MSc Dissertation Thesis

MSc in Sustainable Energy Systems

Low-carbon pathways to net-zero carbon emissions for a historic university building using an energy modelling approach.

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DECLARATION OF ORIGINALITY

I declare that this thesis is my original work, except where stated otherwise. This thesis has bever been submitted for any degree or examination to any other University.

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AUTHOR’S NOTE

Please note that this dissertation intended to be viewed on-screen or printed in colour. If an electronic version or colour copy is required, please contact the dissertation author at s1231046@ed.ac.uk.

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1 INTRODUCTION

This dissertation project is in collaboration with the Edinburgh University Estates Department and seeks to shed light on possible pathways to decarbonise Minto House, a 19th century listed building, which serves as the Edinburgh University School of Architecture and Landscape Architecture. All primary data needed to complete this study has been kindly provided by the Estates Department, which includes, utility data, record drawings and building services information.

1.1 BACKGROUND

1.1.1 The Challenges of Decarbonising Buildings

The Paris Agreement established by the 21st Conference of Parties (COP) commits the UK to reduce greenhouse gas emissions by at least 80 per cent by 2050, relative to 1990 levels [1]. In 2019, the UK intensified Climate Change Act emission targets to bring all greenhouse gas emissions to net-zero by 2050 [2]. Policy has been a key driver for the decarbonisation of the UK economy and the main mechanism for responding to anthropogenic climate change, yet it is important to contextualise what has been achieved so far against the backdrop of the aforementioned political objectives. Provisional figures from 2019 estimate a 45.2 per cent reduction in greenhouse gas emissions relative to 1990 levels, of which Carbon Dioxide (CO_2) is the leading greenhouse gas, accounting for 81 per cent [3]. In sum, to meet the UK's net-zero emissions target a 54.8 per cent cut in emissions is required over the next 30 years from the point of writing.

It is estimated that in 2050, some 70 per cent of the existing building stock will still be in use and 40 per cent will have been built prior to 1985 [4]. In 2019, their operation alone accounted for 38 per cent of all carbon emissions in the UK, and stresses the crucial role that buildings must play in carrying the decarbonisation imperative of legislative greenhouse gas targets [3]. Given that most of the buildings in 2050 are already existing, there is a strong focus towards decarbonising the existing building stock and this forms a key part of the Scottish Government's energy strategy for 2050 [5]. However, modifying existing buildings can be challenging due to technical, economic and social factors that can perpetuate 'carbon lock-in' [6]. Within existing buildings, decarbonising the subset of heritage buildings can magnify these challenges by constraining the scope of potential low-carbon interventions (LCIs), due to cultural designations or listings. Scotland has around 400,000 pre-1919 buildings, comprising of approximately 20 per cent of the total building stock, 47,000 of which are listed [7]. In light of these challenges, greater research is needed in assessing retrofit low-carbon solutions and energy efficient adaptation of historic buildings.

In addition to developing technically robust approaches for heritage buildings, low-carbon solutions must also be scalable to overcome financial barriers of widespread building decarbonisation. Case studies are useful in this way as they can provide insight into possible solutions that could be applied on a wider scale, without necessitating modelling every individual building. Furthermore, robust assessments of LCIs are required to inform wider decarbonisation strategies and goals, particularly for organisations responsible for managing groups of buildings, such as universities.

This study seeks to shed light on some of these challenges by exploring retrofit decarbonisation strategies through the lens of both technical and financial limitations for a heritage case study building. By adopting a modelling approach, detailed assessments are made about the opportunities and barriers for decarbonisation. This does not imply that other social and environmental factors are unimportant, indeed indoor environment, waste, natural resource consumption, preservation of ecology and water consumption all form part of the wider sustainability agenda, but fall outside the scope of this study [8].

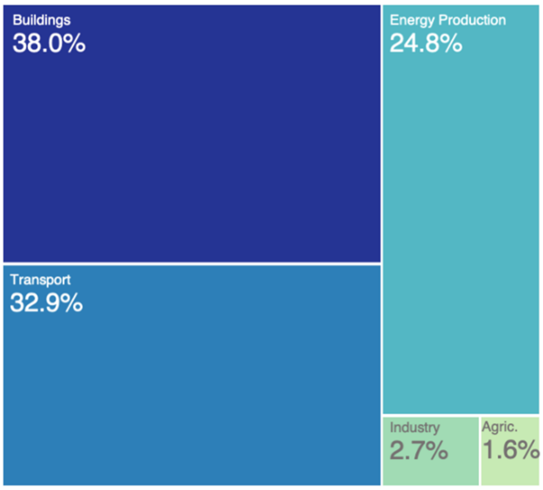

Figure 1.1: Carbon dioxide emissions for the UK in 2019 by key sectors, showing that buildings account for the greatest sectoral emissions. Created from GOV.UK Department for Business, Energy and Industrial Strategy data [3]

1.1.2 Industry Response and The University of Edinburgh

With mandated carbon reporting and stricter government environmental reporting guidelines, decarbonisation of business operations forms a central role in corporate social responsibility. Largescale organisations and of those higher education recognise the long-term and strategic advantages of low carbon buildings in environmental preservation and energy savings and have committed to institutional decarbonisation targets. Within the built environment, building owner-occupiers see net-zero carbon as a strategic advantage for saving operational costs.

The University of Edinburgh has committed towards carbon neutrality across all operations, including the maintenance and operation of all buildings and infrastructure by 2040 [9]. The scale of this ambition is best highlighted by the 550 University buildings spread over five campuses across the city of Edinburgh, which include historically and culturally sensitive buildings. This dissertation takes the form of a case study, which assesses Minto House, the University of Edinburgh School of Architecture and Landscape Architecture and explores what net-zero carbon means for historical buildings both, quantitatively and qualitatively.

1.2 Case Study Building: Minto House

1.2.1 Architecture

Minto House is a mixed-use building which provides lecture spaces, seminar rooms and offices and has served as a University of Edinburgh faculty building since 1973. Located in the heart of Edinburgh's Old Town on Chambers Street, in its present form it comprises of two historically separate buildings constructed in the late 19th century. Minto House and The Maltings were later linked in 2007 by an intermediate structure, and schematically, the building can be understood in relation to these three key areas, which possess different building fabrics and architectural styles.

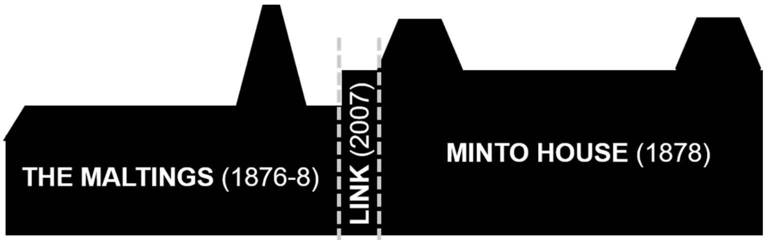

Figure 1.2: High-level elevation diagram of Minto House in its present form, comprising of three distinct structures, viewed from Chambers Street.

Minto House is designated as a 'Grade B' listed building by Historic Environment Scotland, since 1977 [10]. This is defined as a building possessing special architectural or historic interest and inhibits alterations to the external character of the building. Moreover, any alterations must be applied through listed building consent from planning authorities. Within the context of building energy performance, the architectural style of Minto House gives rise to two key challenges. Firstly, the building is an amalgamation of two historically distinct buildings, formed by three separate structures, which are serviced homogenously. Secondly, the building is listed as a whole, which will constrain the possible options for externally visible building interventions.

Figure 1.3: Isometric view of The Maltings and Minto House viewed from the South-West direction, image adapted by author from Google Maps.

1.2.2 Location Map

Figure 1.4: Minto House and surroundings viewed in 3D from the South-West direction, image adapted by author from Google Maps. Shows local environment and high building density.

1.2.3 Energy Characterisation of Minto House

Minto House is a mixed-use building which accommodates offices, teaching spaces, a library and workshops. The building heating demand is served by eight 115kW gas-fired condensing boilers, which are operated in a cascade formation, to supply the primary heating demand and the domestic hot water demand. Radiators and fan-coil units are used throughout the building as heat emitters for space heating, with a specialised air hand unit serving a large lecture room. Beyond the air handling unit and small local extract fans in workshops and WCs, Minto House is naturally ventilated through openable windows. The electrical demand is grid-connected and is served centrally. The cost of primary energy for Minto House is 2.68 pence/kWh for natural gas and 14 pence/kWh for electricity, these are averaged figures obtained from the Estates Department and include all standing line, VAT, Climate Change Levy (CCL) and service charges.

1.3 Dissertation Aims

1.3.1 Quantitative Research Objectives

- Assessment of existing building energy performance using IES modelling software and comparison to empirical metered utility data.
- Analysis of individual LCIs by comparing reduction of carbon emissions and lifetime cost.
- Quantification of the summative impact of combined LCIs, ‘carbon pathways’, using IES.

1.3.2 Qualitative Research Objectives

- Identification of barriers and opportunities for reducing carbon emissions for Minto House by 2040.
- To explore at what scale net-zero carbon should be administered for heritage buildings.
- To explore the role of renewable energy generation in delivering low-carbon heritage buildings.

1.4 Methodology

1.4.1 IES Modelling

This dissertation adopts a modelling-based approach to compare the impact of LCIs on carbon emissions from Minto House over a typical year by using IES building energy modelling software. Energy modelling tools are used extensively in industry to demonstrate compliance with Building Regulations and has been adopted as the primary tool for the energy assessment of Minto House. IES is an integrated design suite, which provides flexibility to assess different building design options, by bringing together six key datasets when assessing low-carbon potential: climate, geometry, fabric, services, renewables and patterns of use. Modelling is highly useful in providing a priori assessment of design strategies and can be used as a design tool in order to support decision making processes for building refurbishments [11].

The methodology adopted is a stepwise modelling approach, in which the carbon reduction achieved from different LCIs are compared to a base case (baseline) model. The first stage of the modelling involves creating an energy model for the existing building, which will be used as a base case, in accordance with best practise methodology outlined by the Chartered Institution of Building Services Engineers (CIBSE) TM54 [12]. Through site visits and access to building management data, the base case model seeks to represent the existing building as closely as possible, however, limited building information necessitates research-based assertions.

Two areas of LCIs are assessed, which are building fabric improvements and building services interventions. These are applied separately to the base case model and can enable evidence-based conclusions to be made regarding the technical viability of LCIs, based on carbon emission reductions. Financial viability is assessed through a cost-benefit analysis which relates carbon savings ($kgCO_2$), capital cost (GBP), lifetime (years) and comparison with a nominal carbon offset price ($GBP/kgCO_2$).

Amalgamation of LCIs gives rise to the development of low-carbon pathways, which are constructed based on particular scenario-logics. Pathway 1 is a services-only refurbishment with limited building disruption and expected to be low cost. Pathway 2 is a services and fabric refurbishment, which is representative of a comprehensive refurbishment programme leading to greater building disruption and cost. Finally, Pathway 3 is a combination of high performance LCIs, which provide the greatest carbon savings over their capital investment and lifespan. Pathways are subsequently modelled in IES and compared against the base case model to assess possible opportunities and barriers towards low-carbon refurbishment of Minto House.

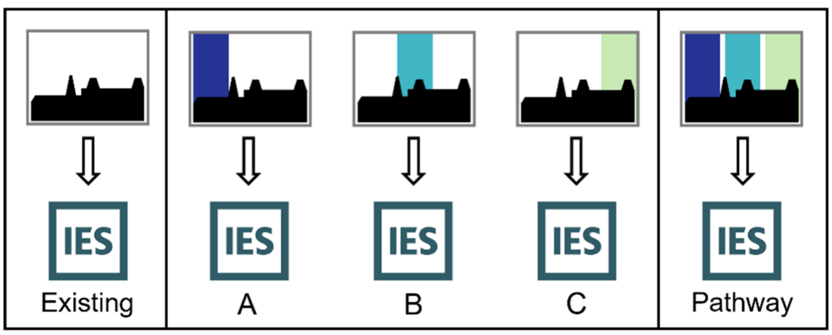

Figure 1.5: Modelling process with IES, where A,B and C are shown as arbitrary low-carbon building interventions from which a low-carbon pathway is constructed; A,B and C are modelled collectively and compared to the existing building performance.

2 LITERATURE REVIEW

The objective of the literature review is to define what net-zero carbon means for buildings and identify technical, economic and social challenges of applying low-carbon frameworks in practise. It seeks to shed light on key technical considerations relating to heritage buildings and how these can be accommodated within the decarbonisation process. Additionally, it aims to assess IES thermal modelling and how energy modelling can be leveraged as a low-carbon design tool.

2.1 NET-ZERO CARBON

2.1.1 Definitions and Frameworks

Operational energy and carbon emissions from buildings are proportional to one another. Building energy consumption entails use of fuel, which inevitably emits carbon emissions along its supply chain and at point of use. This coupling means that net-zero carbon buildings must also inherently be low-energy buildings to minimise all possible operational emissions. This does not mean that net-zero carbon buildings must be net-zero energy buildings (NZEBs), but rather, on-site renewable generation or carbon offsetting should be applied to deliver the negative carbon emissions needed to achieve a net balance of zero carbon (neutral) emissions. Another important distinction is that net-zero carbon extends beyond the scope NZEBs, which typically only concern operational energy balance for a building. Only when evaluating the operating, embodied and transport carbon emissions which relate to how the building is used, built and travelled to, can the overall carbon footprint of a building be understood [8]. However, as a case study of an existing building, this dissertation focusses operating emissions, which are caused by electricity, gas and other fuels used on-site. Therefore, the applied carbon accounting includes Scope 1 and Scope 2 emissions, which are caused by burning fuel on-site or purchasing electricity, respectively.

Defining high performance and NZEBs can be challenging given that buildings are highly diverse and individually unique and hence, the need arises for a standardised measure to enable benchmarking and comparison. Performance metrics such as annual energy consumption and carbon emissions, can be calculated in units of kWh/m^2 or $kgCO_2/m^2$ by normalising to the internal area. Practically, benchmarking is an effective tool for communicating and engaging stakeholders through a simple and robust metric for defining energy and carbon performance [8].

Design guidance for applying net-zero carbon strategies in practise, takes the form of either prescriptive or performance-based standards. Performance-based guidance provides a greater degree of design flexibility and stipulates target performance metrics that must be obtained. As such, there is room for design freedom and the methodology for achieving target performance values is open for design interpretation. Conversely, prescriptive standards dictate the methodology that must be adopted to achieve a prescribed performance, hence are more comprehensive in their guidance. Both of these types of design guidance have a place in delivering low-carbon solutions and can be applied in different contexts, which may be sympathetic of project type, complexity or design team experience [13].

The Building Regulations are statutory regulations, which set out specific design and construction objectives to be achieved for buildings to be legally compliant. Conservation of fuel and power: Approved Document L concerns building energy and outlines performance-based targets for different building elements, which may be thermal admittance (U-values) in units of W/m^2K, as well as consolidated building carbon emission rates, measured in $kgCO_2eq/m^2$ [14]. The Notional Calculation Methodology (NCM) is the assessment protocol used to demonstrate compliance with Building Regulations and involves creating an energy model for the designed building to compare performance with a notional (minimum energy performance threshold) building. Therefore, energy modelling for compliance with building regulations is not a prediction of how the building will perform in reality and only serves as a comparison against the notional building, used as the minimum acceptable performance. In this context, energy modelling is often only used as a means to assess compliance, rather than a prediction of how the building will perform in reality and this can lead to large disparity between the Part L energy model for a building and its actual performance. The TM54 technical memoranda, published by the CIBSE, seeks to overcome the limitations of Part L modelling and provides a roadmap for developing a more representative energy model of the building in reality. This serves the purpose of providing accurate insights into the building performance that will be delivered to the client and overcomes the large disparities seen in Part L energy models. Crucially, it highlights that energy performance is highly dependent how the building is run and maintained, and this is currently outside of the scope of prescriptive and performance-based standards.

In 2019, the UK Green Building Council (UKGBC) launched a 'low-carbon framework', in collaboration with industry partners, which outlines a structured approach to achieving net-zero carbon and seeks to unify the construction industry towards a single definition [15]. This is a landmark publication as prior to this, a lack of clarity and consensus meant that net-zero carbon agenda was poorly understood or perceived as risk-fraught in industry [13]. It defines a roadmap for achieving net-zero operational and construction emissions with key guiding principles of measurement, transparency, and energy benchmarking. The operational net-zero carbon path first adopts an energy-efficiency approach, which subsequently cascades down to renewable energy generation and carbon offsetting. Whilst this has been effective at moving the construction industry towards one definition, at the time of writing, the first draft lacks the technical detail of more established prescriptive and performance-based guidance that has emerged from municipal planning regulations, for example, the London Plan. High building density and environmental footprint has prompted municipalities to play a key role in developing low-carbon strategies within local and regional planning code. The London Plan, first published by the Greater London Authority (GLA) in 2004, has progressively sought to address the climate impact of buildings, through minimising carbon emissions from the built environment [16]. Planning requirements stipulate minimum performance targets which go beyond Building Regulations thresholds and greatly improve upon the notional building. A hierarchical methodology feeds into the design guidance and carbon reporting framework expected from new build projects, in the form of three stages: 'be lean, be clean and be green'. Administering this policy on a large scale resulted in 10 per cent carbon emission savings a year after the introduction of the policy [17]. In this manner, cities and local governance have been crucial for accommodating niche energy technologies within the net-zero carbon agenda and highlights the need for robust guidance. The City of Edinburgh Council's Sustainable Energy Action plan sets out high level energy objectives for the built environment, but lacks integrated design guidance, which has been central to the regional success of The London Plan [16] [18].

Unlike local and central planning regulations, the London Energy Transformation Initiative (LETI) is a bottom-up approach to reducing emissions from the built environment and is led by industry professionals in response to the climate emergency through the publication of design guides [19]. Publications address client expectations and design guidance through both prescriptive and performance-based methods with greater detail than the UKGBC's framework. Despite being a regional response, LETI outline key principles for policymakers to build upon, and have leapfrogged Building Regulations' incremental ratcheting process for tightening energy regulation. Hence, LETI represents a solution-driven and proactive approach to low-carbon building, rather than a reactive one, which is led by regulation. Through adoption of a clear plan and methods, the LETI is more developed than the UKGBC's net-zero carbon framework. This may be due to their scopes of influence, as LETI seek to create change at a grassroots level, whilst the UKGBC framework seeks to influence Building Regulations, as such the widespread adoption of the UKGBC framework may be slower, due to government consultation processes.

Table 2.1: Comparison of low-carbon frameworks discussed and Part L of Building Regulations, identifying the scope of carbon and energy reporting required in each instance.

	UKGBC	**LETI**	**The London Plan**	**Building regs. Part L2B**
Transport CO_2	-	-	-	-
Construction CO_2	-	✓	-	-
Operational CO_2	✓	✓	✓	✓
Embodied CO_2	✓	✓	✓	-
Type	Design principles only	Performance	Performance & Prescriptive	Performance
Methodology	i. Fabric ii. Supply iii. Offset	i. Energy-use target ii. Space-heating target iii. Maximise renewables	i. Be lean ii. Be clean iii. Be green	i. Target fabric values
Building Type	New Build	New Build	New Build	Refurbishment
Region	UK	London	London	UK
Last revised	2019	2020	2016	2016

This highlights that at the time of writing, there are different approaches towards addressing the decarbonisation imperative. It also stresses that guidance and regulation operate at different scales, which may impact the extent to which decarbonisation can be delivered. A key learning from this is the adoption of a hierarchical approach to low-carbon buildings, which focusses upon fabric, equipment efficiency and then supply. However, there is limited guidance, which is specific for heritage buildings, and this reinforces the qualitative objectives of this project.

Amongst frameworks above, a key commonality is that the first step towards reducing carbon emissions is the reduction of energy demand. To this end, fabric upgrades can enable significant energy efficiency gains through improving thermal fabric efficiency. This highlights two important points, firstly, contemporary construction techniques are able to deliver the improvements that are needed on the ground, thereby overcoming technical barriers to zero-carbon. But secondly, by virtue of this, it eludes that other economic issues may be inhibiting the wider adoption of net-zero carbon. As such, the technical know-how surrounding net-zero carbon is available, but the environment for deploying them is not being fostered, through financial or social issues [4].

Financially, the Carbon Trust highlights that building must play leading role in the UK's transition to a low carbon economy. They highlight that reductions of 75 per cent can be achieved by 2050 at no net cost, using the building technology that exists presently [20]. Whilst retrofit LCIs may incur capital expenditure, the financial cost is neutral through savings mechanisms and increased financial penalties for carbon emissions. Hence, false perceptions of financial implications may be impacting net-zero carbon ambitions on the ground.

On a social level, the acceptance of low-energy buildings is also key. Building users can play a critical role in steering the carbon footprint of buildings through their behaviour and purely technical solutions may fail to achieve the decarbonisation required [21]. In addition, the notion of net-zero carbon buildings is still niche and will inevitably require time and nurturing in order to break into the current construction regime and fulfil its potential. This ties into LETI guidance, which recognises the urgency around providing robust guidance proactively, rather than reactively in order to disrupt the existing socio-technical regime.

However, existing building are unique and pose distinct challenges to the net-zero carbon ambition, which may encompass wider technical, social and economic factors. For heritage buildings in particular, these challenges may even be heightened, due to planning restrictions and tension between preservation and renovation. Therefore, a number of obstacles may impact the application of low-carbon frameworks, which may involve occupant disruption, compatibility with existing systems, insufficient understanding of appropriate analysis and planning, payback periods and an endemic skills shortage in the built environment sector [4]. This further substantiates the objectives of this dissertation in assessing opportunities and barriers through a tailored analysis of Minto House.

2.1.2 Refurbishment of Heritage buildings

Existing buildings can pose substantially different challenges in comparison to new builds, often the project scope can be poorly defined and budgetary constraints can detract from a robust refurbishment strategy. In recognition of this, sustainability assessment tools, such as the Ska rating system, established by the Royal Institution of Chartered Surveyors (RICS) and the Building Research and Establishment Research Method (BREEAM), provide refurbishment-specific guidance [22] [23]. These both seek to overcome refurbishment challenges and identify opportunities for exercising sustainable building practises.

The Ska rating system is specifically designed for fit-out and refurbishment projects and in 2016, the Ska Higher Education 1.0 was published to provide a set of sustainability criteria targeting higher education buildings, which have unique building regulations, uses and requirements. The sustainability criteria outlined by Ska include waste, water, materials, pollution, wellbeing and transport, and as a self-assessment tool, Ska has seen a large uptake amongst UK universities. A more rigorous approach to sustainability is the long-established BREEAM, which is widely cited as the main building sustainability tool within UK for both new builds and refurbishments [8] [23] . It is a United Kingdom Accreditation Service (UKAS) accredited third party certification scheme and requires each project requires auditing by a certified BREEAM assessor, which can increase project costs. The BREEAM Refurbishment and Fit-out makes a distinction for heritage building refurbishment, recognising that heritage buildings may need unique solutions. Despite the availability of such guidance, it is important to adopt a bespoke view of heritage buildings [7].

Table 2.2: Comparison of BREEAM and Ska rating tools in the context of heritage buildings of higher education.

	BREEAM	**SKA**
Organisation	BRE	RICS
Existing Buildings	Refurbishment & Fit-out	Refurbishment & Fit-out
Heritage	✓	-
Higher Education	-	✓
Last Revised	2014	2016
Established	1990	2016

Heritage buildings often have characteristics that challenge contemporary technical interpretations of energy efficiency outlined by BREEAM and Ska [7]. This may arise from a difficulty in understanding how the building functions and how it was originally designed. The Chartered Institute of Building (CIOB) have published guidance on refurbishments, highlights that key risks of retrofit actions arise through lack of knowledge of heritage assets [24]. Beyond this, the CIOB identify similar strategies to Ska and BREEAM, which relate to retrofit improvements to the thermal envelope. The Better Building Partnership, a consortium of industry companies, assert that the first step of improving performance for heritage buildings is understanding the property; “Collating as much information as possible regarding the fabric, roof and systems” [7]. Without full information on the building, any works could result in untold, invasive damage [25].

Understanding heritage buildings is challenging for two main reasons: detailed records of the construction methods and material build-ups are not known. However, some uncertainty may be reduced through analysis of record drawings to identify material build-ups, whilst construction methods may be assumed based on heritage literature. Heritage construction techniques differ and heavy thermal mass elements, however, with such uncertainty, in-situ empirical measurements of U-values (W/m^2K) have proven to be successful in assessing thermal performance [26].

The functionality of heritage buildings can be best understood by consulting literature published by regional heritage public bodies. Functionally, many traditional buildings are designed with passive ventilation to ensure air flow around the building elements, helping to disperse moisture [27]. High levels of passive ventilation are necessary for transporting moisture and preventing the build-up of condensation, and the building fabric acts as a humidity buffer [28]. The key challenge is that heritage buildings are designed to have high levels of infiltration to regulate internal humidity, but this compromises their thermal efficiency through the constant infiltration of unheated external air. There is a strong consensus among research that moisture should adequately managed when improving the thermal fabric of historic buildings, which can be best achieved through the use of hygroscopic insulation materials that are pervious to moisture transfer [26] [27] [29]. Therefore, not all the typical building interventions are appropriate for heritage properties and may give rise to detrimental recommendations [7]. Research by Historic Environment Scotland supports the view that there are two key principles for improving thermal performance in traditional buildings. Firstly, the materials used should be appropriate for the building, and in most cases water vapour permeable, and secondly, that adequate ventilation should be maintained to ensure the health of the building and its occupants [26]. Ensuring that this is taken into account it is entirely possible to improve the thermal fabric of a traditional building, implying that challenges of heritage buildings can be overcome, however, this will need a balance between environmental and historical significance [7] [26].

2.1.3 Low-carbon Interventions for Heritage Buildings

Key challenges for low-carbon buildings are the energy performance gap, maintaining a comfortable internal environment and optimising building intervention choices [30]. These represent some of the technical, social and economic challenges, which must feed into selection of LCIs and building refurbishment strategy.

