. The case study is conducted in the field of real active substations, doing so will test the interventions in an environment that is suitable and comparable to the wider substation population. Whilst testing under a controlled experimental environment would be suitable for establishing the technical effectiveness of mechanical/electrical systems such as dehumidifiers and heaters, deploying them in the field (within live substations) tests the effectiveness in the very conditions where they are intended on being deployed. The environment in which the interventions effectiveness will be determined, whilst not artificially controlled as it would be in an experimental method will be monitored to allow for the effect of changing variables such as temperature and humidity to be quantified. This avoids the complex process of replicating these conditions within a controlled environment. Furthermore, as the research aims not only to just test the effectiveness of building fabric or mechanical/electrical systems in decarbonisation of substations but is the around the wider identification and implementation of appropriate interventions to decarbonise, an experimental approach is not suitable.

4.6.6 Justification: Research Strategy

This research will be completed using a case study method. As there is no known existing research into decarbonisation of substations, the case study method is applicable as it is suitable for exploring subjects where relationships are ambiguous and uncertain. In this context the relationships are between variables such as environmental conditions and energy consumption along with those applicable to substations condition, construction, usage, and occupancy. A robust case study design will be ensured by utilising previously completed surveys of substation asset management data ensuring the findings from the case study can be generalised. These outlined research methods are well suited to the industrial collaboration from which the research was originated in which the researcher, an employee of University of Salford is seconded to ENWL an electricity network operator.

4.7 Time Horizon

The penultimate layer of the research onion is the time horizon. This refers to the time over which the researcher undertakes the research (Saunders & Tosey, 2012). There are two options for how the time horizon is considered, Cross-sectional and Longitudinal. Selection can be driven by the timescales available to the researcher but also the aims of the research.

Cross-sectional studies are often likened to snapshots taken at a particular time, involving the study of a particular phenomenon. Longitudinal studies are more akin to a series of a snapshots combining to make a diary over a given period (Saunders et al., 2016).

Research objective O3 states "Develop a method to evaluate the current building performance of electrical substations and improvements made after the application of energy efficiency interventions". To meet this objective a longitudinal horizon is necessary to take multiple snap shots capturing the change in building performance both pre and post intervention.

The timescales available to the project allow for the multiple snapshots required of a longitudinal study to meet the research aims.

4.7.1 Justification: Time Horizon

This research will employ a longitudinal time horizon. As the research aims dictate the building performance of substations are determined at multiple stages; pre and post intervention, a cross-sectional time horizon would not satisfy this requirement and hence a longitudinal time horizon will be utilised.

4.8 Research Design / Method

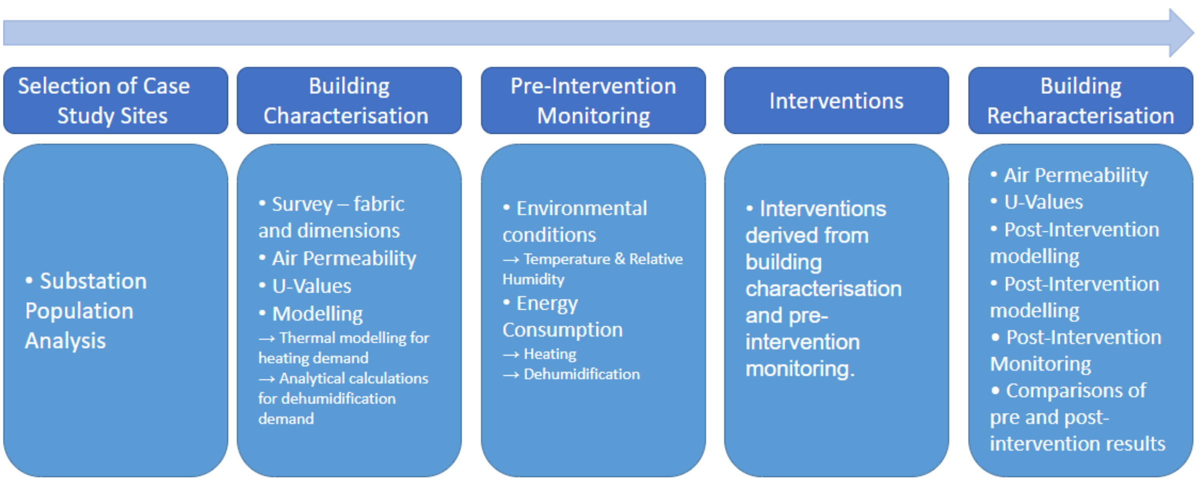
Having arrived at the centre of the research onion the final stage is to pull together the attributes selected as appropriate though the layers into a research design and method capable of reaching research objectives O3 and O4, restated below for clarity.

O3: Develop a method to evaluate the current building performance of electrical substations and improvements made after the application of energy efficiency interventions.

O4: Derive a method to select and evaluate the effectiveness of fabric and systems upgrades to decarbonise substations.

The two objectives will have unique outcomes and will require a concurrent method to address both as required. This method is broadly outlined in Figure 25, and the process of conducting this method is described in detail within the remainder of this chapter.

Figure 25: Method Structure



4.8.1 Selection of Case Study Sites

Prior to commencing work towards the research aim it is necessary to identify sites for investigation as case studies. Three substations were selected that display the characteristics archetypal to the wider substation population presented in Chapter 2 and repeated below for clarity.

Table 2: Substation Building Population Analysis

Building Aspect	**Most Popular Criterion**	**Percentage of the Substation Population that this applies (%)**
Building type	Standalone	96
Building Construction	Stone/Brick	95
Roof Type	Flat	72
Roof Construction	Asphalt	67
Substation Commissioned	1960's	41

An effort was made to select sites across the distribution area that ENWL operate to capture any variables caused by climatic variation in the geography.

The substation sites selected (and their location) are:

- Pendleton (Salford)
- Southeast Macclesfield (South Cheshire)
- Windermere (Cumbria)

Images of all three are shown in Figure 26.

Figure 26: Archetypal Substations Selected for Case Studies (From left to right Pendleton, Southeast Macclesfield & Windermere)

Sites were selected that are representative of the wider substation population in terms of the variables of built form (construction & age) and geographical location. These items are likely to have an impact on the environmental control applied within the buildings. The performance of the building fabric can be linked with age, both through original design and the occurrence wearing/defects within the fabric. Climatic variations in geography of temperature and humidity would also impact the demand of environmental control deployed within the sites.

Through this selection process capturing either the most prominent criterion (building age) or a range of variables (geography) external validity is promoted within the case study sites. This is required to ensure the findings can be related to the wider substation population. Additionally, three sites were selected as this was commensurate with the resource and time allowances available for carrying out this project. By analysing three sites, as opposed to just a single site, the breadth of investigation widens further improving the external validity.

4.8.2 Building Characterisation

The substation buildings hold many factors that contribute to the efficiency and overall effectiveness of environmental control. Such items include the geometry and size of the building that of course will be proportional to the energy demand of the environmental control systems. Additionally, the performance of the building fabric and how well it retains the heat and the low moisture conditioned air inside the building will determine the demand of the heating and dehumidification devices. As such it is necessary to characterise the relevant aspects of the case study substation buildings. This will entail both measurement of specific metrics such as building dimensions, U-values and air permeability then utilising these measurements in appropriate modelling systems to calculate the energy demand of environmental control systems for the three substations. The activities that form this section of the method are outlined in Figure 25 and detailed as followed:

- Building Geometry and Dimensions
- Air Permeability Testing
- U-Value Assessment
- Thermal Modelling
- Dehumidification Demand Modelling

By determining these aspects relating to environmental control for the buildings as they were found at the start of the research project, it allowed for creation of a baseline from which improvements made to the efficiency of environmental control could be measured, allowing for the research aim to be met.

4.8.2.1 Building Layout and Geometry

The building geometry and dimensions naturally is a key consideration in environmental control within the substation buildings. The size of the building and that of its conditioned areas will correspond to the demand of the heating and dehumidification systems. Moreover, when constructing models of building energy performance it is necessary to have the same size, shape and zoning as the actual building to enable the models to accurately perform representative calculations (Harish & Kumar, 2016). Hence, having a defined layout of the substation buildings was required.

As as-built construction drawings of the substations were not available, a dimensioned layout of each site was produced depicting the width, length and height of each room within the substation as well as the dimensions and locations of openings (doors, windows and trench coverings). *A Leica Disto*

D510 laser measure was used to complete the measurements as traditional metallic tape measures are not permitted in substations due to electrification risk. From these obtained measurements, Autodesk Fusion 360 software was used to transpose the sketch into a digital drawing. The layout, dimensions and volumes calculated were to be required for following assessments within the method to assess the environmental control including air permeability testing, thermal modelling, and analytical dehumidification calculations.

4.8.2.2 Air Permeability Testing

Measuring the air permeability of a building quantifies the uncontrolled air infiltration occurring through the building fabric (ATTMA, 2010). In the case of substations there is no requirement for ventilation, hence infiltration accounts for the entirety of air change rate within the building. The rate of air change is directly proportional to dehumidification demand and heat loss occurring through infiltration will be contributing to the heating demand to maintain minimum temperatures. This makes the air permeability of the buildings an important metric to quantify.

The air permeability was calculated by conducting a blower door test in line with ATTMA TSL2 technical standard (ATTMA, 2010). The test was performed by Stroma Built Environment and a ENWL SAP (Senior Authorised Person) was in attendance to supervise the works as it was a not a routine activity. In addition to measuring the air permeability of the substation, whilst the building was pressurised an air tightness audit was undertaken with a smoke stick to determine areas of infiltration around the substations, this was documented by the Stroma Built Environment operative and forwarded to the researcher. Figure 27 shows a blower door test being completed in Pendleton primary.

Figure 27: Blower Door Test Underway

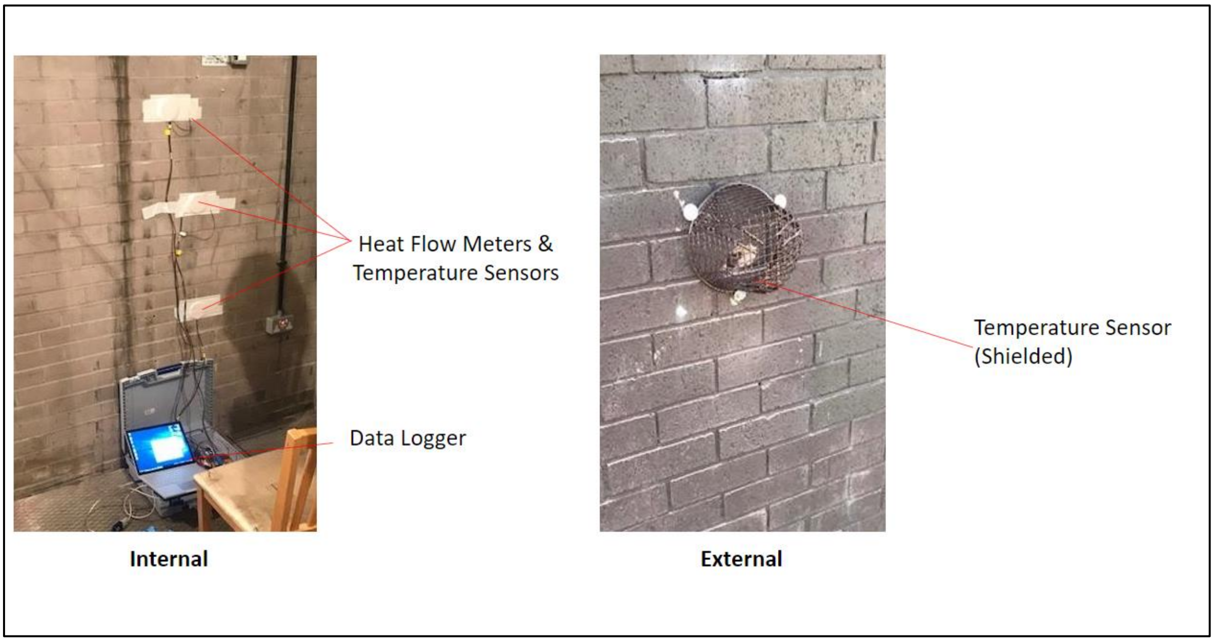
The air permeability rating of each substation in $m^3m^{-2}hr^{-1}$@50pa was recorded and to be inputted as a parameter when constructing thermal models of the buildings. This would also be used to estimate the air change rate under normal conditions from which analysis on dehumidification demand can be completed. A limitation of this method is that the flow rate recorded is not representative of what would occur under normal conditions and hence this needs to be estimated through analytical means or computational modelling. Alternative measurement techniques exist that measure flow rates at lower pressure that is more representative of normal conditions (X. Zheng et al., 2019). However, procuring these services for the project was not possible due to budget constraints and availability of resources. Comparatively, completing air permeability testing was possible through an appropriately approved contractor known to ENWL.

4.8.2.3 U-Value Assessment

As detailed within Chapter 3, a U-value relates to the quantity of heat passing through a building fabric element against internal / external temperature difference. Having an accurate assessment of the U-values within the fabric of the substation buildings is necessary to quantify how much heat is lost through the building fabric and therefore calculate heating demand to maintain the required temperature through thermal modelling. There are several methods for determining U-values though both measurement and analytical methods. A combination of these methods was utilised owing to the availability of measurement equipment and the suitability of methods for measuring specific building fabric elements.

Measurement of the U-Values of the roof and walls of Pendleton primary was completed with in-situ heat flux measurements measurement in line with ISO 9869 (BSI, 2014). The roof and the walls were measured as they make up make up the majority of the external building fabric area, external doors were not measured as they account for a very small proportion of the external area comparatively. For these external fabric elements, conducting in-situ heat flux measurements is possible as the required internal/external temperature difference can be achieved either side of the building fabric. This could not be achieved for internal elements. In conducting the measurement heat flux meters and temperature probes were fixed to the wall with thermal conductive paste and tape, external temperature monitoring probes were shielded with a flue guard style shield to avoid tampering or vandalism. The instrumentation was left in-situ for two weeks. Whilst the minimum testing time in line with ISO 9869 is 72 hours, elongating this period ensured further accuracy in measurement and that the values obtained within a 24hour period would not deviate +/- 5% from the previous 24 hours, a further condition of ISO 9869 (BSI, 2014). Figure 28 shows the U-Value measurement equipment deployed at Pendleton Primary.

Figure 28: HFM and Associated Equipment Deployed in Substation



Alternative methods of measuring U-Values exist such as through quantitative thermography (Marshall et al., 2018). This has the advantage of measuring the overall U-Value of a building element whereas In-situ measurement only gives point values (Soares et al., 2019). However, undertaking quantitative thermography would not be suitable as it would require equipment being left outside substations for long periods of time being at risk of theft or damage. Comparatively when carrying out in-situ measurement the majority of the instrumentation remains indoors, and the instrumentation outside can be shielded as shown in Figure 28. To promote mono-directional heat transfer through the elements being measured the minimum temperature inside the room was elevated to ensure an internal / external temperature difference of at least 5°C (Ficco et al., 2015). The heating demand to maintain this temperature was negated from the collection of monitoring data to be discussed in section 4.8.3 as to not distort the measurement of heating demand that is required for maintain the minimum temperatures.

Due to the limited availability of measurement equipment and programme constraints, these measurements were undertaken solely at the Pendleton substation. From these measurements the U-Values at the remaining substations could be estimated. Whilst it would be preferable to conduct repeat measurements at each substation, this was not possible. As the construction of the substations is comparable with uninsulated brick and blockwork construction and concrete/asphalt roofs with all three constructed in the 1960's it is expected that the U-values of all three are comparable.

For building fabric elements that were not measured such as internal and external doors, partitions, and openings these U-Values were modelled based on their apparent material and construction.

DesignBuilder software has a database of materials and their thermal properties, this was used to determine the U-values of the necessary fabric elements. For example, a steel cable trench cover of approximately 5mm thickness equates to a U-Value of 3.70 $Wm^{-2}k^{-1}$ when modelled in DesignBuilder. Furthermore, within DesignBuilder there are a number of templates for construction elements consisting of multiple materials e.g., windows (this was only applicable in only one substation) where a suitable template could be selected based on the visual appearance of the fabric and the known time at which it was constructed. Default U-Values in modelling software are known to deviate from the true measured value (Marshall et al., 2018) hence this approach has limitations when compared to the situation where all elements were to be measured, if availability of equipment allowed for this.

4.8.2.4 Thermal Modelling

An understanding of the expected energy demand of the building was necessary to further characterise the building. Due to the complexity of heat transfer in buildings to do so analytically would be a challenging and extensive task. Thermal modelling, either dynamic or steady state is a commonly used process to calculate the predicted heating energy demand of buildings (Saelens et al., 2004). Steady state modelling can be undertaken using SAP (BRE, 2012) or SBEM models for domestic and non-domestic properties respectively. When comparing dynamic simulation modelling (DSM) to these steady state systems there are functionalities that are advantageous to the application of modelling the energy demand of substations (Raslan & Davies, 2010). Notably, incorporating non-standard controls, schedules and materials into the models will be beneficial as these elements will be unique when compared to more conventional commercial buildings where SBEM is used to demonstrate compliance. Because of these advantageous functionalities, DSM modelling is a more appropriate tool for use than SBEM and SAP is not suitable as its purpose is to assess dwellings rather than commercial buildings. DesignBuilder software, capable of running DSM models was available to the researcher and has successfully been utilised by the University of Salford in energy performance related research (Marshall et al., 2018) and was therefore a suitable solution for conducting modelling of substations heating demand. The software was used to simulate one year's heating energy demand as a characteristic of the substations, this would also act as a baseline from which any improvements can be measured in line with objective O3.

To construct models of the three case study substations the dimensions and geometry captured in the digital drawings were recreated within the 3D workspace of DesignBuilder. Figure 29, Figure 30 and Figure 31 show the floor plans for the three substations identifying what areas require both temperature and humidity conditioning, only temperature or where no conditioning is required.

Figure 29: Pendleton Floor Plan Showing Level of Conditioning Required Throughout Substation

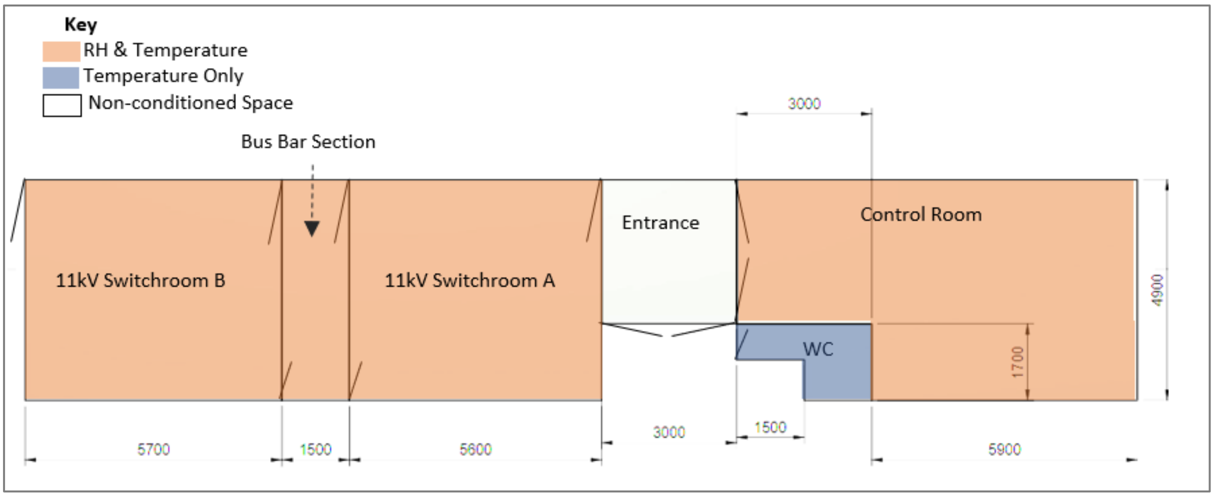


Figure 30: Southeast Macclesfield Floor Plan Showing Level of Conditioning Required Throughout Substation

