University of Southampton

Faculty of Engineering and Physical Sciences

School of Engineering

"Assumptions and Realities of Heating Demand in Social Housing"

by

Victoria Aragon

ORCID ID https://orcid.org/0000-0002-6175-9454

Thesis for the degree of Doctor of Philosophy

June 2023

University of Southampton

Abstract

Faculty of Engineering and Physical Sciences

School of Engineering

Doctor of Philosophy

Assumptions and Realities of Heating Demand in Social Housing

by

Victoria Aragon

The transition towards net zero in the United Kingdom, includes a particular focus on decarbonising heat demand in domestic buildings, due to ageing energy inefficient building stock and the large dependence on fossil fuel systems. Consequently, the UK aims to reduce space heating loads and provide it from clean sources, as well as ensure homes are warm and bills are affordable.

Social housing is a primary candidate for decarbonisation given its public ownership and the vulnerability of its occupants; local authorities need to retrofit their building stock whilst assuring energy efficiency and affordability of comfort. For home energy upgrade programmes to succeed, it is necessary to understand the characteristics of current and future heating demand and identify what assumptions should be re-evaluated. Thus, this work sets out to evaluate the current state of knowledge on heat demand in social housing, and specifically aims to: (i) identify evidence gaps in the prediction of heating demand in domestic buildings in the United Kingdom, (ii) map current knowledge on heating related occupant behaviour (ii) evaluate methodologies and assumptions for estimating domestic heat demand and develop evidence-based suggestions to improve them and, (iv) add empirical evidence on occupant behaviour and their impact in heating demand within the context of social housing.

First, a systematic literature review is performed to addresses objectives (i) and (ii). This review highlights lack of large-scale data collection on occupancy and heating, and insufficient evidence on the impact of smart heating controls. Secondly, in relation to objective (iii), a

mapping of household typologies through the English Housing Survey 2014-15 sample suggests that current models are not representative. Results show that the most frequently household typologies used in UK building simulation, (a) a family with dependent children where the parents work full time; and (b) a retired elderly couple who spend most of their time indoors, amount to only 19% of England's households. A more representative selection of household typologies is identified, and occupancy patterns of each group are generated using 2015 UK Time Use Survey diaries.

Furthermore, to address objective (iv), the heating demand in two social housing case studies in the South of England is evaluated through the exploration of: heat billing records from 462 dwellings from a tower block complex, and setpoint records from smart thermostatic radiator valves in 47 flats in a care home. The first discovers a very low heating demand and three main types of residents: households that do not use space heating (11%), irregular households, where the transition towards the heating season is not identifiable (33%), and households with marked seasonal thresholds (56%). behaviour. The second shows evidence on distinct heating strategies and types of interactions with heating controls, as well as poor understanding of the heating systems (only 50% of residents showed a behaviour consistent with the principles of operation of the system). Overall, this analysis finds distinct user profiles and heating strategies, highlighting the variability of heat demand and the contrast between expected and actual usage of home heat controls.

These findings underline the importance of moving towards a more disaggregated approach in energy modelling and have a direct application in bottom-up models, thermal comfort, and compliance assessment. The heterogeneity of heating demand calls for fit-for-purpose large scale data collection on occupant behaviour and heating, to update national standards and forecasts, as well as tailor local interventions to promote energy efficiency in homes. Defining the pathways towards net zero homes and low carbon heat supply requires understanding residents, and the potential impact of measures in terms of carbon, comfort, and health. In the current context of energy crisis and devolution, this work is highly relevant for local authorities who play a key role in assuring buildings are livable, and affordable.

Table of Contents

Table of Tables

Table of Figures

List of Accompanying Materials

Main publications

	Reference
1	Gauthier, Stephanie, Aragon, Victoria, James, Patrick and Anderson, Ben (2016) “Occupancy Patterns Scoping Review Project”, Department for Business, Energy & Industrial Strategy, http://eprints.soton.ac.uk/id/eprint/403390
2	Aragon V. et al (2019) “Developing English domestic occupancy profiles”, Building Research & Information, 47 (4), pp375-393, https://doi.org/10.1080/09613218.2017.1399719
3	Aragon V. et al (2018) “Unpacking mid-season heating demand in social housing”, 2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA Chicago, IL September 26-28, 2018
4	Aragon V. et al (2022) “The influence of weather on heat demand profiles in UK social housing tower blocks”, Building and Environment, Volume 219, 109101, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2022.109101.
5	Aragon V. et al (2022) "Revisiting Home Heat Control Theories through a UK Care Home Field Trial" Energies 15, no. 14: 4990. https://doi.org/10.3390/en15144990

SUPPORTING PUBLICATIONS

	Reference
1	Aragon V. et al (2018), Evaluation of Retrofit Approaches for Two Social Housing Tower Blocks in Portsmouth, UK. Future Cities and Environment, 4(1), p.4, DOI: http://doi.org/10.5334/fce.8
2	Ornaghi C. et al (2018), The effect of behavioural interventions on energy conservation in naturally ventilated offices, *Energy Economics*, 74, pp582-591, https://doi.org/10.1016/j.eneco.2018.07.008

DATASET

	Reference
	Aragon, V., Gauthier, S., James, P., Anderson, B., & Warren, P.(2017). England’s domestic occupancy patterns. Southampton: University of Southampton. doi:10.5258/SOTON/D0142 [Data set].

Research Thesis: Declaration of Authorship

Print name: Victoria Aragon

Title of thesis: “Assumptions and Realities of Heating Demand in Social Housing”

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while as a member of Staff at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Main publications

- Gauthier, Stephanie, Aragon, Victoria, James, Patrick and Anderson, Ben (2016) “Occupancy Patterns Scoping Review”, Project Department for Business, Energy & Industrial Strategy”, http://eprints.soton.ac.uk/id/eprint/403390

- Aragon V. et al (2019) “Developing English domestic occupancy profiles”, Building Research & Information, 47 (4), pp375-393, https://doi.org/10.1080/09613218.2017.1399719

- Aragon V. et al (2018) “Unpacking mid-season heating demand in social housing”, 2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA Chicago, IL September 26-28, 2018, https://www.ashrae.com/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C104.pdf

- Aragon V. et al (2022) “The influence of weather on heat demand profiles in UK social housing tower blocks”, Building and Environment, Volume 219, 109101, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2022.109101.
- Aragon V. et al (2022) "Revisiting Home Heat Control Theories through a UK Care Home Field Trial" Energies 15, no. 14: 4990. https://doi.org/10.3390/en15144990

Supporting publications

- Aragon V. et al (2018), Evaluation of Retrofit Approaches for Two Social Housing Tower Blocks in Portsmouth, UK. Future Cities and Environment, 4(1), p.4, DOI: http://doi.org/10.5334/fce.8,
- Ornaghi C. et al (2018), The effect of behavioural interventions on energy conservation in naturally ventilated offices, Energy Economics, 74, pp582-591, https://doi.org/10.1016/j.eneco.2018.07.008.

Signature: Date:

Acknowledgements

I am incredibly grateful to the University of Southampton and to all the institutions and partners that collaborated in the research projects that led to this work. Each are acknowledged in the individual publications. This section is for thanking the people that made and continue to make a difference. May I one day be able to give back to all of you.

To Prof. Patrick A. B. James, for support beyond the role, for being an extraordinary person and supervisor, for the drawings that make everything clear.

To Dr. Stephanie Gauthier, for consistently clearing my head and showing me solutions. For somehow always knowing the perfect reference and the right pathway. You are truly remarkable.

To Prof. AbuBakr S. Bahaj, for continuously giving me opportunities. For believing I could do a good job.

To my colleagues, Philip, Tom, Luke, Leo, Phil, Rodolfo, and Maj, for their advice and outlook. For the shared struggles and the long hours, for the many meals and talks with infinite topics. For the dad jokes.

To my 'commensali', Giulia, Sheila, Ale and Marina, for the companionship, friendship, and endless laughter. For being my family in Southampton.

To my 'Chengues', Aye, Andy, Sabru, Sofi, Pili, and Flor, for being examples of hard-working incredible women. For a friendship that could withstand a Big Bang. For choosing to celebrate life together again and again.

To Bel, for mirroring my thoughts and fears, for non-stop laughing fits. For understanding each other from across the ocean.

To Jake, for years of companionship, for loving Lola even more than I do.

To all my dogs, own and borrowed, for the unconditional love and playfulness that was much needed.

To Matt, for giving me perspective. For a wonderfully weird and beautiful bond, for creating stories together. For the much-needed gravity.