In all the low-carbon frameworks identified in Section 2.1.1, the first stage of reducing carbon emissions requires demand-side energy interventions and can be achieved by two main methods: upgrading building controls and systems or increasing the thermal fabric efficiency. By undertaking a thought experiment in deconstructing a building from inside out, it becomes apparent that inner layers of the building structure, such as controls and services are easier to replace and change than fabric elements. Indeed, over the lifetime of heritage buildings these would have been installed and replaced numerous times. Likewise, it becomes clear that interfering with fabric elements necessitates removal or disturbance of building services layers. Hence, services interventions are understood to be less disruptive to heritage structures than fabric interventions. This ties into the understanding of building 'shearing layers', which change at different rates over the lifetime of a building, highlighting that building services are more superficial than building fabric elements [31]. This is relevant for refurbishment strategies which may aim to reduce occupant and building disruption.

For existing buildings, heating regimes can have a larger impact than fabric improvements [14], which can be both costly and invasive. Moreover, low cost, non-intrusive retrofitting works such as control system upgrades and set-point changes can offer low-risk energy saving advantages [5]. Similarly, building system upgrades which may involve replacement of mechanical or electrical equipment can offer additional energy efficiency savings without disturbing sensitive building fabric. This 'controls-first' approach is substantiated by several case studies, which successfully delivered carbon reductions through heating and cooling set-point changes [32]. Other studies highlight the potential of an integrated approach to refurbishments and demonstrate greater overall carbon emissions reductions at higher capital cost [33].

Beyond building services interventions, fabric interventions have the potential to deliver energy demand reduction through higher performance insulation and airtightness. This is particularly relevant for climates such as Edinburgh's where space conditioning loads comprise principally of heating load. Hence, improving the thermal fabric has a direct impact upon reducing heating load by reducing the convective and conductive losses from heated spaces. However, many modern insulation materials are unsuitable for application in heritage buildings and can lead to moisture issues such as mould [29]. In addition, the effects of thermal bridging at building element junctions such as windows and walls can influence overall performance significantly and heighten risk of interstitial condensation [34]. As a more interventionist approach, fabric upgrades lead to more occupant disruption and inherently higher project costs. Consequently, fabric upgrades typically occur alongside services and system upgrades due to the opportunity to simultaneously undertake services upgrades. The scope of fabric improvement may extend to roof, wall, floor or glazing system improvements and these are discussed below.

When insulating roofs, floors or walls, impermeable modern insulating materials should be avoided and vapour permeable materials such as sheep's wool, hemp fibreboard or a wood-wool mix are recommended [26]. Laying non-permeable insulating materials will inhibit water vapour movement and may give rise to timber decay and damage to existing fabric [27]. Although specific material choices for insulation may be impacted by the nature of the existing building fabric and access. Every installation will yield different results, however, Historic Environment Scotland trials have shown strong improvements in thermal performance through thermal fabric upgrades which are presented.

Table 2.3: Typical roof insulation upgrades applied to heritage buildings with empirically measured U-values before and after improvement.

Insulation type	**Unimproved U-value** (W/m^2K)	**Improved U-value** (W/m^2K)
280mm Sheep's wool insulation applied to ceiling	1.4	0.2 [35]
275mm hemp wool insulation applied to ceiling	1.5	0.2 [36]

Table 2.4: Typical wall insulation upgrades applied to heritage buildings with empirically measured U-values before and after improvement, adapted from [27].

Insulation type	**Unimproved U-value** (W/m²K)	**Improved U-value** (W/m²K)
100mm hemp board between timber straps	1.1	0.21
90mm wood fibre fitted between timber straps	1.1	0.19
30mm insulated board onto timber straps	1.1	0.36
50mm cellulose fibre damp sprayed between timber straps	1.1	0.28
40mm insulated board onto timber straps	1.1	0.22
50mm bonded polystyrene bead	1.1	0.31

Table 2.5: Typical floor insulation upgrades applied to heritage buildings with empirically measured U-values before and after improvement.

Insulation type	**Unimproved U-value** (W/m²K)	**Improved U-value** (W/m²K)
80mm wood fibre insulation batts	2.4	0.7 [35]
30mm Aerogel board	3.9	0.8 [37]

Traditional glazing can be a source of significant heat loss as single-glazed windows suffer from a high U-value and do not provide adequate thermal insulation from external conditions. Installation of double-glazing can improve this, however for historically sensitive buildings this would be deemed as altering the façade and may not be feasible. Secondary glazing systems can improve thermal performance without comprising heritage preservation through the installation of an additional internal window within existing window reveals. Other improvements such as installation of shutters may deliver improved thermal performance, however their limitations relate to unpredictable occupant use and can comprise natural daylighting.

Table 2.6: Typical glazing upgrades applied to heritage buildings with empirically measured U-values before and after, adapted from [27].

Improvement method	**Reduction in heat loss**	**U-value** (W/m²K)
Unimproved single glazing	-	5.4
Closing shutters	51%	3.2
Secondary glazing system	63%	1.7
Secondary glazing with shutters	75%	1.1
Double-glazed pane fitted in existing sash	79%	1.3

The goal for net-zero carbon buildings is not only in minimising energy demand, but also developing an optimal design to find balance between energy performances, energy generation, and variation of occupant needs and indoor environmental quality [30] . Therefore, a key challenge lies in optimising building intervention choices to best achieve these objectives and assessment of retrofit options [38]. Prior academic studies have undertaken a multi-step and multi-objective optimisation approach to addressing this issue; with objectives considering cost, incentives, indoor comfort, energy demand for heating and cooling [39]. Key outcomes reveal that optimising decision-making processes can lead to beneficial energy-saving outcomes. However, the process used is novel and highly computationally intensive and only applicable with the use of open-source thermal modelling software.

Moreover, such studies rely on calibrating the virtual model to existing energy performance, which has been shown to be highly unreliable [8] [21].

A stepwise single-objective optimisation is useful for assessing impacts of individual building interventions from a purely energy-saving viewpoint and overcomes the major hurdle of trying to calibrate a digital energy model to actual performance. This is the methodology accepted under the London Plan energy reporting and hence, has a direct application in industry for demonstrating net-zero carbon performance [16]. The energy model can be set up so that other factors such as occupant comfort (set point temperatures) and energy generation capacity remain constant, whilst varying specific factors and assessing their outcomes against the baseline performance. This methodology is based on the notion that performance improvement above the baseline model is reflective of the scale of improvement seen in the actual building.

2.1.4 Measuring Performance

Robust simple energy benchmarks are necessary for comparing carbon emissions across buildings and what this means in the real world. Whilst every heritage building upgrade is bespoke, benchmarking with standard energy and carbon intensity metrics is employed to understand how they perform in comparison to other buildings. Similarly, energy and carbon intensity metrics allow comparison with good, average and poor performance buildings and can feed into energy management strategies for multiple buildings. CIBSE provide energy benchmarks for typical buildings and are presented in Table 2.7.

Table 2.7: Comparison of CIBSE benchmarking guidelines for building energy performance, table adapted from [8].

	Electricity (kWh/m^2)		**Gas (kWh/m^2)**		**$KgCO_2eq/m^2$ of GIA**	
CIBSE Energy Benchmark (TM46: 2008)						
School	40		150		54	
University Campus	80		240		96	
CIBSE Guide F (2012)	Good	Typical	Good	Typical	Good	Typical
Lecture rooms – arts	67	76	100	120	60	70
Library – naturally ventilated	46	64	115	161	51	71
Office – naturally ventilated, cellular	51	66	93	137	49	67

CIBSE Guide F data is based on 1996 Higher Education Funding Council Publication, as such, these values may be lower than expected as there has been a significant increase in use of IT within the education sector [40]. Conversely, CIBSE TM46 data was published in 2008 although this only provides for mixed use school buildings and university campuses which include accommodation [41]. The CIBSE Guide F data is used for benchmarking the performance of Minto House, by adopting a hybrid benchmark taking account of the percentage internal area of different rooms, which includes offices, lecture rooms and the basement library.

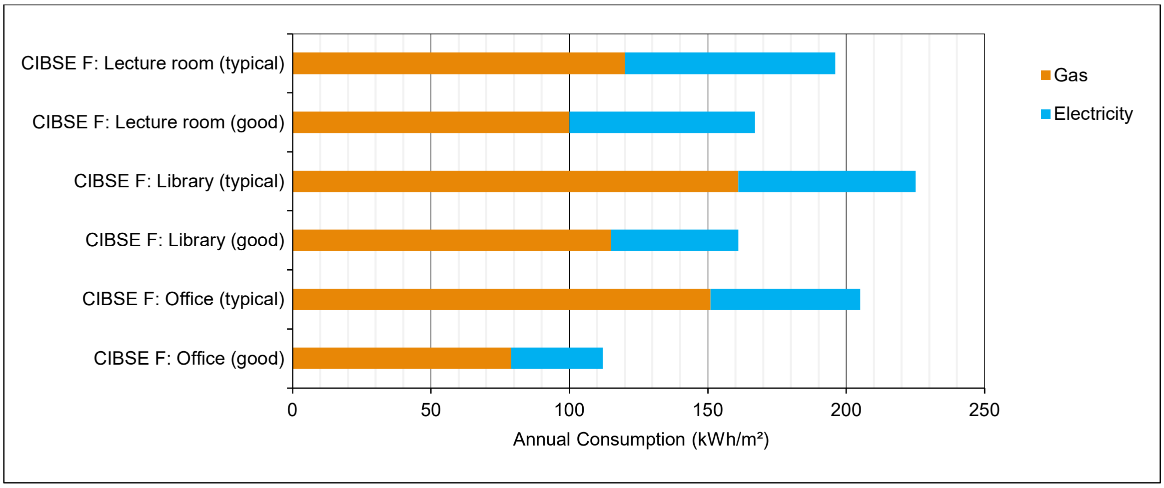

Figure 2.1: CIBSE F benchmarks for good and typical use for room types, Gas and Electricity demand is presented in units of kWh/m², significant variance is seen across building use type benchmarks.

Table 2.8: Hybrid benchmark adopted for Minto House based on use of internal floor area: 50% teaching, 40% office, 10% library, in line with the CIBSE TM46 guidelines for hybrid benchmarking [41].

	Electricity (kWh/m²)		**Gas (kWh/m²)**		**$KgCO_2eq/m^2$ of GIA**	
Hybrid Benchmark for Minto House	Good	Typical	Good	Typical	Good	Typical
CIBSE F: Hybrid	51.3	66	93.1	136.5	55	69

2.2 BUILDING ENERGY MODELLING

2.2.1 CIBSE Simple Method

Building energy modelling involves creating a virtual prototype of the building and simulating scenarios under different user-inputted conditions. A key utility of energy modelling for net-zero carbon buildings is in enabling assessment of different building options and comparisons of results against an established baseline. In this way building energy modelling can be used a design tool, unlike evaluation tools such as BREEAM and Ska which were discussed in section 2.1.2 [11].

The CIBSE simple model for simulation is a steady-state calculation which enables plant sizing based on total heat losses from fabric (conductive losses) and airtightness (ventilation losses). It is widely adopted as a simplified model for sizing heating equipment and forms the basis of building energy modelling processes, outlined in CIBSE guide A: Environmental Design [42].

$$\text{Heat loss} = \text{fabric loss} + \text{air loss} \tag{1}$$

$$\Phi_t = [F_1\,\Sigma(AU) + F_2\,C_V]\,(\theta_C - \theta_A) \tag{2}$$

Where Φ_t is the total heat loss (W), F_1 and F_2 are nondimensional factors related to characteristics of the heat source in relation to operative temperature, $\Sigma(AU)$ is the product of surface area, A, (m^2), and corresponding thermal transmittance through a surface, U, (W/K), C_v is the ventilation conductance (W/K), θ_C is the room temperature and θ_A is the outside ambient temperature (˚C). To apply this method, information relating to building geometry, infiltration rate, thermal properties, heat emitters and external and target temperature are required [42]. In IES the user can input data into different software modules, from where data is pulled for the simulation.

Table 2.9: IES calculation process for thermal modelling across IES modules and how information is 'pulled'.

IES Module	Function	Parameter Information
ModelIT	Building geometry creation	A, area of building elements
ApacheSim	Thermal calculation toolbox	U, thermal properties of building elements F_1, F_2, heat emitter properties C_V, ventilation and infiltration rate
VistaPro	Results viewing toolbox	Φ_t, heating demand from heat loss

Due to its simplicity, this model has several assumptions which limit its application for modelling real buildings. This includes assuming no heat storage in building fabric, one directional and time constant heat flow and no solar or internal gain within the building [43]. In the real world, building thermal conditions are never steady and highly impacted by variations in occupancy and solar gains. The building fabric will heat up and cool down in cycles, which cannot be accounted for using the steady-state CIBSE simple model alone [44]. Its main advantage lies in ease of application and it can provide an initial estimate of heating loads, without demanding detailed design data and its application is largely limited to initial design development.

2.2.2 CIBSE Admittance Method – cooling demand

The CIBSE admittance method was established by the Building Research Establishment (BRE) alongside CIBSE and seeks to overcome the limitations of steady-state modelling and calculate peak cooling demand. The calculation process is based on the analogy between current flow in an alternating current resistor and capacitor circuit, and energy flow through in a building structure, which includes thermal resistance and thermal storage capacity [42]. It is a cyclic model that reaches steady conditions after 24 hours, in which heat gains are represented as sinusoidal functions defined in terms of amplitude and phase lag. The method is designed to predict the cooling demand caused by the constructive interference of heat gains from separate flow paths over 24-hour cycles. Despite being a quasi-steady-state modelling method, it is able to model thermal mass exposure with reasonable accuracy and results are comparable to more complex modelling approaches [42]. However, it uses a simplified treatment of loads which limit its application, for example, when assessing cooling loads, it treats the outdoor daily temperature profile as being constant over a repeating number of consecutive days [44]. Therefore, it is not deemed to be suitable for modelling the energy performance of Minto House.

2.2.3 IES Dynamic Thermal Modelling

ApacheSim is a dynamic thermal simulation module within IES, which combines first-principles mathematical modelling of the heat transfer processes with empirical experimental data to model heat transfer around a building. ApacheSim qualifies as a Dynamic Model in the CIBSE system of model classification and the heat diffusion equations used are governed by two partial differential equations, which express principles of conduction heat transfer and thermal storage by using equations 3 and 4, respectively [45].

$$\overrightarrow{\mathrm{W}} = -\lambda \nabla \mathrm{T} \tag{3}$$

$$\nabla . \overrightarrow{\mathrm{W}} = -\rho c \frac{\delta \mathrm{T}}{\delta t} \tag{4}$$

Where $\overrightarrow{\mathrm{W}}$ is the heat flux vector at position (x,y,z), T is the temperature (°C) in the solid position (x,y,z), λ is the conductivity of the solid (W/m²K), c is the specific heat capacity of the solid (J/kgK) and ρ is the material density (kg/m^3).

This calculation method differs from the CIBSE methods by including time variance and secondly, it takes account of conductivity, density and specific heat capacity. This enables heat transfer and heat storage to be modelled, which offers greater rigor than the CIBSE methods. To simplify the calculation, ApacheSim assumes conduction in each building element to be uni-dimensional and thermo-physical properties for λ, ρ and c of each layer are assumed to be uniform. In order to solve Equations 3 and 4 over continuous building elements, ApacheSim adopts a finite difference method, which breaks up building structures into discrete elements [46].

Where fundamental equations such as the heat diffusion equation cannot be applied due to complexity, empirical models area applied. The McAdams and Alamdari & Hammond equations are used for external and internal convection from a surface, respectively [42]. These have been shown to fit experimental data and are applied to physical wall properties for specific temperature and dimensions and are calculated at every time step and adjusted dynamically [43].

IES software can use CIBSE Test Reference Years using historical data from the Met Office. Unlike the CIBSE methods, the ApacheSim modeller can use dynamic weather conditions to effectively model diurnal temperature cycles and effects of solar gains on each zone. Other areas which IES has dynamic modelling capacity include heat transfer by air movement, long-wave radiation heat transfer, solar radiation and internal gains. Detailed explanations of these calculation mechanisms lie beyond the scope of this dissertation.

2.3 Low-Carbon Pathways and Scenario Building

2.3.1 Energy and Carbon Scenarios

Energy scenarios have been widely used to consider potential future outcomes from the current position. The benefit of this is that scenarios can provide strategic insight on how different futures can arise under certain assumptions and three key energy scenario typologies are identified as trend-based studies, technical feasibility studies and modelling studies [47]. This dissertation seeks to apply scenario-based thinking on a microscale to answer key dissertation questions outlined in Section 1.4. A hybrid approach of a technical feasibility study and modelling study is applied, which is bounded by technical feasibility of energy systems and evaluated on the basis of modelling outputs.

In the context of existing buildings, energy scenarios can be applied based on incremental levels of building interventions. Previous studies have adopted a "no refurbishment", "minimum refurbishment" and "high-quality refurbishment" to represent different possible pathways [48]. Other studies have adopted an optimum intervention pathway by combining outputs from optimisations [39]. However, it is important to recognise that procurement processes are dominated by socio-economic concerns, such as disruption to occupants and cost. As such, it is rare for refurbishments to be undertaken as a combination of integrated interventions which may selectively span across both fabric and systems interventions. All refurbishment projects have greater risk profile than an equivalent new building project therefore, the incremental intervention approach is more likely to dictate the procurement process in reality [49].

2.3.2 Carbon Offsetting

Carbon offsetting is the process through which emissions can be offset by financing carbon savings elsewhere. It involves paying a carbon offset price to achieve a specific carbon saving. It plays a key role in the low-carbon frameworks outlined in Section 2.1, owing to the diversity of the building stock and limitations towards achieving net-zero carbon through on-site means only. As renewable energy generation is highly sensitive to location, carbon offsetting is the taken as a final step towards net-zero carbon emissions. It is important to note that in such cases the building will not be net-zero carbon in essence but would still achieve net-zero carbon status according to the aforementioned frameworks.

The carbon trading price is defined by the UK government, which is part of the European Union's emissions trading scheme, but this does not serve the same function as the carbon offset price, which can be defined in a decentralised manner. Regional building planning law such as Greater London Authority's (GLA) London Plan define an offset price of 95 £/tCO_2e [16]. The price has been defined at a level which is competitive with the cost of building upgrades to encourage higher performance building stocks in lieu of purchasing carbon offsets. Research on by the Committee on Climate Change and Centre for Climate Change Economics and Policy highlight that the carbon price should be set at 30 – 450 £/tCO_2e in order to instigate change to achieve net-zero carbon emissions from the UK building stock [50]. This dissertation adopts a carbon price of 95 £/tCO_2e, in line with the London Plan, which has been effective at stimulating low-carbon technologies at a regional and urban scale [17].

2.3.3 Carbon Factors

The Standard Assessment Methodology (SAP) is used to assess energy use and carbon emissions in line with Building Regulation Approved Document L in domestic buildings, while SBEM is the equivalent tool for non-domestic buildings, these indicate the grid carbon intensity in units of $kgCO_2/kWh$. In reality, the carbon intensity of the grid is highly volatile and varies depending on the energy mix at a given time, which may comprise of varying proportions of renewable generation. Adopting an average carbon factor can be problematic and involve forecasting uncertainties akin to scenario building, however, to avoid complexity in calculations the constant values are used for calculating total emissions related to building energy consumption.

UK national grid future energy scenarios highlight that all possible future scenarios have much higher levels of both overall renewable generation and decarbonised generation compared to today [51]. In light of these long-term electricity decarbonisation trends, the SAP electricity grid factor has been decreasing since 2012 (see Table 2.10). Despite being still in draft format, the SAP 10.1 grid factors will be used for the dissertation, this represents the grid intensity in its present state and is adopted for subsequent calculations.

Table 2.10: Changes to SAP grid carbon intensity factors from 2005 to late-2019

	Mains Gas ($kgCO_2/kWh$)	**Grid Electricity ($kgCO_2/kWh$)**
SAP 2005	0.194	0.422
SAP 2009	0.198	0.517
SAP 2012	0.216	0.519
SAP 10 (2018)	0.210	0.233
SAP 10.1 draft (2019)	0.210	0.136

Reductions in electricity carbon factors indicate that the same unit of delivered primary electrical energy is becoming less carbon intensive. This is important when analysing the feasibility of building technology as these values suggest that shifting primary energy demand from gas to electricity is advantageous from a carbon emissions point of view.

2.4 Summary of Literature Review

The literature review has defined the scope of net-zero carbon emissions in embodied, operational and transport-related emissions. Various low-carbon frameworks and guidance seek to provide clarity on how this can be achieved, although at the time of writing, these only address embodied and operational emissions and adopt either performance-based or prescriptive standards. Of the frameworks discussed, all adopt a hierarchical structure for reducing carbon emissions, with a primary focus on fabric improvement, then energy efficiency and finally greening the supply through renewable generation. Therefore, a low-carbon building must also be a low-energy building. However, in order to understand what low-energy means in practise, standardised energy benchmarking metrics must be used. This is essential for understanding how different building compare to one another irrespective of the building area and a number of best practise figures are published by CIBSE. In the context of heritage buildings, there are no specific low-carbon guidelines. Despite this, technical solutions are available, and case-studies published by Historic Scotland provide detailed guidance on how to implement these. Hence, low-carbon frameworks may be adapted with technical guidance for application in heritage buildings.

Building energy modelling is widely used in industry as a Building Regulations compliance tool and is not representative of the actual building energy performance. The CIBSE TM44 method seeks to overcome this, and combining this with IES modelling, can be used to for robust energy assessments for optioneering of LCIs. Building carbon intensity is highly sensitive primary energy carbon intensities. Grid electricity carbon intensity has been steadily decreasing over the last 8 years in a trend that is expected to continue. This provides windows of opportunity for applying electric technologies which were previously environmentally unfavourable due to greater electric grid intensities.

3 EXISTING BUILDING ENERGY AUDIT

3.1 METRED DATA

Energy utility data has been provided by the University Estates Department, which covers gas and electricity usage in 2019 in kWh. In the absence of submetering, the recorded data provides lumped energy consumption as recorded by the utility provider. This has been aggregated over each month to provide the monthly annual demand profiles for Minto House (see Figure 3.1; 3.2). Due to the lack of submetering, the data fails to provide a demand breakdown of different building loads, which would otherwise be highly useful to refine building energy management strategies through identification of energy performance across different regions of the building or across different types of demand.

All electricity meters must be installed to British Standard specifications and must meet Class 2 accuracy requirements for one of the following standards: BS EN62053-21:2003 or alternatively BS 8431:2010, and ensures that measurement is accurate and mitigates against systematic error and uncertainty [52]. Similarly, depending on the type of gas meter installed the following British Standards are applied: BS EN1359:1999 for a diaphragm gas meter, BS EN12480:2002 for a rotary displacement gas meter and BS EN12261:2002 for a turbine gas meter [53]. This implies that readings obtained are an accurate indicator of actual energy use in Minto House and can serve as a useful measure of current building energy performance.

The total carbon emissions have been obtained by multiplying the relevant carbon emission factors for grid natural gas and electricity. The SAP 10.1 carbon intensity factors have been adopted, which are 0.210 and 0.136 $kgCO_2/kWh$ for mains gas and grid electricity, respectively.

3.2 METERED ENERGY PERFORMANCE FOR 2019

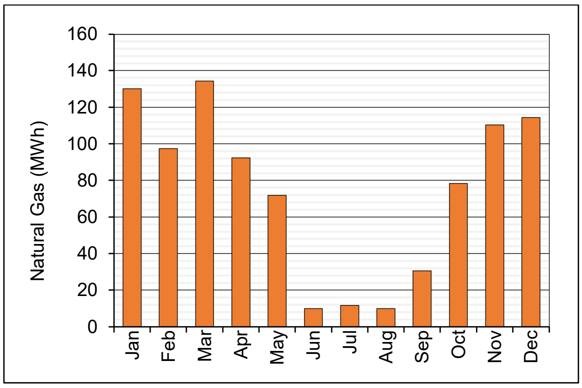

Fig 3.1: Metred monthly gas consumption for 2019, showing seasonal trend for heating demand.

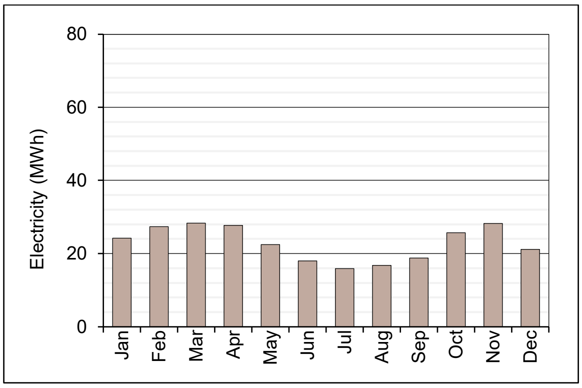

Fig 3.2: Metred monthly electricity consumption for 2019.

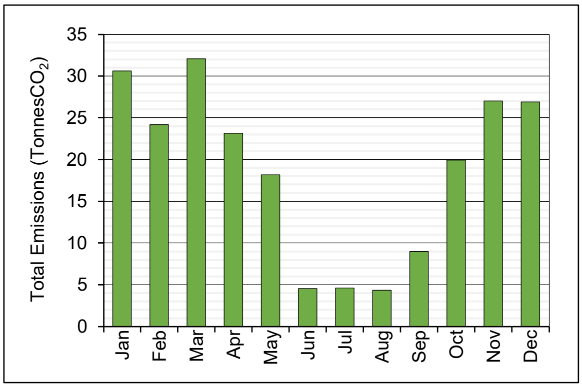

Fig 3.3: Existing building monthly CO_2 emissions based on metred utility data for 2019 and SAP10.1 carbon intensity factors.

Table 3.1: Existing building energy and carbon summary, from 2019 metred data.

	Energy Usage	Carbon Emissions
	(MWh)	(tCO_2)
Gas	891	187.1
Electricity	275	37.3
Total	-	224.5

3.3 SECTION CONCLUSIONS

As expected, natural gas demand exhibits a seasonal response, whereby greater demand is seen during colder months due to central heating demand increase. A dramatic reduction in use over the months of June, July and August, is noted to be indicative of a simple seasonal control system, which turns the central heating off during these months. A baseline demand is present in these months however, which may be due to a persistent hot water demand. The lower than expected demand in February may be accounted for by the Met Office annual summary for 2019, which highlights that February 2019 was “notably warm” across the UK [54].

Electricity consumption also follows a seasonal profile. A reduction in electricity consumption is observed during academic calendar vacation periods, which are most evident in the months of June, July, August and December. The extent of this seasonal variation is indicative of the impact of that occupancy can bear upon overall energy consumption and the electricity demand increases by a factor of 1.8 from July to November 2019.