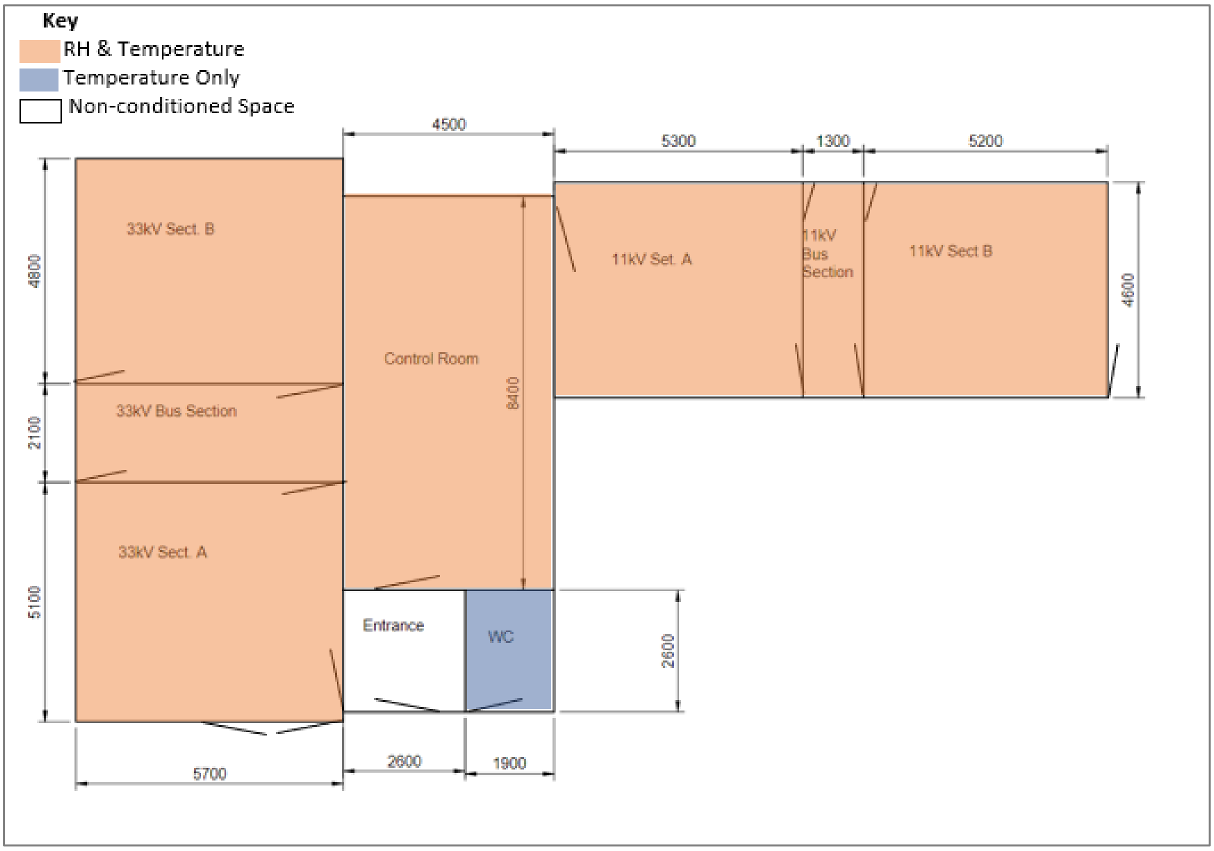
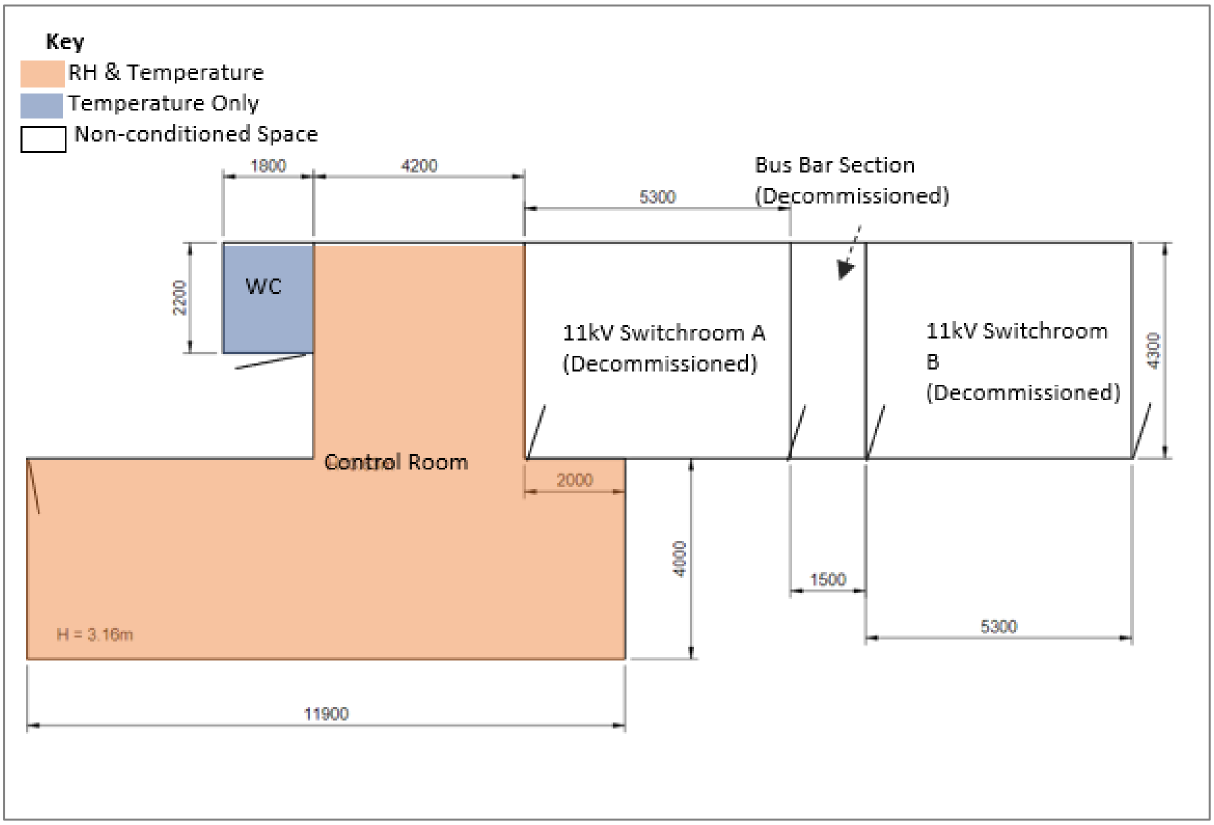
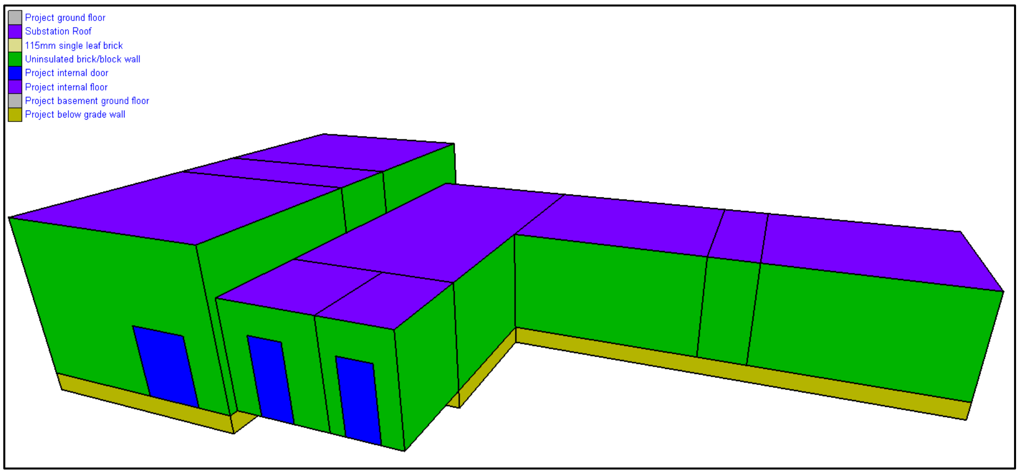


Figure 31: Windermere Floor Plan Showing Level of Conditioning Required Throughout Substation



To align the thermal characteristics of the model with that of the substation building measured U-Values and air permeability measurements were inputted as parameters of the construction. As discussed, where measured U-Values were not available a U-Value was determined through selecting the approximate construction of building fabric elements in design builder, Figure 32 shows the Southeast Macclesfield thermal model, differentiating different fabric elements of the construction. As default modelling U-values are known to vary from real performance, there use introduces uncertainty into the models and restricts the level of calibration that can occur. Calibration techniques can involve adjusting unknown modelling parameters through trial and error to match modelled outputs from measured and are known to reduce performance gap (Marini et al., 2016).

Figure 32: Southeast Macclesfield Thermal Model



The heating system of electric convector heaters is uniform throughout all three substations and hence this was set accordingly within DesignBuilder. The corresponding temperature setpoints were set in line with the relevant ENWL code of practice and designs incorporating the "safety factor" of an elevated background heating temperature against the minimum of 10°C, these are detailed in Table 5.

Table 5: Set Point Temperatures used in Models

Set Point Function	Temperature (°C)
Background Heating (Operational Areas)	12
Boost Heating for Occupants	15
Background Heating (WC Areas)	5

To define the occupancy within the models an occupancy schedule was derived that reflected the substations being almost entirely unoccupied but with occupants entering the substation for 2 hours on the 1st day of every month, activating the boost heating if necessary. Although the occupancy patterns of substations are impossible to predict due to the occupancy largely consisting of reactive maintenance activities, the periodic attendance was included as it appeared representative of patterns observed in substation sign in books although these are not verified records, which may be viewed as a limitation. Differing occupancy patterns are known to cause discrepancies between modelled and observed energy consumption (Elnabawi & Hamza, 2019).

Within all substations and, indeed, the three case study substations there are various electrical systems, including distribution control and switchgear, telecommunications equipment, dehumidification systems and safety and security systems that will be emitting heat gains into the internal environment. To complete an assessment of each item would be an extensive task as all have various levels of nameplate information available and will have been installed at any point between the time of writing and the substation construction in the 1960's. However, quantification or a lack of quantification of heat gains can be a contributing factor to performance gap between measured and modelled energy consumption (De Wilde, 2014). As such, effort was made to quantify the gains applicable to electrical switchgear as multiple units are located throughout the substations. Within ENWL there was little information available on this matter, one possible reason for this is that there is no maximum temperature requirement in substations, so it is not a great matter of concern. There were some experimentally derived relationships to determine the heat gains of switchgear. However, such relationships applicable for the voltage levels used in UK electrical distribution networks and those within the three case study sites could not be sourced. As such, well cited relationships relating to US voltage levels were utilised (White et al., 2004). Here, the voltage levels of 5kV and 15kV are used to represent the switchgear losses of 11kV and 33kV units respectively. The derived relationships between switchgear operation and losses are detailed through equations 16 and 17.

Equation 16

$$15kV\ losses = 13800\ V * 1.73 * I_{rated} * (\frac{I}{I_{rated}})^2 * PF * 0.00006\ W$$

Equation 17

$$5kV\ losses = 4160\ V * 1.73 * I_{rated} * (\frac{I}{I_{rated}})^2 * PF * 0.0001W$$

The variables selected in Equation 16 and Equation 17 are as follows:

- 1.73 is an experimentally derived, dimensionless constant.
- I_{Rated} is the rated current of each individual switchgear unit (A).
- I is the current being drawn from the switchgear (A).
- PF is power factor.

To identify these parameters site visits were undertaken. I_{Rated} was determined through the nameplate information on each switchgear unit and I was recorded by reading current dials on the switchgear units as shown in Figure 33. The power factor occurring could not be measured and therefore taken as a nominal value of 0.9 (White et al., 2004). An evaluation of each switchgear unit in the three substations was performed. These were then summed to give the total heat gains occurring from switchgear in each substation.

Figure 33:Switchgear Current Reading Dial

Equation 16 and Equation 17 were used to determine the heat gains present from switchgear, these will be occurring within the switchrooms of the substations. The majority of other equipment within the substations is situated within the control room. As assessing each individual item was not feasible the total heat gains were estimated by applying benchmarked allowances for heat gains as detailed in CIBSE Guide A, Environmental Design (CIBSE, 2019a). As this document naturally does not cover heat gains in a substation building the figure relating to equipment within meeting/conference space of offices was used, $5Wm^{-2}$. This building type was selected as the equipment found within control rooms, such as telecoms equipment and control systems are not dissimilar to the IT equipment that could be located in such an office environment. The subsequent heat gains that were allowed for in the models are stated in Table 6.

Table 6: Model Heat Gains

Substation	Equipment Heat Gains - Switchrooms (W)	Equipment Heat Gains - Control Room (W)
Pendleton	52.4	192.6
Windermere	NA*	286.3
Southeast Macclesfield	111.0	189.0
*Within the Windermere site the Switchrooms were decommissioned, and switchgear located in a new enclosure, hence 0 gains are assumed.		

Other sources of heat gain, such as through lighting and occupants were not accounted for in the models. This is as these sources of heat are thought to be negligible due to substations being mostly unoccupied assets and hence lighting not being active most of the time.

When modelling, the external climate for the three substations local weather data, obtained through purposely installed weather stations was acquired and selected for use in simulations. This would increase the accuracy of the simulation by creating a modelled climate reflective of what is observed in reality as opposed to a generic data set (D'Amico et al., 2019).

4.8.2.5 Dehumidification Demand Modelling

In addition to heating demand, it was necessary to calculate the predicted energy demand of the dehumidification systems to maintain the required humidity levels throughout the substations. This provides a further characteristic of environmental control within the substation buildings and will provide a baseline to measure the effects of interventions on energy demand. Dehumidification demand is not readily modelled in Design Builder, hence an alternative method of evaluating demand was sought. Analytical calculations based on the balance of moisture between the substation building and the external environment were used to determine the mass of moisture to be removed to maintain 50% RH in operational areas of the substations. This was done using Equation 15, for dehumidification demand, D ($kg_{water}hour^{-1}$), originally presented in section 3.6.3 and restated below for clarity (Narayan et al., 2019).

$$D = \rho \, V \, n \, (\omega_1 - \omega_2) \qquad \textit{Equation 15}$$

The variables in equation 1 were selected as follows:

- V is the total volume of the substation operational areas m^3.
- n is the average air change rate under normal conditions in $hour^{-1}$. This was calculated as a by-product of producing the thermal model that determines air change rate under normal conditions from the air permeability rate inputted in $m^3m^{-2}h^{-1}$@50pa.

- ω_1 is the average specific humidity in $kg_{water}\ kg_{air}^{-1}$, determined as average ambient climatic conditions through 1 years monitoring.
- ω_2 is the specific humidity in $kg_{water}\ kg_{air}^{-1}$ achieved when lowering the RH of ambient air to the target 50%.
- ρ is the density of air is taken as 1.21kgm^{-3}.

To determine the associated annual energy demand, the dehumidification demand was equated to the power demand of 0.46kW and extraction rate stated in the EBAC data sheets (EBAC, 2019). As no information on the effect of temperature on dehumidification ability was available from the manufacturer, the extraction rate of 0.42 kg hour^{-1} was reduced by 60% to 0.17 kg hour^{-1} accounting for the reduced temperature at which they are deployed. This reduction is based on information available on similar condensate dehumidification units (Dantherm, 2016). Using this method to estimate a full year's energy demand characterises the expected dehumidification demand within the case study substations. Applying this method to Pendleton substation is shown below as an example:

<u>Example calculation for Pendleton Substation:</u>

$$D = \rho\, V\, n\, (\omega_1 - \omega_2) = 1.21 * 253.476 * 0.502 * (0.00670 - 0.00434) = 0.363 kg\ hour^{-1}$$
$$Annual\ moisture\ removal\ rate = 0.363 * 24 * 365 = 3{,}183.04 kg\ year^{-1}$$

$$Assoicated\ annual\ energy\ demand = 3{,}183.04\ kg\ year^{-1} \div 0.17\ kg\ hour^{-1} * 0.46kW = 8{,}612.93kWh$$

This approach would be repeated for all substations. The modelling of both heating and dehumidification demand will provide an expected demand based on maintaining the required environmental conditions. A more thorough understanding of the demand can be gained by measurement of actual demand and conducting comparisons.

4.8.3 Pre-Intervention Monitoring

To evaluate the existing methods of environmental control in the three case study sites, their efficiency and effectiveness was to be determined. The time horizon of this research required that this evaluation be longitudinal, occurring both pre and post intervention. This is to enable the difference in efficiency and effectiveness caused through intervention can be determined. Energy monitoring as described in section 3.5.6 is a process of collecting data relating to energy consumption and contributing factors (Fitton, 2013). A suitable energy monitoring campaign was necessary to complete such evaluation covering the following metrics:

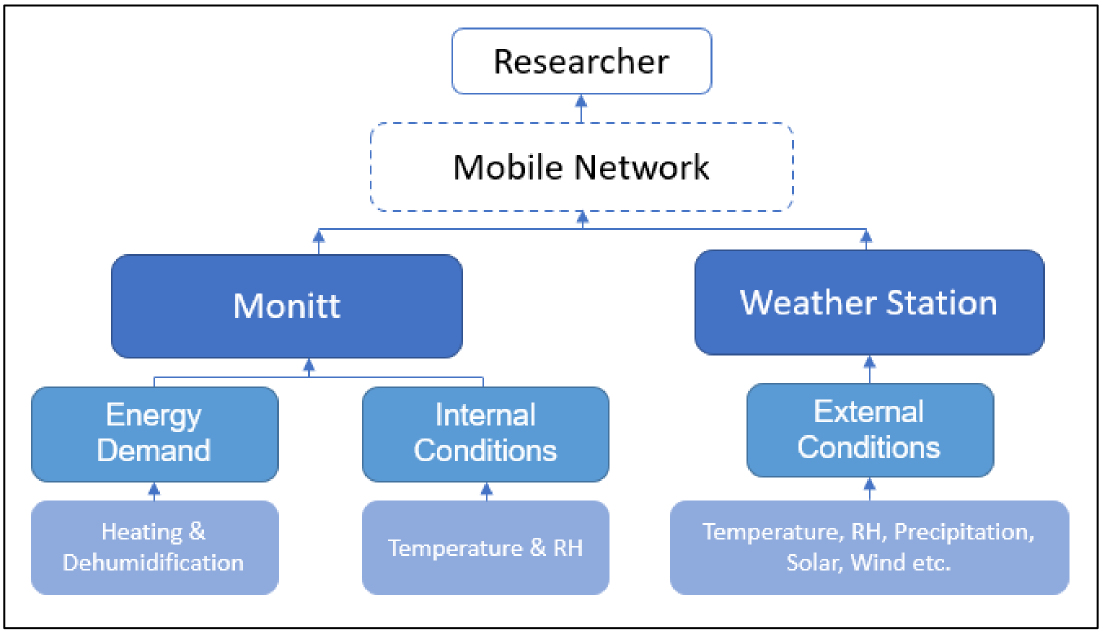
1. *Environmental Conditions Obtained Within the Substation (Temperature and RH).* If the required internal conditions are in line with requirements e.g. temperature at or above 10 °C and RH at or below 50% then the existing systems can be seen as operating effectively.

Inversely, lower temperatures or higher levels of RH would demonstrate the environmental control systems as ineffective.

2. *Energy Demand of Environmental Control Systems.* Through measuring the energy consumption of the environmental control systems comparisons can be made to modelled energy demand and any performance gap identified. If demand exceeds what is modelled this could relate to inefficiencies in the systems.
3. *Ambient Weather Conditions (Temperature, %RH, wind and solar).* The external environmental conditions will impact the internal conditions and demand of environmental control systems. The difference between internal and external temperature is directly proportional to heat losses through the substation and the moisture extraction rate of dehumidification systems varies with temperature and humidity. By monitoring ambient conditions, their impact on internal conditions and environmental control systems can be established and allow pre and post intervention time periods to be normalised and compared, this can be done by quantifying the degree days occurring in a given period. Additionally, the other recorded conditions such as solar radiation, wind speed and direction can be inputted into thermal modelling software to provide a more accurate representation of the weather conditions that the buildings are exposed to.

All of these variables were measured through remote monitoring systems. Modern developments in technology have made solutions to measure these items more affordable (De Wilde, 2014) hence, procuring them for the research was feasible. A summary of the monitoring campaign showing the monitoring systems and associated data flows is shown in Figure 34. Whilst there are manual electricity meters installed within substations, this system was not appropriate for the measuring the demand of the environmental control systems as their demand could not be split from that of the entire substation hence a dedicated system was required.

Figure 34: Monitoring Campaign Summary with Data Flows



A Monnit ™ system was installed to monitor the environmental conditions within the substation and the energy demand of the environmental control systems. This system was selected based on the recommendation of University of Salford who had successfully deployed systems in building research projects. Furthermore, there are several functionalities to the Monnit system that make it suitable for this application such as non-disruptive, simple installation, long battery life and data being accessible through an online portal.

The following Monnit equipment was installed:

- Relative Humidity and Temperature Sensors
- AC current meters
- Wireless gateway

These items are pictured in Figure 35. Due to the functionality of the Monnit sensors, these were used only to capture internal conditions. Additional equipment would be required to capture external conditions.

Figure 35: Monnit Equipment (From left to right Humidity and temperature sensor, AC Current Meter, Wireless Gateway)

The RH and temperature sensors were installed in each room of the three case study sites in a central location in line with the distribution equipment within. This was to ensure the environmental conditions being monitored were representative to that the electrical distribution equipment will be exposed to, acknowledging that the temperature and RH levels are not completely homogenous throughout. Other considerations made in the placement of sensors to avoid spurious readings were to not fix sensors directly adjacent to the environmental control systems, other active electrical equipment that could be a heat source and perimeter doors where drafts could be occurring (Fitton, 2013).

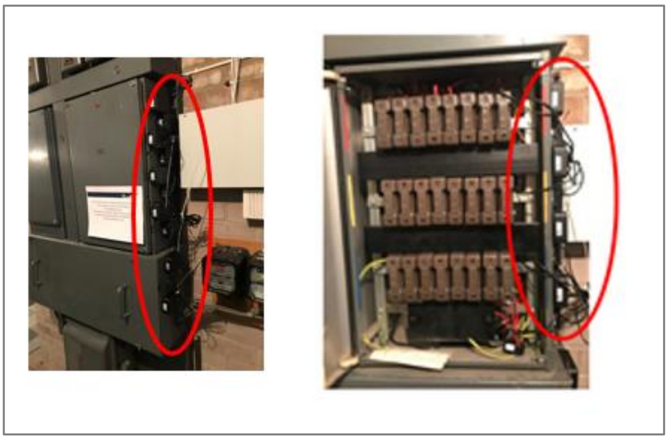
In humidity controlled operational areas (switchrooms and control rooms) two sensors were installed at both a high (2.0m) and low (0.1m) level, this served to capture any stratification of humidity or temperature that is occurring in the areas of substation where environmental control is most critical (Klein et al., 2017). The 2.0m height was selected as this is representative of the top level of switchgear. In other areas where only heating is installed such as WC areas a single RH and temperature sensor was installed in a central location. At the point of installation of monitoring a check was carried out on the thermostats and humidistats to confirm that these were set in-line with the required environmental parameters for substations, this removed the influence that human behaviours would have on the efficiency of environmental control. As stated in section 4.1 this aspect was excluded from the scope of this research.

For analysis purposes, the temperatures and RH levels recorded within the substation operational areas were refined as volume weighted, monthly average conditions at both high and low level for each substation. This was done to determine and analyse the stratification occurring within the substations. The volumes of each room were used to determine representative overall conditions within the substations, this was necessary as all of the buildings consisted of multiple rooms often with dedicated environmental control systems and controls. The data was averaged over monthly periods to determine the how the external weather conditions, changing seasonally, will impact the internal environmental conditions observed. To demonstrate the variation occurring for each month the standard deviation of the daily, volume weighted averages was calculated.

To determine the energy demand of the environmental control systems. AC current meters were installed on the building distribution boards with a dedicated sensor on each relevant circuit capturing the energy consumption of each environmental control devices such as "control room heater" or "switchroom A dehumidifier". Monitoring the separate circuits was necessary to aid diagnoses of any issues relating to the corresponding devices consumption (Fitton, 2013). The physical installation of the sensors and clamping of the current meters to the relevant circuit was completed by an ENWL

Senior Authorised Person (SAP), this was necessary to comply with ENWL's health and safety requirements as this was not a routine activity completed in substations. After installation of the sensors a printed sign was affixed to the distribution board indicating the sensors were not to be removed and the researchers contact details included, this was requested by the ENWL operations team. Figure 36 shows the AC current meters installed on the building distribution board at Pendleton (circled in red).