To my family, for the incredible mix of stoicism, indulgence, and compassion. For the noise, for the days that start and end with food. For celebrating my adventures.

To my sisters, Ale and Leti, for a never-ending childhood that now continues through their marvelous children. For the parts of them that I carry with me.

To my dad, for braving the monsters. For the most wonderful timid smile.

To my mum, for holding my hand from 11,000 kilometers away.

Definitions and Abbreviations

ARHMM................................Auto Regressive Hidden Markov Model

ARIMA ....Auto Regressive Integrated Moving Average

ASHRAE ....American Society of Heating, Refrigerating and Air-Conditioning

BEIS ....Department for Business, Energy & Industrial Strategy

BRE ....Building Research Establishment. Centre of building science in the United Kingdom, owned by the BRE Trust.

BREDEM ....BRE Domestic Energy Model. Methodology for calculating the energy use and fuel requirements of dwellings

BSRIA...................................Building Services Research and Information Association

CIBSE ....The Chartered Institution of Building Services Engineers. International professional engineering association based in London.

CCC......................................Climate Change Committee. Independent, statutory body established under the Climate Change Act 2008

CV ....Coefficient of Variation. Ratio of the standard deviation to the mean; measurement of variability

CV (RMSE) ....Coefficient of the Variation of the Root Mean Square Error

DECC....................................Department of Energy & Climate Change (became part of BEIS in July 2016)

DHW ....Domestic Hot Water

DLUHC ....Department for Levelling Up, Housing and Communities

EER ....Energy Efficiency Ratio

EFUS ....Energy Follow Up Survey. Interview and measurement survey of household heating patterns, thermal comfort, and energy consumption, as a follow up of the English Housing Survey.

EV's..Electric Vehicles

HDD ....Heating Degree Days

HMG ....Her Majesty's Government

HRP.......................................Household Reference Person. This concept was introduced in the 2001 Census to replace the traditional concept of the 'head of the household'. HRPs provide an individual person within a household to act as a reference point for producing further derived statistics.

HVAC ....Heating, Ventilation, and Air Conditioning

IBPSA ....International Building Performance Simulation Association. Non-profit international society of building performance simulation researchers, developers and practitioners

ICE ....Institution of Civil Engineers. Independent professional association for civil engineers in the United Kingdom

IEEE.......................................Institute of Electrical and Electronics Engineers. Professional organization for electronic engineering and electrical engineering.

MHCLG ....Ministry of Housing, Communities & Local Government (now called Department for Levelling Up, Housing and Communities)

MHRV ....Mechanical Heat Recovery Ventilation

RIBA.......................................Royal Institute of British Architects. Professional body for architects

SAP ....Standard Assessment Procedure. Calculation methodology used to develop Energy Performance Certificates (EPCs).

STV ....Smart Thermostatic Valve

TRV ....Thermostatic Radiator Valve

TUS ....Time Use Survey

UK..United Kingdom

UoS..University of Southampton

Chapter 1 Introduction

1.1 Research context

Decarbonising heat supply in the UK

In 2019, the UK extended its commitment to reduce its carbon emissions from 80% to 100% by 2050, relative to 1990 levels (BEIS, 2019). As a result, a ten point plan to accelerate the pathway to net zero was published in 2020, underlining buildings as one of the pivotal areas to focus on (HMG, 2020). Domestic buildings energy consumption accounts for 32% of the UK's energy demand, of which 60% corresponds to space heating (BEIS, 2021a). Consequently, the UK aims to both reduce space heating loads and provide it from clean sources.

The three main strategies to decarbonise domestic heat supply in the UK revolve around: (i) making homes more energy efficient (ii) introducing renewable systems, and (iii) encouraging users to uptake energy efficient practices through social interventions (HMG, 2018; Climate Change Committee, 2020). Selecting the correct strategies requires being able to accurately forecast the effects of each. Better insulated homes and the deployment of more efficient or affordable heating systems can in fact result in higher heat demand (Sorrell, 2007; Galvin, 2014; Belaïd, Bakaloglou and Roubaud, 2018; Flower, Hawker and Bell, 2020). This is known as the 'rebound effect' and is a consequence of users' behavioural changes as improvements allow them to achieve higher degrees of comfort (Greening, Greene and Difiglio, 2000). A better understanding of what triggers and limits heat demand will allow for more accurate predictions diminishing the performance gap, meaning the difference between predicted and observed energy performance in buildings.

The leading pathway to decarbonising the UK's heat supply in domestic buildings is large scale electrification of heating systems (Broad, Hawker and Dodds, 2020; BEIS, 2021b) The most promising technology available are heat pumps, which have the potential to be cost effective in comparison with gas boilers (Kelly, Fu and Clinch, 2016; Kozarcanin *et al.*, 2020; Wang and He, 2021). A change from fossil fuelled boilers to electric heat pumps, however, brings its own challenges in relation to demand prediction and user adaptation. In contrast to boilers, heat pumps give out continuous low-grade heat. It is paramount to understand how this new electricity demand will affect the grid, as well how users will react to the changes in the way the system is operated. Watson et al. (2019) underlines the importance of knowing heat patters of both space heating and domestic hot water, for correctly modelling future electricity loads. Moreover, in the context of electrification, the combination of heat pumps with electric vehicles, dynamic tariffs and grid balancing will require smart controls to be integrated into homes, which could also present a challenge in terms of installation capacity and consumer acceptance (Heat Pump Association, 2019).

Furthermore, when analyzing the potential of large-scale deployment of heating systems, heterogeneity of dwellings and households should be considered. By disaggregating data in heat demand modeling, we can evaluate different types of resident behavior and tailor policies. A preliminary trial in UK households by Lowe et al. (2017) showed that both heat pump performance and user satisfaction varied within different dwellings, controls, and occupant behavior. Another study by Flower et al. (2020) evaluated how building diversity, including both building and social characteristics, affect the potential impact of heat pump systems.

Amongst the three types of tenures found in residential buildings in the UK, 'private occupied', 'private rented' and 'social rented', social housing is a perfect candidate for retrofits and technology upgrades. Firstly, it amounts to 17% of the UK's building stock (DLUHC, 2021) and consists of large-scale developments with similar dwelling characteristics. Additionally, its ownership (local authorities or housing associations) allows for ease of management and replicability of policies and programmes. More importantly, it hosts economically restrained residents thus assuring affordable heating is a priority. On average, social housing hosts a higher proportion of low-income residents, who are less likely to have savings, lone parent households, and families where a member has a disability, than the two other type of tenure (DLUHC, 2022d).

Regarding heat demand in social housing, financial restrictions mean that some households may adapt to living under lower temperatures to save on their heating bills (Teli *et al.*, 2015). This results in low heating loads and reinforces the threat of the rebound effect. For example, Jones et al. (2015) evaluated heating preferences in UK social housing, indicating that dwellings which had undergone fabric improvements showed higher temperature setpoints and longer heating periods. Local authorities and governments need to understand the behavior of social housing occupants and the determinants of their heat demand to guarantee that occupants can afford to heat their homes and achieve comfort.

Future resilience of buildings

An additional challenge of decarbonising heat supply in buildings, is future resilience under a changing climate. In 2022, the UK government published the Heat and Buildings Strategy (DEFRA, 2022) detailing plans to decarbonise commercial and domestic buildings, highlighting the importance of future-proofing buildings, and evaluating future risks such as overheating. Climate projections for the UK estimate an increase in seasonal average temperatures of up to 5.1°C in summer and 3.8 °C in winter by 2070, as well as more intense and frequent extreme events such as heat waves (Met Office, 2022). This increase in outdoor temperature would mean a reduction in heating demand, but it can increase the severity and frequency of overheating events in buildings (Gupta and Gregg, 2013; Gupta, Gregg and Williams, 2015; DEFRA, 2022; Kennedy-Asser *et al.*, 2022) .

Predictions of future building performance should consider not only changes in climate, but also occupant's adaptation. In time, people can adjust to higher or lower temperatures changing their thermal comfort requirements (Nicol and Spires, 2013; Nicol, 2017). A warmer climate can result in higher temperature thresholds, which in turn could mean a reduced need for cooling in summer, and or an increase in heating demand in winter months. Despite this, literature suggests that even with higher mean temperatures, domestic heating demand in the UK will decrease and overheating will be a heightened risk (Gupta and Gregg, 2012; Watson, Lomas and Buswell, 2019; Ciancio *et al.*, 2020; DEFRA, 2022). The last is particularly dangerous for the elderly population who are at higher risk of temperature related mortality, from both cold and heat exposure (Hajat *et al.*, 2014).