Carbon emissions are more sensitive to variations in gas consumption and similar annual consumption profiles are observed. The SAP10.1 carbon intensity value for mains gas is 65 per cent higher than the grid electricity carbon intensity and a proportionally weighted impact is observed on overall carbon emissions, gas consumption accounts for 83 per cent of the total. This is indication that gas demand reduction is a priority area for decarbonising Minto House.

4 IES MODEL FOR EXISTING BUILDING

4.1 MODEL INPUTS

4.1.1 Climate and Site

A large proportion of energy use in building is expended through heating, cooling or lighting and all of these are impacted by the external environment. Irrespective of external environmental conditions, buildings must provide comfortable internal conditions and are expending energy to that end. External climatic conditions have a direct impact on energy consumption and geographically appropriate weather data should be used to model the external environment in energy simulations. Test Reference Year (TRY) hourly annual CIBSE weather data for Edinburgh has been used for energy simulations. TRY weather files are constructed from 30-years of Meteorological Office readings and average months are selected from 1984 – 2013 to cover one year. Applying this dataset represents the expected energy performance of Minto House across an average year.

The site microclimate has been accommodated for by importing satellite data for surrounding buildings and structures. This accounts for topographical shading and wind shelter but does not account for other microclimate impacts such as the urban heat island effect and solar reflectance. This would create further modelling complexity and lies outside the scope of IES modelling capabilities.

Figure 4.1: Plan view of IES model for Minto House, surrounding adjacent structures shown in pink and Minto House shown in purple.

4.1.2 Geometry

Building geometry has been obtained from architectural general arrangement (GA) plan drawings and from historical record drawings provided by the University of Edinburgh Estates Department. Where possible, dimensions from historical record drawings have been validated on site by measuring external façade elements of Minto House. Glazing geometry and positions are been modelled based on historical record elevation drawings. Due to the age of the building, some record information is incomplete or superseded, in such instances, a combination of site analysis and the most recent record information has been used. Internal room volumes are estimated from floor to ceiling heights measured from building elevations and wall thicknesses. The gross internal floor area (GIA) has been generated within IES from room constructions based on plan GA drawings and is equivalent to 4850 m².

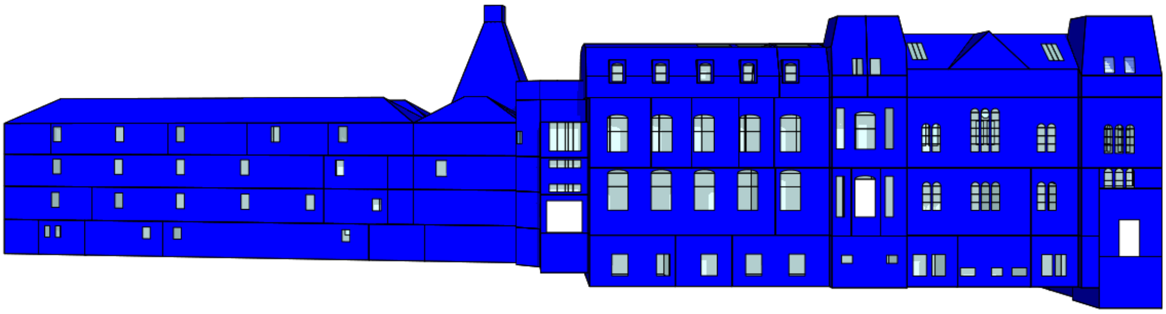

Figure 4.2: IES model geometry for Minto House, showing building structure and glazing. Viewed from the south-facing elevation towards Chamber's Street.

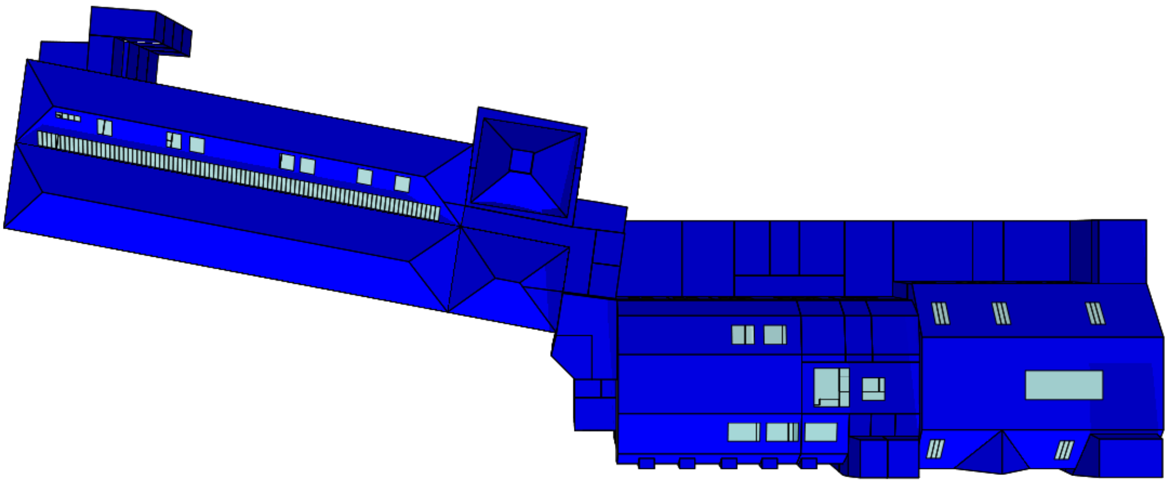

Figure 4.3: IES model geometry for Minto House, showing roof structure and glazing. Viewed in plan, from above.

4.1.3 Fabric

Due to closure of university buildings from Spring 2020, detailed fabric assessments and in-situ measurements of the building thermal fabric were not possible. Hence, a research-based assessment of the thermal performance for building fabric is presented. Building element constructions are modelled using IES construction database manager according to CIBSE guidelines and empirical U-value measurements of similar build-ups, where published literature is available. Where the CIBSE data has been applied, U-value estimates may be conservative, Historic Environment Scotland research highlights that traditional building elements tend to perform better than expected when compared to software calculated U-values [55].

Thermal Insulation

The thermal fabric of the building is compartmentalised into 4 distinct zones. External site analysis indicates that the building envelope differs across these zones in their material build-ups and therefore are modelled with different thermal properties, where applicable. The thermal properties used across these zones are presented in tabular form (see Table 4.1; Table 4.2). Full site assessment details can be found in Appendix 10.2.

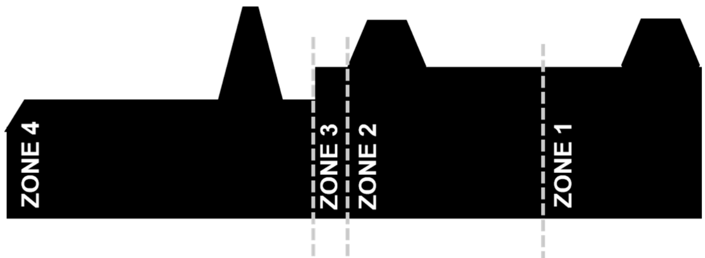

Figure 4.3: Block elevation diagram showing the thermal fabric 'zones' identified across Minto House from external observations of glazing systems, wall and roof constructions.

Table 4.1: Thermal fabric properties zonally assigned to Minto House for modelling.

	Door	**Wall**	**Window**	**Roof**
	(W/m^2K)	(W/m^2K)	(W/m^2K)	(W/m^2K)
ZONE 1	0.16 [56]	1.1 [55]	5.4 [56]	0.7 [55]
ZONE 2	0.16 [56]	1.1 [55]	5.75 [56]	0.7 [55]
ZONE 3	2.76 [56]	2.09 [56]	5.4 [56]	2.35 [56]
ZONE 4	0.12 [56]	1.1 [55]	5.4 [56]	0.7 [55]

Table 4.2: Thermal fabric properties of generic building elements applied across all zones, where appropriate (internal wall A and internal wall B define two different internal wall structures identified from general arrangement drawings).

	Exposed Floor	**Internal Floor**	**Internal wall: A**	**Internal wall: B**	**Roof Skylights**
	(W/m^2K)	(W/m^2K)	(W/m^2K)	(W/m^2K)	(W/m^2K)
Generic	3.5 [55]	1.64 [56]	1.45 [56]	1.1 [55]	3.32 [56]

Thermal Bridging

Thermal bridging is used to describe a path of least thermal resistance which can occur along interfaces between materials of different thermal properties. Thermography is an effective tool which can be used to analyse thermal bridging first-hand and on-site. In practise, thermal bridging is an important aspect of the thermal fabric and can lead to the build-up of interstitial condensation [34]. For dynamic thermal simulations, IES applies thermal bridging by applying a factor to the overall element U-value [43].

Airtightness

An air permeability value of 20.0 ($m^3/m^2.h$ at 50 Pa) has been used from Table 4.16 from CIBSE guide A: Environmental Design [42]. This is applicable to leaky buildings with poor airtightness, as is expected for Minto

House due to its age. This has been translated into an infiltration rate of 0.75 air changes per hour for input into the energy model.

Dynamic performance

The dynamic thermal performance refers to the impact of thermal mass on the energy model. This has been modelled by inputting build-up and construction thicknesses for fabric elements such as walls, doors, roofs and ceilings. The ApacheSim thermal modelling calculation accounts for this through thermal storage, as explained in Section 2.2.

Moisture movement

Moisture movement is accounted for by the basic hygroscopic properties of assigned materials within the building construction manager.

Glazing

Glazing U-values have been obtained from literature (see Table *4.1*; Table *4.2*). No internal blinds or curtains have been assumed, based on no record of such in building management data, which would otherwise increase the level of thermal insulation from external conditions.

4.1.4 Building Systems

The CIBSE Technical Memoranda 54 (TM54) provides a process for accurately modelling building systems and have proven to be an accurate process of energy modelling buildings [57]. This has been adopted as the process for modelling building systems for Minto House. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provide an extensive collection of room data related to type of activity, based on typical room benchmarks. Where it has not been possible to obtain building use data (E.g. occupancy, size of heat emitters etc) due to closure of University buildings, ASHRAE building templates have been used. These have been used in lieu of CIBSE room benchmarks due to a greater granularity in room type data, such as higher education workshops, offices, lecture theatres, seminar rooms and WCs.

Table 4.3: High level modelling inputs according TM54 methodology for Minto House base case IES model.

Step 1	Establishing floor area	Reference
	Gross Internal Area (GIA): 4850 m²	Obtained from geometry information
Step 2	Operating hours and occupancy	Reference
	Mon – Fri (0700 - 2100) Sat – Sun (0900 - 1700)	Building management information
	Floor area per person /m²: based on room type	ASHRAE IES room templates
Step 3	Lighting energy use	Reference
	Lighting use lumens/m²: based on room type	ASHRAE IES room templates
	Lighting efficiency lumens/W: assumed to be fluorescent	IES default for fluorescent lighting
		No record of LED upgrade found
Step 4	Energy for elevators	Reference
	One elevator from GA drawings, 10 ascents/day: 9 kW	CIBSE TM54
Step 5	Energy for small power	Reference
	Small power use W/m²: based on room type	ASHRAE IES room templates
Step 6	Energy use for catering	Not applicable to building type
Step 7	Energy for server rooms	Not applicable to building type
Step 8	Energy use for other equipment	Not applicable to building type
Step 9	Energy use for Domestic Hot Water	Reference
	Linked to occupancy litres/person: based on room type	ASHRAE IES room templates
Step 10	Evaluating internal heat gains	Reference
	Occupancy gains: W	Linked to IES ASHRAE templates and area
	Lighting gains: W	Linked to IES ASHRAE templates and area
	Small power gains: W	Linked to IES ASHRAE templates and area
Step 11	Energy use for space heating, cooling and pumps	Reference
	Boilers seasonal efficiency: 95.44% [58]	Building management information
	Internal set point temperatures target	Building management information
	Maximum heating output: 87 W/m²	CIBSE guide F: Table 13.1
	No cooling present	Building management information
	Hot water system: IES default efficiency values	(No efficiencies available from information)
Step 12	Energy use for dehumidification	Not applicable to building type
Step 13	Estimating management factors	Reference
	No weather compensation	Assumption based on 2019 building utility data
	Heating turns off when building unoccupied	Building management information
	Heating turns off from 01/06 – 31/08	Building management information

Room data has been collated from building management data, record drawings and access to Building Management System (BMS) documents provided by the Estates Department. This defines several different room types, which can differ on the basis of utility, heating system, ventilation type and heating set-point and any variation in these must be defined as a separate room type. Therefore, various room types have been modelled based on these differences (see Table *4.4*).

Table 4.4: Building level and room utility specific system data entered into IES for base case model.

Level	Room Type	ASHRAE Template	Heating System	Ventilation Type	Set Point (°C)
B	Workshops	Workshop	Air handling unit	Local extract only	21
	Offices	Enclosed office	Radiators	Natural	21
	Lecture theatre	Auditorium	Air handling unit	Local supply/extract	20
	Seminar rooms	Lecture room	Radiators	Natural	21
	WC	Restroom	Radiators	Natural	21
G	Teaching space	Lecture room	Fan coil units	Natural	22
	Library	Library	Fan coil units	Natural	22
	Office	Enclosed office	Fan coil units	Natural	22
	WC	Restroom	Radiators	Natural	21
1	Office	Enclosed office	Fan coil units	Natural	22
	WC	Restroom	Radiators	Natural	21
2	Teaching space	Lecture room	Radiators	Natural	21
	Teaching space	Lecture room	Radiators	Natural	21
	Office	Enclosed office	Radiators	Natural	21
3	Teaching space	Lecture room	Radiators	Natural	21
	Teaching space	Lecture room	Radiators	Local extract only	23
	Office	Enclosed office	Radiators	Natural	21
All	General circulation	Corridor/transition	Radiators	Natural	19

4.2 Modelled Existing Energy Performance

This section outlines the modelling results obtained from IES energy modelling of the existing building. Primary energy use by type and carbon emissions have been exported over the test reference year weather file. 'Natural gas' refers to the gross gas demand seen by the boiler and is representative of both heating and domestic hot water demand for Minto House. Electricity demand is broken down into lighting, small power and system. 'Small power' refers to plug loads (unregulated electricity demand), which is driven by occupant usage. Conversely, 'System' corresponds to electrical demand for building services, which includes pumps, fans and ancillary equipment and is defined by efficiency factors, hence is categorised as a 'regulated' load in Building Regulations, which must meet certain efficiency criteria [14].

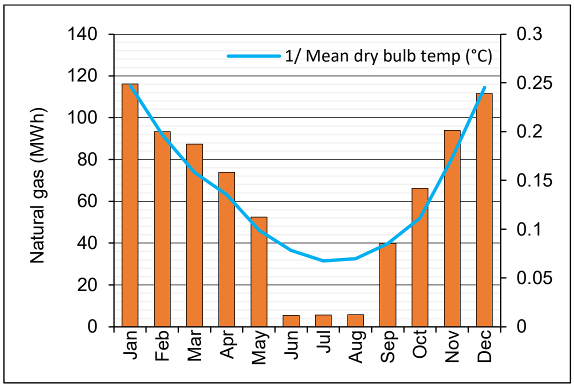

Fig 4.4: Existing building monthly gas consumption output from IES over the test reference year (MWh). Reciprocal of mean monthly dry bulb temperature plotted on same axis to show variation in seasonality and impact of external temperature.

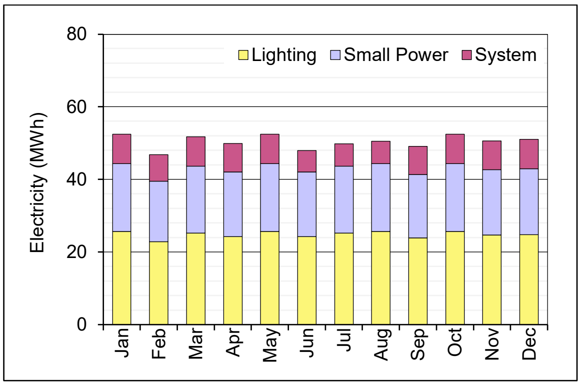

Fig 4.5: Existing building monthly electricity consumption and breakdown from IES over the test reference year (MWh), remains largely constant and minor variations are observed.

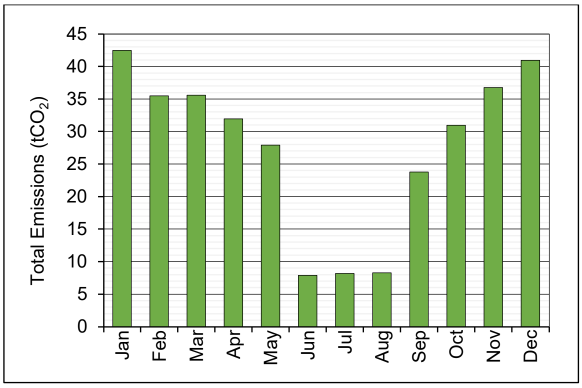

Fig 4.6: Existing building monthly carbon emissions (tCO_2), calculated from cumulative monthly primary energy demand and SAP 10.1 carbon intensity factors.

Table 4.5: Energy use and carbon emission metrics obtained from IES for existing building.

	Energy Usage (MWh)	Carbon Emissions (tCO2eq)
Gas	752	157.8
Electricity	605	82.2
Total	-	240.0

Table 4.6: Peak loads obtained from IES for Minto House

Demand Type	Peak Loads (kW)
Heating Demand	508.6
Electricity Demand	137.8

Natural gas consumption follows a seasonal profile that is dependent upon external conditions, this is evident from reciprocal of the external dry bulb temperatures which correlate to the gas consumption. Shoulder seasons, particularly the months of March, April and October are higher than the external conditions would suggest, however this may be explained by the wet-bulb temperatures as these months generally experience greater rainfall. Higher relative humidity requires more energy to increase the temperature to the setpoint. The majority of this demand arises for space heating, which is diminished in summer months, when the heating is turned off.

Electricity consumption profile follows a consistent profile throughout the year that is less impacted by the external weather conditions. It is largely impacted by behavioural aspects of building use which extends to occupancy factors, room usage type and lighting. Due to the prescriptive nature of the model, which assumed constant occupancy profiles, very little seasonal variation is observed.

Although gas demand is approximately 25 per cent higher per annum, the contribution to carbon emissions is magnified by a factor of 1.54, which represents the difference between mains gas and grid electricity carbon intensity. Where, 0.21 $kgCO_2/kWh$ 0.136 $kgCO_2/kWh$ are carbon intensity factors for mains gas and grid electricity, respectively. As such, interventions which target reductions in gas consumption should be prioritised in order to achieve greater impact on carbon emissions reduction. This also indicates that substituting electric heating in lieu of gas would be advantageous for reducing carbon emissions.

Peak loads are important metrics for understanding how the building demands energy, and this is what building services systems are sized to deliver. In the context of LCIs this is important in assessing how different strategies can lead to reduced energy demand and system output. Peak heating load is indicative of the building thermal performance, whilst peak electrical load is indicative of the processes and equipment utility. Hence, analysing peak loads can provide insight into the efficiency gains of building fabric or systems through LCIs.

Whilst peak heating loads are important metrics to understand building thermal behaviour, annual increases in summer dry bulb temperatures may lead to greater deployment of Air Conditioning (AC) for space cooling. In this scenario, space conditioning loads will no longer be seasonally tied to the coldest months, which is observed in gas boiler demand. Conversely, space conditioning demands will occur across both the coldest and warmest months, taking a larger annual share of the overall building energy consumption. In sum, greater adoption of AC is expected to increase electrical space conditioning demand substantially.

4.3 COMPARISON TO METRED ENERGY PERFORMANCE

This section compares the recorded data for 2019 to the energy modelling results achieved from IES modelling over a typical year.

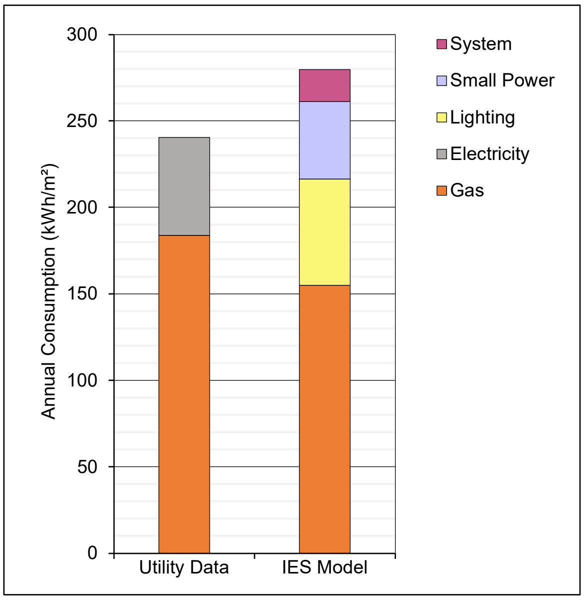

Figure 4.6: Annual performance of existing building based on utility data and IES modelling, consumption normalised over a constant gross internal area of 4850 m^2.

Table 4.7: Metred utility data energy and carbon performance values for 2019.

	Energy Usage (MWh)	Carbon Emissions (tCO_2)
Gas	891	187.1
Electricity	275	37.3
Total	-	224.5

Table 4.8: IES modelling energy and carbon performance values over the average year.

	Energy Usage (MWh)	Carbon Emissions (tCO_2)
Gas	752	157.8
Electricity	605	82.2
Total	-	240.0

Gas consumption follows a similar seasonal trend, with maxima occurring in January and December in both cases. The months of June, July and August have a significantly lower gas consumption for both cases, although the metred data indicates a higher base-load gas consumption which persists over these months. The IES model predicts this base load to be an average of 21 per cent lower over these months and overall annual gas consumption is 16 per percent lower than the utility data. This provides a key insight that the IES model has higher thermal performance than the existing building, based on utility consumption for 2019. A lower thermal performance indicates that the existing building demands greater energy input to achieve the same set-point temperatures, which is reflected in the increased gas consumption. On a wider level, this indicates that model inputs for building fabric have been assumed more favourably than what is evidenced by 2019 utility data. Another insight is that the heating system delivery efficiency may not be as efficient as is assumed by the IES model and therefore losses are incurred in delivery of heat to spaces.

No seasonality is observed for the electricity consumption in the IES model, which differs to the utility data. This is due to the occupancy profiles assigned to the IES model which have been assumed to be constant throughout the duration of the year. In reality, the existing building will see cyclical occupancy patterns in line with the academic calendar and with further model refinement, seasonality could be simulated through occupancy variation. The magnitude of electricity consumption varies significantly between the two cases, and the utility data is seen to be 45 per cent of the IES predicted electricity consumption. By virtue of assigning room templates, it is implicitly assumed that all lighting, equipment and systems are used at a prescribed capacity for the occupied hours of the building. As such, the IES model appears to overpredict electricity consumption, as this would entail constant electricity demand linked to occupancy. In reality, due to the variation in occupancy, these loads are substantially lower, and the building is not fully occupied to its full capacity during hours of operation – as is assumed by the IES model.

For both the utility data and IES model, carbon dioxide emissions are dominated by the gas consumption, which is due to the difference in mains carbon factors. The carbon emissions from the metred data and IES model are within less than 10 per cent of one another. However, this is largely due to the overestimation of electricity loads and underestimation of gas demand in IES, coupled with grid carbon intensity factor, has smoothed differences when observing lumped carbon emissions. The heating accounts for 83 per cent per cent of carbon emissions for utility data, whilst accounting for only 66 per cent according to the IES model, which is indicative of the share of gas and electricity demands.

The CIBSE F hybrid benchmark states 'typical' energy performance for a similar building as 136.5 kWh/m^2 for gas consumption. Both the metered utility data and existing base case data indicate that Minto House is in excessive of this performance benchmark, achieving 184 kWh/m^2 and 155 kWh/m^{2,} respectively. In both scenarios it highlights that Minto House performs poorly and is indicative of poor thermal fabric efficiency. The 'good' performance benchmark is stated as 93.1 kWh/m^2, the difference between current performance (measured and simulated) highlights the crux of the decarbonisation challenge for Minto House.

The IES model overpredicts the electricity consumption by a factor of 2.2 and underpredicts the heating demand by a factor of 0.8. This discrepancy has two key reasons, firstly, the model is subject to a number of research-based assumptions which dictate the modelling results. Secondly, metered energy data is a measure of energy used in 2019, whereas the IES energy model is based on the average climatic year. However, further to personal communications and academic research, it is understood that the energy model need not be a true representation of the actual building and that discrepancies with utility data do not devalue the conclusions presented in this dissertation.

4.4 Sensitivity Analysis

This section assesses the sensitivity of results obtained from IES, based on changes to assumptions made during the initial modelling process. The sensitivity analysis of the IES model provides useful insight into how underlying modelling assumption can impact the overall energy consumption. The degree of impact these assumption have on the final consumption is indicated (see Table 4.9) .

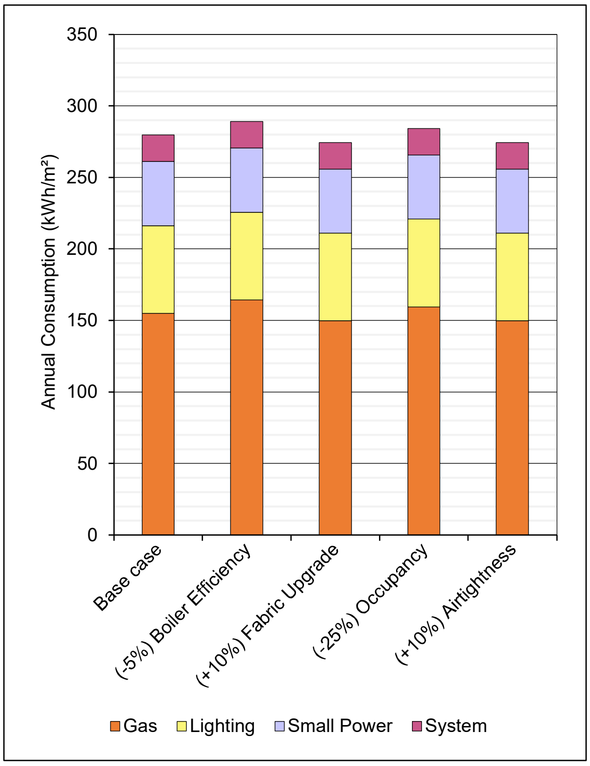

Figure 4.7: Sensitivity testing of overall energy consumption breakdown (normalised over a constant GIA), results displayed in kWh/m^2 for different variations in base case model.