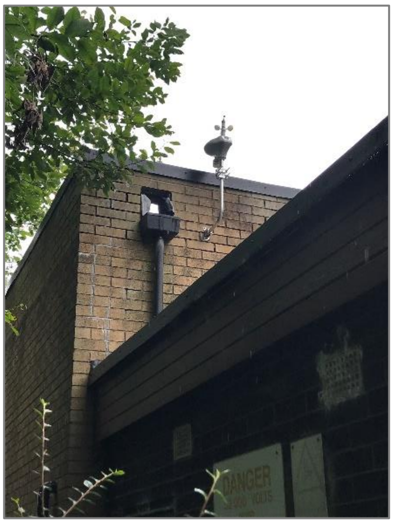
Figure 36: AC Current Meters Installed on Pendleton Distribution Board



The AC current meters purely measure current (Amps) passing through. To convert this to energy (kWh) a simple calculation is incorporated into the Monnit online portal where an assumed voltage is selected. As the UK operates at a voltage of 230V, this figure was used to determine the energy demand for each system.

To capture the ambient weather conditions to the three case study substations an Aercus™ Weather Ranger was installed at a high level on the three sites. This unit was selected as it was agreeable with the budgets of the project and had functionality to push data to an online database where it could be accessed remotely. The sensor array was procured by the researcher however installation was instructed through ENWL's authorised framework civils contractor. Both Pendleton and Southeast Macclesfield sites are situated in urban environments, hence an effort was made to position the sensors out of view from passers-by to avoid any risk of vandalism. Figure 37 shows the device installed at the rear of Southeast Macclesfield.

Figure 37: Weather Station Installed at Southeast Macclesfield



The captured weather data consisting of temperature, RH, wind speed, wind direction and solar radiation was used in the dynamic thermal modelling of the substations to ensure the models included weather conditions most representative to that occurring in reality. CSV files of the weather data were converted to .EPW format so that they could be recognised by DesignBuilder software. This was done using *Elements* software, a free open source tool for creating weather files for the purposes of building energy modelling (Elements, 2015).

Both the Aercus^{TM} Weather Ranger and the Monnit wireless gateway were connected to a mobile 4G network router connected to the internet via a data sim. This enabled remote access and analysis of the data being recorded.

The installation of all monitoring equipment was completed as follows:

- Pendleton: April 2019
- Windermere: August 2019
- Southeast Macclesfield: July 2019

To meet the research objective O3 with respect of evaluating *current building performance* and that *after the application of energy efficiency interventions*, these remained in situ with no interventions or changes occurring until March 2020. This enabled the environmental conditions to be monitored over a range of climatic conditions and their effectiveness under these conditions to be determined. A full 12 months of monitoring pre-intervention would have been preferential to establish the effectiveness of the existing systems under all seasons of the calendar year, although time constraints associated with the knowledge exchange programme did not make this possible. Where a full 12 month's energy demand for the environmental control systems was not captured an estimate was made based on available data. For dehumidification demand monthly averages were used to determine a full year's value. For heating demand, a relationship was established between recorded monthly heating demand and the quantity of heating degree days occurring as recorded by the weather stations (CIBSE, 2006). As described in section 3.5.6 such a correlation can be used for estimating heating demand based on the recorded degree days. This was used to estimate a full 12 months heating demand using degree day data from available sources (The Energy Management Register, 2019) to account for months before monitoring systems were installed (D'Amico et al., 2019).

4.8.4 Interventions

Objective O4 refers to *fabric and system upgrades to decarbonise substations*, such upgrades can be seen as an energy efficiency intervention. Energy efficiency interventions are designed to improve the fabric of housing stock and/or the energy consuming services within through the refurbishment of existing stock (Crosbie & Baker, 2010). Whilst this definition relates to housing stock, the same principle is relevant in the context of substation buildings. Such measures include improving fabric performance, replacement mechanical and electrical systems and their controls. The term efficiency when used in relation to building systems or energy management has a specific meaning, being the ratio of useful energy output to energy input (Patterson, 1996). It is however also common for the term to be used interchangeably with effectiveness, efficacy (Vesma, 2009) or reducing waste (Patterson, 1996). Applying the term to this research aim, both the ratio definition and using the term as a synonym for effectiveness and waste reduction are applicable. The research sponsor ENWL, had also expressed a desire to identify interventions that are economic, meaning that any energy savings obtained as a result of the intervention would pay back the cost of the delivering the intervention. Considering these desired effects, and in reference to the research aim and objectives, the energy efficiency interventions will have any of the following outcomes.

- Improving the environmental conditions being obtained against the required parameters.
- Lower energy consumption of environmental control systems whilst still maintaining required environmental conditions.
- Reduced cost of energy that offsets the cost of the intervention.

When applying energy efficiency interventions, a hierarchy is often followed that details what measures should be addressed first to be most effective and ensure compatibility with the current and future use of the building (D.-L. Zheng et al., 2019). Often such hierarchy's are centred around a *fabric first* methodology whereby improving the performance of the fabric is prioritised ahead of other items (Hurst & O'Donovan, 2019). Such approaches are designed around housing, the needs of which will differ from substation buildings in respect of energy efficiency measures. As such it was necessary to devise a bespoke hierarchy of principles that would be used to select interventions across the three case study substations. These principles are listed in the following approximate hierarchical order:

1. Enhanced control systems
2. Reduction of air and moisture infiltration
3. Segregation of conditioned and con-conditioned spaces
4. Lowering the thermal conductivity of building fabric
5. Alternative dehumidification systems

Whilst the outline principals of intervention are described in this section. Site specific interventions would be derived based on the results of building characterisation activities and pre-intervention monitoring, these interventions and their justifications are detailed in Chapter 5 - Results.

4.8.4.1 Enhanced Control Systems

Control systems that are accurate and suitable for the environment in which they are deployed are necessary for ensuring the required temperature and RH parameters within substations are not breached. Regardless of the level of building fabric performance and effectiveness of the heating and dehumidification systems within a substation, an accurate control system is necessary to ensure conditions are maintained in line with requirements. Furthermore sensor drift, the change of a measured value from a given input over time (Sawhney, 1985) is known to occur often in RH sensors with calibration often needed annually or more frequently (Cavlier, 2012). Similarly, the accuracy and suitability of thermostats is known to cause performance gap and increase heating demand. It is not known if any calibration checks are performed on sensors within the substation estate. It is foreseen that the cost of enhancements to control systems will be relatively small as humidistats and thermostats can cost less than £100 and installation is straightforward with some electrical supplies and wiring already in-situ throughout the three case study sites. As enhancements to control systems can be seen as a relatively straightforward area of intervention with the potential to significantly improve the effectiveness of environmental control systems and reduce associated energy consumption, they are the first in the hierarchical order of intervention principles.

4.8.4.2 Reduction of air and moisture infiltration

Uncontrolled infiltration of air within substation buildings is a mechanism in which heat loss occurs placing demand on heating systems to maintain a minimum temperature. As the case study substations were constructed in the 1960's, it is expected there are areas within the fabric where such infiltration would be occurring. This infiltration of external air will also allow moisture to enter the substation building as detailed in equation 15, increasing the quantity of moisture to be removed and also the energy demand of dehumidification systems within the substation. Resolving such areas of infiltration within the building fabric can be done in a straightforward manner by utilising materials suitable for application to the wider building fabric element to "plug the gaps" of the affected areas, as such it is expected the cost of doing so will be relatively small. As reducing infiltration is a straightforward principle that will reduce both heating and dehumidification demand it is high in the hierarchy of interventions.

4.8.4.3 Segregation of Conditioned and Non-conditioned Spaces

Within substation buildings there are areas that require the temperature and RH to be maintained to specified levels such as control rooms and switchrooms (operational areas). There are also spaces within that have no requirement for environmental control such as entrance areas and cable trenches or where there are lesser requirements such as WC areas minimum temperature of 5°C. By ensuring that there exists segregation between these spaces or by enhancing the physical segregation through applying insulation, the energy demand of the environmental control systems will be reduced. Reduced heat loss and conditioned air passing to the non-conditioned space will in turn reduce energy demand of heating and dehumidification. Such measures are likely to be more complex than simply reducing infiltration as will likely require the construction of structural supports or stud walling although the anticipated impact is expected to be similar, hence they are placed lower on the hierarchy of deriving interventions.

4.8.4.4 Lowering the Thermal Conductivity of Building Fabric

Naturally, the insulation levels of building fabric elements such as roofs and external walls are a key consideration in the building performance of any heated building and substations are of course no different. Building fabric with lower thermal conductivity through the application of insulation will better retain heat and possibly also result in lower levels of infiltration, both of which would be advantageous to the efficiency of environmental control systems. However, retrofitting insulation to the building fabric of the three substations would be complex and significantly more expensive compared to other principles of intervention. Such work would require the coordination of scaffolding and temporary security arrangements as well as the cost of materials of which is expected to be in the order of tens of thousands of pounds possibly compromising the economics of the intervention. As such, long payback periods are associated with such fabric improvements when applied in conventional commercial buildings (Fernandez-Luzuriaga et al., 2021; The Carbon Trust, 2018), it is expected that these would be further elongated by the comparatively lower temperature requirements in substations. As such, this intervention area was not a priority principle within the hierarchy.

4.8.4.5 Alternative Dehumidification Systems

As detailed in chapter 3, there is a key constraint associated with the operation of condensate dehumidifiers which are currently used to maintain humidity levels within electrical substations. The effectiveness of these systems is largely dependent on air temperature and, hence, there is a requirement for a minimum temperature to be maintained within the substations. Alternative systems exist such as desiccant based dehumidification systems. Such systems have the benefit of their extraction rate not being as adversely affected by temperature so they are able to operate at sub-zero temperatures without supplementary heating (Dehum, 2019). Additionally, they are compatible with ductwork to promote an even distribution of the conditioned air around the space they are installed. The disadvantages of such systems is that the installation of such a system is expected to be complex due to fixing and penetration requirements for additional air outlets in addition to a high upfront cost when compared to the condensate units currently utilised by ENWL. Furthermore, condensate dehumidification systems are installed in all substations under ENWL's operation, any new technology would not have the advantage of the availability of spares and established repair process that is already in place in over 500 buildings. Consequently, this area of intervention is of low priority within the hierarchy.

Upon deriving site specific interventions based on the above principles, they were to be delivered across the three case study sites. This would take place no earlier than April 2019 as to not compromise the pre-intervention monitoring data being reflective of the untouched, baseline substations. Delivery would be conducted by ENWL's framework contractors for all non-electrical based interventions. The electrical elements of the interventions were carried out by ENWL maintenance electricians due to them being authorised to conduct such works. Detail of these interventions is detailed in section 5.4.

4.8.5 Building Re-characterisation

To complete the objective O3 in its entirety, measuring the change or improvement to building performance as a result of interventions was necessary. This was largely done through a continuation of the building characterisation activities, modelling and monitoring of environmental conditions and energy demand to allow for pre-post intervention comparisons to be completed (Broderick et al., 2017; Parker et al., 2019).

Interventions within the outlined principle of reduced air & moisture infiltration are expected to improve (lower) the air permeability of the substation buildings. This improvement was measured through a repeat blower door test as conducted within the initial building characterisation process and the improvement determined by the difference between the pre and post intervention air permeability value. Likewise, for interventions relating to the principle of lowering building fabric conductivity, repeat in-situ U-values were undertaken on relevant building fabric elements to determine the improvement achieved through intervention.

These refined, post-intervention building characteristics were used to calibrate the already produced thermal models of the substation buildings to reflect their post-intervention performance and estimated heating demand. The modelled dehumidification demand was adjusted by using the post-intervention air change rate as determined by thermal modelling software. Where alternative dehumidification systems were installed their respective dehumidification rate ($Kg_{moisture}$ / hour) and rated power (W) was used to refine the analytical dehumidification models and compute a post-intervention dehumidification demand. In doing so comparisons between the pre and post modelled energy demand can be undertaken. By updating the weather data used in the simulation for the pre-intervention period, more meaningful comparisons between the two periods and with measured energy consumption can be undertaken.

Improvements to the environmental conditions occurring were measured through continuing to monitor the temperature and RH levels throughout the substations as was done through the pre-intervention period. As was done during the pre-intervention period conducting monitoring through a full calendar year will determine the improvements under varying weather conditions.

By continuing to monitor the energy consumption of the environmental control systems throughout the post-intervention period, changes or improvements in energy demand can be measured. As heating demand is driven by outside temperature, a like for like comparison between pre and post-intervention periods was enabled by using the previously established relationship between heating degree days and monthly pre-intervention heating demand. Heating demand was re-estimated based on recorded degree days through the post-intervention period (D'Amico et al., 2019). It is expected that all interventions will have an impact on energy demand and hence the associated impact can be determined by undertaking these comparisons.

To evaluate the economics of interventions a simple straightforward payback period calculation was conducted based on the associated energy savings as determined by comparing pre and post intervention energy demands and the cost of delivering the interventions. This was completed as detailed in Equation 18.

$$Payback\ Period\ (Years) = \frac{Cost\ of\ Intervention}{Annual\ Energy\ Savings\ *Unit\ Price\ of\ Energy} \quad \text{Equation 18}$$

This payback period relates only to the cost savings of reduced energy demand. This excludes any further benefits that could be realised through intervention such as reduced cost of maintenance & repair due to lower risk of partial discharge occurring within substations or reduced regulatory fines due to reduced risk of network power outages. Whilst this metric is relatively crude and not fully representative of the benefits, it will serve as an indicator of the economic viability of interventions.

4.9 Summary

This chapter has outlined a research methodology to enable successful completion of the research aim and objectives. To do so the analogy of the research onion was utilised to determine the most appropriate research philosophies, strategies, and methods to deploy to conduct this research. This then enabled selection of the appropriate techniques to form the research design.

It was determined that a positivist research philosophy is most appropriate to apply in the context of this project. This was justified considering that this research can be considered, at its core, a technical problem on limiting moisture and temperature control in buildings. This will involve determining relationships between variables and is research that is value-free. These aspects align with the positivist approach, hence its selection.

In respect of approach to theory development an abductive approach is most suitable to apply. This is as no specific hypothesis is being set out to be proved / disproved or linked to existing findings. As abduction allows for research to explore a phenomenon and identify themes and patterns, this is an appropriate approach.

This research is best viewed as a quantitative study as the nature of the subject area will require quantification of variables including temperature, humidity and energy consumption relating to environmental control within substations. This also fits with the basis of the positivist research approach. As data from a variety of sources is to be acquired a mixed method approach is to be utilised.

As there is no known existing research into this subject area a case study research strategy is appropriate. Case studies are suitable for exploring subject areas where relationships are ambiguous and uncertain, this can be said of the relationships between energy consumption and environmental conditions within a substation environment. Additionally, this strategy is suitable in the context of the research in which the researcher is seconded to industry sponsor ENWL through an academic / industry partnership. As such the researcher has access to the substation estate to conduct case studies.

The time horizon of this research is longitudinal. As the research objectives dictate the evaluation of substation building performance at multiple stages, both pre and post intervention a cross-sectional view would not suffice and hence longitudinal is most suitable.

Following navigation of the outer layers of the research onion, at the centre a research design and method is described as necessary to meet the research aim. To form the basis of case studies for investigation, three substations were selected that are archetypal of the entire substation selection, this was done by selection of sites that possess the criteria that is most popular for various building attributes as defined from asset management data held by ENWL. This consisted of sites that were of stone/brick construction, flat roof and commissioned in the 1960's. The three selected were Pendleton, Southeast Macclesfield and Windermere.

To understand the characteristics relevant to environmental control of the three case study sites a series of building characterisation activities were undertaken. This included undertaking dimensioned surveys to define the building layout and geometry and specialist building performance evaluations such as air permeability testing and U-value measurement. The heating and dehumidification demand to maintain the required environmental conditions within was modelled by use of dynamic thermal modelling and analytical calculations respectively, incorporating the results of characterisation activities to calibrate said models.

A pre-intervention remote monitoring campaign was undertaken to capture the environmental conditions occurring within the substations, the energy consumption of environmental control systems and ambient weather conditions at the substation location. By measuring the internal temperature and humidity levels occurring within the case study substations the effectiveness of the existing systems could be established. The measured energy demand of the environmental control systems compared to the previously established modelled demands will identify any performance gap and subsequent inefficiencies associated with the systems.

Interventions were derived to improve the efficiency of the environmental control systems. Whilst these were to be site specific and based on the results of the building characterisation and pre-intervention monitoring, they were derived from the following principles, listed in a hierarchical order of priority.

1. Enhanced control systems
2. Reduction of air and moisture infiltration
3. Segregation of conditioned and con-conditioned spaces
4. Lowering the thermal conductivity of building fabric
5. Alternative dehumidification systems

The ordering is based on prioritising interventions that will ensure the minimum required environmental conditions are maintained within the substations being necessary. Then lowering energy consumption but still maintaining required conditions and the intervention being economic being the secondary desired outcomes.

Following the delivery of interventions building re-characterisation was necessary to measure the improved efficiency of environmental control. This was done by repeated building performance testing (air permeability testing and U-Value measurement) to determine improvements in the building fabric, continued monitoring of energy consumption and environmental conditions to compare to pre-intervention measurements and identify improvements such as more compliant environmental conditions or reduced energy consumption. When comparing heating demand from both pre and post intervention periods it was necessary to normalise the effect of outside temperature to enable a meaningful comparison. This was done by quantifying the degree days occurring in the monitoring periods from data recorded by monitoring the external conditions at the substations. The economics of conducting the interventions was evaluated by determining the payback period of interventions based on reduced energy consumption offsetting the cost of delivering the interventions.

Completing the method described within this chapter will allow for collection and calculation of results necessary to evaluate the three case study sites and the efficiency of their environmental control systems, both pre and post the application of interventions. These results will be presented in the following chapter.

Chapter 5 Results

5.1 Introduction

This chapter will present the results acquired through completion of the method detailed in the previous chapter. For the three case study substations: Pendleton, Southeast Macclesfield and Windermere, results are presented against the following four distinct stages of the research method in order to meet the research aims as defined in Chapter 1.

- Building Characterisation
- Pre-Intervention Monitoring
- Interventions
- Building Re-characterisation

The results of building characterisation will detail metrics relating to how the building fabric and form will impact environmental control within the substations. This, along with the results of Pre-Intervention monitoring of environmental conditions and energy demand will allow evaluation of the environmental control systems as they are found prior to any intervention. Forming part of objective O4, this creates a baseline from which improvements to the building performance can be measured.

Interventions to improve the efficiency of environmental control are detailed based on the results of the building characterisation and pre-intervention monitoring stages, these are developed from the principles of intervention outline in section 4.8.4. The impact of these interventions is then measured through a building re-characterisation process that includes post intervention measurement of building fabric metrics along with data from post-intervention monitoring and modelling of the energy demand of environmental control systems. The results of these activities are a precursor to completing objective O5, allowing for the recommendations to decarbonise electrical substations to be developed from the acquired data.

5.2 Building Characterisation

Presented within this section are the results that depict relevant features and parameters of the buildings that are relevant to environmental control.

Through completing surveys of the three case study substations the construction of the building fabric was evaluated through visual inspection. In-situ U value measurement in line with (BSI, 2014) was conducted at Pendleton site of the walls and roof. For other sites these measured U-values were assumed where appropriate as the constructions appeared similar and the substations were constructed within the same decade. For other building elements, U-values were modelled based on minimum U-values from the time of construction and using templates from DesignBuilder software. Both measured and modelled U-Values are displayed in Table 7.

Table 7: Substation U-Values

Substation	**U-Value ($Wm^{-2}k^{-1}$)**							
	Ext. Walls	**Roof**	**Ext. Doors**	**Int. Doors**	**Floor**	**Windows**	**Int. Partitions**	**Cable Trench Covers**
Pendleton	1.4*	1.2*	3.1**	2.8**	2.1**	NA	1.7**	3.7**
Windermere	1.4*	1.2*	3.1**	2.8**	2.1**	5.8**	1.7**	2.8**
Southeast Macclesfield	1.4*	1.2*	3.1**	2.8**	2.1**	NA	1.7**	3.7**
*Measured value ** DesignBuilder Template / Calculation								

These figures depict thermal performance of the substation building fabric which will affect the heating demand required to maintain minimum temperatures. The U-Values of the external facing elements of the roof, floor and walls are as expected for buildings constructed in the 1960's without insulation present in the building fabric (Jones et al., 2013). In comparison to modern standards of construction these U-Values reflect poor building performance.

The geometry of the three substations was determined through measured surveys. The internal volume and floor area are required parameters for understanding the energy demand of environmental control systems. Moreover, they are required for determining the air permeability of a building in line with (ATTMA, 2010). Table 8 shows the internal volume and floor areas for the three substations along with the result of the air permeability test and estimated air change rate under normal conditions as calculated through DesignBuilder software.

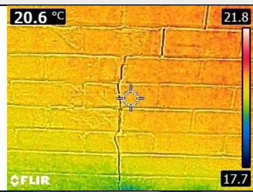
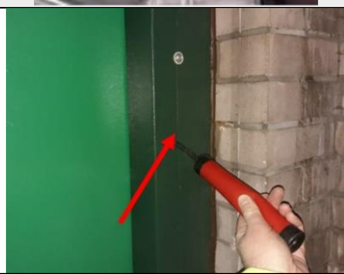
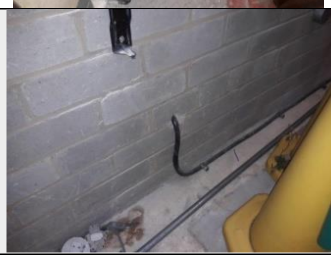
Table 8: Substation Geometry, Measured Air permeability and Estimated Air Change Rates

Substation	**Internal Floor Area (m^2)**	**Internal Volume (m^3)**	**Pre-Intervention Air Permeability ($m^3m^{-2}h^{-1}$@50pa)**	**Pre-Intervention Air change rate ($hour^{-1}$)**
Pendleton	101.2	273.3	9.3	0.50
Windermere	65.7	223.2	11.1	0.86
Southeast Macclesfield	160.5	554.3	9.3	0.32

The range of air permeability's for the three substations of between 9.3 - 11.1 $m^3m^{-2}h^{-1}$@50pa is comparable to the current target of 10 $m^3m^{-2}h^{-1}$@50pa as per UK building regulations for new dwellings (HM Government, 2016). Whilst building regulations and subsequently this target is not applicable to the construction of the substation buildings in a regulatory sense, it provides a benchmark to compare the measured rates of air permeability against. As this metric affects the demand on heating and dehumidification systems, improving (lowering) the value through intervention is desirable.