Decarbonising strategies need to account for risks expected during the planned life of buildings. The challenge is to select measures that contribute to meeting net zero targets whilst ensuring comfort now and in the future. For example, measures to make buildings more energy efficient such as improving thermal efficiently and air tightness, can increase the risk of overheating and even result in an increment of energy demand as cooling becomes necessary (Gaterell and McEvoy, 2005; Holmes and Hacker, 2007; Crawley, 2008; BEIS, 2021b; Khosravi, Lowes and Ugalde-Loo, 2023).

Overall, in the pathway to decarbonising heat supply in the UK, the national government and local authorities need to take climate informed decisions, considering future implications of measures, and the vulnerability of residents.

1.2 Formulation of research question

At a first glance, heat demand in buildings is defined by the local climate, building characteristics such as thermal performance and types of systems and users, their behavior and needs as well as the social norms and habits that affect this behaviour. The convergence of these characteristics leads to unique heat consumption patterns, which makes forecasting and replicability difficult. Furthermore, in view of a changing climate, it is imperative to develop both energy policies and a building stock that will perform as needed in the future. Thus, in the context of net zero targets and the upcoming building retrofits and deployments of new heating systems and controls, it is of the essence to understand the variability of heat demand and the drivers behind it to reduce the energy performance gap.

What will the effect of new technologies be on thermal comfort and heating demand? How will decarbonization strategies impact the most vulnerable homes? What do we know; and particularly do we know enough to predict current and future heating patterns in the UK?

With these questions in mind, this research project set out to evaluate the current state of knowledge on heat demand for one of the most vulnerable sectors of the UK's population, social housing. What assumptions are we making today to estimate heating demand? How do people use their heating?

1.3 Aims and objectives

Based on the questions posed in the previous section, this work aims to contribute to reducing the energy performance gap in buildings. It sets out to identify and evaluate determinants and predictors of heating demand in a social housing context, comparing assumptions to observed behaviour in real case studies in the UK. This research project attempts to provide a better understanding of occupant behavior in social housing buildings by delivering evidence-based analysis and suggestions.

The following specific objectives are identified for the research project:

i. Identify knowledge and evidence gaps in the prediction of heating demand in domestic buildings in the United Kingdom

ii. Evaluate the state of knowledge on aspects of occupant behaviour that relate to domestic heating demand, including: short- and long-term routines, thermal preferences, and engagement with technology.
iii. Review the main methodologies and assumptions used for estimating domestic heat demand, evaluate their limitations and develop evidence-based suggestions to improve them.
iv. Contribute empirical evidence on the elements identified in (ii) and their impact on heating demand within the context of social housing, highlighting recommendations to update body of knowledge.

Overall, objectives (ii) to (iv) aim to address the gaps identified in (i). Specific objectives and detailed outputs are identified in each individual publication and explained in 'Chapter 2 Research Structure'.

These contributions can be useful to a variety of stakeholders, from building developers, property managers, researchers, and policy makers.

1.4 Background

1.4.1 UK households

The UK's residential building stock comprises almost 28 million dwellings (24 of which are in England) and is characterized by its old age and very low renovation rate. It has the oldest housing stock in comparison to European countries; around 38% of dwellings are pre 1946 and 40% 1946 to 1980 (Piddington *et al.*, 2020). Additionally, the development of low-energy housing in the UK is still in its infancy, despite the emission reduction goals set by the government (Martiskainen and Kivimaa, 2019). These characteristics are the biggest challenge towards decarbonizing the UK's home energy demand, and heating in particular. The focus of policies and government programs needs to be on retrofitting the existing building stock, to both reduce the current energy demand and meet the needs of future climate.

The UK government needs to understand the conditions and characteristics of its building stock, to assure adequate housing supply, as well as reduce fuel poverty. In addition to knowing building properties, such as age and type of construction (terraced, semi-detached, detached, bungalows and flats) (Piddington *et al.*, 2020), it is also essential to comprehend the characteristics of people living in the buildings. An important metric to consider is tenure, which can be classified in three types: 'owner occupied', 'private rented' and 'social rented'. The main demographic and socioeconomic characteristics of each tenure group for England, are evaluated in the English Housing survey headline report (DLUHC, 2021) and following detailed reports for each tenure (DLUHC, 2022b, 2022c, 2022d). This is the largest housing survey in England, which surveys information on housing conditions, occupant information and energy efficiency. Table 1 presents a summary of the main characteristics of each group based on these reports.

Table 1 - Summary of main household characteristics in England by tenure, as presented in the English Housing Survey 2020 to 2021

	Private owned (DLUHC, 2022b)	**Private rented** (DLUHC, 2022c)	**Social housing** (DLUHC, 2022d)
Number of households	15.4 million (64%)	4.4 million (19%)	4 million (17%)
***EER Band* ***			
A/B	3%	2%	3%
C	39%	39%	62%
D	46%	45%	31%
E	9%	10%	3%
F/G	3%	4%	1%
Age of HRP* *			
16-34	12%	43%	18%
35-64	53%	48%	57%
65 or over	35%	9%	26%
Household composition			
Single person	33%	38%	46%
Couple, no children	33%	23%	11%
Couple, dependent children	20%	18%	14%
Lone parent, dependent children	3%	11%	18%
Income			
% in the highest quintile	25%	18%	3%
% in the lowest quintile	12%	22%	50%
Employment* **			
In employment	59%	73%	38%
Retired	36%	9%	25%
Unemployed	2%	7%	11%
Other inactive	3%	5%	25% ****

* Energy Efficiency Ratio; the higher the ratio, the more efficient the home
** Household Reference Person
*** Excludes full-time education
**** 55% of households have at least one member with a long term illness or disability

Each tenure group contains residents with significantly different socio-economic characteristics and should hence be evaluated separately. Amongst the three types of tenure, social housing hosts the most economically vulnerable type of residents; it has the highest proportion of low-income households and as inactivity (meaning not in employment). Additionally, more than half of households within social housing have at least one member with a long-term illness or disability, and a quarter host residents aged 65 or over. This adds the dimension of health to the vulnerability of social housing residents. Poor households are at higher risk of fuel poverty and are more likely to be under consuming consequently not being able to reach comfort levels (Bao and Li, 2020).

Whilst building improvements are aimed at reducing energy demand, the aspect of health should not be excluded when forecasting the impact of local and national policies. Improving warmth in residential buildings is a cost-effective measure when considering health in the picture, in particular for elderly populations (Bray *et al.*, 2017). There seems to be a disconnect between housing, health and energy sectors; a holistic approach is needed to improve living conditions, in particular of ageing population (NoRodger, Callaghan and Thomson, 2021).

1.4.2 Heating consumption & energy attitudes in social housing

Social housing is defined as affordable housing for people on a low income (DLUHC, 2021). Hence, local authorities and housing associations that own and manage this type of properties, aim to meet occupant's thermal comfort in an efficient and affordable way to avoid fuel poverty (Ministry of Housing Comunities & Local Government, 2020; BEIS, 2021c). This can be done through ensuring buildings are liveable and perform to minimum health and comfort standards, and or by providing financial support to residents to meet their heating bills, or access to financial mechanisms for home energy and fabric improvements (DLUHC, 2013; BEIS, 2023).

In relation to building performance, despite the fact that the social housing building sector is more efficient than other tenures (which can be observed in the distribution of Energy Efficiency Ratings by tenure in Table 1), outdated poor constructions are still a threat for people's health and an obstacle towards the UK's energy efficiency goals (Roberts, 2008; Piddington *et al.*, 2020). Such is the case of decayed tower blocks, which still represent approximately 5% of the existing social housing building stock (DLUHC, 2022a).

Regarding occupant behaviour, poor building conditions and economic restraints can affect social housing residents' energy usage, resulting in distinct indoor temperatures and heating patterns. For example, some residents may adapt to lower temperatures to save on their heating bills leading to indoor quality conditions that are detrimental to health (Teli *et al.*, 2015). Other measures can include reducing hours of heating and areas of the house which are heated and increase clothing and bedding (De Haro and Koslowski, 2013). These adaptations can result in very low heating demand, and should be considered when modelling the social housing building stock, to avoid overestimation of potential energy savings (Elsharkawy and Rutherford, 2018) .