Table 4.9: Sensitivity testing gas and electricity consumption values with percentage difference from the base case.

Modelling Scenario	Gas		Electricity
	(kWh/m^2)	± %	(kWh/m^2)
Base case	157	-	125
(-5%) Boiler efficiency	164	+4.5	125
(+10%) Fabric U-values	150	-4.5	125
(-25%) Occupancy	159	+1.3	125
(+10%) Airtightness	150	-4.5	125

Key insights gathered from this process include:

- Reducing the boiler efficiency from 95.44% to 90% results in an almost proportional increase in overall gas consumption of 4.5 per cent.
- Increasing the fabric U-values for walls, windows and roofs by 10% has been shown to achieve a 4.5 per cent reduction in gas consumption.
- Reducing occupancy by 25 per cent, results in a small 1.3 per cent increased gas consumption. This is a relatively small change in comparison to other measures, which highlights the model is not highly sensitive to occupancy changes.
- Airtightness improvements deliver similar improvements to fabric efficiency.

The sensitivity analysis indicates that the model is more sensitive to boiler and system efficiency, than thermal fabric properties. Although improvements to thermal fabric have been shown to reduce gas consumption, they do not do so with the same magnitude of impact. Occupancy factors have been shown to have a very limited impact on the IES model, as this only impacts the amount of sensible heat gain from occupants. Therefore, reducing the occupancy by 25 per cent has resulted in greater gas consumption, due to the need to supply more heating to spaces. Of the variables assessed, none had any impact on the electrical consumption due to the prescriptive nature of small power demand modelling.

4.5 Uncertainties in Modelling

Energy modelling provides estimates into energy performance of a building over a typical year, whilst the utility data indicates how much energy the building used over a defined period of time. These two measures represent different aspects of building energy performance and it is widely accepted that they should not be mixed [8] [12]. Conversely, an energy model should be used as a baseline upon which design interventions can be assessed based on their relative merits [11]. Within this, there are inherent assumptions and limitations of energy models which will be discussed in this section. Furthermore, due to the absence of internal site visits and prolonged closure of university buildings, a number of assumptions have been made in order to construct the IES model and the full input parameters are shown in Section 4.1.

The first key assumption which has been made relates to the building fabric. Typically, assessment of building fabric would take place through in-situ U-value testing, however in the absence of such a detailed assessment, literature-based assertions have been made relating to the expected thermal envelope performance. The sensitivity analysis shows that 10 per cent variation in assumed U-values can impact the overall gas consumption in the order of ± 5 per cent.

As well as the macro-level properties of fabric, such as thermal performance, assumptions have been made surrounding the construction and build-up for building elements such as roofs, floors, walls, doors and glazing. In historic buildings the material build-up can play an important role in regulating internal humidity and temperature through the use of appropriate material finishes and thermal mass. As such, the dynamic thermal response is subject to assumptions which relate to building fabric construction layers. Where possible, these assumptions have been grounded in heritage literature from Historic Scotland and CIBSE. Assessment of airtightness shows that this has a similar impact on the overall thermal performance, when compared to proportional improvements to U-values. A constant infiltration rate (airtightness) has been assumed for the building, however the reality is that different parts of the building may possess different infiltration properties, which is exacerbated by thermal bridging and a greater number of glazed openings. However, the sensitivity analysis shows that a 10 per cent variation would result in less than ± 5 per cent. Therefore, this assumption is not expected to significantly detriment the validity of the energy model.

Occupants can play a key role in steering building energy demand and occupancy factors have been applied based on ASHRAE room templates [21]. These are assumed to be representative of how individual spaces are used within the building, based on their function. Whilst this is a useful tool for assessing the maximum possible loads, in reality, the occupancy varies significantly throughout the hours of building operation. In addition, the base case model fails to capture individual occupant behaviours and agency towards energy consumption. A more complex model could replicate assumed occupancy factors and statistical probabilities, however, this level of complexity falls outside of the scope of this dissertation and would not provide any additional significant benefit to assessing

LCIs in Minto House. For the base case model all loads related to the room types remain fixed, and lighting, small power (plug loads) and system remain static.

In the absence of a site visit, existing building services system operation has also been assumed, where possible data from existing building services have been used. Boiler efficiency has been obtained from manufacturer data sheets, however ancillary equipment including, fan coil units, fans and pumps have been assumed based on IES default typical values. Of these assumptions, the most significant is the boiler efficiency, the sensitivity analysis shows that a 5 per cent reduction in efficiency results in a 4.5 per cent increase in gas consumption. The boiler is more sensitive to changes in efficiency due to its relative power output, which has a greater bearing on overall energy consumption, due to a substantial annual gas demand. Smaller power ancillary equipment efficiencies are not expected to have a significant impact on the overall energy profile, due to being substantially lower power and therefore influencing the overall energy consumption and carbon emissions far less. Hence, the assumptions for smaller power equipment are not expected to impact the modelling results and validity of the energy modelling.

4.6 Section Conclusions

This chapter shows that the existing building consumes more natural gas than predicted by the IES model, which highlights that the existing building has an inferior thermal efficiency to what has been assumed in the modelling. Conversely, the IES model predicts significantly more electricity consumption that what was recorded in 2019, which brings into question some of the underlying assumptions relating to equipment (and lighting) efficiency and patterns of use. Specifically, this brings into question the assumption regarding LED lighting and suggests that an LED upgrade may have already occurred within Minto House. However, both the metred and modelled data evidence that the gas consumption should be targeted and prioritised to reduce carbon emissions.

The IES model is used as the baseline model and is adopted as a representation of the existing building for this study. Any improvements to the IES model through LCIs are indicative of the improvements that may be expected in reality, therefore modifying input parameters and developing virtual prototypes for LCIs can be an informative process in assessing carbon impact. This is not possible when using the metred data as the baseline model cannot be interrogated and built-up from in the same manner. In addition, by virtue of the measurement period being for 2019 only, it cannot be used to predict what will occur on average, but rather it serves as purely a measurement of what was used by the building over 2019. Hence, for this study, the base case IES model provides the precedent upon which LCIs can be compared and evaluated. In addition, the methodology of using an energy model as a base case is supported by low-carbon frameworks and regional planning code, and is therefore established as the base case model for this study [16] [19].

Due to the scale of the heating demand, boiler efficiencies have a substantial impact on overall energy consumption and carbon emissions. From an operational point of view, this highlights that the University should be cognizant of equipment efficiency loss and adopt a robust maintenance system to ensure high power equipment is operating as close as possible to peak efficiency. In a wider sense, this also ties into submetering and energy measurement in order to identify opportunities for improving system efficiency, something that Minto House is currently lacking [12].

5 IES MODELLING LOW CARBON INTERVENTIONS

5.1 Fabric Interventions

This section compares and contrasts the carbon impact of several different fabric interventions, which are applied to the base case model individually. These interventions improve the thermal performance of the building, hence are expected to result in reduced heating demand (MWh) and peak heating loads (kW) for Minto House. The interventions assessed are upgrades to roof insulation (F1), internal wall insulation (F2), floor insulation (F3) and secondary glazing (F4). These have been selected based on their demonstrated applicability within a listed building and have been guided by the literature review.

5.1.1 Roof Insulation (F1)

Literature from Historic Environment Scotland shows that insulation levels can be improved through the use of proprietary organic insulating materials, which are vapour permeable. A U-value improvement to 0.2 W/m²K has been shown to be achieved through the use of hemp wool [35] [36].

Table 5.1: Proposed roof insulation target U-values with the appropriate methodology.

	Current Roof Performance	**Improved Performance**	**Proposed Methodology**
	(W/m²K)	(W/m²K)	
ZONE 1	0.7 [55]	0.2 [35] [36]	275mm hemp wool insulation applied to ceiling
ZONE 2	0.7 [55]	0.2 [35] [36]	275mm hemp wool insulation applied to ceiling
ZONE 3	2.35 [56]	0.2 [35] [36]	275mm hemp wool insulation applied to ceiling
ZONE 4	0.7 [55]	0.2 [35] [36]	275mm hemp wool insulation applied to ceiling

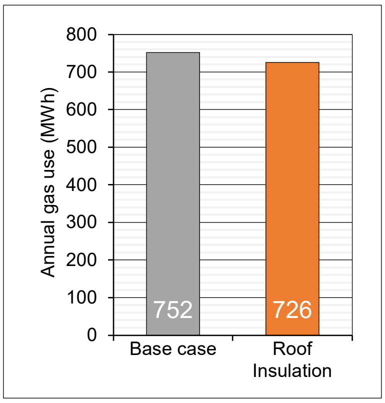

Figure 5.1: Roof insulation LCI model and base case model annual gas consumption comparison. Roof insulation reduces annual gas demand by 26 MWh.

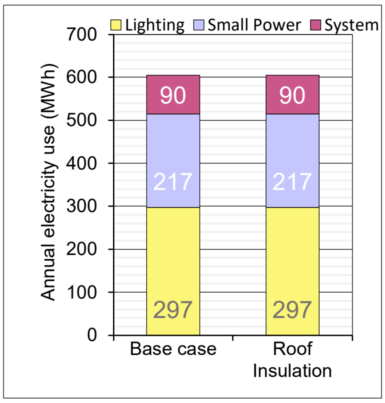

Figure 5.2: Roof insulation LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the application of roof insulation.

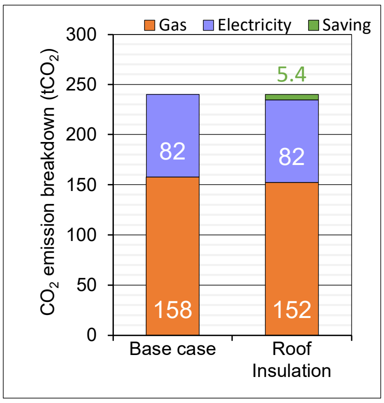

Figure 5.3: Roof insulation LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 5.4 tCO_2.

Table 5.2: Comparison of peak heating and electricity loads before and after roof insulation LCI.

	Peak Loads: Base Case	**Peak Loads: F1 LCI**
	(kW)	(kW)
Heating Demand	508.6	507.6
Electricity Demand	136.7	136.7

- Improvement of roof insulation alone achieves a reduction of 26 MWh (3.5 per cent) of annual gas consumption.
- Electricity demand remains constant as the roof fabric does not impact the electrical usage patterns of the building. These are directly impacted by room types and electrical equipment efficiency, which is outside of the scope of impact for a fabric upgrade.
- As a consequence of the reduction in gas demand, 5.4 tCO_2 (2.3 per cent) are reduced from the base case scenario.
- Improvement of thermal fabric means that the boiler maximum power demand is reduced, although this constitutes only a marginal reduction in the peak heating load (> 0.5 per cent). Peak electrical loads remain constant as no impact is observed upon the electrical energy demand.

5.1.2 Internal Wall Insulation (F2)

Historic Environment Scotland research indicates that internal wall insulation of historic buildings can vary in type and thermal performance [27]. Based on this, the appropriate internal wall insulation has been applied, which is sensitive to the expected wall constructions in different building zones.

Table 5.3 Proposed internal wall insulation target U-values with the appropriate methodology.

	Current Wall Performance	**Improved Performance**	**Proposed Methodology**
	(W/m²K)	(W/m²K)	
ZONE 1	1.1 [55]	0.21 [27]	100mm hemp board between timber straps
ZONE 2	1.1 [55]	0.21 [27]	100mm hemp board between timber straps
ZONE 3	2.09 [56]	0.31 [27]	50mm bonded polystyrene bead
ZONE 4	1.1 [55]	0.21 [27]	100mm hemp board between timber straps

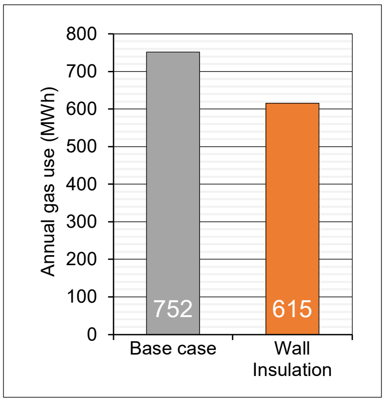

Figure 5.4: Wall insulation LCI model and base case model annual gas consumption comparison. Wall insulation reduces annual gas consumption by 137 MWh.

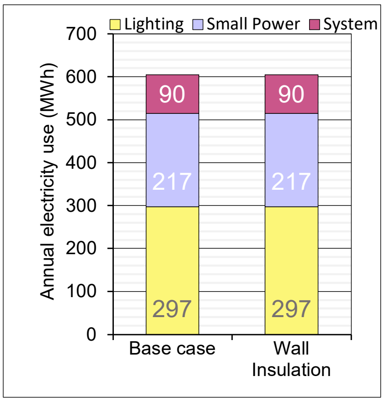

Figure 5.5: Wall insulation LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the application of wall insulation.

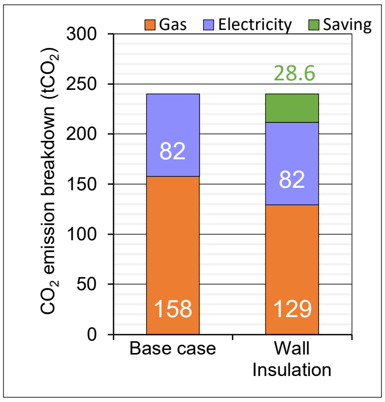

Figure 5.6: Wall insulation LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 28.6 tCO_2.

Table 5.4: Comparison of peak heating and electricity loads before and after wall insulation LCI.

	Peak Loads: Base Case	**Peak Loads: F2 LCI**
	(kW)	(kW)
Heating Demand	508.6	498.6
Electricity Demand	136.7	136.7

- Improvement of wall insulation achieves a 137 MWh (18.2 per cent) reduction in annual gas consumption.
- Electrical consumption remains constant as fabric improvements do not impact how electricity is used within the building.
- A reduction of 28.6 tCO_2 (11.9 per cent) is achieved in carbon emissions against the base case model.
- The peak heating demand is reduced by 2.0 per cent, by virtue of improving the thermal fabric. Peak electrical loads remain constant as no impact is observed upon the electrical energy demand.

5.1.3 Floor Insulation (F3)

Floor insulation upgrades are proposed based on case studies of similar retrofit upgrades [35] [37]. These have been applied based on the type of floor, which varies from exposed floors (basement floors) and internal floors between building levels.

Table 5.5: Proposed floor insulation target U-values with the appropriate methodology.

	Current Performance	Improved Performance	Proposed Methodology
	(W/m²K)	(W/m²K)	
Exposed Floor	3.5 [55]	0.8 [37]	30mm Aerogel board
Internal Floors	1.64 [56]	0.7 [35]	80mm wood fibre insulation batts

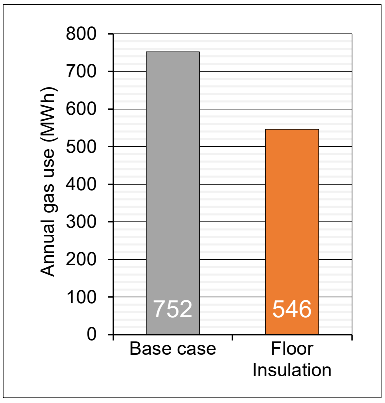

Figure 5.7: Floor insulation LCI model and base case model annual gas consumption comparison. Floor insulation reduces annual gas consumption by 206 MWh.

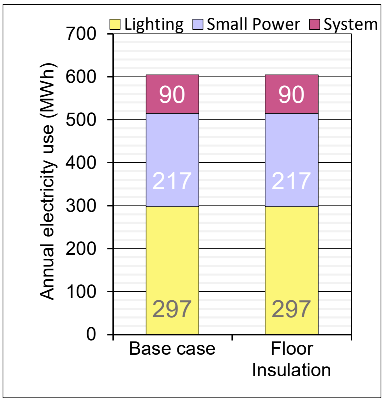

Figure 5.8: Floor insulation LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the application of floor insulation.

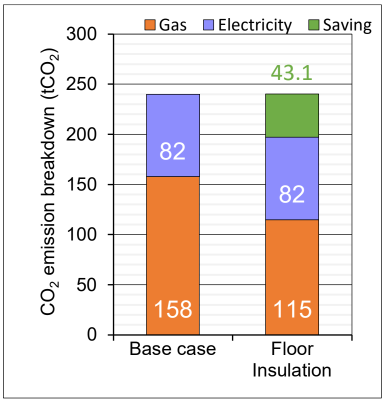

Figure 5.9: Floor insulation LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 43.1 tCO_2.

Table 5.6: Comparison of peak heating and electricity loads before and after floor insulation LCI.

	Peak Loads: Base Case	Peak Loads: F3 LCI
	(kW)	(kW)
Heating Demand	508.6	454.0
Electricity Demand	136.7	136.7

- Improvement of floor insulation achieves a reduction of 206 MWh (27.4 per cent) reduction compared to the base case annual gas consumption.
- No change is observed to electrical consumption or breakdown and remains constant.
- A reduction of 43.1 tCO_2 (18 per cent) is achieved against the base case carbon emissions.
- Peak heating demand is reduced by 10.7 per cent through improvements to the floor insulation. Peak electrical loads remain constant as no impact is observed upon the electrical energy demand.

5.1.4 Secondary Glazing (F4)

Secondary glazing systems are installed with the primary objective of increasing thermal performance of glazing in situations where the external windowpane may be visually sensitive, or prohibitively expensive to replace completely. Secondary glazing involves installation of a windowpane into the existing window reveal to provide an additional thermal barrier. This is assessed as a possible fabric LCI for Minto House due to its designation as a Grade B listed building and poor existing glazing performance.

Table 5.7: Proposed glazing systems upgrades and target performance metrics.

	Current Window Performance (W/m²K)	Improved Performance (W/m²K)	Proposed Methodology
ZONE 1	5.4 [56]	2.00 [27]	Single pane installed within existing internal window reveals
ZONE 2	5.75 [56]	2.13 [27]	Single pane installed within existing internal window reveals
ZONE 3	5.4 [56]	2.00 [27]	Single pane installed within existing internal window reveals
ZONE 4	5.4 [56]	2.00 [27]	Single pane installed within existing internal window reveals

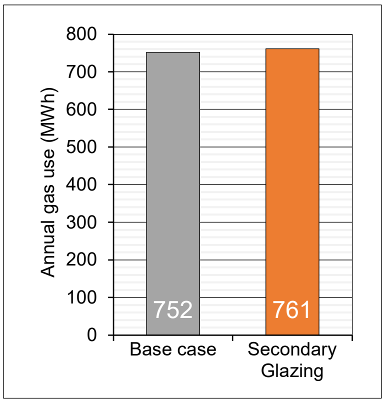

Figure 5.10: Secondary glazing LCI model and base case model annual gas consumption comparison. Secondary glazing, without modelling improvements to airtightness results in an annual gas demand increase of 9 MWh.

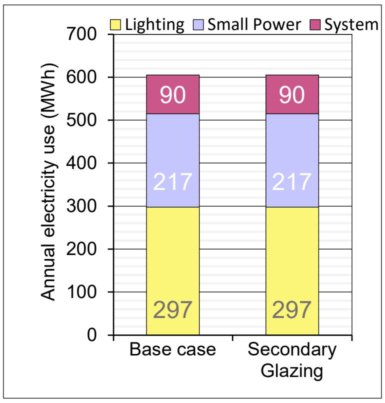

Figure 5.11: Secondary glazing LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the application of secondary glazing

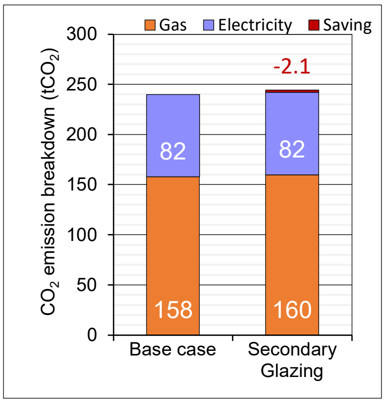

Figure 5.12: Secondary glazing LCI model and base case model annual CO_2 emissions breakdown, with comparative gain of 2.1 tCO_2 emitted without modelling improvements to airtightness.

Modelling secondary glazing without improvements to building airtightness results in a detrimental impact upon overall energy use, and annual gas demand increases by 9 MWh. This highlights that the building energy losses are dominated by convective heat losses, rather than radiative heat losses, which would have been reduced through improvements to glazing U-values. The observed increase in heating demand results from loss of solar gains from shortwave solar radiation due to reflection by the secondary glazing system, which reduces the overall system G-value (the ratio of total solar heat gain to incident solar radiation). The above results indicate an oversimplification of secondary glazing modelling, in reality an improvement to airtightness would also be expected. Hence, in order to model the impact of secondary glazing accurately, improvements to the airtightness must also be accounted for. As such, the infiltration rate has been reduced to 0.55 air changes per hour (ACH) from 0.75, (from peak to average ACH for a leaky building according to CIBSE) and the secondary glazing LCI has been remodelled.

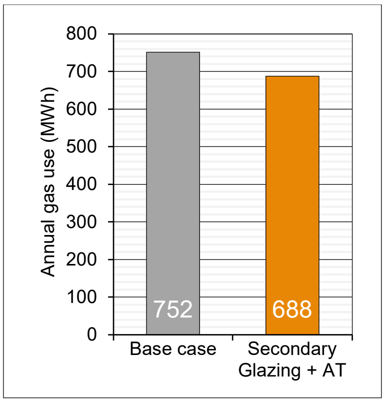

Figure 5.13: Secondary glazing and airtightness improvements LCI model and base case model annual gas consumption comparison. Including airtightness improvements results in an annual gas demand reduction of 64 MWh.

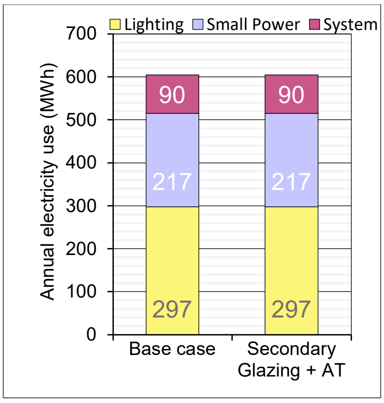

Figure 5.14: Secondary glazing and airtightness improvements LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the application of secondary glazing, nor increase in airtightness.

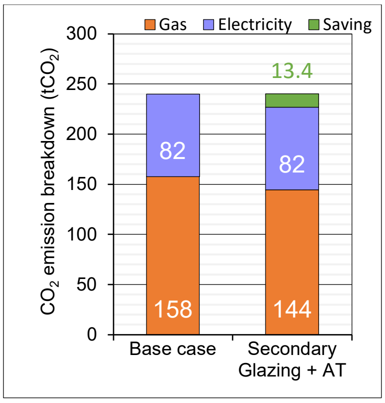

Figure 5.15: Secondary glazing and airtightness improvements LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 13.4 tCO_2 achieved by including improvements to airtightness.

Table 5.8: Comparison of peak heating and electricity loads before and after secondary glazing and airtightness improvements LCI.

	Peak Loads: Base Case	**Peak Loads: F4 LCI**
	(kW)	(kW)
Heating Demand	508.6	475.1
Electricity Demand	136.7	136.7

- A reduction of 64 MWh (8.5 per cent) in annual gas consumption is observed compared to the base case model.
- No change is observed to electrical consumption or breakdown and remains constant.
- A 13.4 tCO2 (5.9 per cent) reduction is achieved against the base case carbon emissions.
- Peak heating demand is reduced by 6.6 per cent from installation of secondary glazing systems with appropriate improvements to airtightness. Peak electrical loads remain constant as no impact is observed upon the electrical energy demand.

5.1.5 Fabric Intervention Comparison

Table 5.9: Summary of fabric LCIs with percentage improvement upon base case energy model.

LCI	**Annual Gas Demand**	**Annual Electric Demand**	**Peak Heating Demand**	**Peak Electricity Demand**	**CO_2 Emissions**
Base case	752 MWh	604 MWh	508.6 kW	136.7 kW	240 tCO_2
F1: Roof	- 3.5%	0%	- 0.2%	0%	- 2.9%
F2: Wall	- 18%	0%	- 2.0%	0%	- 12%
F3: Floor	- 27%	0%	- 11%	0%	- 18%
F4: Glazing	- 8.5%	0%	- 6.6%	0%	- 5.9%

5.1.6 Critical Analysis of Fabric Interventions

The roof insulation upgrade results in the smallest improvement to the annual gas demand, peak heating demand and carbon emissions. This may be due to the roof upgrades occurring over a small fabric area in comparison the total exposed building area. Minto House is spread over four storeys; hence roof area represents a small proportion of the total building envelope. This may be an advantage for reducing building disruption and cost, which are often the key limiting factors for fabric upgrades, whilst still capitalising upon reduced gas bills. Wall insulation results in a significant annual gas demand and carbon emission reduction. This may be due to a greater proportion of the building envelope being upgraded, in comparison to roof upgrades alone. Despite this, a relatively modest reduction in peak heating demand is observed, this indicates that on the coldest days, wall insulation does not reduce the gas demand substantially. Therefore, the benefits of wall upgrades are dispersed over the year in the form of reducing annual gas consumption. This also indicates that the wall performance is not as critical as other fabric elements in driving down the peak heating demand, which relates to the instantaneous balance between heat loss and internal gains. Hence, wall insulation can reduce annual heating utility bills substantially, but does not provide any distinct advantage in reducing peak demand and moreover, the size of plant heating equipment.

Floor insulation provides a substantial improvement to both annual gas demand and gives the greatest observed carbon emission reduction amongst the fabric interventions tested. This may be explained by the percentage improvement to U-values for the exposed floor which reduces from 3.5 W/m²K to 0.5 W/m²K, a seven-fold improvement to thermal resistance. This improvement upon the base case is linked to the initial assumptions relating to the existing building, therefore, if the existing building envelope performs better than assumed, the benefit of floor insulation will be reduced, stressing the importance of in-situ U-value measurement and validation. The addition of floor insulation also reduces peak heating demand substantially, this highlights that this LCI is critical for improving the dynamic performance of the building on the coldest days of the year, and when the heating system would otherwise be delivering peak heating power output (kW).