When the air permeability tests were undertaken, air leakage audits were undertaken throughout the substation buildings. Several areas of air leakage were identified in all three of the sites, examples of these are shown in Table 9.

Table 9: Example Areas of Air Leakage

Area of Air Leakage	Picture
Unused and Unsealed Cable Ducts (Pendleton)	
Cracks in brickwork in perimeter wall (Thermographic Image) (Pendleton)	
Exposed cavity at perimeter doors (Pendleton)	
Leakage occurring in joins in door frame (Southeast Macclesfield)	
Unsealed Cable Trench Cover (Southeast Macclesfield)	
Cable trench unsealed leading to decommissioned and unconditioned area (Windermere)	
Unsealed dehumidifier extract pipe (Windermere)	

The potential of reducing air leakage by remedying the areas of leakage shown in Table 9 will be explored within the interventions.

Through the building parameters identified in Table 7 and Table 8, the energy demand of the environmental control systems was modelled. Heating demand was modelled by constructing a thermal model of the three substation buildings in DesignBuilder software and dehumidification demand was modelled through analytical calculations as described in section 4.8.2 of the methodology chapter. The modelled energy consumption of both systems is shown in Table 10.

Table 10: Pre-Intervention Modelled Environmental Control Demands

Substation	**Pre-Intervention Modelled Annual Heating Demand (kWH)**	**Pre-Intervention Modelled Annual Dehumidification Demand (kWH)**
Pendleton	444	8,613
Windermere	1,132	11,382
Southeast Macclesfield	1,346	10,542

Table 10 shows that the modelled dehumidification energy consumption is larger than that of heating across the three substations. The information presented in this section creates an understanding of the substation buildings and provides a baseline to which the measured energy consumption can be compared and inform the deriving of interventions to improve the efficiency of environmental control.

5.3 Pre-Intervention Monitoring

Monitoring of both the environmental conditions being obtained within the substations and the energy consumption of the heating and environmental control systems was undertaken so that the methods of environmental control could be evaluated in respect of their efficiency and effectiveness.

The environmental conditions recorded within the three substations were recorded between April 2019 and March 2020 prior to any interventions being delivered within the sites. The monthly average, high and low, volume-weighted temperature and relative humidity levels recorded in the operational areas of the three case study sites and their standard deviations are presented in Table 11.

Table 11: Pre-Intervention Environmental Conditions within Case Study Sites

Month	Pendleton				Windermere				Southeast Macclesfield			
	High		Low		High		Low		High		Low	
	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)
Apr-19	19.7 (2.2)	41.7 (2.5)	18.1 (1.8)	49.2 (1.7)								
May-19	19.5 (1.9)	47.1 (2.8)	18.3 (1.8)	53.0 (2.2)								
Jun-19	20.6 (2.1)	49.6 (1.7)	19.5 (1.9)	56.4 (1.6)								
Jul-19	24.9 (1.5)	48.1 (1.0)	23.4 (1.2)	55.1 (1.3)					24.3 (0.8)	57.1 (0.6)	22.8 (0.7)	62.9 (0.8)
Aug-19	23.6 (1.6)	49.8 (1.3)	22.3 (1.4)	57.7 (1.3)	20.3 (2.1)	60.9 (1.8)	19.0 (1.8)	66.4 (0.9)	23.5 (0.4)	55.3 (1.7)	22.0 (0.4)	61.2 (1.8)
Sep-19	20.5 (0.9)	51.1 (1.1)	19.5 (0.8)	57.6 (1.3)	17.8 (0.5)	62.3 (1.4)	16.4 (0.6)	68.5 (1.2)	22.5 (0.2)	52.8 (2.0)	20.9 (0.2)	58.8 (2.0)
Oct-19	16.8 (1.2)	56.8 (1.5)	15.7 (1.1)	65.1 (2.0)	17.0 (0.6)	58.4 (2.8)	14.4 (0.9)	68.9 (1.8)	20.5 (0.8)	52.0 (2.8)	18.8 (0.9)	58.1 (2.8)
Nov-19	13.5 (0.9)	58.3 (0.8)	12.1 (1.0)	67.4 (0.7)	15.4 (1.0)	50.3 (3.2)	11.8 (1.3)	63.3 (2.6)	18.7 (0.6)	49.0 (2.7)	16.7 (0.5)	56.0 (2.9)
Dec-19	12.4 (0.7)	56.9 (1.7)	10.8 (0.7)	67.5 (1.5)	14.8 (0.8)	50.7 (1.8)	11.0 (1.0)	65.5 (1.5)	18.2 (0.5)	47.8 (2.1)	16.1 (0.4)	55.1 (2.3)
Jan-20	12.2 (0.6)	56.6 (1.4)	10.8 (0.5)	67.5 (1.2)	14.9 (0.6)	51.8 (1.6)	11.1 (0.7)	67.0 (1.6)	18.8 (0.4)	45.7 (1.4)	16.5 (0.4)	53.3 (1.6)
Feb-20	11.8 (0.6)	58.9 (1.1)	10.6 (0.5)	69.5 (2.3)	14.5 (0.5)	53.0 (2.0)	10.8 (0.5)	68.1 (2.0)	18.7 (0.3)	43.7 (1.8)	16.4 (1.8)	51.1 (2.0)
Mar-20	13.5 (1.3)	57.4 (3.1)	12.2 (1.3)	70.6 (5.3)	15.6 (0.6)	51.5 (2.2)	12.5 (1.5)	64.1 (5.1)	19.4 (0.6)	40.5 (3.1)	16.8 (0.5)	48.1 (3.6)

The conditions presented in Table 11 demonstrate that throughout all three substations there are instances where the humidity levels are non-compliant, additionally in Windermere and Southeast Macclesfield there are temperatures occurring significantly above the minimum of 10°C throughout the winter months. These observations indicate that there is under and over-conditioning of humidity and temperature occurring within the three case study sites.

The energy consumption of the heating and dehumidification systems in the case study sites recorded within the pre-intervention period is detailed in Table 12 along with the percentage difference against the modelled consumption from Table 10.

Table 12: Pre-Intervention Heating and Dehumidification Demand

Substation	**Pre-Intervention Measured Annual Heating Demand (kWh)**	**+/- % Against Modelled Heating Demand**	**Pre-Intervention Measured Annual Dehumidification Demand (kWh)**	**+/- % Against Modelled Dehumidification Demand**
Pendleton	4,433	+898%	7,381	-14%
Windermere	12,411	+996%	3,125	-73%
Southeast Macclesfield	27,188	+1920%	6,255	-41%

The pre-intervention measured heating demand is substantially greater than that calculated through modelling, identifying a significant performance gap between observed and predicted energy consumption. Similarly, there are notable differences between modelled and measured dehumidification demand albeit less substantial. These performance gaps align with the over and under-conditioning detailed within Table 11 with the average temperatures up to 5°C and 8°C above the required temperature for Windermere and Southeast Macclesfield in December 2019, the coldest month of the pre-intervention monitoring period. Whilst no obvious over conditioning of temperature is apparent in the Pendleton substation in Table 11, this shows only data from the humidity controlled operational areas and it is noted that overheating within the WC was recorded with temperatures as high as 23.3°C occurring within the winter months, over 17°C above the required temperature resulting in the much greater heating demand displayed in Table 12. Full temperature data for non-operational areas of the substations can be viewed in the thesis appendix. A further contributor to the large differences shown in Table 12 would be any discrepancies between the actual performance characteristics of the substation buildings and those included in the thermal models. Many assumed U-Values were used rather than modelled due to limited availability of measurement, in addition to the physical construction of building fabric properties such as moisture can worsen fabric performance through increased thermal conductivity (Marshall et al., 2018), such phenomena was not considered in the thermal models. As the internal setpoint in substations is relatively low, resulting in smaller internal /external temperature difference, any variations in fabric performance would result in a large proportional difference in heat required.

The relationship between the temperature and RH levels observed in the substations and their impact on the energy demand of environmental conditions is to be considered in detail within the discussion chapter. These pre-intervention monitoring results presented, and the outcomes of building characterisation were used to derive interventions to improve the efficiency of environmental control within the case study sites.

5.4 Interventions

As reviewed in the methodology chapter interventions were to be identified and installed to improve the efficiency of the environmental control systems for decarbonisation purposes within the three case study sites. The interventions were derived based on the following principles, listed in a hierarchical order of application as described within chapter 4:

1. Enhanced control systems
2. Reduction of air and moisture infiltration
3. Segregation of conditioned and con-conditioned spaces
4. Lowering the thermal conductivity of building fabric
5. Alternative dehumidification systems

These principles, along with insight gained from the building characterisation activities and pre-intervention monitoring results were used to select interventions. These measures are designed to improve the efficiency of the environmental control resulting in more compliant environmental conditions and reduced energy consumption. These items and their justification are outlined throughout sections 5.4.1 through 5.4.5.

5.4.1 Enhanced Control Systems

When devising interventions, a review was undertaken of the pre-intervention environmental conditions being obtained within the case study sites as detailed in Table 11. This showed that the substations' internal environment was subject to both over and under conditioning of temperature. It is thought this was being driven through existing control systems being inaccurate. Despite the setpoint on thermostats being set at 12°C, temperatures were in excesses of this throughout the winter months in all three sites. It is thought that sensor drift is occurring in these instances leading to an undesired setpoint temperature being maintained and leading to unnecessarily high heating demand. In Table 12 the significantly larger pre-intervention heating demand against what is expected through modelling highlights the magnitude of impact of this fault in the control systems.

To address these issues with the existing heating controls, the existing units were replaced with Ecostat PRE5203EC2 units, shown in Figure 38. This system was selected as it has the following functionality that makes it suitable for efficient operation in a substation environment (Prefect Controls, 2019).

- PIR (Passive Infrared) sensor will detect occupancy in the building and automatically provide a comfortable working environment for operatives working in the substation when required. When occupancy is no longer detected the unit will revert to provide background heating.
- Unit is tamperproof and can only be adjusted by remote control.
- Accurate to +/- 0.5°C

Where necessary the zoning of the heating controls was enhanced so that individual rooms were operating on their own heating zone to ensure optimal heating of individual rooms. The thermostats were programmed in line with the ENWL environmental control requirements with a set point of 12°C in operational areas, 5°C in WC areas and a boost temperature of 15-20°C when the PIR had tripped.

Figure 38: Ecostat PRE5203EC2 Heating Controls

In respect of relative humidity levels, Table 11 demonstrates that under-conditioning is occurring with monthly averages of over 60% RH recorded within all three case study sites throughout the pre-intervention period. Additionally, there is stratification occurring within all sites whereby the low-level readings record significantly higher relative humidity levels than high-level. This inadequate and heterogenous conditioning is contributed to by inadequate control systems. Similarly, to the heating controls, it is possible sensor drift is occurring in the humidistats, leading to an unspecified set point being maintained. Additionally, as the dehumidification systems were only controlled with an in-built humidistat, it is likely that the humidity level measured is only relevant to the space immediately surrounding the unit, with the remainder of the room not conditioned as a result. The dehumidification demands shown in Table 12 are all lower than modelled in maintaining a 50% relative humidity level, this reaffirms that the existing control systems are not sufficient to maintain the required conditioned environment and as such the energy demand is less than expected.

The dehumidification controls were enhanced with twin RS PRO humidistats wired in parallel with one unit installed at high level and another at low level to combat the stratification observed in the pre-intervention monitoring. To promote homogenous conditioning throughout the buildings these were positioned on the opposite wall to the dehumidification units. The twin units are pictured in Figure 39 showing both a stock photo and installed.

Figure 39: Enhanced Dehumidification Controls:

The enhancements to the heating and dehumidification controls were applied to all temperature and humidity-controlled areas within the three case study sites.

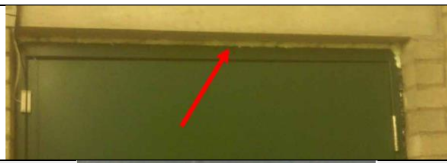
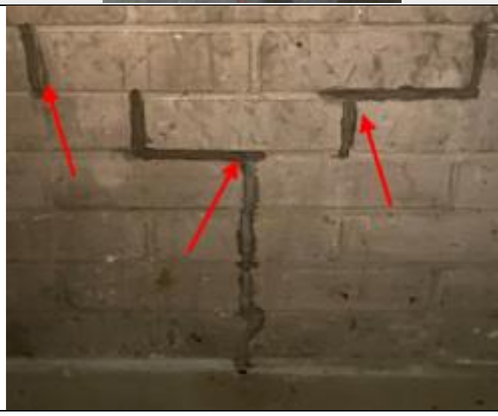
5.4.2 Reduction of Air and Moisture Infiltration

Within the building characterisation stage, air leakage audits were conducted in parallel with the air permeability tests. The audits revealed areas of leakage caused by defects in the building fabric of all three case study sites as pictured in Table 9. This infiltration will act as a heat transfer mechanism, as detailed within Chapter 2, contributing to the heating demand required to maintain the minimum temperature. Similarly, the air infiltration will be contributing to the dehumidification demand. As ambient air enters the building and conditioned air exits the building, the rate at which moisture is required to be removed by the dehumidification system increases. This is demonstrated in equation 15 whereby dehumidification demand is directly proportional to the air change rate in a building. As such, it can be said that by reducing infiltration through interventions, the heating and dehumidification demand of the building will in turn be reduced.

The areas of air leakage identified through audit were addressed through remedial works such as filling in the affected areas by using an appropriate material such as expanding foam, mastic, timber or concrete/mortar. A selection of these interventions are listed in Table 13 below.

Table 13: Remedial Work to Reduce Infiltration

Area of Remedial Work	Picture
Previously unsealed cable ducts filled in with concrete (Pendleton)	
Previously exposed cavity sealed with timber trim (Pendleton)	
Joins in door frame sealed with silicone (Southeast Macclesfield)	

Void between door frame and wall filled with expanding foam (Windermere)	
Cable trench sealed leading to decommissioned and unconditioned area (Windermere)	
Additional motor applied to fill cracks (Pendleton)	

Within two of the case study sites, Southeast Macclesfield and Windermere, it was observed that air bricks were installed in the walls of the building fabric. As per the areas of leakage caused by defects these will be increasing infiltration within the substations. As original construction and design records for the substations were not available, it was not possible to conclusively determine why these air bricks were installed within the building fabric. It is thought these were installed as part of the original construction to provide a form of air conditioning prior to the current requirements for environmental control that were introduced. Newly built substations by ENWL do not have such air vents installed, suggesting that they are no longer required. After consultation with ENWL civil policy, the relevant department for such issues, it was agreed these could be “blanked” for the purposes of understanding their impact on environmental control as no ill-effect could be foreseen from doing so. This was performed with plywood and sealed with a silicone bead. Figure 40 shows a ventilation point before and after it was “blanked”.

Figure 40: Ventilation Point as Installed (Left) and Blanked (Right)

5.4.3 Segregation of Conditioned and Non-Conditioned Areas

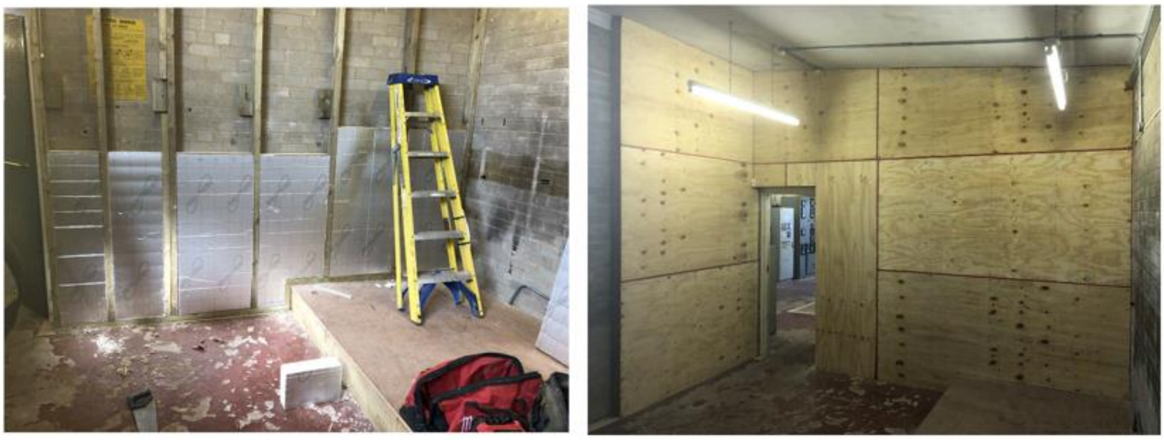
Within the case study sites there were opportunities identified through survey for improving the segregation between spaces in the substations that require environmental control (control rooms and switchrooms) and those that do not. By improving the segregation, infiltration and thermal transmittance losses from conditioned spaces to non-conditioned will be reduced, lowering the heating and dehumidification demand required to maintain the necessary conditions of temperature and relative humidity.

At Pendleton a door leaf on internal double doors between the conditioned control room and non-conditioned entrance area was damaged and no longer hung in the frame. As there was no physical segregation in place the heating and dehumidification systems within the control room were effectively also unnecessarily conditioning the adjacent entrance area. The door leaf was repaired and reinstalled to provide physical segregation. Figure 41 shows the door both damaged and repaired.

Figure 41: Pendleton Control Room Door Damaged and Repaired

A decommissioned area was present in the Windermere substation, in this space the switchgear had been removed and the space left vacant with the environmental control systems removed as they were no longer required. As such the temperature and humidity levels within were uncontrolled. The conditioned space and this non-conditioned space were segregated by a single skin brick partition, to enhance the segregation an insulated partition was erected to reduce conductive heat losses and infiltration between the adjoining spaces, reducing heating and dehumidification demand in the conditioned space. The insulated partition was constructed from a wooden timber frame and 100mm rigid PIR polyurethane foam insulation. The partition both in construction and installed is pictured in Figure 42.

Figure 42: Insulated Partition in Construction and Installed



Within Pendleton a "trench splitter system" was installed to improve segregation between the unconditioned trench space and the control room and switchrooms, where the trenches were located. This system is already utilised by ENWL where a substation is known to have high humidity levels caused by moisture ingress into the trench. The system consists of wooden batons supporting rigid insulation boards fixed directly below the steel trench covers. This improves the performance of the trench covering with transmission losses to the trench space reduced due to the preferable thermal conductivity of the insulation boards. Furthermore, as the boards are cut to size to provide a closer fit than the incumbent steel plates, infiltration between the trench and the conditioned space above is reduced. The system is pictured in Figure 43, showing it both in construction and as installed.

Figure 43: Trench Splitter System in Construction and Installed

The interventions in this category were constructed where there was opportunity to do so, as such they were only applied in two of the case study sites, Pendleton and Windermere.

5.4.4 Lowering the Thermal Conductivity of Building Fabric

The rate of transmittance heat loss through building fabric elements is dictated by its overall U value. By increasing insulation levels of building fabric, the overall thermal conductivity is reduced, as is the U value. Installing insulation to cover entire external building fabric elements is not feasible due to the large cost associated with doing so which is not in agreement with the research budgets and desired economic outcomes of the interventions(Fernandez-Luzuriaga et al., 2021). By this rationale, interventions to lower the thermal conductivity of building fabric were not actively pursued. However, during the site investigation at Pendleton a small amount of water ingress was observed into the substation. This was reported to the relevant maintenance team within ENWL, and it was agreed that rather than a remedial patch repair a full replacement of the roof covering was a more appropriate long-term solution. As well as remedying the building defect this would indirectly provide an intervention to further decarbonise the substation. This roof repair and enhancement through insulation can be considered as a trigger point. Within housing retrofit, a trigger point is a particular point where for practical and financial reasons, improving the energy efficiency of a home is less costly, less disruptive or more important than other times (Fawcett, 2014). This example shows that such trigger points are applicable in the energy efficiency of non-occupied buildings, such as substations.

The existing roof covering was removed and replaced with a 200mm insulation layer as well as a robust multilayer felt covering. The replacement of the roof covering is pictured in Figure 44.

Figure 44: Installation of Replacement Roof Covering

5.4.5 Alternative Dehumidification Systems

The existing method of dehumidification in the case study substations is through EBAC condensate dehumidifiers. An alternative system that operates through desiccant material has several functionalities that would improve the efficiency of environmental control and address some of the issues identified in the pre-intervention monitoring relating to humidity conditioning and improve the overall efficiency of environmental control. These are listed as follows:

- **Distribution of air.** The systems are compatible with ductwork to distribute air throughout the conditioned space, promoting homogenous RH levels throughout substations and avoiding stratification of humidity, as had been observed in pre-intervention monitoring results.
- **More efficient psychrometric process**. A condensate system has a two-step process to humidity control. Firstly, the air is cooled beyond its saturation point to condense the moisture; the air is then heated to lower its relative humidity. A desiccant system removes moisture directly by air passing through a moisture absorbent material, this results in higher moisture extraction rates. By comparing the stated extraction rates from the manufacturers literature (Dehum, 2019) against what is estimated of the EBAC systems it is calculated that at 12°C, 80%RH for 1kWh of energy consumption a desiccant system will extract 26% more moisture than a condensate system.
- **Operation at low temperatures**. The existing condensate systems can only remove moisture at air temperatures above 7°C owing to the condensate cycle that removes moisture by first cooling the air. Additionally, the unit's ability to remove moisture is dramatically reduced at low temperatures. This is compensated for by the requirement for background heating. In theory a desiccant system can remove moisture at temperatures below 0°C meaning background heating would be frost protection only, although in this study the existing heating remained unaltered.

A Dehum AD150 dehumidifier that operates a desiccant system was installed with associated ductwork in the Pendleton Primary control room. Whilst it would have been desirable to install multiple units covering the entirety of a substation to provide a whole site comparison against the incumbent condensate system, after consultation with the relevant stakeholders in ENWL plant policy they would only accept a new system being installed as a trial in a single site to establish that it would operate effectively without adverse effects. Hence, only the Pendleton site had a single system installed in the control room.

The installed unit and associated ductwork are pictured in Figure 45.

Figure 45: Installed Desiccant Dehumidification System and Ductwork

5.4.6 Summary of Interventions

A summary of the interventions applied across the three case study sites is shown in Table 14.