Furthermore, successful programmes to improve the efficiency of social housing should consider other behavioural aspects, such as how residents perceive technologies and welcome change (Moore *et al.*, 2016; McCabe, Pojani and van Groenou, 2018). Brown et al (2014) evaluated how tenants of UK social housing used and adopted heating technologies, showing that most residents did not know how to run their heating systems efficiently and or refused to involve with controls. Additionally, there was a general lack of interest and trust in new technologies, particularly if residents were comfortable with their current living conditions. Walker et.al (2014) analysed the perception of energy saving retrofits within UK social housing residents showing that generally residents will be motivated to incorporate and use new technologies if they imply saving money or are easier to use than the previous technology, but highlighted the difficulty of breaking user habits . Another relevant lesson from past retrofits is the importance of involving residents in the process as people are more likely to welcome a change if they feel their views were considered and respected (Scott, 2014), and of providing training (Moore *et al.*, 2016) .

Altogether. heating supply in the UK's social housing sector shows challenges in multiple fronts. Social landlords need to ensure their building stock performs adequately and be mindful of resident's preferences and adaptation capabilities when planning retrofits and newbuilds. Planners and energy modellers need to better understand resident's behaviour. And residents need to learn how to maximize the thermal efficiency of their homes by using their systems and controls appropriately.

Particularities of Care Homes

As part of their role as social landlords, local authorities provide facilities and assistance for elderly people to live as independently as possible, which are known as nursing homes or care homes (Office Statistics Regulation, 2020). Elderly residents are a distinctively vulnerable group in the matters of building indoor quality and thermal comfort, as they are at higher risk for exposure to low or high temperatures and their behaviour can be limited by health and mobility (BEIS, 2021c; Gupta *et al.*, 2021; Yi *et al.*, 2022). This results in high levels of heat demand, specific heating patterns and operation of heating systems, which should be considered by building managers and energy analysts.

To begin with, senior residents' thermal needs differ from those of the main population. Senior people give high value to comfort and prefer higher temperatures all year long (Guerra Santin, 2011; Guerra-santin and Tweed, 2013; Jones *et al.*, 2016; Yi *et al.*, 2022). Feeling warm is considered essential in relation to health (Day and Hitchings, 2009). These comfort requirements conflict with energy reduction measures, such as recommended indoor temperature setting of 21°C (CIBSE, 2006). In terms of engagement with technology, elderly residents are more reluctant to engage with controls or systems (Lewis, 2015) and when they do, they are unlikely to change their heating behaviour and or adopt new technologies (Day and Hitchings, 2009; Cleary *et al.*, 2019).

Moreover, an important dimension of care homes to be considered in the operation and modelling of care homes is the presence of two types of occupants: elderly residents and staff (carers and building maintenance). Firstly, this introduces the challenge of comfort when occupants with conflicting thermal requirements and behaviours are sharing a space (Tartarini, Cooper and Fleming, 2018). Secondly, there is the question of who operates the controls. As some resident's cognitive capabilities and or mobility may be limited, carers need to aid with thermal regulation of spaces adjusting the heating systems for them (Tartarini, Cooper and Fleming, 2018; Cleary *et al.*, 2019). Understanding these aspects of building operation is important to ensure adequate living conditions, fit-for-purpose heating systems and accurate energy demand projections.

1.4.3 Prediction of building's energy demand

The performance gap, also known as the prebound effect refers to the difference between predicted and observed energy performance of buildings. The source of this divergence can be attributed to individual stages of a building's life cycle: design, construction and operation (De Wilde, 2014). The efficacy of simulations and modelling in the design stage depends on the assumptions made and knowledge of the building and its occupants. During the construction stage, quality of work and installations, as well as the handover process can affect how energy is consumed. Finally, operation depends on occupant behavior, which is often quoted as the main source of uncertainty and complexity in buildings (Gram-Hanssen, 2010; Guerra Santin, 2011; Dar *et al.*, 2015; Gaetani, Hoes and Hensen, 2016; Hong *et al.*, 2016)

The same sources of uncertainty can be found in large scale projects, in the design and implementation of energy policies or programs. The prediction of buildings energy demand and carbon emissions at large scale is based on housing stock models with specific parameters. Swan & Ugursal (2009) appraised modeling techniques for the residential sector, underlining two types of models, top-down and bottom-up. The first perform regression on historical energy usage data against macroeconomic indicators to identify the relationship between them. The second, in contrast, extrapolate energy usage based on the characteristics of a representative household sample and can be further divided into statistical or engineering, based on how end-use energy is estimated. This engineering or building-physics models have the greater flexibility and allow the evaluation of new technologies. However, the same disaggregation that gives flexibility requires detailed quantitative information, and is heavily impacted by the assumptions on occupant behavior.

Cheng & Stemmers (2011) evaluated the most used bottom up building physics models in the UK, highlighting that they are all based in one calculation engine: the BRE Domestic Energy Model (BREDEM). This model defines a 'typical household' with a default occupancy schedule and temperature setpoints (Anderson *et al.*, 2002). In the UK, where domestic energy demand is driven by heating and electricity with little to no cooling, it is generally assumed that heating routines or patterns, coincide with occupancy and the routines activities in the household. Hence this model assumes that heating and occupancy patterns are the same.

Regarding the estimation of heating demand, the BREDEM methodology calculates it based on the energy balance of the building. This is defined by the thermal losses and gains, which depend on both the building characteristics and occupant behaviour. Regarding the latter, BREDEM assumes that both active occupancy and heating patterns occur at the same time and defines household typologies with specific occupancy and heating schedules. In relation to seasonality, the heating period is defined as eight consecutive months, from October until May (8 months), and the same temperature set point is used throughout the entire heating season, 21°C in living rooms and 18°C in the rest of the house.

Additionally, the Energy Follow up Survey (Department for Business Energy & Industrial Strategy, 2021), which is the largest household survey on heating and occupancy patterns and thermal comfort, evaluates the results from interviews, temperature measurements, gas and electricity records from a representative sample of dwellings in England derived from the English Housing Survey (HM Department for Communities and Local Government and Department for Communities and local government, 2017). The results from this survey indicate some differences with BREDEM assumptions. Firstly, the most common heating season was October to April (23% of household reported this) and the median length was of 5.7 months. What is more, some houses, mostly those with elderly residents, reported using heating all year. Furthermore, EFUS included questions on occupancy which were not present in the previous edition of the survey (Hulme, Beaumont and Summers, 2013). Results from this questionnaire reported that households with higher occupancy during weekdays were pensioners, unemployed or sick, lower income fuel poor.

These and other assumptions regarding occupancy and thermal comfort in modelling have been evaluated by multiple authors (Kavgic *et al.*, 2010; Cheng and Steemers, 2011; Zhang, Siebers and Aickelin, 2012), suggesting improvements or updates to increase the accuracy of energy prediction. Table 2 summarizes the main critiques & recommendations made to BREDEM and other bottom-up building models.

Table 2 - Limitations of BREDEM and other bottom-up models

Model Limitation	**Study**	**Evaluation method**	**Suggested improvement / recommendation**
Household typologies need to be updated	(Zhang, Siebers and Aickelin, 2012)	Evaluation of bottom-up residential models of energy demand	Incorporate occupant behavior characteristics, generating consumer type profiles
	(Kavgic *et al.*, 2010)	Review of bottom-up residential building stock models for demand, and performance evaluation through a UK case study	Regular update with continuous representative quarterly surveys and incorporation of socioeconomic factors.
Lack of diversity in occupancy profiles	(Cheng and Steemers, 2011)	Review of the most used bottom-up building physics models in the UK.	Incorporate an occupancy model based on employment status data
	(Buttitta and Finn, 2020)	Development of a representative and scalable occupancy model from UK Time Use Survey data	Incorporate different occupancy archetypes
Rigidity of heating patterns	(Huebner *et al.*, 2013)	Comparison of BREDEM assumptions on heating patterns against the Carbon Redution in Buildings Home Energy Survey (Shipworth *et al.*, 2010)	Revisions be made in the distinction between wekdays and weekends; reality is much more variable
	(Kane, Firth and Lomas, 2015)	Assessment of heating patterns from 249 homes in Leicester	Consider socio eoconomic and demographic information of residents
	(Gesche M Huebner *et al.*, 2015)	Assessment of indoor temperatures from 248 homes in England	The BREDEM model over estimates both heating duration and setpoint temperature. More variability is needed
Occupant behaviour	(Sousa *et al.*, 2017)	Review of UK housing stock energy models, modelling approaches, and data sources,	More, better, and newer data is needed for calibration of Housing stock models

Previous studies have provided evidence of differences between the BREDEM model and reality. To improve this and/or other models however, it is necessary to understand what factors impact heat demand and how. Huebner et al. (Gesche M. Huebner *et al.*, 2015) evaluated the EFUS data sample comparing energy demand (gas and electricity) against a set of variables: building characteristcs, household sociodemographic characteristics, heating behaviour. Building characteristics were found to account for most of the variability in the energy demand; in particular building age and size. Other relevant factors were household size (number of people living in ahouse) and length of the heating season.