Secondary glazing installation alongside airtightness improvements delivers reasonable reductions to annual gas use, peak heating demand and carbon emissions, although this is lower than wall and floor LCIs. This is because the building envelope area improved through secondary is significantly smaller than either of the aforementioned LCIs, hence has a reduced impact on the overall lumped heating demand. On the other hand, secondary glazing may offer other advantages in occupant comfort through the reduction of perceived chill and draughtiness near existing cold single-glazed windows. In comparison to other fabric LCIs, secondary glazing has a disproportionately high impact on reducing peak demand, this highlights that heat losses from the building are highly influenced by convective losses through infiltration, which airtightness upgrades can help to reduce.

All of the above LCIs are based upon improving the existing building fabric. This implies that a better-performing base case building envelope will result in diminished carbon emissions. Similarly, a lower-performing base case building envelope will increase the carbon footprint. Hence, the uncertainty of these values, relates directly to the assumed thermal performance of the existing building. Despite being highly disruptive and invasive, all fabric LCIs have successfully demonstrated how gas demand and peak heating demand can be reduced by upgrading the thermal envelope. As such, this can be advantageous in reducing the size and cost of plant equipment, which could otherwise be prohibitively expensive, and can facilitate application of alternative low-carbon generation technologies.

5.2 Building Services Interventions

This section compares and contrasts the carbon impact of building services interventions, which influences how the building delivers and generates energy. These interventions are a mixture of efficiency-led and demand-side changes to reduce carbon emissions. The interventions assessed are heating set-point reduction (S1), upgrading to LED lighting (S2), Air-Source Heat Pump (ASHP) installation (S3), solar PV generation (S4) and solar thermal hot water generation (S5).

5.2.1 Heating Set-Point Reduction (S1)

Although thermal comfort can be subjective, standards and research indicate best-practise values for internal room temperatures. These are based on the predicted mean-vote, which is a measure of the number of people dissatisfied with internal thermal conditions. The CIBSE Guide A: Environmental Design, states that an acceptable internal temperature range is between 19 - 21°C [42]. Based on this, the heating set-point reduction LCI applies an internal set-point of 19°C throughout, which previously ranged from 19 - 23°C in Minto House. The methodology proposed involves changing the current building management system (BMS) target space temperatures.

Table 5.10: Proposed changes to internal heating set-points and methodology

	Current Heating Set Point	**Proposed Set Point**	**Proposed Methodology**
	(°C)	(°C)	
Occupied Spaces	20 - 23	19	Zonal control through the existing BMS
General Circulation	19	19	Zonal control through the existing BMS

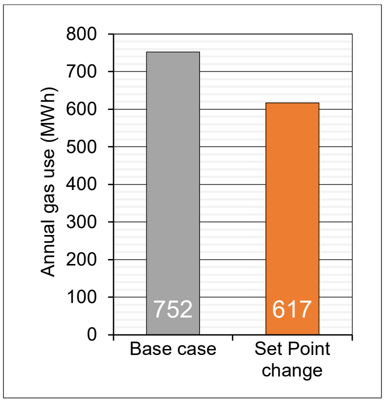

Figure 5.16: Set point reduction LCI model and base case model annual gas consumption comparison. Set point reduction results in an annual gas demand reduction of 135 MWh.

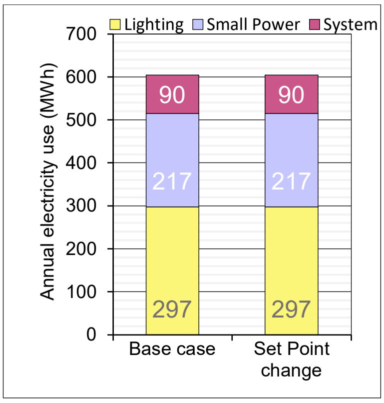

Figure 5.17: Set point reduction LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through the set point reduction.

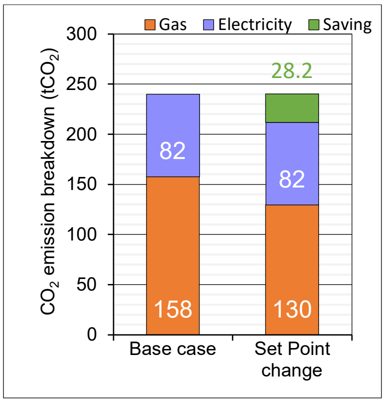

Figure 5.18: Set point reduction LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 28.2 tCO_2.

Table 5.11: Comparison of peak heating and electricity loads before and after set point reduction LCI.

	Peak Loads: Base Case	**Peak Loads: S1 LCI**
	(kW)	(kW)
Heating Demand	508.6	497.2
Electricity Demand	136.7	136.7

- Heating set point reduction achieves a reduction of 135 MWh (18 per cent) in annual gas consumption compared to the base case model.
- No change is observed to electrical consumption or breakdown and remains constant.
- A 28.2 tCO2 (11.8 per cent) reduction is achieved against the base case carbon emissions.
- Peak heating demand is reduced by 2.2 per cent by reducing heating set points to 19°C. Peak electrical loads remain constant as no impact is observed upon the electrical energy demand.

5.2.2 LED Lighting (S2)

LED lighting can offer substantial efficiency gains when compared to compact fluorescent lighting. This LCI quantifies the carbon saving achieved from such an upgrade. The Society of Light and Lighting (SSL) provide technical guidance and performance benchmarks for lighting systems, however, “data for LEDs are changing rapidly and no values are given” [59]. Therefore, data has been obtained from LED manufacturer, Philips, in order to be in line with LED efficiencies at the time of writing [60].

Current Lighting Efficiency (Fluorescent)	Improvement (LED)	Proposed Methodology
(W/m²/100 lux)	(W/m²/100 lux)	
Various (ASHRAE room templates)	45% efficiency improvement [37]	Fit out of new LED luminaires

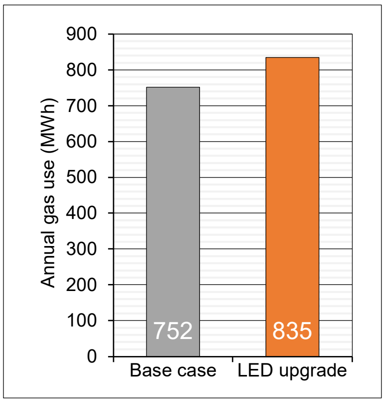

Figure 5.19: LED upgrade LCI model and base case model annual gas consumption comparison. LED upgrade results in an annual gas demand increase of 83 MWh

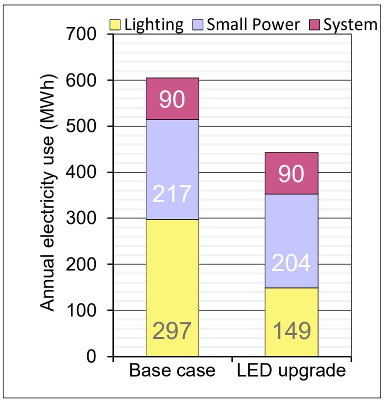

Figure 5.20: LED upgrade LCI model and base case model annual electricity breakdown and use comparison. Lighting demand reduces by 148 MWh.

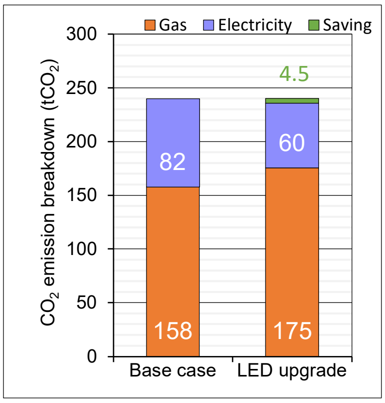

Figure 5.21: LED upgrade LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 4.5 tCO_2.

Table 5.12: Comparison of peak heating and electricity loads before and after the LED upgrade LCI.

	Peak Loads: Base Case	Peak Loads: S2 LCI
	(kW)	(kW)
Heating Demand	508.6	509.3
Electricity Demand	136.7	100.6

- The LED upgrade results in increased annual gas consumption by 83 MWh (11 per cent) compared to the base case model. This is due to electrical efficiency increases which means that less heat is generated from light fittings, which have previously been contributing to room space heating through inefficient operation.
- As expected, higher efficiency LED fittings lead to reduced electrical consumption, by an overall reduction of 26.7 per cent. The most significant reduction is seen in lighting demand, which reduces from 297 MWh to 149 MWh, equivalent to a 49.8 per cent reduction.
- The increase in gas consumption coupled with reduction in energy use results in 4.5 tCO2 (1.9 per cent) carbon emission saving.
- Peak heating load increases (> 1 per cent). Electrical peak load reduces by 26.4 per cent by virtue of replacing light fittings with higher efficiency LED lighting.

5.2.3 Electric Heat Pumps (S3)

Natural gas boilers represent the greatest obstacle towards achieving net-zero carbon for Minto House. With the introduction of SAP 10.1 emissions factors, the same unit of primary energy for natural gas carries a greater carbon emission intensity compared to electricity. The decarbonisation of the electric grid, alongside higher coefficient of performances from electric heat pumps mean that the same heating demand can be delivered more efficiently and with less carbon emissions than gas boilers. This LCI assesses replacement of existing gas boilers with air-source heat pumps (ASHP). Efficiency data has been obtained from ASHP manufacturer Mitsubishi Electric [61].

Table 5.13: Existing heating system efficiencies with proposed ASHP upgraded system efficiencies

Existing Heating System	Proposed Heating System
Gas boiler	Air Source Heat Pump
60°C hot water	55°C hot water
Efficiency = 95.44% [58]	Efficiency = 319 % [61]
	(with immersion heaters to supply at 60°C)

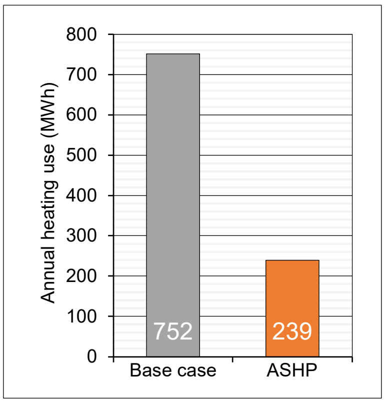

Figure 5.22: ASHP upgrade LCI model and base case model annual primary energy demand for heating comparison. ASHP upgrade results in a total displacement of annual gas demand of 752 MWh, and a 239 MWh electric demand for heating.

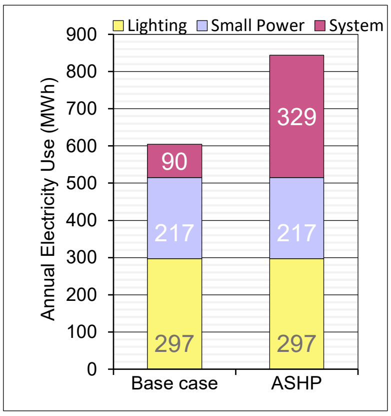

Figure 5.23: ASHP upgrade LCI model and base case model annual electricity breakdown and use comparison. 'System' electricity absorbs the increase in electric heating demand of 239 MWh.

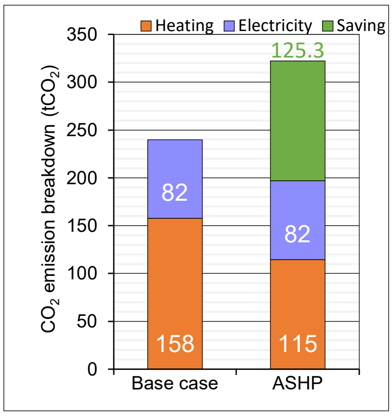

Figure 5.24: ASHP upgrade LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 125.3 tCO_2.

Table 5.14: Comparison of peak heating and electricity loads before and after the air-source heat pump upgrade LCI.

	Peak Loads: Base Case	Peak Loads: S3 LCI
	(kW)	(kW)
Heating Demand	508.6	508.6
Electricity Demand	136.7	308.9

- Annual gas demand reduces to zero due to electrification of heating when compared to the base case. Annual heating use reduces significantly by 513 MWh (68.2 per cent) due to the greater coefficient of performance delivered by the air-source heat pump.

- Electrical lighting, small power demand remains constant, however increase in system demand increases due to substitution of electric heating for gas boilers.
- A reduction of 125.3 tCO_2 (52.2 per cent) is achieved through air source heat pump replacement. This is largely due to a reduction in primary energy demand, which is achieved through greater efficiency.
- Peak heating demand remains constant as the heat demanded by the building does not change. Peak electricity demand increased by 172.2 kW (126 per cent), as a result of the electric heating system. Peak heating load and peak electrical load represent two distinct quantities. Peak heating load is kW of thermal power, whilst peak electrical load is kW of electrical power. Factoring in system COP, the thermal power demand can be delivered from a smaller electrical power and hence, these two values differ.

5.2.4 Solar PV Generation (S4)

Renewable generation can be used to offset energy demand from carbon intensive systems or grid electricity. For Minto House, solar conversion technologies are explored as an option for installation on The Maltings' south-facing pitched roof. This area has been identified as a possible region for installation of solar Photo-Voltaic (PV) panels, although would require further investigation into structural properties of the roof and appropriate planning consent.

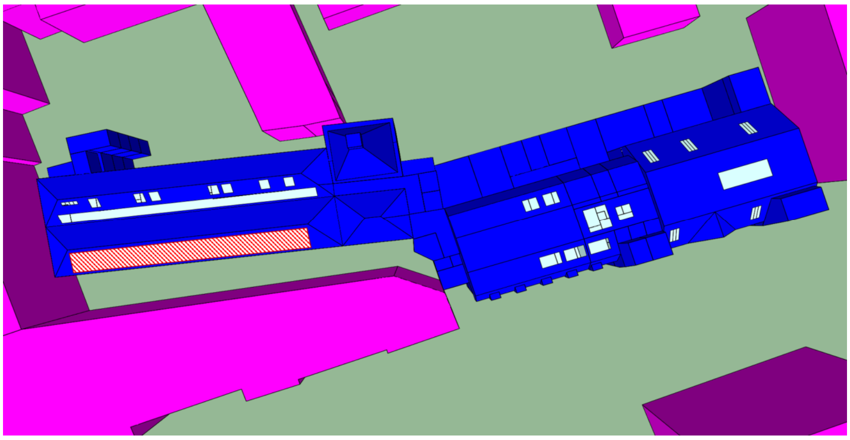

Figure 5.25: Roof area identified for possible installation of solar conversion technology on the South-facing pitched roof of the Maltings.

Table 5.15: Key guiding principles and assumptions for modelling PV generation

PV system proposed: assumptions and IES inputs
Roof Area: 30m x 4.5m
Azimuth Angle: 173.23°
PV Module: Sharp NU-E235 (E1) 235 Wp [62]
Number of Modules: 54
PV array kWp: 12.69 kWp
Shading factor estimated from sun path: 0.75
Module efficiency: 0.143 [62]
Electrical conversion efficiency: 0.85

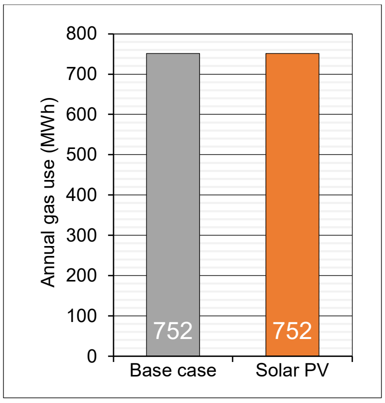

Figure 5.26: Solar PV generation LCI model and base case model annual gas consumption comparison. PV generation results in no change to annual gas consumption.

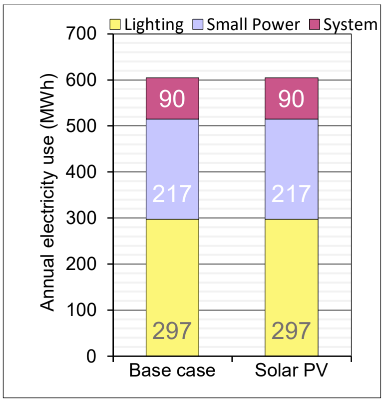

Figure 5.27: Solar PV generation LCI model and base case model annual electricity breakdown and use comparison. PV generation results in no change to the electricity demand of the building

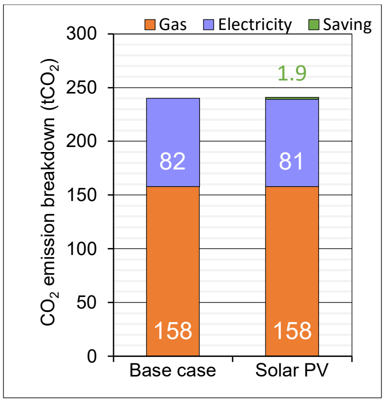

Figure 5.28: Solar PV generation LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 1.9 tCO_2 by offsetting grid electricity.

Table 5.16: Comparison of peak heating and electricity loads before and after the air-source heat pump upgrade LCI.

	Peak Loads: Base Case	**Peak Loads: S4 LCI**
	(kW)	(kW)
Heating Demand	508.6	508.6
Electricity Demand	136.7	136.7

- No reduction in annual gas consumption is observed.
- No reduction in annual electricity consumption is observed as the total electricity demand remains constant, but the supply has been offset through PV generation.
- Solar PV generation offsets electricity which would otherwise be imported from the grid. This results in an annual reduction of 1.9 tCO_2 (0.8 per cent) in carbon emissions compared to the base case model.
- No changes are observed the peak energy demands for the building. Peak electrical output from PV generation does not occur at the same time as peak electrical demand so does not act to reduce the electrical grid demand.

5.2.5 Solar Thermal (S5)

Solar thermal hot water generation technology can offset gas consumption by preheating water, the impact of this is assessed assuming the south-facing pitched roof of The Maltings can be utilised. Manufacturer data has been used to validate the assumptions used in the energy model (see Table 5.17) [63].

Table 5.17: Key guiding principles and assumptions for modelling solar thermal collectors

Solar thermal system proposed: assumptions and IES inputs
Roof Area: 30m x 4.5m
Azimuth Angle: 173.23°
Solar Collector: Viessmann Vitosol 300-F SH3A
Number of Modules: 36
Shading factor estimated from sun path: 0.75
Optical efficiency: 83.4 [63]
Heat loss factor, k1: 3.66, Heat loss factor. k2: 0.0169

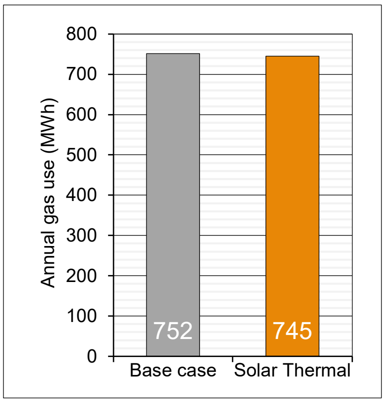

Figure 5.29: Solar thermal generation LCI model and base case model annual gas consumption comparison. Solar thermal generation results in a 7 MWh reduction to annual gas consumption.

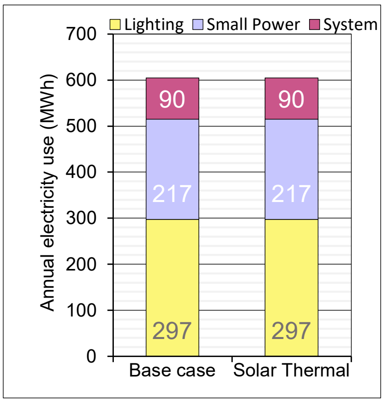

Figure 5.30: Solar thermal generation LCI model and base case model annual electricity breakdown and use comparison. No change in electricity consumption is observed through solar thermal generation.

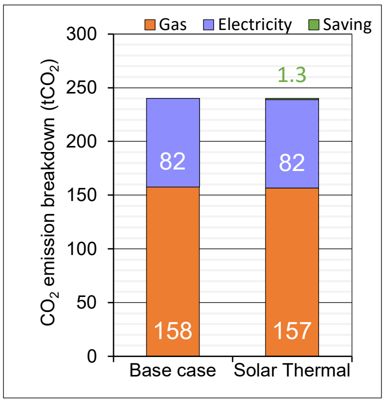

Figure 5.31: Solar thermal generation LCI model and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 1.3 tCO_2.

Table 5.18: Comparison of peak heating and electricity loads before and after the solar thermal upgrade LCI.

	Peak Loads: Base Case	**Peak Loads: S5**
	(kW)	(kW)
Heating Demand	508.6	508.6
Electricity Demand	136.7	136.7

- Solar thermal results in a 7 MWh (>1 per cent) reduction in annual gas consumption, through preheating water for heating up to temperature.
- Electrical consumption remains constant
- Carbon emissions are reduced by 1.3 tCO2 (>1 per cent) compared to the base case model.
- Peak heating and electrical loads remain unaffected as hot water generation occur does not occur at times of peak demand.

5.2.6 Services Intervention Comparison

Table 5.19:Summary of services LCIs with percentage improvement upon base case energy model

LCI	Annual Gas Demand	Annual Electric Demand	Peak Heating Demand	Peak Electricity Demand	CO_2 Emissions
Base case	752 MWh	604 MWh	508.6 kW	136.7 kW	240 tCO_2
S1: Set-point	- 18%	0%	- 2.2%	0%	- 12%
S2: LED	+ 11%	- 27%	+ 0.1%	- 26%	- 1.9%
S3: ASHP	- 100%	+ 40%	0%	+130%	- 52%
S4: Solar PV	0%	0%	0%	0%	- 0.8%
S5: Solar Thermal	- 0.9%	0%	0%	0%	- 0.5%

5.2.7 Critical Analysis of Building Services Interventions

Reducing internal set-point temperatures leads to a substantial reduction in annual gas demand. By substituting gas, which has a higher primary fuel carbon intensity than grid electricity, a large reduction in carbon emissions is achieved. Similarly, this LCI reduces peak heating demand, which implies that it reduces the demand on boilers on the coldest days. The net-zero implications of this LCI depend upon occupant comfort and user behaviour, and further assessment would be required to understand occupant comfort at the new set-point across the building. In doing so, this could avoid energy consumption rebounding through occupants using local electric heaters to remain comfortable, which would simply transfer carbon emissions saved from reducing heating demand to a occupant end-use electricity.

The LED upgrade leads to increased heating demand and annual gas consumption. By virtue of installing higher efficiency luminaires, less heat is lost to the internal environment and therefore reducing internal gains. Consequently, the boilers must work harder in order to make up for this shortfall in heating demand and this is evident by the increase. Conversely, a strong reduction in annual electricity demand is observed, alongside peak electricity demand, and the cumulative impact of this, is a modest reduction upon carbon emissions. Despite the annual gas demand increase, upgrading to LED lighting would offer savings in utility bills and may be financially favourable. It should be noted that inefficient lighting, which may displace heating demand through generating excessive heat is not an optimal use of primary energy. Electricity is a high-grade fuel and the heat-shedding by luminaires is a low-efficiency process, the heat demand would be better served from more efficient heat production methods such as electric heat pumps, which can achieve COPs in excess of 3.0. Overall, demand-side changes led by efficiency gains have a greater impact on carbon emissions.

The ASHP reduces all of the natural gas consumption on-site. In doing so, a large proportion of the carbon emissions are being displaced through substitution of demand to more efficient electric heating. This acts to reduce carbon emissions substantially and occurs two-fold. Firstly, by serving heating demand through a lower primary carbon intensity fuel, and secondly, a high COP from the ASHP means that the effective carbon emissions per kWh of delivered thermal energy is further reduced. The overall impact of this is evidenced by a 52 per cent reduction in overall CO_2 emissions and highlights the importance of electric heating towards achieving net-zero objectives. An increase in annual electricity demand is seen which corresponds to the substitution of heating demand. Likewise, this results in a substantially higher peak electricity demand as an additional load would be added to the electrical ring main.

Local renewable electricity generation from solar PV does not impact overall energy demanded by the building, hence, no improvement is seen upon the base case annual gas and electricity demands. This is because the demand does not change, but rather, the supply of energy changes, which offsets electricity that would otherwise be imported from the grid. Therefore, a reduction in carbon emissions is achieved through this substitution of supply. However, the scale of emission reduction is modest, which highlights the surrounding environmental constraints. Firstly, Minto House, experiences local shading from adjacent buildings, and secondly, the availability of solar irradiance throughout the year in Scotland is diminished in the winter months due to lower solar altitude angles. Despite this, solar PV may still be advantageous in offsetting electricity utility bills. Peak demands are unaffected by PV generation, this indicates that solar energy is not available at times of peak demand, hence in this regard the PV generation does not offer any additional benefit.

Solar thermal generation offsets natural gas consumption by preheating water, which results in a modest reduction in annual gas demand. Overall, this results in the least reduction in carbon emissions, which is due to the availability of solar thermal generation potential, and is dependent upon ambient air temperatures, rather than direct solar irradiance. Climatic conditions lead to modest gains in renewable hot water generation, which is evident from the carbon saving achieved.

5.3 Costing Low Carbon Interventions

5.3.1 Cost Matrix

Table 5.20: Levelised costs of carbon emission savings for LCIs modelled, based on material cost estimates, scale of upgrade and expected lifetime.

LCI	Carbon saving	Methodology	Benchmark cost	Reference	Specific cost	Lifetime	Levelised Cost of carbon
	(tCO_2/Yr.)				(GBP)	(Years)	(GBP/tCO_2)
F1	5.4	275mm hemp insulation	£23.65/m² [64]	Roof: 1600m²	37,800	100 [65]	70
F2	28.6	100mm hemp insulation	£8.60/m² [64]	Wall: 3500m²	30,100	100 [65]	11
F3	43.1	1: Aerogel board 2: Wood fibre 80mm	1: £31.00/m² [64] 2: £10.15/m² [64]	Exposed:1500m² Internal: 3350m²	80,500	50 [65]	37
F4	13.4	Secondary glazing	£270 - 325 per unit [65]	150 units	40,500	90 [65]	33
S1	28.2	Use existing BMS	-	-	-	-	-
S2	4.5	Modular linear LED 600 × 100 mm	286.70 per unit [65]	1 unit/ 10m²	140,000	20	1500
S3	125.3	New installation	£ 469.7 /kW [65]	239 kW peak	112,000	20 [65]	45
S4	1.9	PV roof mounted panels	1300 - 2750 £/kWp [65]	12.69 kWp install	16,500	25 [62]	350
S5	1.3	1000L capacity	£8292.88 [65]	[65]	8,300	25	260

Prices for LCIs have been estimated based on material cost, this does not include installation cost and secondary costs incurred from building closure or loss of income. Installation costs are expected to be much higher for fabric upgrades due to the level of building intervention required and labour hours. Price contingency is not included in this assessment and is expected to be significantly higher for fabric upgrades, due to unknown factors that may influence the overall cost of install. In the case of fabric LCIs this is heightened due to lack of knowledge surrounding the current building fabric and what may be uncovered when the fabric upgrades are commenced. It is common estimating practise is to include price contingency that would take account of this uncertainty, however, this has been omitted from this comparison for simplicity.