Table 14: Summary of Interventions

Intervention Principles	Pendleton	Windermere	Southeast Macclesfield
Enhanced control systems	• Heating and Dehumidification Controls.	• Heating and Dehumidification Controls.	• Heating and Dehumidification Controls.
Reduction of air and moisture infiltration	• Multiple remedial works to reduce air leakage.	• Multiple remedial works to reduce air leakage. • Blanking of Vents	• Multiple remedial works to reduce air leakage. • Blanking of Vents.
Segregation of conditioned and con-conditioned spaces	• Trench splitter system • Internal door repair.	• Insulated partition wall.	
Lowering the thermal conductivity of building fabric	• Insulated roof.		
Alternative dehumidification systems	• Desiccant Dehumidification system installed in control room.		

The impact of these interventions will be evaluated within the re-characterisation of the three substations.

5.5 Building Re-characterisation

Within this section results are presented that demonstrate the impact the interventions have had on the relevant parameters of the substation buildings and the efficiency of their environmental control systems.

The post-intervention U-Values of building fabric within the substations are shown below in Table 15, where these have been enhanced through intervention, they are shown in **bold** with the original pre-intervention value in brackets.

Table 15: Substation U-Values Post-Intervention

Substation	U-Value ($Wm^{-2}k^{-1}$)							
	Ext. Walls	Roof	Ext. Doors	Int. Doors	Floor	Windows	Int. Partitions	Cable Trench Covers
Pendleton	1.4*	**0.4*** (1.2)	3.1**	2.8**	2.1**	NA	1.7**	**0.3**** (3.7)
Windermere	1.4*	1.2*	3.1**	2.8**	2.1**	5.8**	**0.2**** (1.7)	3.7**
Southeast Macclesfield	1.4*	1.2*	3.1**	2.8**	2.1**	NA	1.7**	3.7**
*Measured value ** DesignBuilder Template / Calculation								

Significant improvements of the enhanced U values achieved through intervention is visible in Table 15. This is a result of adding insulation to previously uninsulated elements. The outcome of these improvements is expected to be reduced both modelled and measured heating demand.

The air permeability of the substations will have been enhanced through interventions, and with this the air change rate under normal conditions will be improved. The post-intervention air permeability of the substation as measured in line with (ATTMA, 2010) is shown in Table 16 along with the corresponding calculated air change rate under normal conditions. The absolute difference between the pre and post intervention figures is given to highlight the improvement achieved, as the air permeability follows a non-linear scale the difference achieved in air permeability at 50Pa will differ proportionally to that at normal conditions.

Table 16: Post-Intervention Substation Air Permeability and Air Change Rate

Substation	Post-Intervention Air Permeability ($m^3m^{-2}h^{-1}$@50pa)	+/- Difference against Pre-Intervention Air Permeability ($m^3m^{-2}h^{-1}$@50pa)	Post-Intervention Air change rate ($hour^{-1}$)	+/- Difference against Pre-Intervention Air change rate ($hour^{-1}$)
Pendleton	6.5	-2.9	0.35	-0.15
Windermere	5.9	-5.2	0.45	-0.40
Southeast Macclesfield	4.7	-4.6	0.13	-0.16

Here it is demonstrated that the interventions have had a significant and measurable difference on reducing the air permeability of the substations and in turn the estimated air change rate under normal conditions. This is favourable for the reduction of energy demand of heating and dehumidification systems as the quantity of infiltration leading to heat loss and moisture entering the building is reduced.

Through the enhanced U-values, air permeability measurements and corresponding air change rates the modelled demand of the heating and dehumidification systems was revised to reflect the post intervention building characteristics. These values are presented in Table 17 and compared against the pre-intervention values through the percentage difference. For the purposes of this comparison the pre-intervention models were updated with the post-intervention weather data. Using the same data set for both models allowed for a direct comparison and detaches the effect of weather when comparing the two heating demands.

Table 17: Post-Intervention Modelled Environmental Control Demands

Substation	**Post-Int. Modelled Annual Heating Demand (kWH)**	**+/- % against Pre-Int. Modelled Heating Demand***	**Post-Int. Modelled Annual Dehumidification Demand (kWH)**	**+/- % against Pre-Int. Modelled Dehumidification Demand**
Pendleton	732	-30%	5,929	-31%
Windermere	1,050	-28%	6,112	-46%
Southeast Macclesfield	1,143	-37%	5,304	-50%
*Comparison is made against pre-int. building characteristics using post-intervention weather data. Figures for both sets of weather data can be viewed in the thesis appendix.				

This shows that the modelled energy demand of heating and dehumidification in all three sites is significantly reduced as a result of the enhanced building characteristics. It should be noted that the models used to calculate these figures are based on maintaining the precise environmental parameters of 50% RH and 10°C. As the pre-intervention monitoring results show these conditions have not been consistently upheld, it is expected that the difference presented in modelled energy demand will differ from what is recorded in measured energy demand.

To determine the difference in measured heating demand of the three substations between pre and post-intervention periods, the post-intervention heating demand is displayed in Figure 46. This is compared against the pre-intervention heating demand which has been adjusted to correspond with the quantity of recorded heating degree days within the post-intervention heating period as to allow a direct comparison. This is also compared to the post-intervention modelled heating demand.

Figure 46: Post-Intervention Heating Demand Comparison

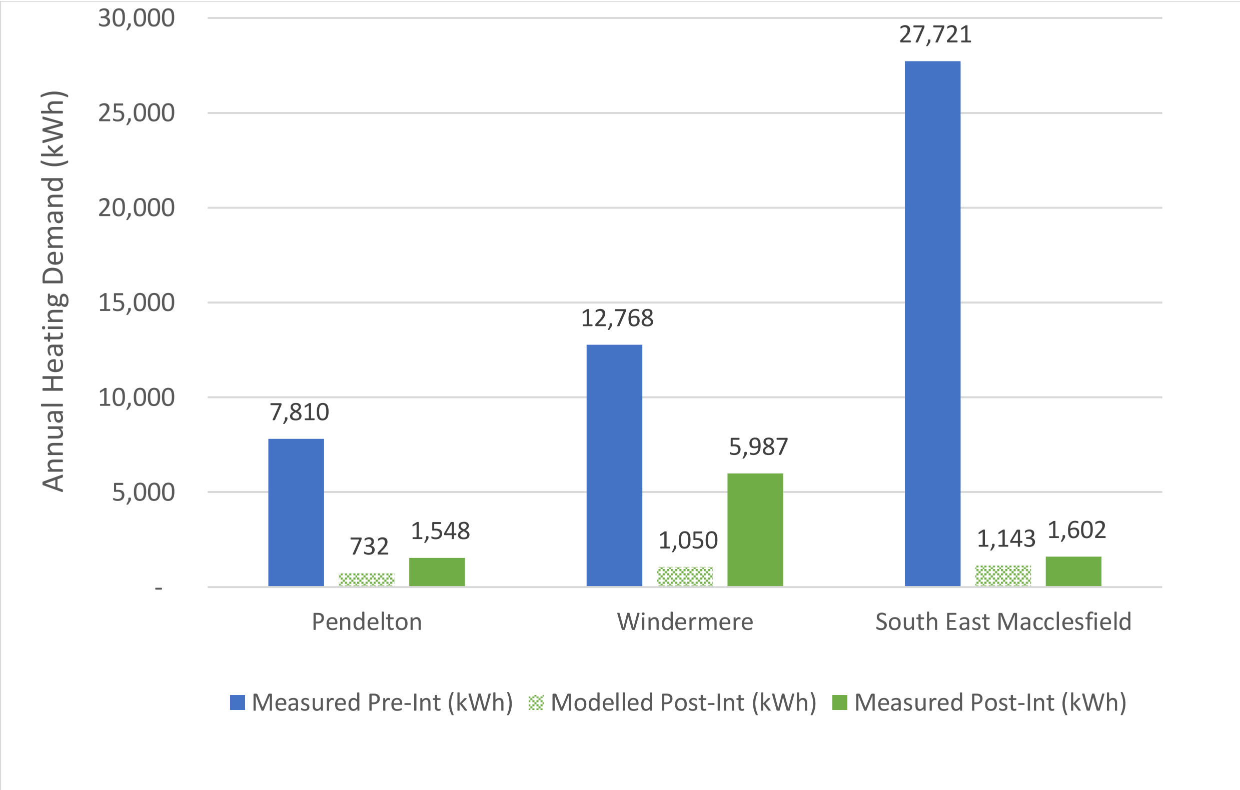


Figure 46 highlights that considerable reductions have been made against the pre-intervention heating demand in all three substations. Most significant is that of Southeast Macclesfield where the post-intervention demand is 5.6% of that recorded in the pre-intervention period. This indicates that the interventions applied have been effective in reducing the energy demand of environmental control systems. Notably, there are clear deltas between the measured and modelled post-intervention heating demand demonstrating a performance gap with the modelled demand being consistently lower than that of the measured demand. The cause of this performance gap including any possible discrepancies in the models are to be explored thoroughly in the discussion chapter.

The post-intervention dehumidification demand for the three substations is shown in Figure 47. This is shown alongside that measured in the pre-intervention period and modelled demand. The demand associated with the control room within the Pendleton substation is shown in isolation in addition to the whole site. This is to allow for analysis of the desiccant dehumidification system that was installed only within the control room.

Figure 47: Post-Intervention Dehumidification Demand Comparison

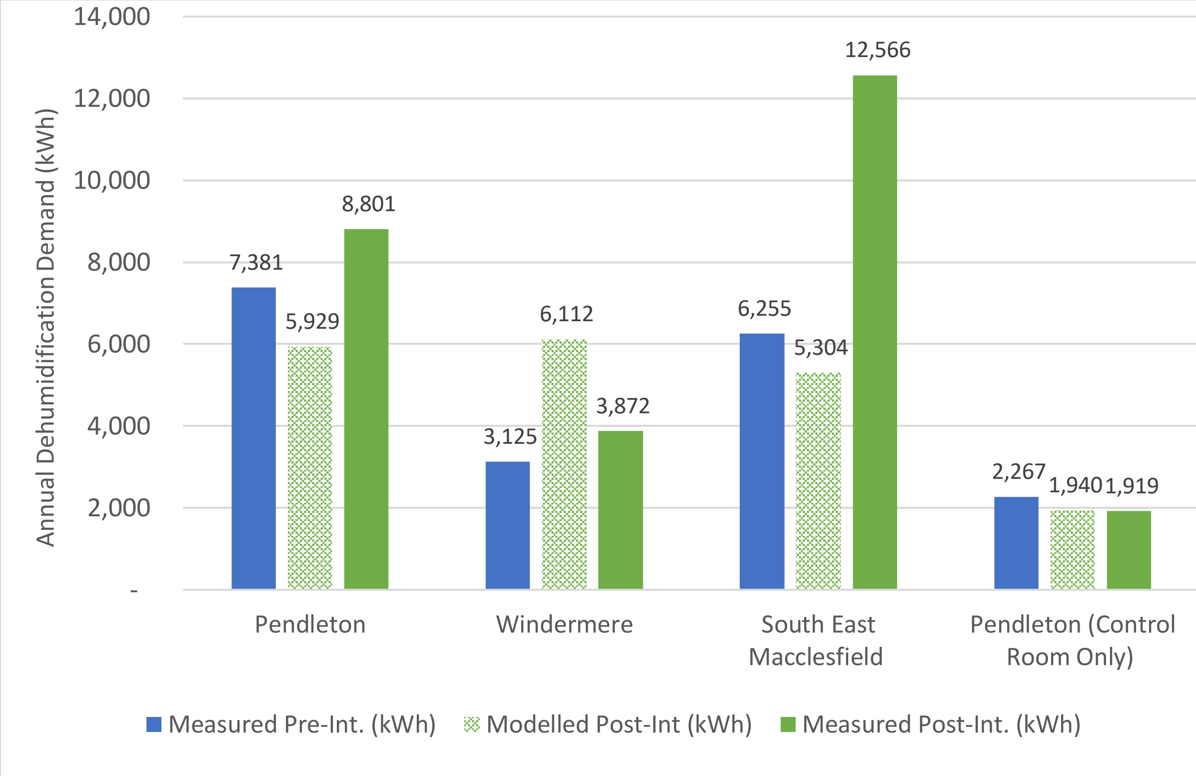


Figure 47 shows that the dehumidification demand has increased across all three sites, this is as expected, due to the under-conditioning of humidity levels that were observed in the pre-intervention period. However, a performance gap is still present between post-intervention modelled and measured dehumidification demand with significant differences identified. The possible reasons for this difference and its impacts are to be detailed within the discussion chapter.

To form a holistic view of the impact the interventions have had on the efficiency of the environmental control systems, it is necessary to view the environmental conditions occurring in the post-intervention period compared to those recorded in the pre-intervention period and the minimum required parameters. The changes viewed should be considered alongside those observed in the energy demand of the heating and dehumidification systems. Figure 48 to Figure 54 inclusive show the average volume-weighted RH and temperature levels recorded in the operational areas of the three case study sites for both pre and post-intervention periods. The standard deviations for each month are shown in the form of error bars. Whilst this data is presented graphically to enable comparisons between pre and post-intervention periods, it is included in a tabulated format in the thesis appendix. Figure 48 and Figure 49 show the environmental conditions recorded within the Pendleton site.

Figure 48: Pendleton Pre and Post-Intervention RH Levels

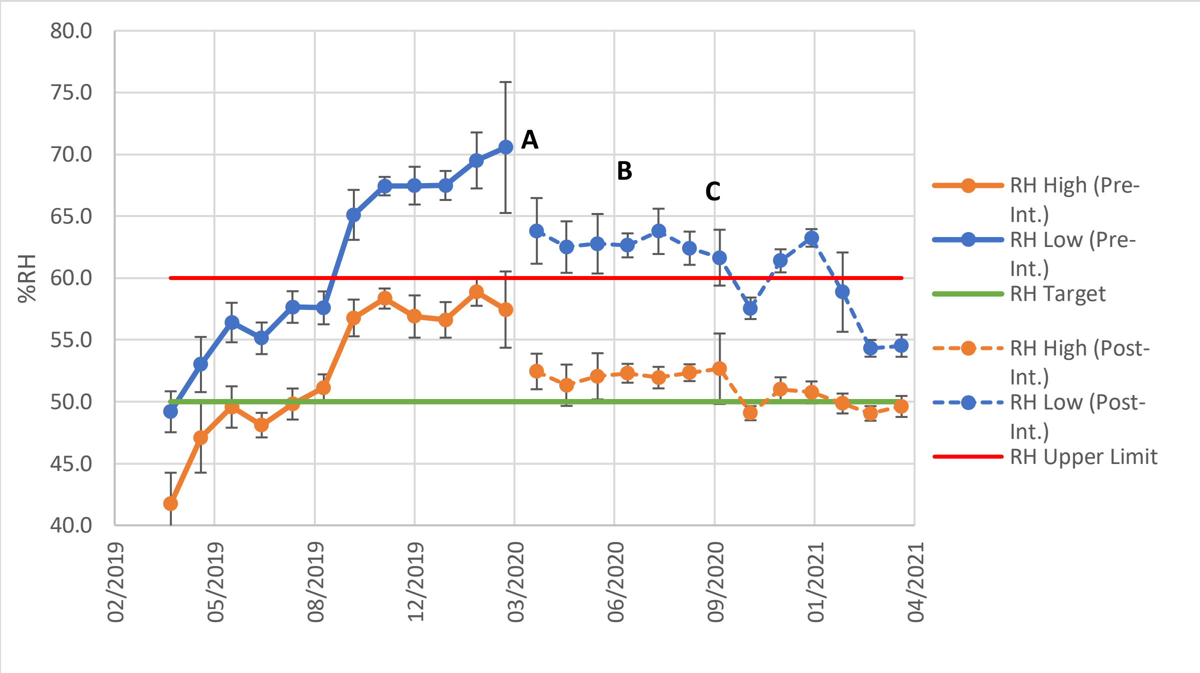
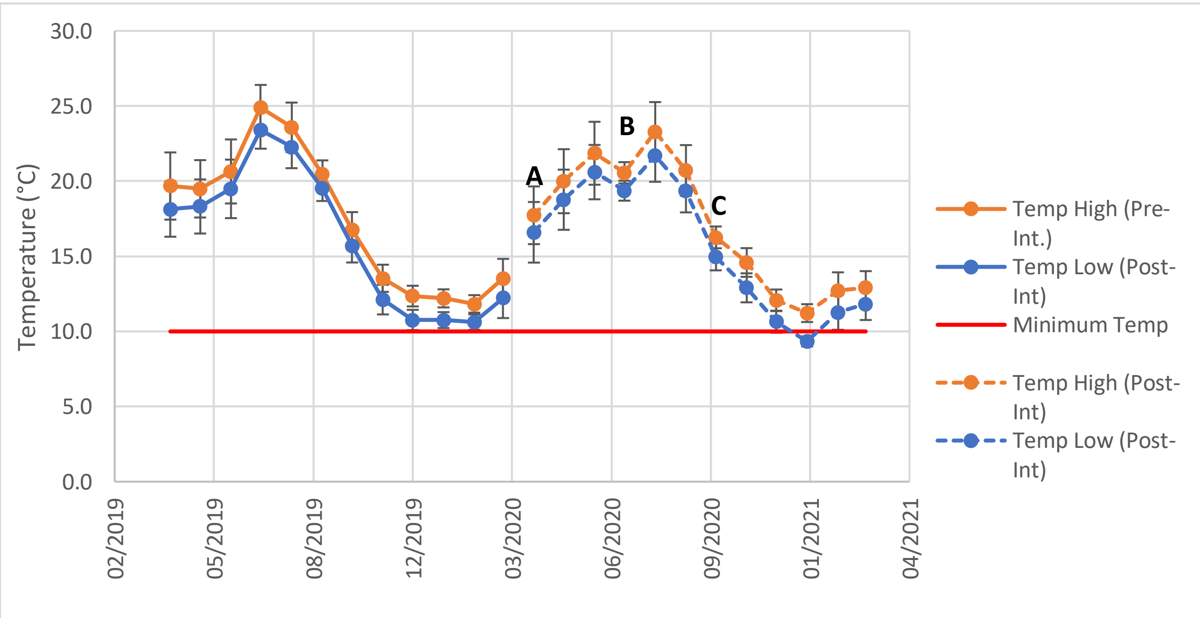


Figure 49: Pendleton Pre and Post-Intervention Temperature Levels



The annotations shown on the graphs depict the point at which interventions were delivered within the substation these are as follows:

A (March 2020): Multiple remedial works, trench splitter system, internal door repair, insulated roof.

B (June 2020): Heating Controls, Desiccant Dehumidification System (Control Room Only)

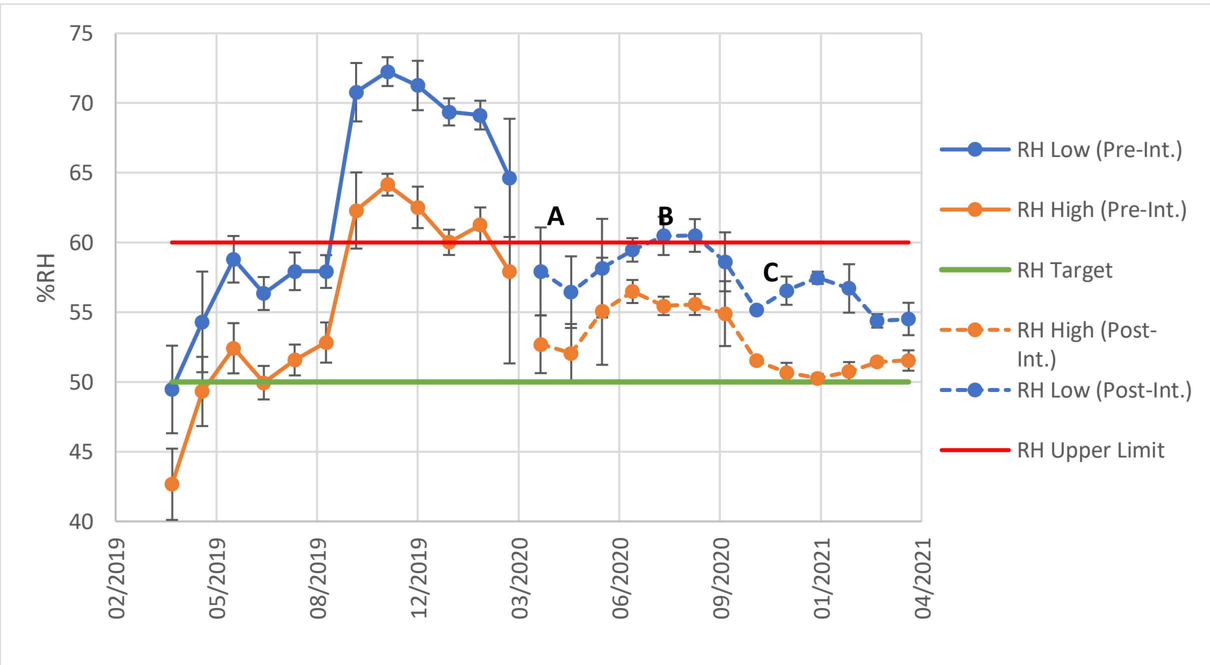
C (October 2020): Dehumidification Controls

Figure 48 shows that the RH levels recorded during the post-intervention period there is an overall trend towards less stratification and more compliant RH levels, indicating that the interventions have improved the conditions against the required parameters. However, the RH at low level is positioned mostly above the upper limit of 60%, albeit with much reduced standard deviation from point C onwards at which the humidity controls were enhanced. This is possibly due to the placement of equipment in the substation in front of the RH sensors between November 2020 and February 2021 that restricted the flow of conditioned air to the sensors, after this period the low level RH dropped below 50%RH as expected.

The temperature levels visible in Figure 49 show that no monthly averages breaching the 10 °C minimum with the exception of January 2021 at low level. The measured temperatures are affected by the ambient conditions external to the substation that are not presented in this graph. It is possible this breach of the minimum temperature is a result of more extreme winter conditions compared to that recorded in the pre-intervention period.

One of the interventions within the Pendleton substation, installation of desiccant dehumidification system, was localised within the control room only and not throughout the entirety of the operational spaces as others. To analyse the impact of this intervention accordingly, the average RH levels recorded within the control room are displayed in Figure 50.