In relation to occupant behavior, this can refer to presence and location within a building, and active interaction with façade, lights, electrical appliances, air conditioning and heating. Occupant's "thermal routines", as defined by Hanmer et al. (2019) are the results of social factors, activities and thermal preferences, and can lead to vast energy variation within the same type of building (Gram-Hanssen, 2010). Modelling occupant behaviour can help developing high resolution estimations of energy demand, which is of particular importance for electricity forecasting and the development and operation of heat networks (Zhang and Jia, 2016). Models that use simple occupant profiles, such as BREDEM, do not reflect the complexity of occupant behaviour accurately, however more complex models are not necessarily better (Gaetani, Hoes and Hensen, 2016). The information needed will depend on the performance indicator to be evaluated.

Overall, literature suggests that to more precisely represent and forecast energy demand in buildings, futher data is needed in relation to occupancy and household characteristics. Large scale data collection on buildings needs to be part of the UK's policy. Housing models need heterogeneity and wider representation to generate better forecasts.

Chapter 2 Research structure

This Doctorate project is pursued as a Staff Candidature and performed by submission of published works as per “Regulations for Members of Staff in Candidature for the Degree of Doctor of Philosophy- Section A” (University of Southampton, 2022).

This section details the structure of such publications and the relationship between them. The body of this thesis consists of seven publications, five main and two additional or supporting ones. Each investigates a different aspect of heating usage in domestic buildings with a focus on social housing. Figure 1 shows the structure of the research detailing the connection between each publication and how they addressed the objectives (i) to (iv). A summary of each publication is presented in this section, indicating their main findings and the methodology employed. The main publications are referenced in the main chapters of this thesis and supporting ones can be found in the Appendix.

This work explores the non-technical performance gap in a UK social housing context. The key issues of non-standard heating patterns and understanding of heating controls are investigated. Overall, this research project follows a deductive process starting with an assessment of the existing body of knowledge on occupancy and heating patterns in the UK to identify gaps in literature. The literature review addresses objective (i) identifying what information is needed to better predict heating demand, and objective (ii) mapping the existing knowledge on heating patterns and occupant related behaviour.

This is followed by an exploratory analysis of existing large scale representative datasets: the English Housing Survey 2014–15 (Department for Communities and Local Government, 2017) and the Time Use Survey (Gershuny and Sullivan, 2017) to address objective (ii) evaluating modelling assumptions and suggesting possible improvements. Additionally, two new datasets from social housing case studies in the South of England are explored: a group of tower blocks and a care home. The goal when exploring these datasets is to appraise assumptions found in literature on how people live and consume heating, against observed behaviour, adding evidence on a vulnerable sector of the population.

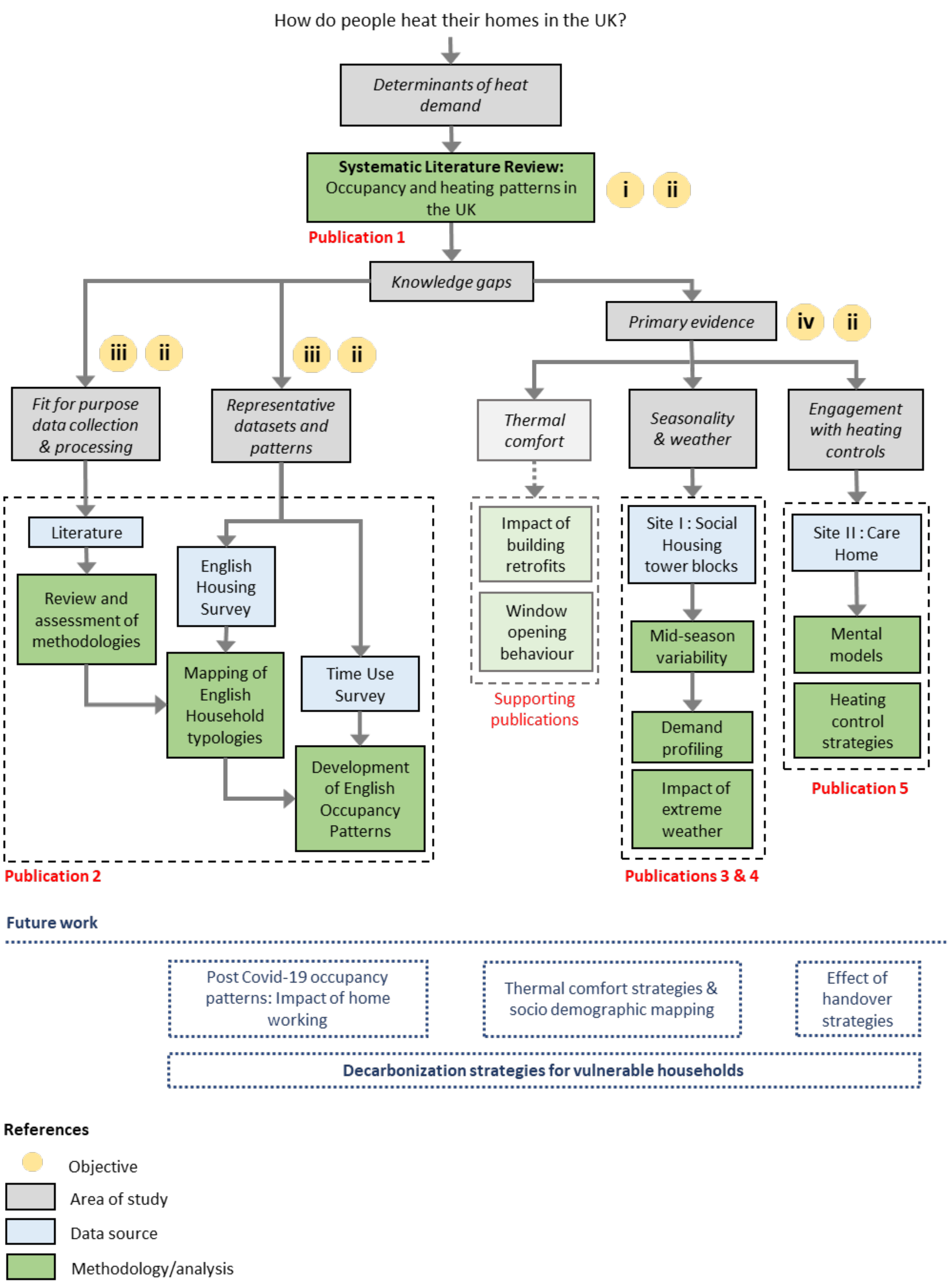

Figure 1 - Research outline and future work. This work is composed of five main publications (1 to 5) and two supporting ones

2.1 Main publications

As shown in Figure 1, the work starts from the basis of a literature review of occupancy and heating patterns in a UK housing context, commissioned by the former Department of Energy and Climate Change (DECC), now called Department for Business, Energy & Industrial Strategy (BEIS). This systematic literature review was performed and presented to BEIS by the candidate as main author. Co-authors collaborated in the supervision of the research process, writing, reviewing, and editing of the report.

1. Occupancy Patterns Scoping Review Project
Contributions to new knowledge • Review and assessment of methodologies for data collection and simulation of occupancy and heating patterns • Status of evidence for generalized occupancy & heating patterns in domestic buildings • Status of evidence of impact of smart heating controls in domestic buildings
Keywords: domestic, occupancy, patterns, profiles, behaviour, heating, smart controls
Specific objectives: This report provides findings from a scoping review on occupancy patterns carried out by the University of Southampton (UoS) on behalf of the Department of Energy and Climate Change (DECC). DECC commissioned this scoping review with the aim to explore the evidence for occupancy-based smart heating controls to contribute to one of the Department's key policy priorities to decarbonise heat. The specific objectives of this publication were *(see in brackets the general objective they relate to)*: • To report on the current state of knowledge on domestic occupancy patterns (ii). • To review any evidence on the relationship between domestic occupancy patterns and heating patterns (i) (ii) • To map out the key evidence gaps (i)
Methodology The scoping review applied systematic literature review techniques following the guidance provided by DECC. First the boundaries of the scoping review were established. The search terms were defined as *'occupancy and/or heating patterns/profile/behaviour/schedule'* and included domestic and non-domestic, UK and non-UK studies. The second stage of the scoping review identified databases and search engines as well as journals, which addressed the relevant studies on occupancy and heating patterns. Initial searches lead to a total of 3,681 references on occupancy patterns and 2,818 references on heating patterns. A preliminary review of the papers' abstracts screened for the topic addressed, this brought total number down to 212 for occupancy patterns and 72 for heating patterns. The third stage of the scoping review applied two-tier filtering process using inclusion and exclusion criteria and DECC's Quality Assessment Scale. This detailed screening resulted in 67 peer reviewed research papers, of which 41 specifically address domestic occupancy patterns in the UK.