6 LOW-CARBON PATHWAYS

This section analyses the performance of 'low-carbon pathways', which have been developed through aggregating LCIs. Energy performance results from IES, benchmarked performance, techno-economic evaluation and critical analysis of modelling is presented for each of the pathways modelled. In addition, Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is used to encapsulate key features, whilst the practical implications of applying pathways is subsequently discussed with reference to Minto House.

6.1 Pathway 1: Services Only Refurbishment

6.1.1 Interventions

Pathway 1 has been constructed by adopting a pragmatic approach to how building refurbishment projects are procured. This pathway involves a building services only refurbishment, which results in less occupant disruption and financial risk, compared to more invasive fabric LCIs. The procurement process for this, would involve appointing Mechanical and Electrical (M&E) building services contractors to implement the scope of works defined below.

The services LCIs adopted for Pathway 1 are:

- S1: Set-point reduction
- S2: LED upgrade
- S3: ASHP installation
- S4: Solar PV generation

Solar PV generation has been applied in lieu of solar thermal generation due to a greater carbon reduction potential and limited availability of roof area for installation of solar conversion technologies.

6.1.2 Energy Performance

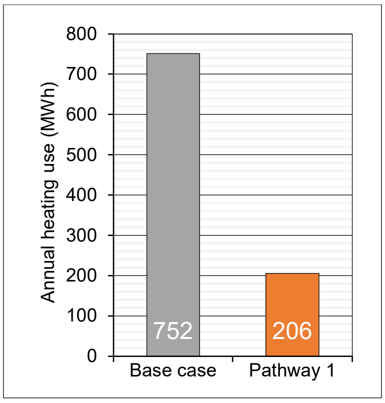

Figure 6.1: Pathway 1 and base case model annual heating primary energy demand. Pathway 1 substitutes all gas consumption with 206 MWh electric heating demand.

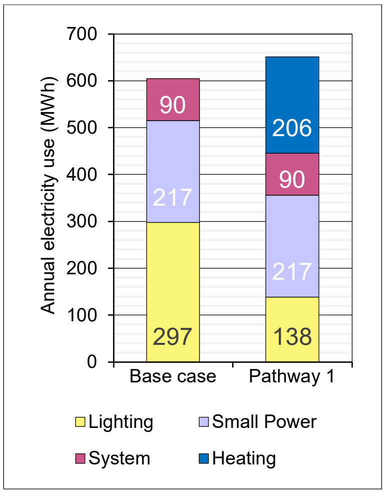

Figure 6.2: Pathway 1 and base case model annual electricity breakdown and use comparison. Pathway 1 increases lumped annual electricity consumption by 47 MWh.

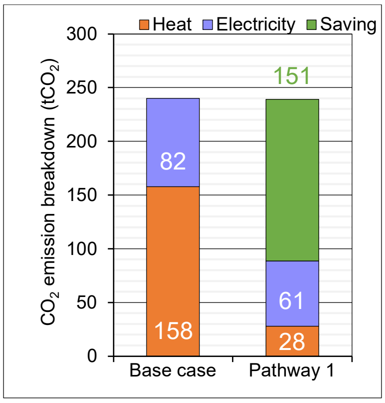

Figure 6.3: Pathway 1 and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 151 tCO_2.

Table 6.1: Comparison of peak heating and electricity for base case and LCI Pathway 1.

	Peak Loads: Base Case	Peak Loads: Pathway 1
	(kW)	(kW)
Heating Demand	508.6	505.2
Electricity Demand	136.7	272.3

- Pathway results in a total substitution of primary gas demand for heating through the use of electric heating. The primary electricity demand required to meet the building heating load is significantly smaller than the base case scenario which relied upon gas.
- Annual electricity consumption increases by 7.8 per cent. This is due to the introduction of electric heating, which is directly added to the overall consumption. However, the LED upgrade results in a much-reduced lighting electricity demand (53 per cent). Small power demand remains constant due to no changes to occupancy patterns,
- Overall carbon emissions are reduced substantially by 63 per cent. The most striking carbon saving is achieved from electric heating, which is only responsible for 28 tCO_2 in Pathway 1, in comparison to 158 tCO_2 of the base case.
- Peak heating demand for Pathway 1 results in a marginal reduction (0.7 per cent). Peak electrical demand increased by 200 per cent due to the shift towards electric heating.

6.1.3 Benchmark Performance

Benchmarking Pathway 1 highlights the extent to which energy performance has been improved for Minto House. Electrification of heating results in zero gas demand, which exceeds 'good' performance benchmarks. Conversely, this demand is shifted into the electricity demand for Minto House, which results in a higher than expected normalised electricity demand, exceeding the 'typical' expected performance. It should be noted, however, that the carbon intensity of Minto House is far superior to the benchmarks after LCI Pathway 1. This indicates that consumption benchmarks alone may be misleading when considering overall building carbon footprint. Furthermore, the benchmarks for all electric buildings may differ substantially to those with fossil fuel heating systems [40].

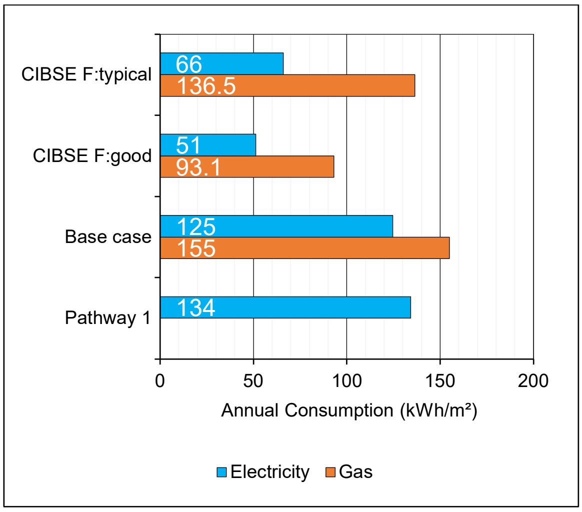

Figure 6.4: Comparison of LCI Pathway 1 with good and typical energy consumption benchmarks, derived from CIBSE Guide F.

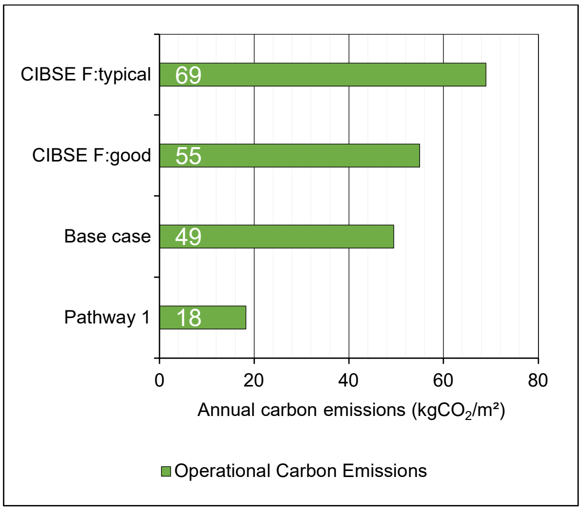

Figure 6.5: Comparison of LCI Pathway 1 with good and typical carbon emission benchmarks, derived from CIBSE Guide F.

6.1.4 Critical Analysis of Modelling Results

Modelling results indicate that a substantial carbon emission reduction can be achieved. The key interventions for achieving this are installation of the ASHP, reducing heating set-points and upgrading to LED lighting. Reducing set-point temperatures results in a lower building heating demand, which is expected. Despite upgrading to LED lighting, which had previously been shown to increase heating demand, this remains below the base case building. What remains is met by efficient electric heating and this results in a substantial reduction in carbon emissions. This is expected due to two key factors, the high efficiency of the ASHP and lower grid carbon intensity of electricity compared to gas (per kWh). This means that the 206 MWh of electric primary energy demand for heating is able to provide approximately 650 MWh of thermal energy, which is substantially less carbon intensive than the 752 MWh of natural gas demand of the base case scenario.

Lumped electricity demand increases due to electric heating, which is expected. To illustrate this point further, the heating demand made up approximately 60 per cent of the total primary energy demand for the base case model, hence, is an expected result. Lighting demand reduces in direct proportion to the efficiency gains applied to the IES model and this is consistent with the assumptions outlined in Section 5.2.2. Small power demand remains constant across the base case model and Pathway 1 and this is indicative of the assumptions around patterns of use for Minto House. Although no efficiency gains are realised here, it is important for showing a fair comparison between how the building scenarios are being used. Electric heating demand is absorbed within the system demand for the building, aside from this, system demand remains constant, which indicates systems, pump and fans remain the same. Assuming any changes to these efficiencies would create an unfair comparison between the LCI pathway and the base case model, hence these remain constant.

As expected, peak heating load reduces from a reduction in heating set-point. However, this is lower than the reduction achieved from applying set-point reduction as an isolated LCI. Due to more efficient LED lighting, the heating demand increases from a reduction in radiant losses from luminaires. Therefore, the combined impact of these LCIs results in a peak heating demand reduction compared to the base case model, but it is not as significant as the reduction obtained from set-point change alone.

Peak electricity demand increases, which is due to the electrification of heating. This is the largest contributor to electricity demand, therefore, peak electricity demand occurs on the coldest days, when the ASHP is working the hardest. The increase in peak electricity demand is reduced when compared to the ASHP LCI in isolation, this is due to higher efficiency lighting, which brings the overall demand down.

Solar PV generation provides the same output as when it is applied separately as an LCI and offsets the imported electricity demand. However, as noted when modelled individually, solar PV generation does not occur at the same time as peak electricity demand and therefore, does not influence the building in this manner. Conversely, solar PV provides generation throughout the year, upon availability, which leads to a modest electricity offset and carbon emission reduction.

6.1.5 Techno-Economic Evaluation

At the time of writing, Pathway 1 material cost of install would be in the region of 253,500 GBP. This is based on system equipment sized to meet peak loads for electric heating and general electricity consumption, which are derived from IES modelling.

Table 6.2: Estimated installation costs for Pathway 1, based on system sizes modelled in IES.

LCI	Benchmark cost	Reference	Specific cost (GBP)
S1	No cost	-	-
S2	286.70 per unit [65]	1 unit/ 10m²	140,000
S3	£ 469.7 /kW [65]	206 kW peak	97,000
S4	1300 - 2750 £/kWp [65]	12.69 kWp install	16,500
Pathway 1			253,500

Taking stock of the overarching commitment from the University of Edinburgh to achieve net-zero carbon emissions by 2040, extrapolating modelling results from IES, Pathway 1 would achieve a reduction of 151 tCO_2 per year, which would cumulatively be 3020 tCO_2 from the time of writing to 2040 (over a 20 year period). This assumes that the individual LCIs which constitute Pathway 1 have a lifetime of at least 20 years, which is justified based on Section 5.3.1. Over this period, the levelised cost of carbon saving would be equivalent to £84 tCO_2 saved. This is a significant result as it is lower than the adopted carbon offset price of £95 tCO_2. This indicates that Pathway 1, represents a financially feasible low-carbon future for Minto House, when compared to carbon offsetting. However, this metric only considers carbon impact, hence financial analysis is required to better understand the impacts of Pathway 1 on utility bill payments and the overall cost of achieving net-zero carbon emissions.

Pathway 1 is not a complete net-zero solution, which is expected due to a lack of on-site renewable generation potential and the remaining carbon balance must be offset in order for Minto House to achieve net-zero carbon emissions by 2040. Therefore, the cost breakdown of Pathway 1 can be constructed based on these assumptions. Table *6.3* summarises the financial performance and payback period for Pathway 1, based on average gas and electricity tariffs paid by the University of Edinburgh at the time of writing. This analysis indicates that a payback period of 19 years may be achieved and demonstrates the financial feasibility of implementing Pathway 1.

With the objective of achieving net-zero carbon by 2040, carbon offsetting would be required in both the base case and Pathway 1 scenarios. Table 6.4 outlines the expected financial costs incurred in year 2040 in order to reach net-zero emissions through carbon offsetting and financing implementation of Pathway 1.

Table 6.3: Annual utility consumption, savings and simple payback calculation for Pathway 1. Based on Gas price of 2.68 pence/kWh and electricity price of 14 pence/kWh.

Annual Utility Consumption	**Base case**	**Pathway 1**
Heating	752 MWh	206 MWh
Electricity	604 MWh	651 MWh
Gas bill	£20,200	-
Electricity bill	£84,600	£91,100
Total utility bill	£104,800	£91,100
	Annual saving	£13,700
	Total install cost	£253,500
	Payback period	**19 years**

Table 6.4: Summary of expected costs for achieving net-zero carbon status in 2040 for Minto House, comparing the base case scenario and Pathway 1.

	Base case	**Pathway 1**
CO_2 emissions per year	241.1 tCO_2	89.6 tCO_2
Upfront cost	-	£253,500
Offset price	£90/ tCO_2	£90/ tCO_2
Cost of Net-Zero in 2040	£21,700	£8,000
Annual savings up to 2040	-	£274,000

Pathway 1 delivers carbon emissions reduction at lower than the carbon offset price and can achieve a payback within 19 years through reduced utility bill expenditure alone. In 2040, carbon offset payment of £8,000 would be required in order to achieve full net-zero carbon status, by offsetting the remaining 89.6 tCO_2. By 2040, the net financial benefit attained through annual saving means that Pathway 1 would provide a more financially favourable option when compared to the base case scenario in 2040. The base case scenario would incur annual carbon offset payments of £21,700 on an annual basis thereafter, without any prior financial savings on utility bills.

Under different carbon pricing scenarios, Pathway 1 still offers economic incentives over the base case. Significantly reducing the carbon price would reduce the cost of achieving net-zero carbon proportionally, however, the difference in offset payments would still be directly proportional to the difference in CO_2 emissions per year. Furthermore, changes to carbon pricing will not impact the financial gain realised from utility bill saving delivered by Pathway 1.

6.1.6 Strengths, Weaknesses, Opportunities and Threats Analysis for Pathway 1

Strengths

i. Significant carbon emissions reduction achieved at relatively low building and occupant disruption.
ii. Procurement process is simple and will involve appointment of an M&E contractor to carry out services upgrades.
iii. Shorter project life cycle is expected due to reduced building disruption, compared to more disruptive pathways.
iv. Gas consumption is completely offset to zero.
v. Strong annual financial savings are demonstrated upon the base case utility bills.

Weaknesses

i. High peak energy demand remains, which necessitates higher equipment rating, leading to greater installation costs for ASHP, which is defined per kW.
ii. Early replacement of gas boilers leads to end of life embodied carbon emissions.
iii. Increase in peak electrical demand may result in further costs for capacity upgrades.

Opportunities

i. On-site renewable generation may be leveraged for subsidies.

Threats

i. Overall climate impact is sensitive to grid carbon intensities, hence there is limited autonomy over building carbon performance.
ii. Financial benefits are underpinned by retail energy prices, the financial modelling assumes fixed prices for gas and electricity, which can change.
iii. Planning and consent issues may arise for installation of solar PV modules.

6.1.7 Practical Implications of Implementing Pathway 1

Pathway 1 is a services only combination of LCIs and it is expected to have a reduced impact on occupant and building disruption. LED upgrades will require access to all rooms and is expected to be the most significant impact on building usage. Meanwhile, upgrades to ASHP and solar PV installation will result in localised disruption, that can be managed zonally. The process for delivering these upgrades will be through installation and commissioning processes which can be undertaken in a phased approach to minimise undue disruption. The cumulative impact of disruption should not necessitate long-term building closure, which is advantageous as the building is used by academic staff all year round.

Set-point reduction will be straightforward to implement but difficult to maintain as a management policy. Comfort is a subjective matter, and whilst CIBSE guidance indicates that a comfortable internal temperature lies between 10-22 degrees, this is highly dependent on factors such as clothing levels, air speed, level of activity and individuals' metabolic rate [42]. At a management level, 19 degrees may be established as a set point, however, occupant comfort will dictate the effectiveness of this LCI. For example, if building users feel cold, they will look to use local electric heaters and this additional heating load will be added to added to the unregulated building plug loads, which cannot not be controlled as easily. Therefore, implementing this LCI will require some occupant feedback and engagement to ensure carbon savings are not compromised elsewhere.

The ASHP upgrade would require interfacing the new installation with the existing hot water pipework and distribution networks in the building. This will require specialist contractors to install and commission. The air-side condenser of the ASHP would require external space which may be difficult to accommodate within the existing surrounding spaces. Furthermore, planning permission may be required for such external plant equipment to ensure that visual and acoustic impacts are minimised. Likewise, PV installation will be subject to planning constraints that must be adhered to.

Delivering Pathway 1 on the ground may also carry additional risk and financial cost incurred from unforeseen remedial or consequential refurbishment works arising from undertaking building services upgrades. Although, these are expected to arise locally, rather than across the entire building fabric and envelope and can be managed effectively.

6.2 Pathway 2: Fabric & Services Refurbishment

6.2.1 Interventions

Pathway 2 is representative of a more expansive refurbishment programme, which includes both services and fabric upgrades. Fabric upgrades may involve stripping back finishes and constructions, in which case, services upgrades can be undertaken opportunistically. The procurement process for this would be more involved and would require specialist subcontractors to deal with fabric and services upgrades separately, with expertise in heritage buildings.

The fabric and services LCIs adopted for Pathway 2 are:

- F1: Roof insulation upgrade
- F2: Wall insulation upgrade
- F3: Floor insulation upgrade
- F4: Secondary glazing
- S1: Set-point reduction
- S2: LED upgrade
- S3: ASHP installation
- S4: Solar PV generation

As in Pathway 1, Solar PV generation has been applied in lieu of solar thermal generation due to a greater carbon reduction potential.

6.2.2 Energy Performance

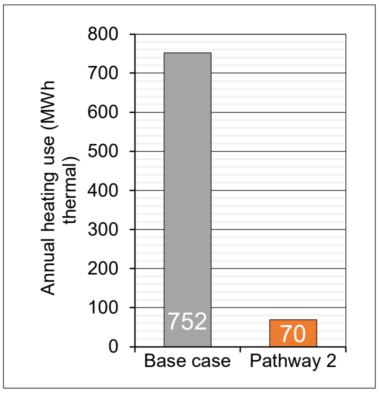

Figure 6.6: Pathway 2 and base case model annual heating primary energy demand. Pathway 2 substitutes all gas consumption with 70 MWh electric heating demand.

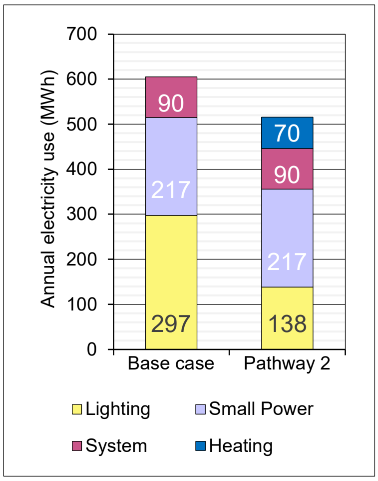

Figure 6.7: Pathway 2 and base case model annual electricity breakdown and use comparison. Pathway 2 reduces lumped annual electricity consumption by 89 MWh.

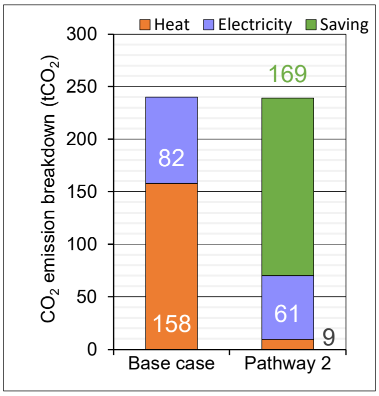

Figure 6.8: Pathway 2 and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 169 tCO_2.

Table 6.5: Comparison of peak heating and electricity for base case and LCI Pathway 2.

	Peak Loads: Base Case	**Peak Loads: Pathway 2**
	(kW)	(kW)
Heating Demand	508.6	283.1
Electricity Demand	136.7	196.1

- Pathway 2 results in a total substitution of primary gas demand for heating through the use of electric heating. The primary electricity demand required to meet the building heating load is significantly smaller than Pathway 1, which has been achieved through thermal efficiency improvements.
- Annual electricity consumption reduces by 15 per cent. This is due to demand-side reduction of electric heating demand. Small power demand remains constant due to no changes to occupancy patterns,
- Overall carbon emissions are reduced substantially by 70 per cent. The most striking carbon saving is achieved from electric heating coupled with thermal insulation upgrades, which result in heating carbon emissions of only 9 tCO_2, in comparison to 158 tCO_2 of the base case.
- Peak heating demand reduces substantially by 56 per cent, compared to the base case scenario. Peak electrical demand increases by 140 per cent, due to the shift towards electric heating. This is less than the peak electricity demand observed for Pathway 1.

6.2.1 Benchmark Performance

Benchmarking Pathway 2 highlights the extent to which energy performance has been improved for Minto House. Electrification of heating results in zero gas demand, which exceeds 'good' performance benchmarks. It should be noted, however, that the carbon intensity of Minto House is far superior to the benchmarks after LCI Pathway 2.

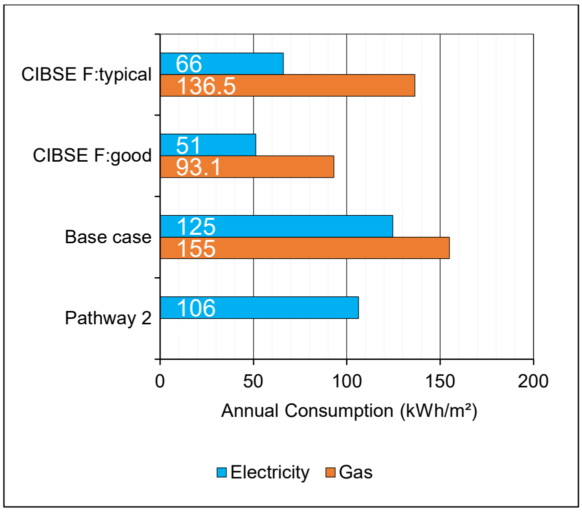

Figure 6.9: Comparison of LCI Pathway 2 with good and typical energy consumption benchmarks, derived from CIBSE Guide F.

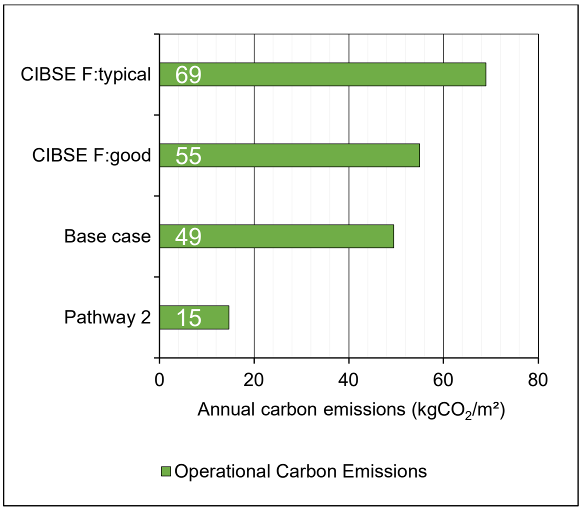

Figure 6.10: Comparison of LCI Pathway 2 with good and typical carbon emission benchmarks, derived from CIBSE Guide F.

6.2.2 Critical Analysis of Modelling Results

Heating demand is reduced substantially due to improvements to building fabric, which achieves the desired effect of improving the thermal envelope efficiency. The primary electric energy demand for heating reduces from 206 MWh to 70 MWh, across Pathway 1 and Pathway 2, a 66 per cent decrease, which is attributable to thermal fabric upgrades. Electricity demand is impacted insofar as reducing the contribution from electric heating, other electricity consumption remains unchanged from Pathway 1, which is as expected. The carbon emissions generated are proportional to the source of electricity consumption, the 66 per cent decrease in heating demand results in an additional reduction of 19 tCO_2 compared to Pathway 1. The carbon reduction is derived directly from reducing the heating demand under Pathway 2. The CO_2 emissions that persist, are largely (85 per cent) driven by unregulated loads from plug and equipment loads are driven by occupancy factors that are beyond the scope of fabric or services LCIs. Further improvement to building fabric, would result in diminishing returns for overall carbon emissions due to this large proportion of emissions stemming from occupancy factors. Peak heating demand is reduced substantially when compared to both the base case and Pathway 1 modelling results. This is advantageous for reducing capital costs of plant equipment, which is based on peak load.

6.2.3 Techno-Economic Evaluation

At the time of writing, Pathway 2 material cost of install would be in the region of 378,400 GBP. This is based on system equipment sized to meet peak loads for electric heating and general electricity consumption, which are derived from IES modelling.

Table 6.6: Estimated costs for Pathway 2, based on system sizes modelled in IES.

LCI	Benchmark cost	Reference	Specific cost (GBP)
F1	£23.65/m^2 [64]	Roof: 1600m²	37,800
F2	£8.60/m^2 [64]	Wall: 3500m²	30,100
F3	1: £31.00/m^2 [64] 2: £10.15/m^2 [64]	Exposed:1500m² Internal: 3350m²	80,500
F4	£270 - 325 per unit [65]	150 units	40,500
S1	No cost	-	-
S2	286.70 per unit [65]	1 unit/ 10m²	140,000
S3	£ 469.7 /kW [65]	70 kW peak	33,000
S4	1300 - 2750 £/kWp [65]	12.69 kWp install	16,500
Pathway 2			£378,400

Pathway 2 would achieve a reduction of 169 tCO_2 per year, which would cumulatively be 3380 tCO_2 from the time writing to 2040 (over a 20-year period). Over this period, the levelised cost of carbon saving would be equivalent to £112 tCO_2 saved, which is higher than the adopted carbon offset price of £95 tCO_2.

Table 6.7 summarises the financial performance and payback period for Pathway 2, based on average gas and electricity tariffs paid by the University of Edinburgh at the time of writing. This analysis indicates that a payback period of 12 years may be achieved.