Figure 50: Pendleton Control Room Pre and Post-Intervention RH Levels



Similarly, to the entirety of the substations conditioned areas, the RH levels within the control room become noticeably more complaint with the application of interventions. At point B where the desiccant dehumidification system is installed no further enhancement of the environmental conditions is noticeable with the more significant improvement already occurred at point A. However, overtime the conditions tend towards more complaint RH levels.

The monthly average RH and temperature levels recorded at Windermere are shown in Figure 51 and Figure 52.

Figure 51: Windermere Pre and Post-Intervention RH Levels

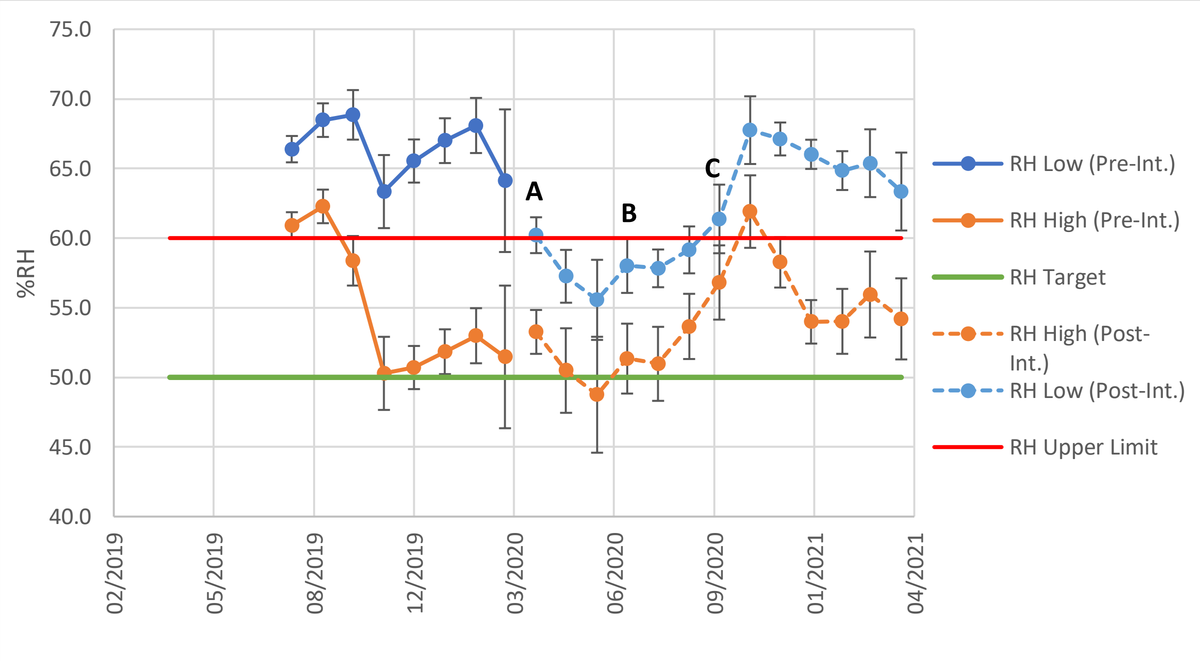
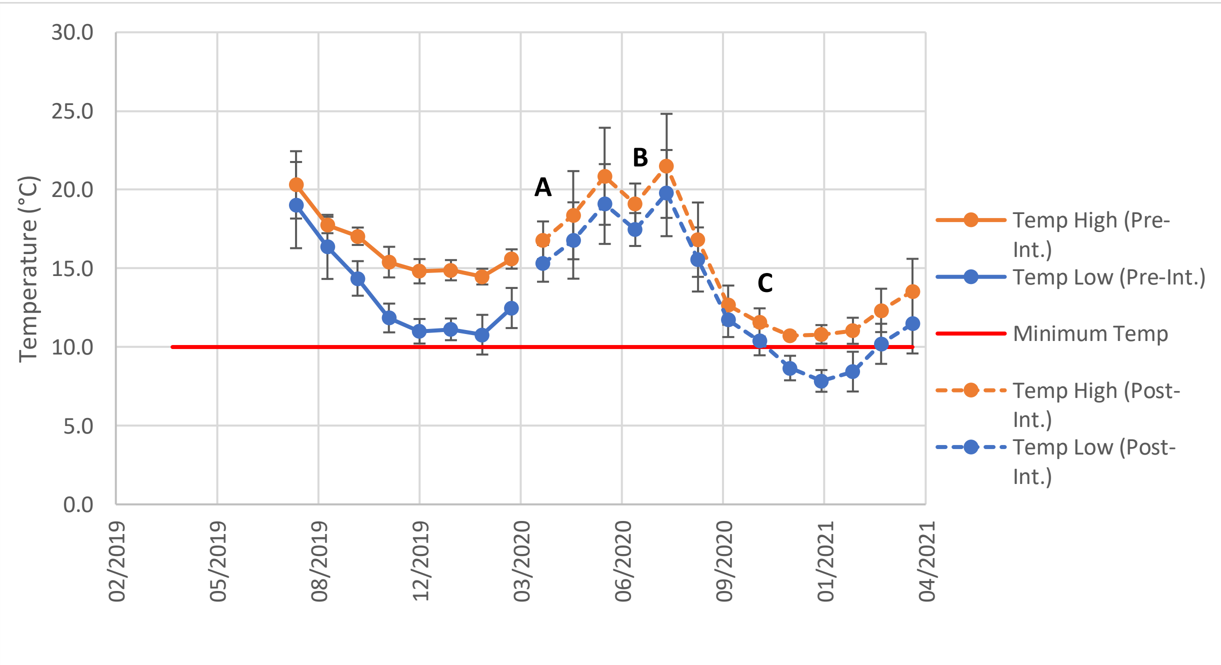


Figure 52: Windermere Pre and Post-Intervention Temperature Levels



The annotations on Figure 51 and Figure 52 identify when the interventions were applied in the Windermere substation, these are as follows:

A (March 2020): Multiple remedial works, blanking of vents, insulated partition

B (June 2020): Heating controls

C (October 2020): Dehumidification Controls

Within Figure 51 the RH levels observed within the Windermere site are more complaint from point A to C with less stratification occurring in comparison to the pre-intervention results, this is a result of the reduced infiltration occurring through interventions, although could also be attributed to higher ambient temperatures increasing the effectiveness of the dehumidification systems. However, from point C the humidity levels rise becoming less compliant. Interestingly it as at point C that the dehumidification controls were enhanced. As this occurred in October it is likely that the dehumidification systems are being negatively affected by the seasonal lower air temperature. The profile illustrated in Figure 52 shows that over conditioning of temperature with measurements as high as 15°C throughout the winter months is not occurring. However, the minimum temp of 10°C appears to be breached at low level on multiple occasions throughout the winter months of the post-intervention period possibly contributing to the under conditioning of RH.

Figure 53 and Figure 54 show the monthly average RH levels and temperatures recorded within the Southeast Macclesfield substation.

Figure 53: Southeast Macclesfield Pre and Post-Intervention RH Levels

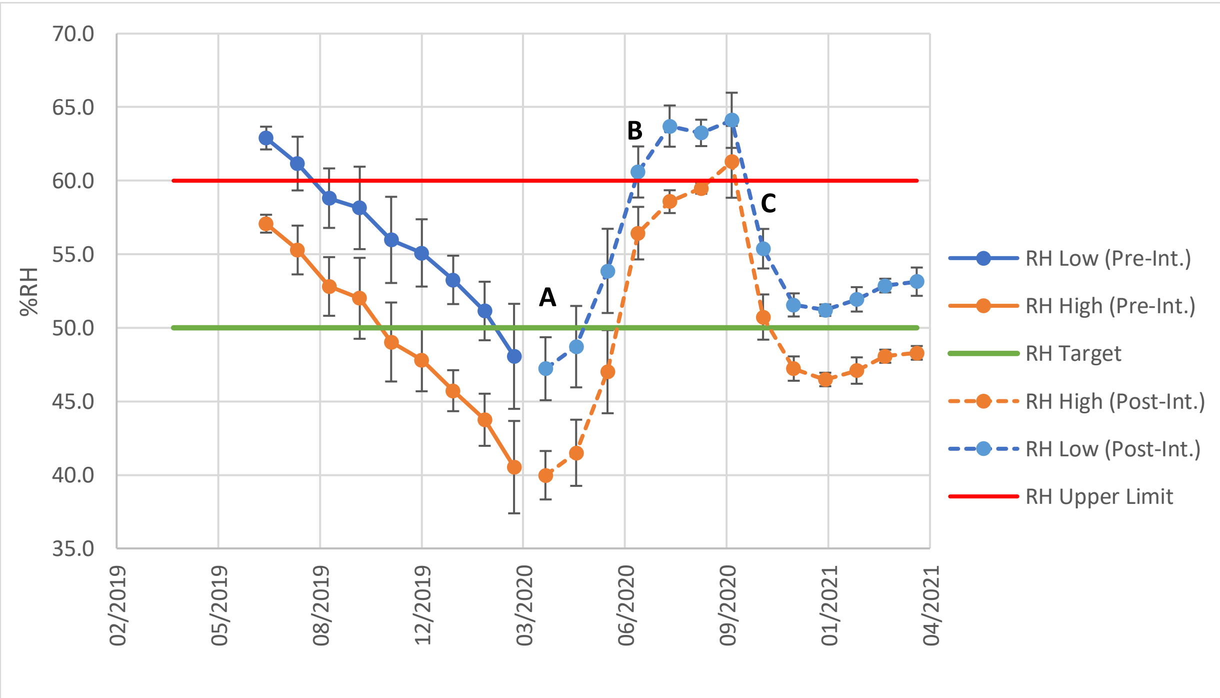
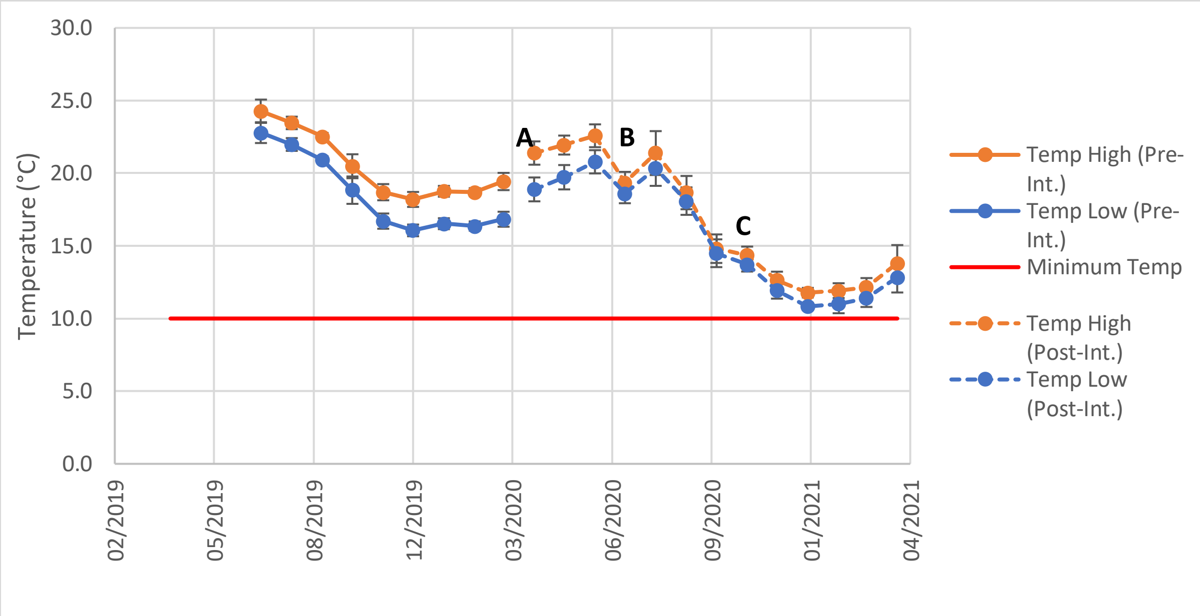


Figure 54: Southeast Macclesfield Pre and Post-Intervention Temperature Levels



The annotations shown on Figure 53 and Figure 54indicate the points at which interventions were installed, these are:

A (March 2020): Multiple remedial works, blanking of vents

B (June 2020): Heating controls

C (October 2020): Dehumidification Controls

Interestingly the pre-intervention humidity levels observed at Southeast Macclesfield are largely compliant albeit with large deviations. At point A they begin to rise away from the required parameters and then at point C steeply tend towards compliance. Throughout the pre-intervention period overheating was recorded with temperatures as high as 18°C in the winter period and a heating demand of over 20 times of what is estimated through modelling, this could, in this instance inadvertently be lowering RH levels within the substation. The monthly and seasonal variation along with considerable standard deviations within each month, align with this hypothesis. From point C onwards the humidity levels are both compliant and stable with much narrower bands of standard deviation. This suggests that from this point the humidity levels are being controlled as intended through the dehumidification systems as opposed to through the heating systems during the pre-intervention period.

The temperature profile illustrated in Figure 54 shows that the over-conditioning observed in the pre-intervention period is no longer occurring in the post-intervention period. Furthermore, the minimum temperature is not breached indicating that temperature is now effectively being conditioned.

Payback calculations for all three case study sites are shown in Table 18. This considers the cost of intervention delivery against the *measured difference* in energy consumption from increased or reduced energy demand for heating and dehumidification systems as a consequence of the interventions installed. It is noted that the costs of the insulated roof at Pendleton is excluded from this analysis as this was primarily required as a maintenance activity and the budget was not provided through this research project, a schedule of the costs associated with each intervention are presented in Table 19.

Table 18: Payback calculations for interventions

Substation	Annual Energy Savings Heating and Dehumidification (kWh)	Annual Energy Cost Savings	Cost of Interventions	Payback Period (Years)
Pendleton	4,842	£755	£13,260	17.6
Windermere	6,034	£941	£4,220	4.5
Southeast Macclesfield	19,807	£3,090	£5,674	1.8

Table 19: Schedule of Intervention Costs

Pendleton		
Ref	**Intervention**	**Cost (% of total)**
1	Insulated roof	£0 - cost excluded
2	Heating and Dehumidification Controls	£1,441 (11%)
3	Trench Splitter System, Multiple remedial works to reduce air leakage, Internal door repair	£5,742 (43%)
4	Desiccant Dehumidification system	£6,077 (46%)
	Total	**£13,260**
Windermere		
1	Heating and Dehumidification Controls	£1,670 (40%)
2	Multiple remedial works to reduce air leakage, Blanking of Vents, Partition Wall	£2,550 (60%)
	Total	**£4,220**
Southeast Macclesfield		
1	Heating and Dehumidification Controls	£1,974 (35%)
2	Multiple remedial works to reduce air leakage, Blanking of Vents	£3,700 (65%)
	Total	**£5,674**

Table 18 shows the interventions applied across all three sites result in energy savings through overall reduced demand of environmental control systems. The associated cost of energy creates a positive payback period for all three sites. Notably, Pendleton has a much longer payback period in comparison to Windermere and Southeast Macclesfield. This is due to the high install costs associated with the interventions installed. The installation of the desiccant dehumidification system and the total of the non-electrical works (including the trench splitter system) which were installed only at Pendleton were the two most expensive costs, as shown in Table 19. Windermere and Southeast Macclesfield have very favourable payback periods of under five years demonstrating that the installation of interventions has the additional benefit of reducing costs in addition to providing a more compliant internal substation environment. It is noted Southeast Macclesfield, with the shortest payback period of 1.8 years, had the fewest interventions installed and only form the highest priority intervention areas of "enhanced control systems" and "reduction of air and moisture infiltration", demonstrating the cost effectiveness of these intervention areas. As the payback calculations are based on *measured energy reduction* they are not impacted by any discrepancies between measured and modelled parameters that have been discussed in the results.

The post-intervention results presented have drawn attention to changing environmental conditions as a result of intervention. In most cases these have been more compliant against the targets of 10°C and 50% RH and as such reducing the risk of damage to distribution equipment throughout the substations. There are significant differences recorded between the modelled and measured energy performance of the heating and dehumidification systems, the causes and impact of this performance gap are to be explored further throughout the discussion chapter of this thesis.

5.6 Summary

This chapter has presented the results obtained by carrying out the method detailed in Chapter 4.

Through building characterisation, the features of the substations that are relevant to environmental control are detailed. These include metrics relating to the building fabric performance such as U-values and air permeability measurements. Such metrics along with the geometry of the building are used to compute the estimated heating and dehumidification demand required to maintain the parameters of 10 °C and 50%RH in the three case study sites. This provides a baseline for which to compare measured energy demands.

The pre-intervention monitoring results show several discrepancies in the environmental conditions recorded within the case study sites. These include over conditioning of temperature and under conditioning of humidity levels, with significant stratification occurring. The measured energy demands of the heating and dehumidification systems compared against the pre-intervention modelled demands reflect the over and under-conditioning with significant differences between the modelled and observed energy consumption.

The building characterisation and pre-intervention results were utilised to derive interventions to improve the efficiency of environmental control within the case study sites for the purposes of decarbonisation. These were based on the outline principles identified in the methodology chapter. These principles and the discrete interventions applied are listed as follows:

- **Enhanced Control Systems**
    - Replacement tamperproof thermostats.
    - Twin high and low control humidistats.
- **Reduction of air and moisture infiltration**
    - Remedial works to address passages of leakage.
    - Blanking of existing air vents.
- **Segregation of conditioned and non-conditioned spaces**
    - Insulated partition wall.
    - Internal door repair.
    - Splitting of trenches.
- **Lowering building fabric thermal conductivity**
    - Insulated roof
- **Alternative Dehumidification Systems**
    - Desiccant Dehumidification system

Post-intervention monitoring shows that the environmental conditions within the three sites are all improved against the target parameters; however, some stratification is still recorded, and breaches of the minimum temperature recorded in Pendleton and Windermere. The post-intervention heating demands have decreased significantly against the pre-intervention demand, however significant performance gaps are present when comparing the measured heating demand to modelled heating demand. In respect of dehumidification demand, the post-intervention demands have increased against the pre-intervention period. This is expected due to the under-conditioning observed in the pre-intervention periods. However, and similarly to heating demand, there are substantial differences in the observed demand and what has been calculated through modelling. These differences between modelled and measured consumption, along with the reasons and impacts are to be explored throughout the discussion chapter.

A cost benefit analysis shows that in all three substations, the total energy consumption of environmental conditions has dropped in the post-intervention period. The associated reduction in energy costs against the cost of installation of the interventions relates in a positive payback period for the three sites. This demonstrates that the interventions have a strong commercial benefit along with decarbonisation potential and improving the environmental conditions within the substations, preventing damage to the electrical distribution equipment.

Chapter 6 Discussion

6.1 Introduction

This chapter will review the findings and resultant themes that have emerged from the data collected through this study and the results presented within Chapter 5. From the three case study sites under investigation, trends are highlighted that will impact on, or be transferable to the decarbonisation of the wider substation estate. Key to this will not only be the interventions and their impact on substation operation, but also the condition of the assets as they are found prior to retrofit. For the purposes of this structuring this chapter the discussion points can be categorised into the following five themes:

- **Suitability of assets for efficient environmental control** – How does the form and condition of buildings of the three case study substations affect the efficiency of environmental control systems and why is this?
- **Pre-intervention environmental conditions** – How do the environmental conditions occurring within the case study substations prior to intervention compare against targets?
- **Priority and Selection of Interventions –** How do the principles of intervention derived for this study compare against approaches for more conventional building types?
- **Impact of Interventions –** What has the impact of the interventions been on the environmental control within the three case study substations?
- **Review of Method –** What are the limitations of the method applied and how could it be improved?

Investigating these areas will enable recommendations to be made for the decarbonisation of substations, meeting research objective O5 as stated in the Introduction.

6.2 Suitability of Assets for Efficient Environmental Control

The building characteristics of the three case study substations prior to any intervention do not reflect that of an efficient building. So much so that, rather than contributing to the environmental control systems within the substations, they can be viewed as impeding their effectiveness when compared against modern building standards. There are two main contributing factors to this; the initial design is not conducive to efficient environmental control and the condition of the assets is further decreasing their performance in respect of environmental control.

6.2.1 Original Design and Construction

The three substation buildings were constructed in the 1960’s. At this time the requirement for energy efficient buildings was not commonplace and the results of the building characterisation process show that this was not considered in their design. The construction of the building fabric has resulted in U-Values that would be non-complaint to current building regulation (Jones et al., 2013). Moreover, the measured U-Values of external walls and roofs are comparable against the first edition of building regulations introduced in 1965: 1.4 W/m^2K against 1.7 W/m^2K in walls and 1.2 W/m^2K against 1.4 W/m^2K in roofs (Jones et al., 2013).

Interestingly, the pre-intervention air permeability rates of the three substations are comparable to the current regulated target of 10 $m^3m^{-2}h^{-1}$@50pa ranging from 9.1 -11.1 $m^3m^{-2}h^{-1}$@50pa. This could be caused by the construction of substations being relatively simple and making them relatively air-tight even if they were not explicitly designed to be. The buildings consisting of solid concrete floors and roofs, and without features such as loft hatches, windows and fireplaces means some common airtightness issues are not applicable (Johnston et al., 2011). However, whilst the air permeability is comparable to the current regulatory target, this is still not what would be expected of a modern building where environmental control is required. Best practice for building functions such as factories or offices is considered to be between 2 and 3 $m^3m^{-2}h^{-1}$@50pa respectively (ATTMA, 2010). An air permeability target would not have formed part of the original design criteria as this was not introduced to building regulation till 2006 (Love et al., 2017).

Comparing the performance of the building fabric against modern standards makes for harsh assessments. However, it is clear that for buildings that are temperature and humidity controlled, the fabric is doing little to aid the efficiency of environmental control. In addition to the buildings being reflective of construction practices of the period they were built; they were also not originally designed for environmental control. The requirement for substation environmental control as it is described within this thesis did not exist in the original design for the three substation buildings. It is not known when exactly this requirement was introduced throughout ENWL, however it is noted in the 2007 design code of practice (Electricity North West Limited, 2007). As such, specified building performance criteria would not be necessary or advantageous for those designing and constructing the substations in the 1960's. This lack of designing for environmental control is also evident in the presence of air vents within two of the substations that are increasing air permeability rates and increasing energy demand.