Key findings	Related objectives
• There is not enough evidence to generalise representative categories of occupancy patterns in domestic buildings in the UK. Similarities across studies were found, but results cannot be generalised. BREDEM proposed patterns need to be updated; one schedule does not fit all;	**(i), (iii)**
• To date Time Use Surveys are the main source used for inferring domestic occupancy patterns at a regional or national scale;	**(iii)**
• Heating patterns are considered highly dependent on occupancy patterns in most cases and based on the same characteristics as occupancy, such as number of occupants, age, level of income, type of employment and the nature of domestic activities. However, further analysis is required to determine how each parameter affect heating and occupancy separately;	**(i), (ii)**
• Heating patterns depend on the type of control system installed and the possibilities for programming and heating zones independently. Additionally, user engagement with controls plays a key factor in heating demand;	**(ii)**
• There is not enough evidence to evaluate the efficiency of smart heating controls in domestic buildings and its impact in comfort and energy usage.	**(i), (ii)**

This first work discovers that there is not consensus on occupancy patterns for UK households. Additionally, it identifies a gap in the existence of generic representative data, which is needed for regional or national estimations. Moreover, it recognizes Time Use Surveys as the main data source for inferring occupancy, used internationally. These findings set the ground for the following publication, which aims to generate a set of representative patterns for England, by using the 2015 UK Time Use Survey. This work was also performed as main author; co-authors collaborated directly in the literature review of monitoring methodologies and editing of the paper, and indirectly through the supervision of the analysis of the datasets.

2. Developing English domestic occupancy profiles
Contributions to new knowledge • Mapping of English households and evaluation of their representativity in literature • Dataset of stochastic occupancy patterns for English household (see details in Appendix 1)

Keywords: households, modelling, monitoring, occupancy patterns, occupant behaviour, occupants, social survey, time use
Specific objectives: Occupancy patterns are necessary to estimate energy demand and evaluate thermal comfort in households. Because of this, many European countries are developing representative domestic schedules to replace outdated criteria. This paper aims to *(see in brackets the relevant general objective)*: • characterize and analyse the quality methods for collecting occupancy data and inferring patterns; (iii) • identify and assesses the quality of categories of occupancy patterns used in building simulation; (ii), (iii) • Generate representative occupancy patterns that can be used for simulation (ii), (iii)
Methodology: • Systematic Literature Review following the technique from "Occupancy Patterns Scoping Review Project" to assess the methodologies used to collect data on occupancy and inferring patterns • Exploratory analysis of interview samples from the English Housing survey 2014–15, to identify main household typologies based on family composition and work status. • Generation of Occupancy patterns for previously identified main household typologies, based on UK 2015 Time Use Survey Data.

Key findings	**Related objectives**
• Social and monitoring surveys are the most deployed data-collection methods.	**(iii)**
• The occupancy categories most frequently used in UK building simulation are (a) a family with dependent children where the parents work full time; and (b) a retired elderly couple who spend most of their time indoors.	**(iii)**
• The interview sample from the English Housing Survey 2014–15 was used to map household typologies. Results show that categories (a) and (b) combined amount to only 19% of England's households, which suggest models are over-reliant on these groups.	**(iii)**
• Occupancy patterns derived from the 2015 UK Time Use Survey diaries were significantly different across households with different work status	**(ii), (iii)**
• The presence of children in a household resulted in decreased daytime occupancy. In contrast elderly or retired households showed high daytime occupancy.	**(ii), (iii)**

This work adds evidence to the gap previously identified in the scoping review: the lack of large-scale data collection on occupancy. Identifying occupancy, and in particular 'active' status, is key to developing heating demand models. It allows identifying when people are at home and can engage with their heating controls. Additionally, it highlights the problem of representation in occupant behaviour modelling. Some household typologies, such as the 'family with small children' presented in BREDEM are overrepresented, whereas other are not even included. Lone parent households, which represent 18% of social housing, are shown to have a significantly different occupancy profile to other household typologies.

Furthermore, both publications identify sociodemographic characteristics as determinants of both heating and occupancy patterns. Household work status was found to have a significant impact on daytime occupancy, which accentuates the importance of analysing population with different income levels and work status separately. These findings serve as motivation to focus on the social housing sector and the need to gather primary evidence to update existing assumptions. Thus, the following three publications explore the heating demand records from two social housing case studies. Publications three and four focus on seasonality and patterns of heat demand in a social housing tower block complex, and publication five on the usage of heat controls in a care home. Both sites are located in coastal cities in the South of England.

The case studies analysed were part of Thermoss (European Comission, 2020), an EU funded project that aimed to evaluate the impact of specific heating technologies across European countries with different climates. This project involved substantial field work, including recruiting and surveying participants, installation and maintenance of multiple monitoring systems, and overseeing the upgrade of heating systems. The author of this thesis was directly involved in the coordination and deployment of these tasks and performed the control and analysis of monitoring data used to develop the subsequent publications.

The first site analysed is a social housing tower block complex in the city of Southampton. Publication number three examines heat billing records from this site, focusing on seasonal heating patterns and the transition from heating to non-heating periods, areas which were previously identified as knowledge gaps. This work was also performed as main author, and it was presented at the "2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA Chicago", in September 2018.

3. Unpacking mid-season heating demand in social housing
Contributions to new knowledge • Identification of variability of heating demand at end and start of the heating season, in a social housing case study
Keywords: heating, social housing, mid-season, weather
Specific objectives: Heat load variability is mainly rooted in space heating demand variations which is expected to fluctuate the most during mid-season. This is when users thermally adapt to warmer or colder weather, resulting in what is known as the "thermal adaptation lag". The aim of this paper is to investigate this weather variability during mid-season leading to fluctuations of heating demand that impact the efficiency of the heat supply. The following objectives were defined *(see in brackets the general objective they relate to)*: • Evaluate the characteristics of heating & hot water demand in a social housing context (ii), (iv) Identify seasonality trends & relationship with outdoor temperature (ii), (iv)
Methodology Descriptive analysis of monthly heat billing records from 520 flats within five high-rise social housing tower blocks located in the city of Southampton, United Kingdom, from 2013 to 2017. These readings include heat used for space heating and hot water. The proportion of each demand is estimated, and annual demands are estimated separately. The variability of space heat demand is evaluated by comparing the ratio of monthly heat demand against Heating Degree Days (HDD)

Key findings	Related objectives
• Heating demand is very low in all towers: median domestic hot water demand of 33 kWh/m^{2}year and median space heating demand of 16 kWh/m^{2}year	**(iv)**
• The variability of the heating demand is higher in the period November to March and is related to temperature variation,	**(ii), (iv)**
• The ratio of heat required by Heating Degree Day is not constant.	**(ii), (iv)**

This preliminary analysis of the case study in Southampton, UK, indicates that the heat demand in the social housing buildings is very low and it shows a relationship to outdoor temperature (measured by Heating Degree Days). Additionally, it suggests that heat load variability is higher at the start of the heating season and indicates that further monitoring and analysis is needed, including an evaluation of weather variability. This work serves as an introduction for the next paper, which evaluates heating demand records from the same case study and the relationship to outdoor temperature in more detail. It was also performed as main author, co-authors collaborated through the supervision of the analysis of the dataset and editing of the paper.