With the objective of achieving net-zero carbon by 2040, carbon offsetting would be required in both the base case and Pathway 2 scenario. Table 6.8 outlines the expected financial costs incurred in year 2040 to reach net-zero emissions through carbon offsetting and financing implementation of Pathway 2.

Table 6.7: Annual utility consumption, savings and simple payback calculation for Pathway 2. Based on Gas price of 2.68 pence/kWh and electricity price of 14 pence/kWh.

Annual Utility Consumption	Base case	Pathway 2
Heating	752 MWh	60 MWh
Electricity	604 MWh	514 MWh
Gas bill	£20,200	-
Electricity bill	£84,600	£72,000
Total utility bill	£104,800	£72,000
	Annual saving	£32,800
	Total install cost	£378,400
	Payback period	**12 years**

Table 6.8: Summary of expected costs for achieving net-zero carbon status in 2040 for Minto House, comparing the base case scenario and Pathway 2.

	Base case	Pathway 2
CO_2 emissions per year	241.1 tCO_2	70 tCO_2
Upfront cost	-	£378,400
Offset price	£90/ tCO_2	£90/ tCO_2
Cost of Net-Zero in 2040	£21,700	£6,300
Annual savings up to 2040	-	£656,000

Pathway 2 delivers carbon emissions reduction at lower than the carbon offset price and can achieve a payback period of 12 years through reduced utility bill expenditure. In 2040, carbon offset payment of £6,300 would be required in order to achieve full net-zero carbon status, by offsetting the remaining 70 tCO_2. By 2040, the net financial benefit attained through annual saving means that Pathway 2 would provide a more financially favourable option when compared to the base case scenario in 2040. The base case scenario would incur annual carbon offset payments of £21,700 on an annual basis thereafter. Under different carbon pricing scenarios, Pathway 2 still offers economic incentives over the base case. Changes to carbon pricing will not impact the financial gain realised from utility bill saving delivered by Pathway 2.

6.2.4 Strengths, Weaknesses, Opportunities and Threats Analysis for Pathway 2

<u>Strengths</u>

i. Significant carbon emissions reduction achieved.
ii. Gas consumption is completely offset to zero.
iii. Strong annual financial savings are demonstrated upon the base case utility bills.
iv. Simple payback achieved within 12 years.

<u>Weaknesses</u>

i. High level of building disruption and project risk related to invasive fabric upgrades.
ii. Early replacement of gas boilers leads to end of life embodied carbon emissions.
iii. Increase in peak electrical demand may result in further costs for capacity upgrades.
iv. More complex procurement and project management process.
v. Building will need to be closed for a duration of an extended duration of time.

<u>Opportunities</u>

i. On-site renewable generation may be leveraged for subsidies.
ii. Grants from Historic Environment Scotland for fabric upgrades.

<u>Threats</u>

i. Overall climate impact is sensitive to grid carbon intensities, hence there is limited autonomy over building carbon performance.
ii. Financial benefits are underpinned by retail energy prices, the financial modelling assumes fixed prices for gas and electricity.
iii. Planning and consent issues may arise for installation of solar PV modules.
iv. Contingency pricing may increase capital installation costs.
v. Decant or building closure may increase indirect project costs.
vi. Fabric upgrades may be detrimental to historic building fabric if undertaken improperly.

6.2.5 Practical Implications of Pathway 2

The practical implications of the delivering services upgrades of Pathway 1 remain largely relevant for Pathway 2. The key distinction lies within additional considerations, which arise due to fabric upgrades, which are fundamentally more invasive and disruptive for building use and occupants.

As highlighted by several technical reports relating to thermal upgrades for existing buildings, it is paramount to ensure that the quality of workmanship and materials is not detrimental to the building operation [7] [25]. Therefore, this will involve specialist contractors and will require detailed assessment of the existing building fabric to develop methodologies which are sympathetic to the existing building elements. Financially, this will involve additional costs beyond those stated in Table 6.7 and greater contingency upon project completion timescales.

The procurement process will inevitably be more complex than Pathway 1 and will involve contracting various sub-contractors in order to undertake works together. This may include M&E contractors, architects, structural engineers and historic building specialists. Operationally, this will necessitate prolonged building closure and displacement of current building occupants, which will carry further financial implications due to moving and decanting. However, a phased approached may be applied to fabric upgrades to mitigate the need for total building closure and reduce decanting costs. Furthermore, a decant strategy may be developed in line with the phased refurbishment. This would require discussion at a building and estates management level in order to balance building disruption and project timescales, which would inevitably be extended with a phased project plan. After completion of any level of thermal fabric upgrade, Minto House would require continual monitoring of internal humidity to ensure that the fabric upgrades do not cause moisture build-up and damage to occupant and building health.

6.3 Pathway 3: Integrated Refurbishment

6.3.1 Interventions

Pathway 3 has been constructed by selecting the best performing LCIs, based on levelised cost of carbon emission reduction over their lifespan (£/tCO_2). These are LCIs F2, F3, F4 and S3, which achieve levelised costs of £11, £33, £37 and £45 per tCO_2, respectively.

The services LCIs adopted for Pathway 3 are:

- F2: Wall insulation upgrade
- F3: Floor insulation upgrade
- F4: Secondary glazing
- S3: ASHP installation

6.3.2 Energy Performance

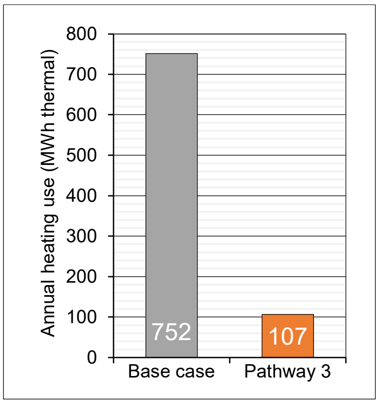

Figure 6.11: Pathway 3 and base case model annual heating primary energy demand. Pathway 3 substitutes all gas consumption with 645 MWh electric heating demand.

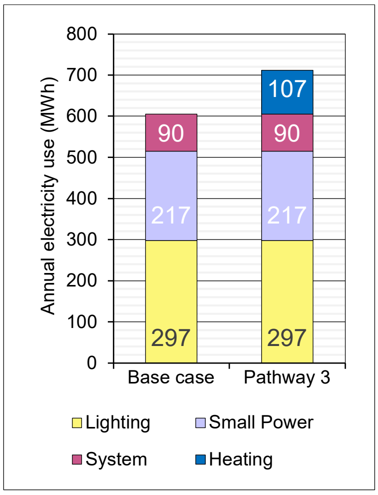

Figure 6.12: Pathway 3 and base case model annual electricity breakdown and use comparison. Pathway 3 increases lumped annual electricity consumption by 107 MWh.

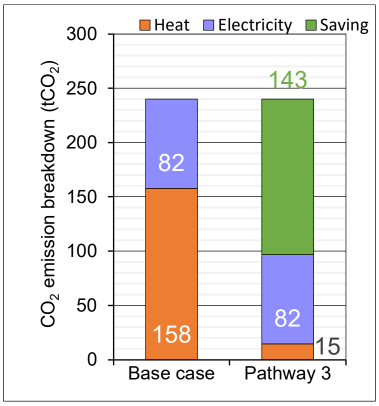

Figure 6.13: Pathway 3 and base case model annual CO_2 emissions breakdown, with comparative savings achieved of 143 tCO_2.

Table 6.9: Comparison of peak heating and electricity for base case and LCI Pathway 3.

	Peak Loads: Base Case	Peak Loads: Pathway 3
	(kW)	(kW)
Heating Demand	508.6	423.7
Electricity Demand	136.7	279.7

- Pathway 3 achieves a primary energy heating demand reduction of 645 MWh (86 per cent).
- As expected, electricity consumption increases due to the addition of electric heating. Other electricity demands remain constant due to the omission of the LED upgrade, which has previously been shown to reduce electric lighting demand.
- Carbon emissions are significantly reduced compared to the base case (by 60 per cent). Heating-related emissions are reduced by means of fabric upgrades and the main contribution towards carbon emissions arises from end-use electricity demand.
- Peak heating demand reduces by 17 per cent, but not as significantly as a full fabric upgrade, which is expected. Peak electricity demand increases by 205 per cent, which is attributable to electric heating, omission of LED upgrades and the reduced scope of fabric interventions.

6.3.3 Critical Analysis of Modelling Results

Despite not applying all possible fabric upgrades, Pathway 3 demonstrates that a significant carbon reduction may still be achieved from a reduced refurbishment scope. The omission of the LED upgrade from Pathway 3, results in electricity end-use consumption accounting for a large proportion of the overall carbon emissions. It also highlights that the LED upgrade LCI is important to reducing the peak electricity demand and also the carbon contribution from end-use electric demand, which becomes more substantial as heating demand is diminished through the use of efficient ASHPs and thermal envelope upgrades.

Pathway 3 also demonstrates that local renewable generation does not impact the overall carbon savings, nor the peak electricity demand, which is predisposed to the site and environmental conditions. When thermal fabric upgrades are applied, the set-point reduction LCI becomes less critical to reducing heating demand and heating demand accounts for only a small proportion of the building carbon emissions. This indicates that past a certain point, reducing heating demand further may bring diminishing returns, and instead the decarbonisation imperative should fall upon the end-use electricity demand.

6.3.4 Benchmark Performance

Pathway 3 electricity consumption exceeds the benchmark performance standards, however, as noted earlier all electric buildings possess different demand characterises which make it difficult to apply benchmarks shown in Figure 6.14. Conversely, as significant improvement upon operational carbon emissions intensity is observed, whereby Pathway 3 performance 2.75 times better than the good CIBSE Guide F benchmark.

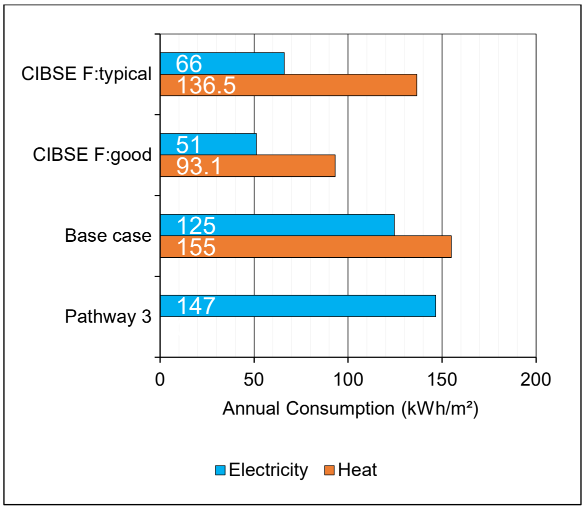

Figure 6.14: Comparison of LCI Pathway 3 with good and typical energy consumption benchmarks, derived from CIBSE Guide F.

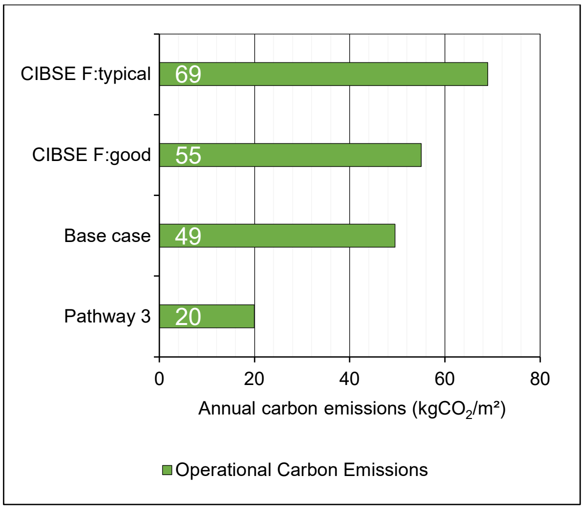

Figure 6.15: Comparison of LCI Pathway 3 with good and typical carbon emission benchmarks, derived from CIBSE Guide F.

6.3.5 Techno-Economic Evaluation

At the time of writing, Pathway 3 cost would be in the region of 204,400 GBP. This is based on system equipment sized to meet peak loads for electric heating and general electricity consumption, which are derived from IES modelling.

Table 6.10: Estimated costs for Pathway 3, based on system sizes modelled in IES.

LCI	Benchmark cost	Reference	Specific cost
			(GBP)
F2	£8.60/m^2 [64]	Wall: 3500m²	30,100
F3	1: £31.00/m^2 [64] 2: £10.15/m^2 [64]	Exposed:1500m² Internal: 3350m²	80,500
F4	£270 - 325 per unit [65]	150 units	40,500
S3	£ 469.7 /kW [65]	107 kW peak	50,300
Pathway 3			£204,400

Pathway 3 would achieve a reduction of 143 tCO_2 per year, which would cumulatively be 2860 tCO_2 from the time writing to 2040 (over a 20-year period). Over this period, the levelised cost of carbon saving would be equivalent to £71.5 tCO_2 saved, which is lower than the adopted carbon offset price of £95 tCO_2.

Table 6.11 summarises the financial performance and payback period for Pathway 3. This analysis indicates that a payback period of 39 years, substantially higher than those delivered from Pathway 1 and Pathway 2.

With the objective of achieving net-zero carbon by 2040, carbon offsetting would be required in both the base case and Pathway 3 scenario. Table 6.12 outlines the expected financial costs incurred in year 2040 to reach net-zero emissions through carbon offsetting and financing implementation of Pathway 3.

Table 6.11: Annual utility consumption, savings and simple payback calculation for Pathway 3.

Annual Utility Consumption	Base case	Pathway 3
Heating	752 MWh	107 MWh
Electricity	604 MWh	711 MWh
Gas bill	£20,200	-
Electricity bill	£84,600	£99,500
Total utility bill	£104,800	£99,500
	Annual saving	£5,300
	Total install cost	£204,400
	Payback period	**39 years**

Table 6.12: Summary of expected costs for achieving net-zero carbon status in 2040 for Minto House, comparing the base case scenario and Pathway 3.

	Base case	Pathway 3
CO_2 emissions per year	241.1 tCO_2	97 tCO_2
Upfront cost	-	£204,400
Offset price	£90/ tCO_2	£90/ tCO_2
Cost of Net-Zero in 2040	£21,700	£8,730
Annual savings up to 2040	-	£106,000

6.4 Pathway Matrix Comparison

Table 6.13: Comparison of LCI pathways modelled in the context of carbon emission reductions obtained from IES modelling and key financial metrics.

Low Carbon Interventions	**Carbon Saving**	**LCI Cost**	**Pathway 1**	**Pathway 2**	**Pathway 3**
	(tCO_2)	(GBP)			
F1: Roof insulation upgrade	5.4	37,800			
F2: Wall insulation upgrade	28.6	30,100			
F3: Floor insulation upgrade	43.1	80,500			
F4: Secondary glazing	13.4	40,500			
S1: Set-point reduction	28.2	-			
S2: LED upgrade	4.5	140,000			
S3: ASHP installation	125.3	112,000			
S4: Solar PV generation	1.9	16,500			
S5: Solar thermal	1.3	8,300			
CARBON REDUCTION			151 tCO_2	169 tCO_2	143 tCO_2
CAPITAL COST			£253,500	£378,400	£204,400
ANNUAL SAVINGS			£13,700	£32,800	£5,300
PAYBACK PERIOD			19 years	12 years	39 years
2040 LEVELISED COST			£84/tCO_2	£112/tCO_2	£71/tCO_2

6.5 Section Conclusions

- Significant improvement can made upon the base case building through the use of LCIs, Minto House can outperform CIBSE good benchmarks for carbon intensity.
- The levelised cost of LCI pathways analysed can be competitive with current carbon pricing.
- Payback periods can vary based on the overall cost and pathway adopted.
- The pathway with the lowest levelised cost may not provide the greatest saving potential on bills.
- Capital costs can vary depending upon the sequencing of LCIs, e.g. the capital cost of heating equipment can reduce through improving the building thermal fabric.
- A point of diminishing returns may be reached when improving thermal fabric upgrades.
- Carbon offsetting will be required for Minto House to be net-zero carbon by 2040, the scale of this will depend on the LCI pathway adopted in practise.

7 DISCUSSION

7.1 NET-ZERO CARBON MINTO HOUSE

In light of the University of Edinburgh's commitment to be carbon neutral by 2040, opportunities and barriers for decarbonising Minto House are discussed, which can inform the wider University of Edinburgh Estates decarbonisation strategy. With reference to the case study building, the wider context of net-zero carbon buildings is discussed relating to what scale net-zero carbon should be administered for heritage buildings to meet carbon emission reduction targets. Additionally, the discussion explores the role of renewable energy in delivering low-carbon futures for existing buildings, which have an inherently limited scope for accommodating LCIs. IES modelling has served as a useful tool for quantifying potential improvements upon the base case, enabling well-informed predictions to be made relating to the performance improvements that can be expected in reality. As such, the IES modelling results provide a basis for understanding magnitude and the overall scale of impact expected from LCIs upon Minto House and these results feed into discussions.

7.1.1 Key Learnings from Modelling Fabric LCIs

Amongst the assessed fabric improvement LCIs, floor insulation provided the greatest energy performance improvement against the base case model and achieved an 18 per cent reduction in carbon emissions. This is significant in highlighting that individual targeted fabric improvements can make a substantial contribution towards reducing carbon emissions. Moreover, this can feed into an incremental refurbishment approach, which would feasibly deliver significant carbon reductions. The exposed floor insulation LCI modelled the greatest percentage U-value improvement from 3.5 W/m^{2}K to 0.8 W/m^{2}K, but this occurred over a relatively small proportion of the overall building envelope area. This suggests that thermal efficiency gains are not best sought by upgrading the largest building envelope area, but rather, through targeted upgrades that address poorly performing areas of the building fabric. This should inform refurbishment strategies by targeting priority areas of building fabric, leading to a more effective use of resources for reducing carbon emissions. The lowest impact on carbon emissions was observed from the roof insulation LCI, which was improved from 0.7 W/m^{2}K to 0.3 W/m^{2}K (for zones 1, 2 and 4). This relatively small improvement in thermal performance resulted in a marginal 2.3 per cent reduction of carbon emission savings and this ties into learnings from above, which highlight the importance of prioritising fabric upgrades. Observations from fabric LCIs indicate that assessment of existing U-values and potential weaknesses in the building thermal envelope should be targeted in order to achieve the most dramatic improvements to carbon emissions.

Modelling results for fabric LCIs also indicate that end-use electricity consumption is decoupled from heating demand and changes to both annual and peak heating demand did not influence electricity consumption. This is an important validation of what would be expected from fabric upgrades as these only influence the thermal response of the building. It is assumed that all heat emitters (radiators, air handling units and fan coil units) are served from the gas boilers and hence, improvement to thermal fabric impacts the boiler gas demand, rather than electricity consumption. Hence, fabric LCIs have been shown to be successful at reducing carbon emissions by reducing the primary natural gas demand, which carries a greater carbon intensity than electricity. This is a key learning from the modelling and emphasises a latent potential for reducing carbon emissions by targeting reductions in gas demand.

Peak heating demand is influenced by the thermal fabric performance and results have validated that fabric upgrades will reduce its magnitude. Fabric LCIs that decrease overall gas demand also lead to reduced peak heating demand, however, no proportionality constant observed across annual gas demand reduction and peak heating demand reduction. This is best exemplified by floor insulation, which reduces annual gas demand by 27 per cent and peak demand by 11 per cent, and wall insulation, which reduces annual gas demand by 18 per cent and peak demand by 2 per cent. Peak heating demand is significantly impacted by thermophysical of the building structure and thermal mass of building elements. It is typical for heritage buildings to use passive storage through exposed thermal mass, reducing large temperature swings and peak heating loads. Of the LCIs assessed, those which involve a reduction of exposed thermal mass have reduced the overall peak demand less substantially. For example, the wall upgrade LCI reduces exposed thermal mass through the application of internal wall insulation and the building is less dynamically stable to temperature fluctuations. Coupled with the overall fabric improvement, this results a modest reduction in peak heating load. Conversely, LCIs which target existing lightweight timber-framed structures, such as floor upgrades result in more significant peak demand reduction, as exposed thermal mass and capacity for passive thermal storage is not compromised. This emphasises that fabric upgrades should be sensitive to existing building finishes and should not compromise the temperature buffering of exposed thermal mass, which is used extensively in historic buildings [29].

7.1.2 Key Learnings from Modelling Services LCIs

The ASHP upgrade offers the greatest carbon saving by a significant margin, delivering a 52 per cent reduction upon overall annual carbon emissions, compared to the next highest 12 per cent reduction achieved from heating set-point changes. This result validates earlier hypotheses, based on assessment of primary energy carbon intensity values, which highlighted that gas heating is 1.6 times as carbon intensive than electricity per kWh. Hence, shifting to electric heating provides two key benefits, it displaces a higher carbon intensity fuel of natural gas, which reduces carbon emissions from burning natural gas. Secondly, through a favourable ASHP coefficient of performance, the building heating load can be met with a lower primary energy demand, thereby further reducing carbon emissions. The extent of the carbon emissions reductions achieved through ASHPs, alongside the added benefit of replacing natural gas, stresses the importance of electric heating for decarbonising Minto House. Though relative carbon savings depends upon electric grid intensity, at the time of writing these are favourable for deployment of ASHP technology. Whilst grid carbon intensity is beyond the control of building management, it is understood that the future electricity grid will be decarbonised further [51]. Conditions for deployment may become more favourable in the future, but this should not deter from maximising upon the carbon and energy saving potential which is currently available.

Despite the environmental benefits demonstrated, electric heating results in a dramatic 130 per cent increase in peak electricity load, which may inhibit its feasibility. In order to facilitate this, electric heating should be supported by services upgrades that seek to reduce peak electricity demand, and consequently reduce costs incurred of line or equipment capacity upgrades. Despite possessing the highest levelised cost of carbon saving, the LED upgrade provides the greatest reduction in peak electricity demand, by 26 per cent, and is beneficial for this objective. The operational benefits of LED lighting go beyond carbon savings alone and can play a crucial role in reducing annual electricity bills and also peak demand, which are both critical enablers for electric heating systems. Therefore, electrical efficiency targeting LCIs should be adopted alongside electric heating, where possible, including and extending beyond the LED upgrade, which has been shown to be environmentally and financially favourable.

The lack of available space and appropriate environmental conditions are obstacles for on-site generation at Minto House and this is substantiated by modelling results, which indicate that solar PV and solar thermal technologies have the least carbon impact amongst the assessed services LCIs. Furthermore, no changes are observed to peak heating and electricity demand, indicating that peak generation does not occur concurrently with peak demand and this limits their utility. Due to planning constraints, the scope of application of renewable energy for heritage buildings is further restricted and this results in a grid-dependent electricity demand, inextricably tied to grid carbon intensity. Therefore, renewables must play a key role in driving decarbonisation at the grid-side generation, rather than at a local level for buildings heritage buildings to be net-zero carbon.

7.1.3 Assessment of Pathways: Opportunities and Barriers to Decarbonisation

Constructing low-carbon pathways provides a template for how decision-making may be undertaken for refurbishments. Pathway 1, a services-only refurbishment focusses on less invasive LCIs, Pathway 2, a services and fabric refurbishment represents a more expansive programme of works, and Pathway 3 is an integrated hybrid refurbishment consisting of a combination of LCIs.

Pathway 1 is constructed on the basis of reducing occupant and building disruption and addresses the efficiency and performance of building systems. Applying building services LCIs in conjunction, delivers a significant (63 per cent) reduction in carbon emissions, highlighting the potential for systematic efficiency gains. Despite this, no demand reduction was achieved and the overall end-use MWh demand for heating and electricity remained constant. The building remained thermally inefficient and energy performance was in excess of electricity consumption benchmarks outlined by CIBSE for good and typical buildings of a similar use type. The persistent peak energy demands signify a weakness in this pathway. Electric plant heating equipment must be sized to deliver the unchanged peak heating load and therefore leads to higher capital costs. This highlights that services upgrades can be beneficial in providing a short-term solution in reducing carbon emissions, however they fail to address the thermal efficiency and this can drive up the cost of electric heating upgrades, such that they become prohibitively expensive. As such, some level of fabric intervention would be beneficial in reducing the material cost of plant equipment through peak demand reduction. Bringing this together, Pathway 1 highlights that switching to electric heating can be both an opportunity and a barrier for achieving net-zero carbon emissions. It is an opportunity to capitalise on efficiency gains afforded from ASHP technology, but equally, in the absence of peak demand reduction, may result in prohibitively high installation costs and impede replacement of carbon intensive gas boilers.

Pathway 2 is based on a comprehensive refurbishment process and represents a best-case scenario for decarbonising Minto House. Key outcomes indicate that a maximum possible reduction of 70 per cent may achievable against the base case scenario and is significant for demonstrating the upper bound of the net-zero ambition. Even with all possible LCIs applied, carbon emissions persist and stem from electrical end-use demands, driven by occupancy factors. This is also reflective of diminishing returns, whereby further interventions or capital investment may not reduce carbon emissions proportionally, due to occupant factors. Combining this understanding with environmental goals, a lack of on-site renewable generation means that carbon offsetting will play a crucial and necessary role in the realisation of carbon neutrality for Minto House.

Despite demanding greater initial investment, Pathway 2 achieves a faster payback period of 12 years. This emphasises that there are additional economic benefits of a comprehensive refurbishment programme, which go beyond purely carbon emission reductions. With the lifespan of fabric upgrades exceeding the 2040 carbon neutrality target, the 2040 levelised cost is higher than other pathways due to the capital cost of fabric upgrades being spread only over the next 20 years, rather than their entire life expectancy. Pathway 2 is important for highlighting the limits of LCIs and signifies that the process for achieving net-zero carbon shifts impetus from addressing thermal efficiency, to electric heating and to end-use electricity demand and generation. This is consistent with methodologies adopted for new buildings and this process-based trajectory is mirrored in low-carbon frameworks such as the LETI and London Plan [16] [19].

Financial analysis indicates that Pathway 2 is a more expensive refurbishment based on material costs alone, however, it is expected that installation cost of fabric LCIs will heavily outweigh services LCIs, thus driving up refurbishment costs further. Factors including decant strategy, prolonged building closure and specialist contractors will all conspire to increase costs. Furthermore, greater project management contingency, due to lack of knowledge of the existing fabric will also lead to high project risk and will be manifested as increased project costs. The financial barrier is ever-present in Pathway 2 and this is compounded by the invasive building fabric upgrades. Obtaining clear costs for an interventionist refurbishment strategy contributes to this obstacle and lack of knowledge of building fabric and operation can lead to uncertainty, which can hamper progress towards implementing LCIs in the real world.