6.2.2 Condition and Maintenance

Further to the design and original construction of the substation buildings, their operation and maintenance regime has allowed for multiple instances of defects negatively impacting environmental control to occur. As viewed in Table 9, these defects will be increasing heating and dehumidification demand within the substations. These defects are likely unavoidable in the 60 years of substation operation however, there are several possible reasons as to why they have not been resolved. This could be a result of budget and resource constraints whereby maintenance of electrical equipment is prioritised and that of the building fabric is not undertaken unless it is necessary e.g. an immediate safety or security risk. Additionally, a lack of awareness of the impact building fabric can have on the efficiency and effectiveness of environmental control could be a barrier to these items being reported to maintenance teams.

6.3 Pre-Intervention Environmental Conditions

Conducting pre-intervention monitoring of environmental conditions in the substations has provided a calibration check on the existing systems and their controls demonstrating that *none are consistently being effectively conditioned.* Critically, all three buildings have instances of monthly average RH levels above the upper limit of 60% recorded, as shown in Table 11. This is placing the equipment within at an increased risk of serious damage through partial discharge occurring (Byrne, 2014).

That these conditions were recorded repeatedly at all three substations indicates that the operator is not aware that they are occurring and that methods of checking or monitoring environmental conditions are not sufficient in detecting this non-compliance. Whilst there are alarms installed to sound at 70% RH, this threshold was breached multiple times in the substations and there was no apparent reaction from the operator. This demonstrates the value of the remote monitoring conducted, detecting these non-compliant conditions that would have otherwise gone unresolved. This can be likened to "testing by measurement"(CIBSE, 2019a) where temperature is proactively monitored to ensure thermal comfort in a building.

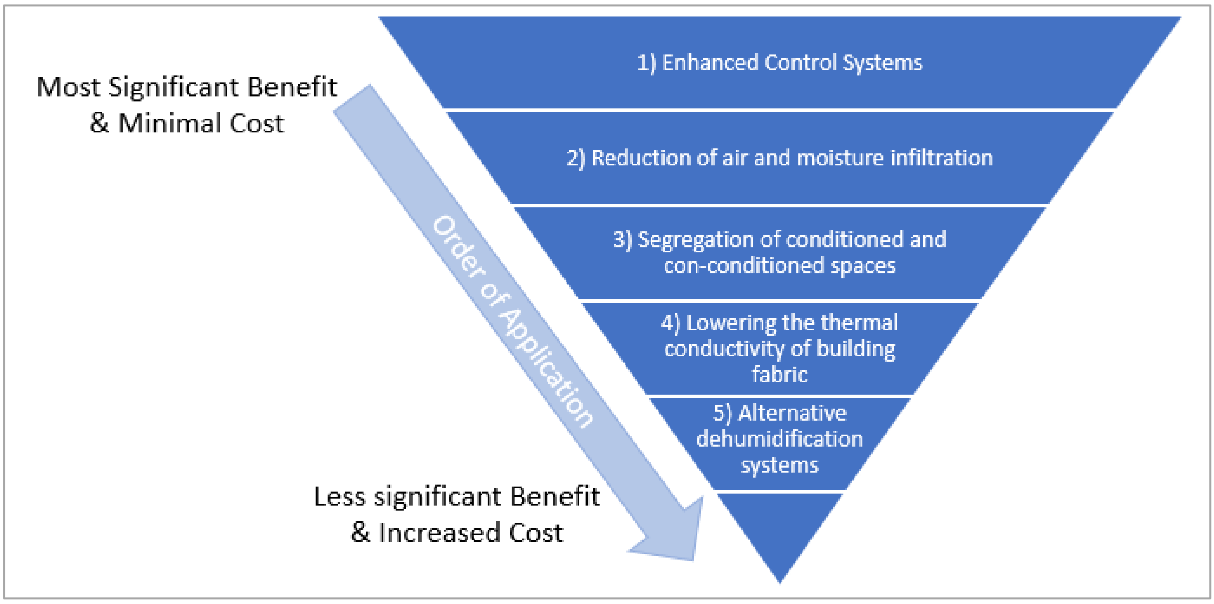
The cause of this under conditioning is believed to be related to the control systems, thermostats, and humidistats. It is thought that *sensor drift* (Sawhney, 1985) is occurring in the controls, such that they are unable to accurately maintain a specified temperature or RH level. In addition to under conditioning of RH, this is also causing over conditioning of temperature with monthly average temperatures above 18°C recorded in the winter months. This has the undesirable effect of significantly increasing heating demand, as demonstrated in the large performance gap between recorded demand and the calculated energy demand expected to maintain the minimum temperatures shown in Table 12. This unpredictable control of temperature is a contributing factor to some of seasonal variation seen in RH levels. Heating space inside the substation will indirectly lower the RH as the air can hold a larger mass of moisture before saturation. In some cases, this has temporarily provided compliant levels of RH but is not a suitable or efficient way of controlling RH levels. Alongside, any interventions to decarbonise the substations undertaking active monitoring of temperature and RH should be recommended to operators to identify substations that are either under conditioned and therefore at high risk or over-conditioned and consuming excessive energy.

As the control systems are not capable of effectively maintaining the required levels of RH and temperature and causing significant inefficiencies, enhancing them was a priority in the selection of interventions.

6.4 Priority and Selection of Interventions

The hierarchical principles of intervention derived in section 4.8.4 are visualised in Figure 55. "Enhanced Control Systems" was positioned as a priority to ensure that the required RH and temperature parameters are maintained in the substations. The non-compliant environmental conditions observed in the pre-intervention period validate the decision to prioritise controls. The enhancements to control systems are shown to reduce or eliminate the non-compliant conditions and result in significant reductions in energy demand.

Figure 55: Hierarchical Principles of Intervention



This priority in the interventions to substations does not align with common practice in retrofit approaches for housing where enhancing the building fabric is a priority. In this *fabric first* approach addressing the insulating properties of external elements (roofs, walls etc) is a priority as this reduces the initial energy demand that is required to heat the house, regardless of heat source or controls (Jones et al., 2013).

Applying such an approach to the case study substations would of course improve building fabric performance and reduce heating demand. However, if sensor drift has occurred in the thermostats or humidistats the benefit of the intervention will be undermined by non-compliant conditions or wasteful over conditioning. On this justification significant improvements to building fabric through intervention principals “Segregation of conditioned and con-conditioned spaces” and “Lowering the thermal conductivity of building fabric” were not prioritised over enhancements to the controls.

Whilst it is possible that sensor drift occurs in thermostats in domestic properties, it is expected that occupants would detect this promptly and take actions to resolve. Comparatively, as substations are not regularly occupied the effects of sensor drift could go on for years without detection, further justifying the *controls first* approach to interventions.

“Reduction of air and moisture infiltration” is listed second in the hierarchy of interventions. This item somewhat mirrors the philosophy of fabric first where continuity of air tightness is required (Hurst & O’Donovan, 2019). In domestic properties the background air change rate, a result of air tightness, contributes to the heating demand, as shown through Equation 5. A difference between substations and housing is that the air change rate is also directly proportional to the dehumidification demand, as demonstrated in Equation 15. Dehumidification is required all year round as ambient RH levels recorded across the three sites were between 76 – 82%RH averaged over the year. Hence reducing the ventilation rate will have a considerable impact on the overall energy demand.

“Alternative dehumidification systems” was the final item of the hierarchy and only applied in one instance, through a desiccant dehumidification system installed in the control room of Pendleton. The results associated with this intervention show improvements to the efficiency of environmental control have been achieved. Not only are compliant RH levels observed within the respective spaces, the post-intervention energy demand is over 10% less than the pre-intervention demand. This is despite significant under conditioning occurring in the pre-intervention period. A further benefit of the desiccant system, although it was not utilised at the time of installation, is that they can operate below 0°C, meaning the requirement for background heating could be significantly reduced or possibly completely removed. This would result in further reductions to the overall environmental control systems’ energy demand and could be likened to the fabric first approach of reducing the initial energy demand of the building. If the relevant stakeholders in ENWL were to approve application of this technology throughout an entire substation cohort, it may justify a higher priority position in the hierarchy of intervention principles. This bespoke approach to selecting energy efficiency interventions could be transferable to other non-domestic retrofits for buildings that have similar operational characteristics as electrical substations such as minimal occupancy and/or environmental conditioning requirements. This could include buildings that form part of other utility networks such as gas substations and water pumping stations or storage facilities

6.5 Impact of Interventions

The interventions applied have had clear impacts on the environmental control systems of the three substations, largely increasing their overall efficiency and resulting in decarbonisation. This can be viewed by the environmental conditions and corresponding energy consumption recorded in the post-intervention period.

6.5.1 Environmental Conditions

The monthly average RH levels in the Southeast Macclesfield and Pendleton substations are dramatically improved against those recorded in the pre-intervention period. Both high and low levels are below the upper limit of 60%RH, eliminating the non-complaint RH levels observed in the pre-intervention period. This shows that the primary function of the environmental control, maintaining specified humidity levels is now being achieved. As such, the risk of damage to the electrical distribution equipment through moisture and the significant impact that this can have, is reduced (Byrne, 2014; Electricity North West Limited, 2007). The RH levels in Windermere have not improved as considerably. Possible reasoning for this is to be considered throughout this discussion.

The over conditioning of temperature recorded in the pre-intervention period is shown to be eliminated in all three substations. However, stratification present in Windermere shows that the temperature at low level breaches in minimum of 10°C, possibly contributing to the non-compliant RH levels in this substation. This removal of overheating has contributed positively to the overall energy consumption of the environmental control systems.

6.5.2 Energy Consumption and Payback Periods

Large reductions in the heating demand of the case study substations have been achieved due to the interventions applied. For the three buildings the post-intervention heating demand is between 2 – 17 times smaller than that recorded in the pre-intervention period. As the minimum temperature requirements have been upheld in Pendleton and Southeast Macclesfield this demonstrates an increase in efficiency for the heating systems by reduction of waste (Patterson, 1996).

An increase in the dehumidification demand is recorded in the three substations as shown in Figure 47. Whilst this increase is not desirable for the overall decarbonisation of substations it is necessary for effectively maintaining the required RH levels.

When considering the combined heating and dehumidification demands, a net reduction has been achieved across the three substations. This has resulted in the payback periods shown in Table 18. For Windermere and Southeast Macclesfield the payback period is less than five years for all of the interventions applied. This demonstrates that in these instances the application of interventions is highly economic. The interventions applied at Pendleton result in a longer payback period of over 17 years. This is a result of more complex and costly interventions applied such as the installation of a desiccant dehumidification system and segregation of trenches. The cost of the roof works at Pendleton was excluded from this analysis as this was primarily required as a maintenance activity that acted as a *Trigger Event* (Fawcett, 2014) for the insulation enhancements that would otherwise not occurred. It is noted that Southeast Macclesfield has the most significant energy reduction and shortest payback period. This is achieved with the fewest interventions applied with only the priority items of enhanced control systems and reduction of air and moisture ingress. This further validates positioning of these items as first and second on the hierarchical principles of intervention derived through this research in section 4.8.4.

Such encouraging payback periods, along with the improved compliance of environmental conditions, demonstrates that the interventions applied are significantly beneficial and should be recommended for decarbonisation to the operators of substations (DNO's) such as ENWL. Introducing these measures across the remainder of the substation estate of over 500 assets would result in realising the same benefits observed in the case study substations on a much larger scale. The benefits of such a policy decision to a DNO would include: a network more resilient to the impact of moisture resulting in increased reliability to customers and a substantial reduction in energy demand along with the associated cost and carbon emissions. From the perspective of this research, there are no compromises or drawbacks to introducing such a policy other that the initial capital investment that would be required to complete the works. The scale of such works and budget should be derived against the principles of intervention with *"Enhanced Control Systems"* being the absolute priority and then further areas of intervention included if agreeable against budget.

6.6 Review of Method

Whilst the method applied in this research has successfully identified means of decarbonising substations through energy efficiency interventions. There are several areas for critique where the method could have been improved to enhance the findings and results. These include the notable difference between modelled and measured energy demand, partial success of interventions at Windermere substation and limitations of the economic analysis.

For both heating and dehumidification demand there is a significant difference between the recorded and modelled energy demands in both pre and post intervention phases. There are multiple factors that could be contributing to this *performance gap.* The modelled heating demand was computed through thermal modelling; computational simulations of building energy were conducted based on selected building characteristics reflective of the case study sites. In the respective models there were several variables that needed to be estimated. These included occupancy schedules and internal gains, these were estimated through analysis of substation sign-in books and empirical relationships respectively. The method applied did not allow for verification of these variables through measurement. The challenge of accurately reflecting these variables in models is established as a contributor to performance gap (De Wilde, 2014; Elnabawi & Hamza, 2019). To enhance the method, the occupancy of the substations could have been measured by widening the scope of remote monitoring systems to include occupancy sensors that would record when the substation was accessed. This data could then be used to produce an occupancy schedule for the thermal models. Measuring internal heat gains occurring is more challenging, although manufactures information for switchgear may be available in more recently constructed substations.

The modelled dehumidification demand is calculated analytically through applying Equation 15 to the moisture extraction rate of dehumidification systems. This model is less complex than the thermal modelling, although, similarly, there are variables that are not explicitly measured. The background air change rate was estimated through the results of air permeability testing at 50pa pressure differential. Alternative methods such as pulse testing measure air change rate at pressures more representative of natural conditions (X. Zheng et al., 2019) removing the need to estimate this from measurements at high pressure. Using this system would have been preferable but procuring the equipment and services was not feasible for this study. Furthermore, the moisture extraction rate of the dehumidification systems was estimated to take account of the temperature at which they are deployed being considerably less than that stated in the manufacturer's documentation. As the modelled demand was generally lower in the substations that were effectively conditioned it is probable that the extraction rates used have overestimated what is actually occurring within the dehumidification systems. Interestingly, the modelled and measured dehumidification demands within the Pendleton control room, where the new desiccant dehumidification system was installed, are very comparable with less than 2% difference recorded. In this instance the uncertainty associated with the extraction rate is minimal as the manufacturer provided information relevant to deployment at temperatures that are reflective of the UK climate, hence the impact of weather did not have to be estimated. It is likely that the uncertainty of extraction rate for the condensate dehumidifiers is a contributing factor to the performance gap associated with dehumidification demand.

Out of the three case study substations, the success of the interventions at Windermere has been limited. Although a significant reduction in heating demand was recorded, non-compliant RH levels remained, and stratification resulted in temperature at low level dropping below the minimum of 10°C throughout the winter months. It is likely the root cause of this is insufficient dehumidification capability. As discussed in relation to performance gap, the extraction rate at ambient UK temperatures was not known and had to be estimated. It is possible, in this instance, that the effect of temperature is limiting the extraction rate to below what is required to condition the space. Installing systems of known extraction rate, as was completed with the desiccant dehumidification system at Pendleton, would eliminate this. The stratification of temperature recorded is likely worsening this effect of temperature on the dehumidification systems. Installing twin high and low thermostats in parallel, mirroring the arrangement of the humidistats would combat this although would in turn increase the cost of interventions.

The payback calculations shown in Table 18 indicates the economic viability of the interventions applied within the three substations in respect of reducing their environmental control demand. The value of these calculations is limited as it treats the substations and the interventions applied as a whole, making analysis of individual interventions not possible. To do so, in respect of analysing measured energy demand only one intervention could be applied in each substation per year to determine its impact in isolation. An economic analysis could be undertaken based on modelled demand; however, it has been identified that there exists a notable performance gap when comparing measured and modelled heating and dehumidification demand so such an exercise could potentially be misleading.

This analysis also excludes any other economic benefits besides that of reduced environmental control demand. Such benefits include the reduced risk of damage to distribution equipment through partial discharge which can result in network outages leading to large regulatory fines, this is in addition to the cost of repairing the damage that has occurred the cost of which can be in the order of hundreds of thousands of pounds (Byrne, 2014). Equating an exact value to this reduced risk is not straightforward and beyond the scope of this study. However, it should be acknowledged that this is a valuable benefit to those operating substations alongside reduced energy consumption and cost.

6.7 Summary

This section has reviewed the results presented in Chapter 5 of this research outlining the findings and emerging themes in relation to the decarbonisation of substations. In the process recommendations for decarbonisation for their operators are identified.

Initially the suitability of the assets for efficient environmental control is addressed. As the substation buildings of the three case study sites were constructed in the 1960’s, their construction is reflective of this period and therefore does not reflect high performance, efficient building fabric. Furthermore, the requirement for environmental control was not present at their initial design and construction, so efficiency of building fabric was not a considered within the design. Additionally, the present condition of the buildings is poor with many defects that are increasing the energy demand for heating and dehumidification systems. That these items have not been addressed, indicates that they are not a priority maintenance item, potentially suggesting a lack of awareness that such defects can impact the efficiency of environmental control.

The pre-intervention environmental conditions observed in the three case study substations show that none are consistently being effectively conditioned. RH levels above the alarm limit of 70%RH are repeatably recorded with no action from the operator recorded. This shows the value in the remote monitoring conducted but also indicates that the current detection systems of the operator are insufficient to detect such non-compliant conditions. These non-compliant conditions are potentially being caused through sensor drift. This is in turn resulting in over conditioning of temperature and excessively high heating demand. Due to the severity of the implications, actively monitoring temperature and RH should be recommended to substation operators as a means of detecting over and under-conditioning.

Due to the severe impact of sensor drift, addressing it through enhanced control systems was a priority in the derived principles of interventions. This differs from approaches such as fabric first, commonly applied in housing, where the performance of building fabric is prioritised to lower the initial energy demand prior to addressing the building systems. Whilst this would be true in a substation building, any enhancements to the building fabric would be undermined if sensor drift was present resulting in under or over conditioning. The lowest priority of the principles of intervention was "alternative dehumidification systems", this was only applied in one instance but displayed very promising results. Further benefits of this intervention could be realised by reduction in the requirement for background heating. If this could be authorised by ENWL, it could be justified as an increased priority intervention item resulting in a significant reduction in energy demand.

For two of the case study substations (Pendleton and Southeast Macclesfield) the interventions have been successful and had the desired outcomes of consistently compliant environmental conditions and reduced energy demand. As well as decarbonisation, this will result in reduced risk of damage to distribution equipment through partial discharge as well as payback periods of under five years showing them to have significant economic viability. Such positive outcomes indicate that if applied to the entire substation estate of ENWL, significant benefits to the organisation would be realised including reduction in energy demand along with associated cost and carbon and increased network reliability. Consequently, the interventions and their respective hieratical approach should be recommended to substation operators.

When comparing the measured and modelled energy demands of environmental control systems, there is a consistently present performance gap. The cause of this is difficult to diagnose, although it is thought uncertainty in variables used in modelling that could not be explicitly measured, such as occupancy schedules, internal gains, and dehumidifier extraction rates are contributing factors. Enhancements to the remote monitoring campaign to account for occupancy detection would have increased robustness in the method and further refined the models. Where new dehumidification systems were installed, the modelled consumption was within 2% of the measured demand. If it were possible to install new dehumidification systems of known extraction rates in all three case study substations, it is expected the performance gap or dehumidification systems would reduce.

Despite the interventions in Pendleton and Southeast Macclesfield having the desired outcomes, the success at Windermere was limited. Heating demand was reduced significantly, however the uncompliant RH levels remained and stratification resulted in low-level temperatures breaching the minimum temperature. It is thought that insufficient dehumidification capability is causing this issue. Similarly, to reducing the dehumidification performance gap, installation of dehumidification systems of known extraction rates would address this issue. As the stratification of temperature was so severe in this substation, introducing twin thermostats at high and low level could be a necessary additional measure to ensure the minimum temperature of 10°C is upheld at both high and low levels.

Whilst the payback calculations conducted indicate the economic viability of the interventions, its value is limited to considering the benefits of reduced energy cost only. The reduced risk of damage to distribution equipment through partial discharge and the serious impacts this can have not been accounted for in these calculations. Equating a value to this reduced risk is not straightforward and beyond the scope of this study, however it should be acknowledged that this is a significant benefit to those operating substations alongside reduced energy consumption and cost.

The identification of the overarching themes reviewed in this discussion chapter affecting the selection of energy efficiency interventions and their impact has enabled recommendations for the decarbonisation of substations to be made. This has allowed meeting the final research objective O5 that will be consolidated within the following conclusion chapter.

Chapter 7 Conclusions

7.1 Introduction

This research project originated with industry partners ENWL who wished to better understand the environmental control systems of the electrical substations within their operation for the purposes of decarbonisation. To govern this research the following research aim was derived:

Aim: Decarbonise the operation of electrical substations whilst maintaining the required internal environmental conditions.

This study has identified an approach to retrofitting *energy efficiency interventions* to substations that are demonstrated to result in decarbonisation whilst improving the environmental conditions that are occurring within the buildings. This approach is unique to the operational requirements of substations and differs to more established retrofit methods in the selection of priority of areas of intervention.

This conclusion chapter will initially review and summarise the work completed in this research project in respect of addressing this aim. Then the aspects of this research that form an original contribution to knowledge are identified, followed by limitations and areas for further work to build on this research.

7.2 Meeting of Research Aim

This study has identified and demonstrated that retrofitting energy efficiency interventions are an effective way of decarbonising the operation of electrical substations, whilst maintaining, or improving the required environmental conditions. To conclude this study we will consider the baseline conditions and arising factors relating to substations that make retrofit measures necessary and suitable for decarbonisation in this application. Then the unique approach required for selecting retrofit interventions in the context of substations is explored as well as the impact recorded.

7.2.1 Why Retrofit Electrical Substations

In the three case study substations investigated it was identified that there was a need to retrofit substations. This was driven through ineffective environmental control approach, a poor standard of building performance and significant energy wastage occurring.

The existing methods of environmental control within electrical substations are deployment of condensate dehumidifier units and electric radiators. This approach was demonstrated as not being either efficient or effective through the results obtained through remote monitoring of environmental conditions and energy consumption of environmental control systems within three case study substation sites. Furthermore, investigations into the building fabric show its performance as poor and lowering the efficiency of environmental control rather than aiding it (Section 5.3, Page 94).

Monitoring results showed that under conditioning of RH levels were occurring in all three sites to varying levels, with monthly averages frequently breaching the maximum of 60%RH and occasionally reaching as high as 70%RH (Section 5.3, Page 94). Consequently, the electrical distribution equipment housed within these sites is at a higher risk of damage through partial discharge. Alongside this under-conditioning of RH levels, over-conditioning of temperature was also recorded. Where a minimum temperature of 10°C is required, all three substations showed areas being heated excessively throughout the winter months, with monthly average temperatures over 18°C recorded (Section 5.3, Page 95). This overheating does not impact negatively on the internal conditions in respect of risk from moisture, however there is a significant impact on the energy consumption.