4. The influence of weather on heat demand profiles in UK social housing tower blocks
Contributions to new knowledge • Heat demand profiles for social housing dwellings • Variation of base temperature across identical dwellings • Evaluation of impact of extreme weather events on heating demand
Keywords: social housing; heat demand; energy signature, regression, seasonality
Specific objectives: This paper aims to increase the understanding of heating demand in social housing in the UK, with a focus on the impact of outdoor temperature. The objectives of the analysis are *(see in brackets the general objective they relate to)*: • Analyse heating demand records from social housing tower block to develop baseline energy models, (iv) • Examine the transition between the heating and non-heating periods, (ii), (iv) • Evaluate the impact of weather-related factors, such as outdoor temperature, wind, and extreme weather events on the heat demand (ii), (iv)
Methodology This paper evaluates weekly heat demand profiles, including Domestic Hot Water and space heating, of 462 social housing dwellings in five tower blocks in the UK over two years. A bottom-up approach was applied to study the relationship between heat demand and outdoor temperature. Linear and segmented models were fitted to generate energy signatures of each flat, which were then grouped by the magnitude and dispersion of the demand. The characteristics of each group were summarized, including: annual demand, dwelling baseline temperature, impact of flat location and orientation, seasonal variation of dispersion, and effect of an extreme weather event such as the 2018 storm 'The Beast from the East'.

Key findings	**Related objectives**
• Three distinct heat demand profiles were found: (i) households that do not use space heating (11%), (ii) irregular households, where the transition towards the heating season is not identifiable (33%), and (iii) households with marked seasonal thresholds (56%). The authors attribute the heterogeneity of heat demand to occupant behaviour.	**(ii), (iv)**
• Amongst the last group, 50% exhibited changes in the demand trend when the mean weekly outdoor temperature ranges between 14°C and 12°C	**(ii), (iv)**

• The extreme weather evaluation showed that during the storm event only ‘regular’ households showed a significant increase in their heat demand compared to predictions from the models.	**(iv)**

The deeper analysis of this case study discovers differences in the heat demand in social housing against standard assumptions, such as the low level of heat demand and the high proportion of households that do not use any space heating. These results support the need to have a more heterogeneous approach to energy modelling and represent different household groups.

The evaluation of household typologies in the second publication, ‘Developing English domestic occupancy profiles’, exhibits that the second largest group in England are elderly couples or single households, over 60 years of age, not working full time. This group was shown to have the highest daytime occupancy and can be considerable as vulnerable. Consequently, evaluating the heat demand within this group presents an opportunity to compare occupancy and heating patterns. The next paper assesses the radiator setpoint records from Smart Thermostatic Valves from a care home in the South of England. This allows to further explore the following findings from the scoping review: (i) that heating patterns depend on the types of controls installed and the level of user engagement, and (ii) there is not enough evidence to evaluate the efficacy of smart heating controls in domestic buildings. This work was also performed as main author, under the supervision of the co-authors.

5. Revisiting Home Heat Control Theories through a UK Care Home Field Trial
Contributions to new knowledge • Empirical evidence of heating control usage and understanding • Lessons learnt on the deployment of heat controls in a care home
Keywords: heating, smart controls, mental models, TRV, occupant behaviour, care home
Specific objectives: This paper aims to increase the understanding of home heat controls and add empirical evidence to validate Kempton’s theory on heat controls mental models. With this purpose it sets the following objectives *(see in brackets the general objective they relate to)*: • Evaluate the state of knowledge on heat usage in care homes and smart heating technologies highlighting usability of home heat controls and users’ mental models (ii) Particularly, for the case study analysed: • Analyse the impact of smart thermostatic valves in occupant’s comfort and heating demand in a care home (ii), (iv)

• Identify thermal comfort preferences, heating routines and methods of engagement with heating controls, performing a direct comparison to Kempton's theory on heat controls mental models (ii), (iv)
Methodology: This study consists of an exploratory analysis of radiator setpoint records, including setpoint temperature and room temperature, from Smart Thermostatic Valves in 47 flats from a care home in the South of England over a 12-month period. The work aims to identify the types of interactions users have with controls, and usage patterns at daily and seasonal intervals. The findings are compared to the control techniques from Kempton's theory on heat controls mental models.

Key findings	**Related objectives**
• Three types of interactions were identified: control interactions with no change in the setpoint (around 2% to 9%), setpoint changes performed in one movement (around 60% to 80%), and setpoint changes done through multiple movements (around 10% to 30%).	**(ii), (iv)**
• Three types of households were found: (i) low interactors who do not/have minimal interaction with controls (24.5%), (ii) medium interactors who adjust their setpoint when the outdoor temperature changes and whose behaviour is comparable to households that have a 'feedback' mental model (49%) , and (iii)) high interactors who adjust the setpoint based on their own strategy, which does not necessarily follow outdoor temperature changes and reflects a lack of understanding of how the controls work (26.5%).	**(ii), (iv)**
• Only half of the residents showed a behaviour that is consistent with the principles of operation of the STVs.	**(ii), (iv)**
• The type of smart heating control analysed (Smart Thermostatic Valves) was shown not to be fitted for the type of residents. This highlights the need to involver final users in the selection of equipment and the particularities of a care home environment.	**(iii) (iv)**

This study provides direct evidence on heating strategies and comfort practices from elderly residents. The level of users' understanding of the heating system and controls is hypothesized based on the interaction patterns and researchers' engagement with residents. The sample analysed is small but succeeds to provide an insight on the challenges of deploying smart heating controls in domestic buildings.

2.2 Supporting publications

The supporting publications included in this submission consist of some of the body of work that was developed in parallel to this candidature, that is relevant to one or more of the objectives presented in Section 1 but do not address the main research question specifically. This aims to strengthen the findings from the case studies analyzed and add evidence on the authors expertise in the field.

The first of the supporting publications aims to add empirical evidence on thermal comfort and heating demand in social housing, as well as reflect on the impact of heating strategies on energy demand and the challenges of retrofitting domestic buildings. It is linked to main publications three and four, as it is also based on a case study which is a social housing tower block in Southeast England owned by a local authority, and to main publication five as it evaluates heating strategies and understanding of controls.

This study involved the analysis of an existing dataset of indoor temperatures and thermal comfort surveys, and the development of a new model to represent the case study and predict the effects of different types of users and building retrofits on thermal comfort and energy demand. It was performed as main author, under supervision of the co-authors.

1. Evaluation of Retrofit Approaches for Two Social Housing Tower Blocks in Portsmouth, UK
Contributions to new knowledge Evidence on: • Vulnerability of residents in poor performing buildings • Overheating risk under a changing climate and the need to adapt existing buildings
Keywords: social housing, retrofit, storage heaters, thermal comfort, overheating
Specific objectives: This study aims to assess the thermal conditions and the energy performance of a group of case study social housing towers in the South of England, before and after different retrofit measures. This is done through thermal simulation, under current and future climates, to provide useful conclusions for the renovation project. With this purpose, the following objectives are identified (*see in brackets the general objective they relate to)*: • Evaluation of thermal comfort & building performance under different heating management scenarios (ii) (iv)

• Evaluation of thermal comfort & building performance under different retrofit scenarios under current and future climate (ii) (iv)
Methodology: The buildings analysed in this paper are two identical social housing tower blocks, in the city of Portsmouth, UK. Information on the building properties and occupants was collected and processed. This includes indoor monitoring of temperature and relative humidity in 21 flats for eight months, thermal comfort surveys, heating electricity usage records were provided. The following steps were developed: • Analysis of existing conditions to identify indoor temperatures in winter and summer, occupant preferences, use of heating controls and occupancy • Development of representative TRNSYS model and evaluation of multiple user and retrofits scenarios • Evaluation of heating demand and related costs under different scenarios • Evaluation of overheating risk through BS EN 15251 in current and future climates

Key findings	Related objectives
• The physical properties of the building lead to a high level of energy consumption and discomfort under all occupancy scenarios.	**(ii), (iv)**
• The simulation of possible retrofits demonstrated that improving the building envelope to meet 2010 Building Regulations or stricter standards would result in a decrease of more than 80% of the heating load but would result in overheating if no adequate shading is installed.	**(ii), (iv)**
• The existing buildings are inefficient, and a retrofit would result in a complete change in their energy performance. A thorough economic appraisal is required to select the best environmentally and economically viable interventions.	**(iv)**

This study highlights the relevance of understanding user behaviour and the impact that different heating strategies can have in the energy demand of a building. Additionally, it underlines the challenges of building retrofits, both in relation to resident's satisfaction, and building performance under a changing climate. The issue of user satisfaction relates directly to the care home case study in main publication number five, pointing out the difficulty user's face in understanding how home heating systems and controls work and how they should be operated.