Pathway 3 adopts the lowest cost LCIs based on levelised cost of tonnes carbon reduced, as such it has the lowest aggregate levelised cost of carbon amongst the pathways assessed. Despite this perceived economic advantage, Pathway 3 provides a significantly longer payback period of 39 years, which questions its financial feasibility. On the other hand, Pathway 1 has been shown to be a low-intervention strategy and Pathway 2 achieves the fastest possible return on capital investment, indicating that there is no overall best refurbishment pathway, and each offer different and distinct advantages that relate to levelised cost of carbon saving by 2040, payback time or building disruption. Therefore, there is an opportunity to maximise economic benefits from refurbishment pathways and to optimise selection of LCIs based on the long-term objectives of the University Estates Department.

7.2 Scale of Net-Zero Carbon

As highlighted in the introduction, heritage buildings represent a significant proportion of the existing building stock in Edinburgh. It is clear that decarbonising all of these will require significant investment and expertise. The financial assessment has been crucial in demonstrating that this can be feasibly achieved with sensible payback times on initial investment. However, as the LCI pathways show, financial return can be independent from carbon emissions reduction and therefore a balance must be sought.

The methodology adopted to reduce carbon emissions is also impacted by scale. Services interventions alone have been shown to be effective at reducing emissions, but do not impact the thermal fabric of the building, which gives rise to high peak heating demand. Therefore, a combination of fabric and services interventions are better suited for application on a wider scale, as this would reduce peak demand and ensure availability of low-carbon grid electricity. This issue may exacerbate through the widespread adoption of electric heating and it is imperative to implement thermal envelope upgrades to reduce peak demand. As more buildings seek to become net-zero carbon, the aggregated demand-side changes will inevitably impact the supply, and may bring into question the security, sustainability and price of grid electricity. Therefore, the issue of scale also relates to issues of supply, and building managers must look for greater energy autonomy, which may be achieved through decentralised generation, private wire networks or contractual agreements with renewable energy generators. It is also important to recognise that whilst every historic building unique, a case study basis upon which to instigate change, will be both too slow and also too resource intensive. Therefore, there is room for exploring whether LCIs can be applied in bulk to various buildings or combined modelling methods to assess clusters of buildings. Practically, another key limitation, which relates to scale would involve availability of labour and expertise, and is indicative of wider construction industry challenges relating to the skills gap.

7.3 The Role of Renewables in Net-Zero Carbon Buildings

The modelling results obtained from IES after application of various LCIs all indicate that LCIs can only go so far towards achieving net-zero carbon, due to electric grid dependency. As substantiated by modelling results for solar PV and solar thermal technologies, the local generation capacity for renewable energy is significantly limited in the context of built up urban areas, and even more so for heritage buildings with historical designations. Therefore, the boundary of the net-zero carbon problem is forced to shift from one which concerns an individual building like Minto House, towards the wider carbon intensity of grid electricity, as mentioned above. Although scope for implementing renewable generation may be limited, it can play a crucial role in delivering net-zero carbon buildings on the supply side. At the time of writing, there have been successive years of decreasing grid carbon intensities which has been beneficial to this end. However, this also highlights a potential weakness in net-zero carbon resilience and organisation such as the University of Edinburgh may wish to have greater autonomy over the supply of electricity and in doing so, may opt for decentralised renewable energy generation in order mitigate the exposure to changing grid intensity. Therefore, it is imperative that renewable energy technologies play a central role in the energy mix, and on a more regional level, may be leveraged to provide a guarantee of clean energy. The University of Edinburgh may wish to explore the option of off-site decentralised renewable generation as this could be a means to offset carbon emissions and provide self-sufficient low-carbon electricity.

Another possible way to guarantee low-carbon electricity would be for the University of Edinburgh to enter Purchase Power Agreements (PPA) with renewable energy providers. Through this mechanism, the University would be able to buy renewable energy directly from providers for a fixed contract duration, thereby guaranteeing low-carbon electricity supply, which has been shown to be critical in driving the net-zero carbon imperative. The scale of the University's electricity demand may require a hybrid approach, which would involve multiple PPAs and off-site generation connected to private wire, with the latter being particularly relevant for University campuses. A similar approach to securing low-carbon electricity has already been explored amongst several universities and has proven to be a successful in building energy resilience and driving net-zero carbon ambitions [66].

7.4 Decarbonisation Hierarchy

This summarises the key findings from the discussion section in terms of actions that should be adopted for Minto House to achieve net-zero carbon emissions. As discussed above, this follows a hierarchical structure, whereby full benefits can only be gained if adopted in a stepwise approach.

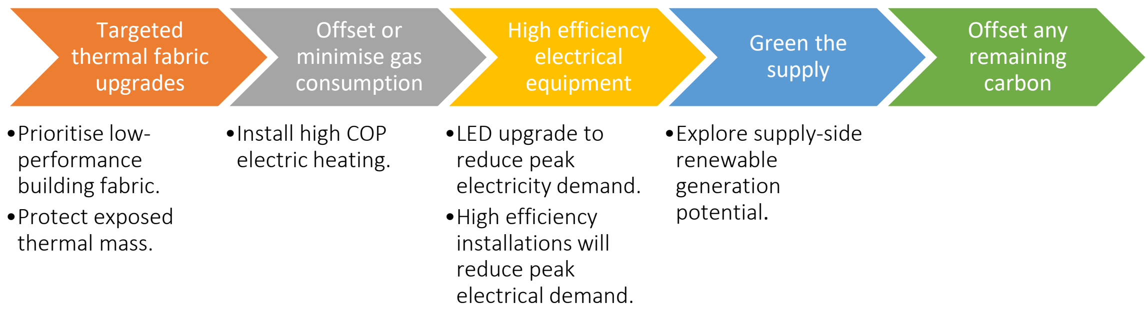

Figure 7.1: Summary of key findings and hierarchical structure of interventions required to for Minto House to achieve net-zero carbon emissions.

7.5 Limitations

Lack of access to the building due to prolonged closure of the University of Edinburgh has resulted in a number of modelling assumptions that are based on historical building information and may not be current. Therefore, the base case model has some embedded assumptions within it, which may not be a true representation of Minto House in its present form. Despite this limitation, it does not impact the validity of modelling, nor the insights gained from this process. By adopting a base case model, relative improvements of LCIs and refurbishment pathways have been measured against this, and this has been indicative of benefits and improvements in energy performance expected from different building interventions. Specific assumptions have been made relating to the lighting fixtures and heat emitters, which have been assumed to be fluorescent lighting and radiators.

Due to pricing uncertainty and site-specific factors, comprehensive costs were not applied for assessing financial cost of refurbishment. Instead, material costs have been applied to provide a simplified basis for financial comparison. In doing so, this obscures the financial implications of fabric interventions which are expected to more expensive due to remedial works, project contingency and labour costs. Therefore, it is expected that the financial LCIs will have significantly higher capital costs, beyond the material costs adopted for the financial assessment. The implications of this would mean that the expected payback periods for Pathway 2 and Pathway 3, involving fabric LCIs would be longer. However, this limitation does not impact the overarching learnings obtained from the financial assessment and pathways can still be optimised to achieve different strategic goals.

IES modelling provides robust thermal analysis, however, does not provide a robust humidity modelling suite. As noted by numerous authors, moisture issues can arise from installation of retrofit thermal insulation in heritage buildings [26] [27] [29]. Therefore, the true extent of impacts of thermal fabric upgrades have not been modelled. Whilst this is not critical to the learnings obtained from energy modelling, this would be an important step for future works to validate the applicability of certain fabric interventions, beyond literature-based research. Another limitation of the IES model is the simulation of occupancy changes and impacts upon small-power electricity consumption. Through the use of ASHRAE room templates, occupant-related energy consumption remained constant and was linked to the building use type. A more sophisticated model would incorporate occupancy schedules, which can be obtained through auditing the existing building.

This dissertation has assessed the technical and financial impacts of LCIs upon Minto House, however, it has not addressed the social aspect of net-zero carbon emissions and what this means for building occupants. For example, factors relating to occupant comfort have not been considered when assessing the impact of LCIs. In reality, LCIs would have to balance expectations of occupants, financial limitations and environmental goals. The social cost of net-zero carbon falls outside the scope of this paper, however future work may focus on this by undertaking occupant surveys to better understand the human implications of LCIs and refurbishments. This may be further leveraged through the application of smart metering, which would enable best use of the existing infrastructure. Smart metering would tie into building maintenance and energy management and can offer advantages in identifying areas for improvement and future LCIs for reducing carbon emissions. This is important for providing two-way information and feedback, which is necessary for optimising building energy performance. Furthermore, this would enable development of more robust energy models, which can better replicate the actual building performance.

7.6 FURTHER STUDY

Further study should tie into the aforementioned limitations and should focus upon improving the robustness of the energy model, which can be achieved through several means. In situ testing of U-values would be advantageous in assessing the current building fabric performance. Firstly, this would be beneficial for refining the base case energy model, but secondly, it would help to identify key areas in the building envelope that should be prioritised for upgrade. In addition to external U-value testing, internal site assessment would provide clarity on existing building fabric and structure and would feed into further model refinement. These measures both have the potential to influence results obtained from energy modelling as the relative improvement delivered from fabric LCIs may be magnified or diminished depending on the current thermal performance. Furthermore, detailed assessment of building services would also contribute towards improving the base case model to be more representative of existing building services and system efficiencies, therefore impacting the benefits delivered from services LCIs.

Engaging with specialist contractors would be beneficial for obtaining expected project costs for different LCIs. This would feed into the financial evaluation of LCIs and may impact the feasibility of particular approaches. This would also build upon the assessment undertaken in this dissertation and may be able to provide further insight into the practical and financial challenges of implementing fabric upgrades in heritage buildings.

Finally, occupancy surveys should be taken in order to understand issues surrounding occupant comfort, but also to ensure that occupancy profiles are being accurately modelled in the base case model. As was found in this dissertation, as LCIs were applied, the occupancy-driven energy consumption become increasingly significant upon overall carbon emissions. Therefore, if these are to be reduced, then understanding must be developed within how this energy is currently being used and how further efficiency upgrades may deliver carbon reductions. In addition, an understanding of occupant comfort must also be gathered from empirical surveys, this will ensure that future LCIs are not compromised through occupant dissatisfaction and agency.

8 CONCLUSIONS

8.1 DISSERTATION CONCLUSIONS

This dissertation has adopted a modelling-based approach to assess the technical and economic feasibility of LCIs for decarbonising Minto House. Through individually assessing LCIs several key insights have been gained, which can inform how these are implemented in practise. Firstly, through assessment of fabric U-values, IES modelling results substantiate that targeted improvements for poorly performing fabric elements have greater potential to deliver carbon savings. This can feed into project planning, enable efficient use of resources through implementing LCIs which target priority areas. Secondly, energy modelling indicates that preservation of exposed thermal mass can play an important role in managing temperature fluctuations and reducing peak heating loads, which is important for both cost management and carbon reduction.

Electrification of heating offers the most substantial reduction in carbon emissions and is therefore, imperative towards achieving net-zero carbon performance. However, in order to facilitate this shift, firstly, fabric LCIs should be implemented beforehand to reduce heating demand and capital costs of plant equipment. Secondly, electrically efficient fittings, such as LED lighting, should be installed to reduce the overall peak electricity demand. These factors are deemed to be critical towards financially enabling a shift towards electric heating, which is central to the decarbonisation of Minto House.

Electrification of heating is both an opportunity and barrier for achieving net-zero carbon emissions. It is central to decarbonising Minto House, however, if applied without improving the thermal fabric and energy performance, it will be a barrier and prohibitively expensive to install. In addition, the best-case scenario highlights that LCIs can reduce carbon emissions up to 70 per cent, from which point emissions are dominated by occupancy-led electricity consumption and thus further technical interventions would achieve diminishing returns for carbon savings. At present occupancy-led consumption is understood to be a barrier towards decarbonisation as it is not currently measured in Minto House, hence cannot be fully understood to identify opportunities for reducing demand and emissions.

Practical barriers have been identified around project planning of fabric upgrades. It is concluded that a lack of understanding of the existing building can lead to higher contingency planning and project costs which may constrain the extent of refurbishment. This is a barrier toward decarbonisation, as it is concluded that a combination of services and fabric upgrades would present the most favourable financial and environmental benefits. This may be further compounded by a ‘skills gap’ in the construction industry for undertaking fabric upgrades which are sensitive and sympathetic of heritage building operation.

Finally, on a more general level, two key conclusions are reached. Firstly, the scale of administering net-zero for heritage buildings is underpinned by electricity demand. This ties into reducing gas demand through electrification of heating, however as noted, is subject to fabric efficiency upgrades. Secondly, renewables must play key role on the electricity supply-side in order to drive down carbon emissions from electricity consumption for heritage buildings that do not possess favourable environmental conditions for on-site generation.

This dissertation has shown that the net-zero carbon challenge evolves along the refurbishment project life cycle. A low-carbon hierarchy has been proposed for Minto House for implementing LCIs viably and it is concluded that Minto House has the potential to achieve net-zero carbon emissions by 2040, through an integrated refurbishment plan, which prioritises targeted fabric upgrades, electric heating and greater electrical efficiency. However, due to a lack of on-site generation, this potential can only be realised through carbon offsetting carbon emissions or securing a low-carbon electricity supply.

8.2 Actions for the Estates Department

The University of Edinburgh Estates Department should adopt the following actions in order to better understand net-zero carbon buildings and the expected financial implications of undertaking the LCIs assessed in this dissertation.

1. In situ U-value assessment should be undertaken to validate the U-values assumed by energy modelling. Benefits accrued from thermal fabric upgrades are dependent upon existing U-values.

2. A building fabric assessment should be undertaken through the use of thermography. This will identify priority thermal fabric areas, which may be targeted in addition to thermal bridges.

3. A detailed occupancy audit must be taken to have a better understanding of occupant comfort levels, expectations and overall building utility. This will not only inform the possible LCI choices, but also the energy modelling inputs. As was shown, occupancy-driven consumption becomes more significant as the building is decarbonised.

4. A detailed building services audit must be undertaken to validate system efficiencies. Benefits gained from services upgrades are dependent upon the efficiency of the incumbent building systems.

5. Routine building services checks should be undertaken to ensure that current equipment is operating properly and at the expected efficiency. The boilers are understood to still be within their warranty period, and this could be facilitated by engaging with the manufacturer. Modelling results indicate that boiler efficiency loss of 5 per cent can drive up overall consumption by 4.5 per cent, which represents substantial carbon and financial costs.

6. Opportunities should be explored for establishing PPA agreements in order to decarbonise University buildings, in the absence of a private wire network.

7. Grant funding opportunities should be explored from Historic Environment Scotland, for upgrading and restoring heritage buildings. This could improve the financial viability of fabric upgrades and assist the net-zero carbon transition as a whole.

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10 APPENDICES

10.1 IES Model Geometry and Surroundings

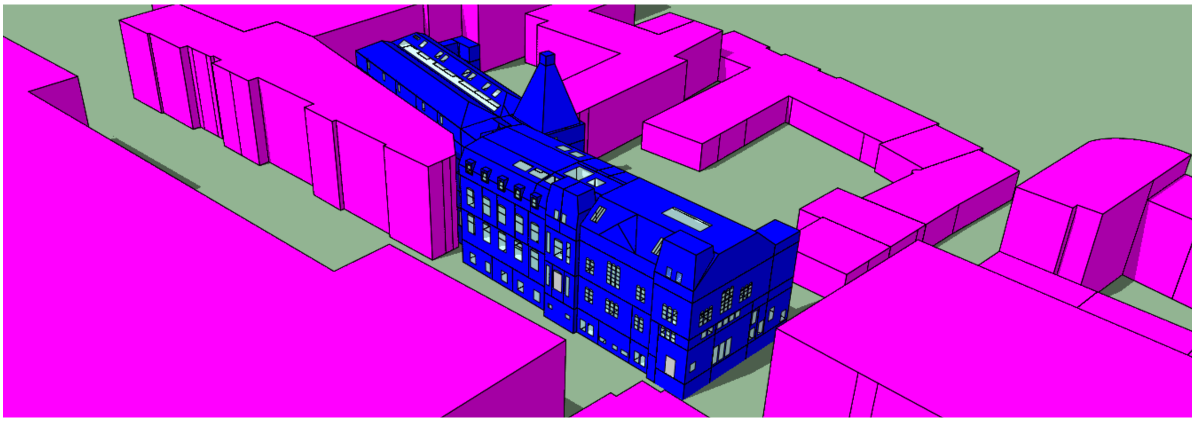

Figure 10.1: IES model geometry, viewed from SE direction.

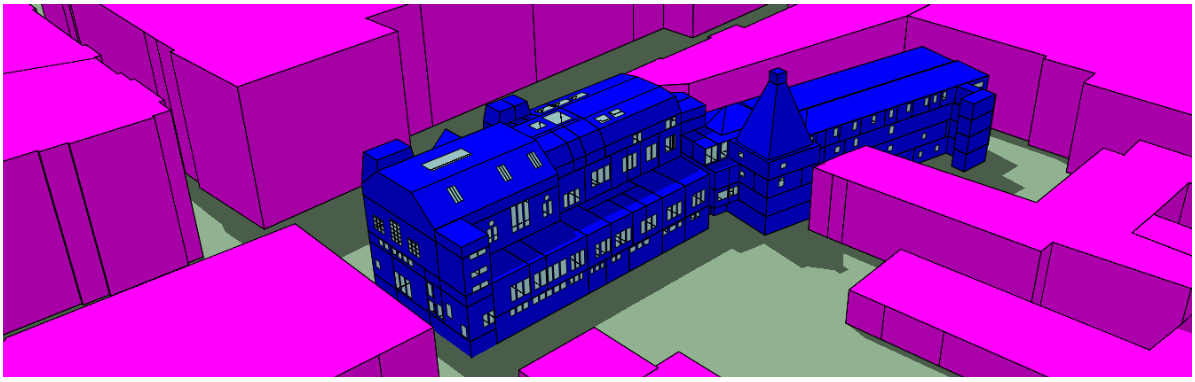

Figure 10.2: IES model geometry, viewed from NE direction.

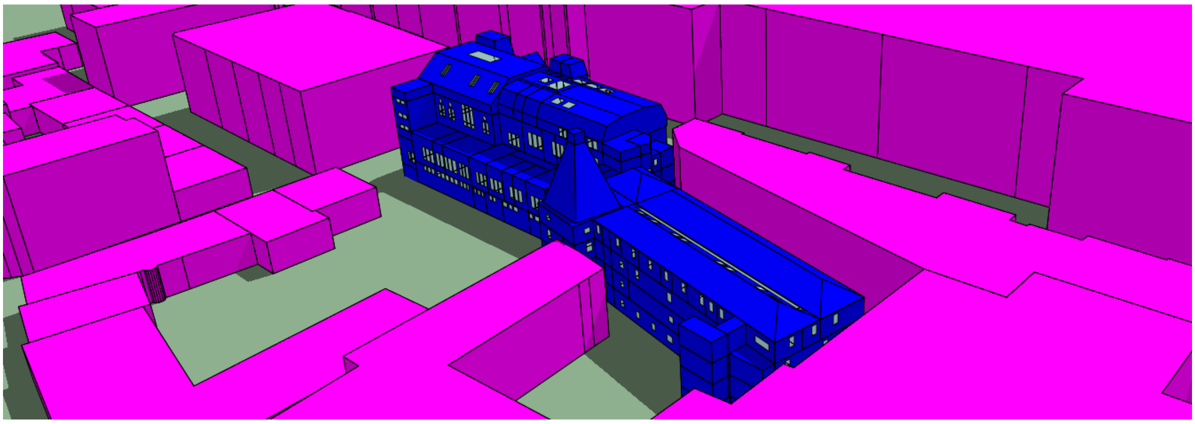

Figure 10.3: IES model geometry, viewed from NW direction.

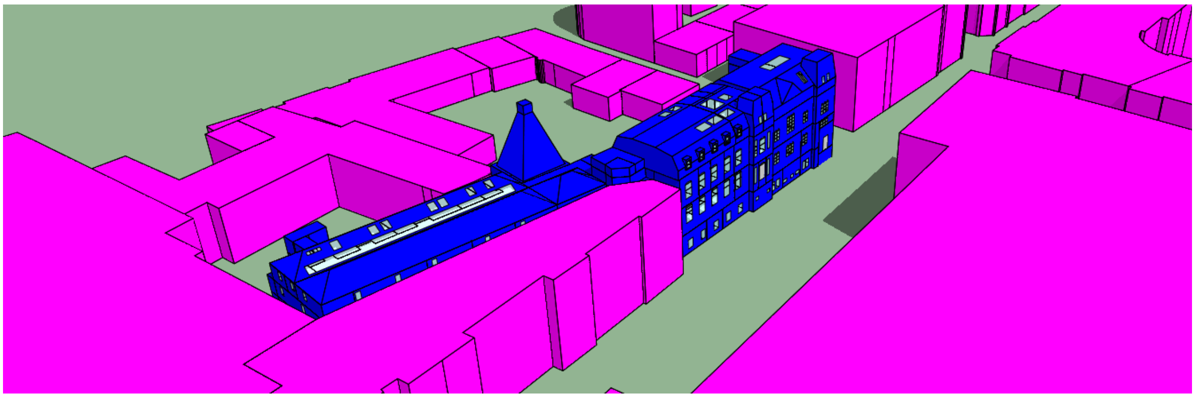

Figure 10.4: IES model geometry, viewed from SW direction.

10.2 EXISTING BUILDING FABRIC ASSESSMENT

Table 10.1: Fabric thermal properties for Zone 1 assigned to IES model.

ZONE 1		
Door		
	Thickness:	100mm
	External Finish:	Solid wood (maple, oak or similar hardwoods)
	Construction Type:	-
	Internal Finish:	Solid wood (maple, oak or similar hardwoods)
	U-value:	**0.16 W/m²K** [33]
Wall		
	Thickness:	600mm
	External Finish:	Sandstone
	Construction Type:	Uninsulated solid stonewall with lath and plaster
	Internal Finish:	Lath and plaster
	U-value:	**1.1 W/m²K** [32]
Window		
	Thickness:	-
	External Finish:	Glazing
	Construction Type:	Single-glazed window with 20mm metal frame
	Internal Finish:	Glazing
	U-value:	**5.4 W/m²K** [33]
Roof		
	Thickness:	-
	External Finish:	Slate
	Construction Type:	Timber roof construction
	Internal Finish:	-
	U-value:	**0.7 W/m²K** [32]

Table 10.2: Fabric thermal properties for Zone 2 assigned to IES model.

ZONE 2		
Door		
	Thickness:	100mm
	External Finish:	Solid wood (maple, oak or similar hardwoods)
	Construction Type:	-
	Internal Finish:	Solid wood (maple, oak or similar hardwoods)
	U-value:	**0.16 W/m²K** [33]
Wall		
	Thickness:	600mm
	External Finish:	Sandstone
	Construction Type:	Uninsulated solid stonewall with lath and plaster
	Internal Finish:	Lath and plaster
	U-value:	**1.1 W/m²K** [32]
Window		
	Thickness:	-
	External Finish:	Glazing
	Construction Type:	Single-glazed window with wood frame
	Internal Finish:	Glazing
	U-value:	**5.75 W/m²K** [33]
Roof		
	Thickness:	-
	External Finish:	Slate
	Construction Type:	Timber roof construction
	Internal Finish:	-
	U-value:	**0.7 W/m²K** [32]

Table 10.3: Fabric thermal properties for Zone 3 assigned to IES model.

ZONE 3		
Door		
	Thickness:	-
	External Finish:	Glazing with metal frame
	Construction Type:	Double glazed with 25mm spacing
	Internal Finish:	Glazing with metal frame
	U-value:	**2.76 W/m²K** [33]
Wall		
	Thickness:	220mm
	External Finish:	Brick with GFRP box panel covering
	Construction Type:	Uninsulated solid brick wall, 13mm dense plaster
	Internal Finish:	Plaster
	U-value:	**2.09 W/m²K** [33]
Window		
	Thickness:	-
	External Finish:	Glazing
	Construction Type:	Single-glazed window with aluminium frame
	Internal Finish:	Glazing
	U-value:	**5.4 W/m²K** [33]
Roof		
	Thickness:	-
	External Finish:	Roofing lead
	Construction Type:	Flat timber roof construction
	Internal Finish:	Plasterboard
	U-value:	**2.35 W/m²K** [33]

Table 10.4: Fabric thermal properties for Zone 4 assigned to IES model.

ZONE 4		
Door		
	Thickness:	-
	External Finish:	Wood
	Construction Type:	Hardwood with glazed panel
	Internal Finish:	Wood
	U-value:	**0.12 W/m²K** [33]
Wall		
	Thickness:	600mm
	External Finish:	Sandstone with rubble face
	Construction Type:	Uninsulated solid stonewall with lath and plaster
	Internal Finish:	Plaster
	U-value:	**1.1 W/m²K** [32]
Window		
	Thickness:	-
	External Finish:	Glazing
	Construction Type:	Single-glazed window with aluminium frame
	Internal Finish:	Glazing
	U-value:	**5.4 W/m²K** [33]
Roof		
	Thickness:	-
	External Finish:	Slate
	Construction Type:	Flat timber roof construction
	Internal Finish:	Plasterboard
	U-value:	**0.7 W/m²K** [32]

Table 10.5: Generic fabric properties assigned to IES model.

GENERIC BUILDING ELEMENTS		
Exposed Floor		
	Thickness:	150mm
	Construction Type:	Solid concrete slab with no insulation
	U-value:	**3.5 W/m²K** [32]
Internal Floor		
	Thickness:	-
	Construction Type:	Timber floor on 100mm joists, plasterboard ceiling
	U-value:	**1.64 W/m²K** [33]
Internal Partition A		
	Thickness:	241mm
	Construction Type:	Single brick leaf with dense plaster
	U-value:	**1.45 W/m²K** [33]
Internal Partition B		
	Thickness:	600mm
	Construction Type:	Solid stonewall with lath and plaster finish
	U-value:	**1.1 W/m²K** [32]
Roof skylights		
	Thickness	**-**
	Construction Type	Double-glazed 25mm pane spacing
	U-value	**3.32 W/m²K** [33]

[End of Document]