These two irregularities have inverse effects on the measured energy consumption of the environmental control systems. When comparing the measured dehumidification demand against what is predicted by analytical models the measured demand is lesser. Comparatively the recorded heating demand is much greater that that calculated through computational thermal modelling, because of the overheating . The combined effect of these is a substantial net increase in the expected energy demand of substations (Section 5.3, Page 96). These uncompliant conditions are thought to be caused through sensor drift occurring in the heating and dehumidification controls, whereby they are unable to accurately maintain the specified humidity or temperature. The detection of these issues highlights the value in conducting active monitoring of RH and temperature and shows it should be considered by substation operators as well as any future interventions.

In addition to the dedicated environmental control systems, the substation building fabric, which can be viewed as either a contributing factor or a separate element of the environmental control approach, was reviewed. A building characterisation campaign consisting of U-Value measurement, air permeability testing and visual inspection analysed the building fabric of the three case study substations. The condition and performance of the building fabric within the three case study subjects was relatively poor in respect of modern construction standards and what might be expected of environmentally controlled buildings (Section 5.2, Page 90). However, it is also reflective of their construction in the 1960's with fabric elements uninsulated and high air permeability rates caused by many defects in the building fabric. Both of these will increase the energy demand of the heating and dehumidification systems, as conditioned air and heat can escape the substations more rapidly. Defects occurring and not being resolved within the building fabric, such as cracks and unsealed penetrations, indicate that they are not a priority item to maintenance teams, possibly as they are unaware on the impact they have on environmental control.

These issues of uncompliant environmental conditions, poorly performing buildings and significant energy wastage occurring, create a situation with unique incentives for retrofitting energy efficiency interventions. Not only is increased energy efficiency and decarbonisation a likely achievable benefit but intervention is necessary to enable compliant environmental conditions as they are expected by the asset operator.

7.2.2 Retrofitting Approach and Impact

As it was identified that substations need retrofit measures for the purposes of decarbonisation and improving compliance of environmental conditions, a method for deriving and delivering these retrofits was required to cater for the unique building use case.

A bespoke approach to identifying interventions for the purposes of improving the efficient management of environmental control was derived. This was necessary due to unique the constraints and requirements of the building differing from building types such as housing, where decision making guides and hierarchies for retrofits are well established. The five principles of intervention listed in approximate order of application are:

1. Enhanced control systems
2. Reduction of air and moisture infiltration
3. Segregation of conditioned and con-conditioned spaces
4. Lowering the thermal conductivity of building fabric
5. Alternative dehumidification systems

Notably in these principles, the immediate focus is on enhanced control systems. This was justified based on the sensor drift observed during the pre-intervention period that was compromising the compliance of the environmental conditions and resulting in significant energy wastage through overheating. This differs from more established approaches to interventions where a fabric first approach is often applied. In the principles derived, addressing the performance and configuration of the fabric (items 2,3 and 4) is secondary, as such improvements would be undermined if faulty control systems remained having the undesirable effects observed. This has implications for DNO's that operate substations, such as research partner ENWL, and could potentially be relevant for other non-domestic building types. The principles of intervention could be transferable to building types with similar functions or occupancy profiles, such as storage facilities, or buildings that form part of other utility networks, such as gas substations or water pumping stations.

Along with the principles outlined, contributing factors in selection of interventions were budgetary constraints and trigger events, in the form of remedial works required to the roof of the Pendleton case study substation. This provided an opportunity to provide an energy efficiency retrofit in parallel with a required maintenance task, providing cost and resource efficiency benefits and making an intervention achievable that would be unfeasible on purely decarbonisation grounds. This showed that incorporating energy efficiency retrofits in maintenance works is an effective way of delivering interventions that would otherwise be too costly and unfeasible.

The impact of the retrofit interventions is clear and significant in respect of decarbonisation and improving environmental conditions. Most significantly, remote monitoring data recorded post-intervention identified that the under conditioning of RH and over conditioning of temperature was largely eliminated (Section 5.5, Page 112). Two of the three substations, Pendleton and Southeast Macclesfield recorded humidity levels no greater than the minimum 60%RH and the previously observed overheating was eradicated. In line with research, the risk of partial discharge and the associated impacts are now reduced in these sites. The third site, Windermere was somewhat of an outlier and did not observe such improvements in environmental conditions the cause of this is thought to be related to the extraction rates of the dehumidification systems that are negatively impacted by temperature although by what capacity could not be confirmed for the units deployed.

Furthermore, the effectiveness of interventions was measured in the enhanced building fabric performance recorded at the substations post-intervention. Lower air permeability rates of the three buildings were recorded and in the case of Pendleton where insulation was applied to the roof, U-Value measurement confirmed an improvement in its insulating properties (Section 5.5, Page 108). These improved performance metrics will result in the buildings better retaining heat and humidity conditioned air lowering the energy demand of environmental control systems.

A final measure of the effectiveness of interventions is their economic benefit. For all three case study substations, the increased efficiency in environmental control systems has resulted in reduced annual energy demand and in turn a positive payback period from reduction in the associated cost of energy (Section 5.5, Page 117). For Windermere and Southeast Macclesfield this payback period is under five years, such a short payback period demonstrates the economic viability of the interventions to those operating substations based solely on reduction of energy costs. Pendleton has a longer payback period of over 17 years, this is due to inclusion of several non-priority interventions such as alternative dehumidification systems. Further monetary benefits that were not quantified in the payback analysis include the reduced risk of costs incurred from damage through partial discharge. The summation of these benefits makes such interventions an attractive prospect for substation operators. A roll out of the measures across the substation estate would make for decarbonisation on a significant scale as well as a more reliable network and is recommended as a policy decision for network operators such as ENWL.

This study has identified ways of decarbonising substations with the required environmental conditions not only maintained but improved upon the baseline conditions occurring pre-intervention. As such, it can be said that its research aim has been conclusively met.

7.3 Further work

This research project has provided an in-depth review of the efficient management of environmental control within electrical substations for the purposes of decarbonisation. In the process of conducting the study, items have arisen that have warranted further investigation, although this not possible in the scope and time constraints of the project.

The first of these items is the use of alternative dehumidification systems, which was positioned as the lowest priority item in the principles of intervention and only had one instance of installation in the form of a desiccant dehumidification system installed in the control room of Pendleton. This system showed promising results maintaining compliant RH levels with lower energy demand than the incumbent condensate-based system despite under conditioning occurring in the pre-intervention period. A functionality that was not fully utilised of the system is its ability to operate at temperatures below 0°C, reducing or completely removing the requirement for a minimum temperature to be maintained. This would further decrease the overall energy demand of environmental control systems although at the request of ENWL the minimum temperature of 10 °C remained in place throughout the study. If ENWL could authorise lowering this minimum temperature it could improve the potential of the intervention and warrant a higher priority in the application of interventions. This would require a further monitoring campaign to demonstrate this efficiency.

The desiccant dehumidification system also performed as expected based on analytical modelling with a minimal performance gap compared to that of the condensate systems. This is due to the system having known extraction rates at various temperatures, operational data that had to be assumed for the condensate systems. This would be beneficial for addressing the under-conditioning exhibited at the Windermere case study site.

The payback calculations conducted act as an indicator of the economic viability of the interventions installed. However, this is an area of analysis that could be expanded to gain a more comprehensive understanding of the benefits achieved. Alongside the reduced energy cost, equating a cost to the reduced risk of partial discharge occurring and avoiding associated expenses is much more complex.

To do so would require knowledge of how the probability of partial discharge occurring has changed and what the likely impact is in terms of cost. This analysis is beyond the scope of this study, but its completion would support the decision to roll out the intervention measures further than the case study sites.

An additional consideration in further work should be to the environmental control in modern, new build substations. This study focused on substations constructed in the 1960's as analysis of the population showed these were representative of over 40% of the substation population. Addressing the approach to environmental control in the design of newly built or yet to be built assets could potentially identify new insights into environmental control. It is understood that while the building fabric of new build substations is more reflective of modern buildings, with insulation specified in the walls and roof, the environmental control systems are alike to those of the 1960's case study substations described within this thesis.

7.4 Original Contribution to Knowledge

At the point of inception of this study the need for environmental control systems for maintaining a low moisture environment inside electrical substations was well established through research. This has been recognised in industry practice through the deployment of environmental control systems, by network operators throughout substation buildings for protecting the distribution equipment within. There was, however at this stage no known research addressing the efficiency and energy demand of these systems in the application of substations for the purposes of decarbonisation. The initiation of this research came in part with industry partners and network operators ENWL, who wished to better understand how the efficiency of environmental control systems in their substation estate could be improved.

The research aim of this study was derived to address decarbonisation in this unique building use case. As reviewed in section 7.2this aim has been comprehensively met with unique findings. To expand on this, the aim has been met through conducting case studies in real, operational substations recording data and undertaking measurements to construct the findings detailed within this thesis. This data that includes energy consumption data, temperature and humidity levels, U-value measurements and air permeability rates are commonplace in decarbonisation projects but their application to substation buildings has not knowingly been performed outside of this research.

Along with the application of this data, the findings in respect of how substations are decarbonised is unique. The derived intervention approach that prioritises enhancing heating and dehumidification controls over the performance of building fabric does not align with energy efficiency interventions in other building uses and is shown to be successful in the case study sites. This unique finding and the associated results could have only been derived through the completion of this research.

7.5 Closing Notes and Researchers Reflections

The opportunity to conduct this research came through an academic-industry partnership known as a HEIF (Higher Education Innovation Fund) knowledge exchange partnership between ENWL and the University of Salford. In this arrangement, the researcher is employed by the university and seconded to the industrial partner, in this case the property team of ENWL. This setting allowed for the creation and delivery of a research project that was not only successful but unique and enormously interesting.

By being positioned within the ENWL property team the researcher was able to gain access to the ENWL substation estate as well as asset databases, documentation and expert individuals within the organisation. All of these were useful for at first gaining an initial understanding of substations and environmental control then crucial for the deriving and delivering of the research method.

The positive impact of the intervention measures are clear benefits to ENWL both in terms of decarbonisation but also operationally as the compliance of environmental conditions in substations is improved. The latter is a benefit that was not foreseen at the inception of this research and encapsulates the overall success of this project.

It is acknowledged that there are limitations in this research that could introduce uncertainty into the impact of interventions. Under conditioning was unresolved and its cause not explicitly diagnosed at the Windermere case study substation. To determine a solution for this a longer duration would be required to capture a further heating season and allow for another iteration of interventions to be derived. This could potentially result in change to the approach of energy efficient interventions to account for substations that are more complex to decarbonise. Likewise, more time would enable the additional benefits of desiccant dehumidification systems to be quantified, possibly justifying a higher position in the hierarchical application of interventions. Whilst the industry – academic partnership enabled such an interesting and original piece of work its finite duration has placed limits on the scope of this study.

ENWL and any other applicable substation operator should be impowered by the contents of this thesis to decarbonise their substations and capitalise on the co-benefits that result in more reliable and economic network operations.

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Appendix 1 – Tabulated Environmental Condition Data

Table 20: Substation Conditioned Areas Environmental Conditions

Month	Pendleton				Windermere				Southeast Macclesfield			
	High		Low		High		Low		High		Low	
	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)	°C (S.D)	%RH (S.D)	°C (S.D)	% RH (S.D)
Apr-19	19.7 (2.2)	41.7 (2.5)	18.1 (1.8)	49.2 (1.7)								
May-19	19.5 (1.9)	47.1 (2.8)	18.3 (1.8)	53 (2.2)								
Jun-19	20.6 (2.1)	49.6 (1.7)	19.5 (1.9)	56.4 (1.6)								
Jul-19	24.9 (1.5)	48.1 (1.0)	23.4 (1.2)	55.1 (1.3)					24.3 (0.8)	57.1 (0.6)	22.8 (0.7)	62.9 (0.8)
Aug-19	23.6 (1.6)	49.8 (1.3)	22.3 (1.4)	57.7 (1.3)	20.3 (2.1)	60.9 (1.8)	19 (1.8)	66.4 (0.9)	23.5 (0.4)	55.3 (1.7)	22 (0.4)	61.2 (1.8)
Sep-19	20.5 (0.9)	51.1 (1.1)	19.5 (0.8)	57.6 (1.3)	17.8 (0.5)	62.3 (1.4)	16.4 (0.6)	68.5 (1.2)	22.5 (0.2)	52.8 (2)	20.9 (0.2)	58.8 (2)
Oct-19	16.8 (1.2)	56.8 (1.5)	15.7 (1.1)	65.1 (2)	17 (0.6)	58.4 (2.8)	14.4 (0.9)	68.9 (1.8)	20.5 (0.8)	52 (2.8)	18.8 (0.9)	58.1 (2.8)
Nov-19	13.5 (0.9)	58.3 (0.8)	12.1 (1.0)	67.4 (0.7)	15.4 (1.0)	50.3 (3.2)	11.8 (1.3)	63.3 (2.6)	18.7 (0.6)	49 (2.7)	16.7 (0.5)	56 (2.9)
Dec-19	12.4 (0.7)	56.9 (1.7)	10.8 (0.7)	67.5 (1.5)	14.8 (0.8)	50.7 (1.8)	11 (1.0)	65.5 (1.5)	18.2 (0.5)	47.8 (2.1)	16.1 (0.4)	55.1 (2.3)
Jan-20	12.2 (0.6)	56.6 (1.4)	10.8 (0.5)	67.5 (1.2)	14.9 (0.6)	51.8 (1.6)	11.1 (0.7)	67 (1.6)	18.8 (0.4)	45.7 (1.4)	16.5 (0.4)	53.3 (1.6)
Feb-20	11.8 (0.6)	58.9 (1.1)	10.6 (0.5)	69.5 (2.3)	14.5 (0.5)	53 (2)	10.8 (0.5)	68.1 (2)	18.7 (0.3)	43.7 (1.8)	16.4 (0.3)	51.1 (2)
Mar-20	13.5 (1.3)	57.4 (3.1)	12.2 (1.3)	70.6 (5.3)	15.6 (0.6)	51.5 (2.2)	12.5 (1.5)	64.1 (5.1)	19.4 (0.6)	40.5 (3.1)	16.8 (0.5)	48.1 (3.6)
Apr-20	17.7 (1.9)	52.4 (1.4)	16.6 (2)	63.8 (2.7)	16.8 (1.2)	53.3 (1.6)	15.3 (1.2)	60.2 (1.3)	21.4 (0.8)	40 (1.6)	18.9 (0.8)	47.2 (2.1)
May-20	20 (2.1)	51.3 (1.7)	18.8 (2)	62.5 (2.1)	18.4 (2.8)	50.5 (3)	16.8 (2.4)	57.3 (1.9)	21.9 (0.7)	41.5 (2.2)	19.7 (0.8)	48.7 (2.8)
Jun-20	21.9 (2.1)	52.1 (1.9)	20.6 (1.8)	62.8 (2.4)	20.9 (3.1)	48.8 (4.2)	19.1 (2.5)	55.6 (2.9)	22.6 (0.8)	47 (2.8)	20.8 (0.8)	53.9 (2.9)

Jul-20	20.6 (0.7)	52.3 (0.8)	19.4 (0.7)	62.6 (1.0)	19.1 (1.3)	51.3 (2.5)	17.5 (1.0)	58 (1.9)	19.3 (0.8)	56.4 (1.8)	18.6 (0.7)	60.6 (1.7)
Aug-20	23.3 (2)	51.9 (0.9)	21.7 (1.7)	63.8 (1.8)	21.5 (3.3)	51 (2.7)	19.8 (2.7)	57.8 (1.4)	21.4 (1.5)	58.6 (0.8)	20.3 (1.2)	63.7 (1.4)
Sep-20	20.7 (1.7)	52.3 (0.7)	19.4 (1.4)	62.4 (1.3)	16.8 (2.4)	53.7 (2.3)	15.6 (2)	59.2 (1.7)	18.7 (1.1)	59.5 (0.4)	18.1 (0.9)	63.2 (0.9)
Oct-20	16.3 (0.7)	52.7 (2.9)	15 (0.9)	61.6 (2.3)	12.7 (1.2)	56.8 (2.7)	11.7 (1.1)	61.4 (2.5)	14.8 (1.0)	61.3 (2.4)	14.5 (1.0)	64.1 (1.9)
Nov-20	14.6 (1.0)	49.1 (0.6)	12.9 (1.0)	57.6 (0.9)	11.6 (0.9)	61.9 (2.6)	10.4 (0.9)	67.8 (2.4)	14.3 (0.6)	50.7 (1.5)	13.7 (0.5)	55.4 (1.3)
Dec-20	12.1 (0.7)	51 (1.0)	10.6 (0.7)	61.4 (0.9)	10.7 (0.2)	58.3 (1.8)	8.7 (0.8)	67.1 (1.2)	12.6 (0.6)	47.2 (0.8)	11.9 (0.6)	51.6 (0.8)
Jan-21	11.2 (0.6)	50.8 (0.9)	9.3 (0.3)	63.2 (0.7)	10.8 (0.6)	54 (1.6)	7.8 (0.7)	66 (1.0)	11.8 (0.3)	46.5 (0.5)	10.8 (0.3)	51.2 (0.4)
Feb-21	12.7 (1.2)	49.9 (0.8)	11.3 (1.2)	58.9 (3.2)	11 (0.8)	54 (2.3)	8.4 (1.3)	64.8 (1.4)	11.9 (0.5)	47.1 (0.9)	11 (0.6)	51.9 (0.8)
Mar-21	12.9 (1.1)	49.1 (0.6)	11.8 (1.1)	54.3 (0.7)	12.3 (1.4)	55.9 (3.1)	10.2 (1.3)	65.4 (2.4)	12.2 (0.6)	48.1 (0.4)	11.4 (0.6)	52.9 (0.5)
Apr-21	15.2 (1.6)	49.6 (0.8)	14 (1.5)	54.5 (0.9)	13.5 (2.1)	54.2 (2.9)	11.5 (1.9)	63.3 (2.8)	13.8 (1.2)	48.3 (0.5)	12.8 (1.0)	53.1 (1.0)

Table 21: Substation Non-Conditioned Areas Environmental Conditions

Month	Pendleton		Windermere		Southeast Macclesfield	
	°C (S.D)	% RH (S.D)	°C (S.D)	% RH (S.D)	°C (S.D)	%RH (S.D)
Apr-19	17.5 (1.7)	90 (5.9)				
May-19	17.6 (1.6)	93.1 (2.7)				
Jun-19	18.9 (2.5)	98.7 (1.1)				
Jul-19	*	*			21.4 (1.8)	69.7 (1.1)
Aug-19	*	*	17.6 (1.8)	76.5 (2.7)	20.1 (1)	71.8 (1.3)
Sep-19	17.5 (0.8)	99.7 (0.6)	14.2 (0.8)	79.1 (3.4)	17.9 (0.7)	70.3 (1.8)
Oct-19	25.1 (0.9)	87.1 (13.3)	11 (1.7)	80.1 (3.3)	15.7 (0.5)	68 (3.8)
Nov-19	23.5 (1.3)	52.1 (5.1)	8.2 (1.5)	78.1 (4)	14.8 (0.5)	59.2 (4.6)
Dec-19	23.3 (1.2)	44.3 (2.5)	*	*	14.2 (0.4)	63.8 (3.7)
Jan-20	24.3 (0.8)	39.3 (2.2)	8 (0.9)	84.2 (2.6)	14.4 (0.3)	59.6 (2.7)
Feb-20	24 (0.9)	35.4 (1.3)	13.5 (5.1)	63.9 (17.6)	14.3 (0.3)	55.8 (2.9)
Mar-20	22.2 (5.2)	35.4 (6)	17 (1)	44.6 (5.5)	13.9 (1.1)	53.7 (6.6)
Apr-20	24.2 (2.5)	36.1 (4.5)	17.8 (0.6)	44.4 (4.8)	15.3 (1)	55.2 (3.3)
May-20	26.9 (2)	35 (3.6)	16.7 (2.1)	53.2 (11.8)	16.8 (2.2)	58.8 (2.5)
Jun-20	20.3 (2.4)	60.7 (8.9)	17.6 (2.6)	65.8 (8)	19.1 (1.7)	63.6 (4.1)
Jul-20	18.7 (0.9)	70.4 (3.3)	16.1 (1)	75.8 (4.1)	18 (0.8)	70.7 (1.4)
Aug-20	21.1 (2.1)	70.7 (4.1)	17.9 (2.6)	77.2 (3.8)	19.8 (2)	74.4 (1.2)
Sep-20	18.1 (2)	69.5 (6)	13.6 (2)	78.2 (3.8)	16.5 (1.5)	75.4 (1.8)
Oct-20	13.3 (0.9)	78.1 (3.9)	10 (1)	83.7 (2.6)	12.7 (0.9)	78 (1.4)
Nov-20	11.5 (1.2)	84.6 (3)	8.9 (1.1)	87.1 (1.8)	11.3 (1)	81.4 (0.6)
Dec-20	8.9 (1.1)	85.7 (3.2)	6.5 (1.6)	84.7 (3.3)	8.7 (1.2)	84.1 (1.7)
Jan-21	7.2 (0.9)	85.6 (2.9)	4.8 (1.4)	82.2 (3.4)	6.9 (0.9)	85.8 (1.9)
Feb-21	8.9 (2.7)	79.7 (5.3)	7.1 (2.6)	77 (6.6)	7.9 (2.4)	86.2 (2.6)
Mar-21	10.1 (1.4)	81.4 (2.5)	*	*	9.3 (1.5)	87.4 (1)
Apr-21	12.7 (1.9)	64.4 (4.6)	*	*	11.3 (1.5)	80.2 (3.8)
* Data not available due to equipment failure						

Appendix 2 – Additional Modelling Outputs

Figure 56: Modelled Heating Demand using both Pre and Post Intervention Weather Files

Substation	**Pre-Intervention Building Characteristics Annual Heating Demand (kWh)**		**Post-Intervention Building Characteristics Annual Heating Demand (kWh)**	
	Pre-Int. Weather Data	**Post-Int. Weather Data**	**Pre-Int. Weather Data**	**Post-Int. Weather Data**
Pendleton	444	1,043	312	732
Windermere	1,132	1,466	811	1,050
Southeast Macclesfield	1,346	1,813	535	1,143