The second supporting publication focuses on another aspect of thermal comfort, users' interaction with the building façade. In particular, this study monitored window opening behaviour in office buildings, and the impact of different behavioural interventions. This work was performed as co-author, and participation in the study revolved mostly around participant recruitment, data collection and editing of the manuscript.

2. The effect of behavioural interventions on energy conservation in naturally ventilated offices
Contributions to new knowledge • Drivers of behaviour change in the context of office buildings
Keywords: Behavioural intervention, window opening, energy conservation, carbon emission reduction, naturally ventilated, office
Specific objectives This paper investigates the effects of behavioural interventions on energy conservation in naturally ventilated offices. The aim is to inform building managers, environmental consultants, and social scientists on the effectiveness of low-cost, easy-to-implement interventions aimed at reducing energy waste and carbon emissions in a setting where individuals do not have direct financial gain and have low awareness of the environmental impact of their actions. This relates to objective (ii) increasing the understanding on occupant behaviour that relates to heating demand.
Methodology Five naturally ventilated office buildings at the University of Southampton were monitored during the 2016/2017 heating season with a bespoke camera-based system that identifies the status “open/close” of the windows. Based on the camera analysis status, emails were automatically sent to the office occupants who were in control of the identified windows. The email interventions aimed at drawing the occupants' attention to the problem of poor window management.

Key findings	**Related Objectives**
• The interventions are effective in promoting energy savings, as the percentage of windows left open by treated occupants is typically halved compared to a control group	**(ii)**
• The impact of the treatment is stronger when we provide specific information about the energy waste of the building, where the email recipients work or when we show them how their behaviour differs from that of their peers	**(ii)**
• Positive behavioural changes are still observed a few weeks after the interventions are terminated, thus suggesting that such interventions do not act only as temporary “cues” which are easily forgotten by recipients	**(ii)**

This study provides an insight on both the patterns of interaction with windows in an office building context and their impact on the energy demand of the building, and the effect of different communication strategies for motivating users to reduce energy wastage. It adds evidence on the relevance of occupant behaviour on building energy demand, and the capacity of adaptation of users when the correct information is provided. These findings are relevant for large property portfolio managers, such as housing associations and local authorities who have the possibility of implementing information campaigns to impact residents' energy related behaviour.

2.3 Publication status

MAIN PUBLICATIONS

	Publication	Status
1	Gauthier, Stephanie, Aragon, Victoria, James, Patrick and Anderson, Ben (2016) "Occupancy Patterns Scoping Review Project", Department for Business, Energy & Industrial Strategy, http://eprints.soton.ac.uk/id/eprint/403390	Published Nov, 2016 LEAD AUTHOR
2	Aragon V. et al (2019) "Developing English domestic occupancy profiles", Building Research & Information, 47 (4), pp375-393, https://doi.org/10.1080/09613218.2017.1399719	Published Nov 2017 LEAD AUTHOR
3	Aragon V. et al (2018) "Unpacking mid-season heating demand in social housing", 2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA Chicago, IL September 26-28, 2018,	Published 2018 LEAD AUTHOR
4	Aragon V. et al (2022) "The influence of weather on heat demand profiles in UK social housing tower blocks", Building and Environment, Volume 219, 109101, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2022.109101.	Published July 2022 LEAD AUTHOR
5	Aragon V. et al (2022) "Revisiting Home Heat Control Theories through a UK Care Home Field Trial" Energies 15, no. 14: 4990. https://doi.org/10.3390/en15144990	Published July 2022 LEAD AUTHOR

SUPPORTING PUBLICATIONS

	Publication	Status
1	Aragon V. et al (2018), Evaluation of Retrofit Approaches for Two Social Housing Tower Blocks in Portsmouth, UK. Future Cities and Environment, 4(1), p.4, DOI: http://doi.org/10.5334/fce.8	Published Jan 2018 LEAD AUTHOR
2	Ornaghi C. et al (2018), The effect of behavioural interventions on energy conservation in naturally ventilated offices, *Energy Economics*, 74, pp582-591, https://doi.org/10.1016/j.eneco.2018.07.008	Published July 2018 CO-AUTHOR

Chapter 3 Occupancy Patterns Scoping Review Project

Please refer to the following publication:

Gauthier, Stephanie, Aragon, Victoria, James, Patrick and Anderson, Ben (2016) "Occupancy Patterns Scoping Review Project", Department for Business, Energy & Industrial Strategy, http://eprints.soton.ac.uk/id/eprint/403390

Chapter 4 Developing English domestic occupancy profiles

Please refer to the following publication:

Aragon V. et al (2019) "Developing English domestic occupancy profiles", Building Research & Information, 47 (4), pp375-393, [*https://doi.org/10.1080/09613218.2017.1399719*](https://doi.org/10.1080/09613218.2017.1399719)

Chapter 5 Unpacking mid-season heating demand in social housing

Please refer to the following publication:

Aragon V. et al (2018) "Unpacking mid-season heating demand in social housing", 2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA-USA Chicago, IL September 26-28, 2018, *https://www.ashrae.com/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C104.pdf*

Chapter 6 The influence of weather on heat demand profiles in UK social housing tower blocks

Please refer to the following publication:

Aragon V. et al (2022) "The influence of weather on heat demand profiles in UK social housing tower blocks", Building and Environment, Volume 219, 109101, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2022.109101

Chapter 7 Revisiting Home Heat Control Theories through a UK Care Home Field Trial

Please refer to the following publication:

Aragon V. et al (2022) "Revisiting Home Heat Control Theories through a UK Care Home Field Trial" Energies 15, no. 14: 4990. [*https://doi.org/10.3390/en15144990*](https://doi.org/10.3390/en15144990)

Chapter 8 Limitations

This section refers to general limitations and weaknesses of the research presented in this Thesis. Specific limitations of individual studies are mentioned in each corresponding publication.

One of the biggest sources of uncertainty in this analysis is data, meaning the datasets evaluated from external sources and from own collection. Firstly, quality of data is heavily affected by monitoring strategies, including the type of technology and corresponding communication system used. In the case of data directly collected in the case studies, a better understanding of the performance and transmission limitations of the equipment and the characteristics of the buildings, could have resulted in more robust and less intermittent datasets. In terms of the accuracy, the data collected is reliable in the sense that it is not subjective behaviour, it is monitored. However, it is dependent on the errors of the monitoring equipment.

Furthermore, having more knowledge about the final use of the data at the moment of collection would have helped to ensure all the necessary information was captured. For example, monitoring window opening behaviour would have improved the quality of the analysis of both case studies, providing a complete profile of heating strategies developed by residents. The same applies to sociodemographic information of residents in the case studies, which would have enhanced the analysis. The collection of this data was envisioned in the beginning of each study, but due to difficulties with recruiting and contacting participants, it was only captured for a handful of properties on each site through surveys.

A further limitation of this research is the generalisation of results, meaning the possibility of extending the findings to a larger population. Firstly, the availability of external datasets limited the extent of the analysis. Using the English Household Survey to map the different household typologies, resulted in focusing only on England. Secondly, the results from the case studies are not generalisable as they relate to a specific context in terms of location, tenure, heating systems and billing methods. Additionally, the monitoring strategies were not the same for the case studies, hence a cross-site comparison was not possible.

However, the findings from the case studies are transferable, and the analysis can be considered novel or original. In the study of the social housing towers, the originality of the work relies on the findings for the type of building analyzed. The case study is a highly controlled environment which consists of a large number of properties (520) which are physically identical, are exposed to the same weather conditions, and host residents with similar socioeconomic characteristics. The results show that even under such conditions the heat demand profiles are significantly different across flats, which is of particular importance in the current context of rising fuel and energy prices. Additionally, the study based on the care home site consists of a small number of participants (less than 50 flats). However, one of the findings of the literature review (main publication 1) is that there is a lack of evidence on the impact of smart heating technologies in domestic buildings. This work targets this gap and aims to start a discussion about the fit between technology and users.

Furthermore, in relation to the findings of this research and its application, it is important to note two events that occurred after this work was developed: the covid-19 pandemic starting in 2020 and the change in energy prices in the UK in the end of 2022. To begin with, the pandemic caused a shift in working patterns and schedules which have an impact in household occupancy and potentially heating demand (Shi, Sorrell and Foxon, 2023). Additionally, household typologies may have shifted, as for example there was an increase in childless adults moving back into the parental homes (DWP, 2023). This means that the household mapping and subsequent occupancy patterns developed in the second main publication will need updating. However, in the case of social housing, this may be less relevant as remote working is predominant in this sector.

The second pertinent change was the increase in UK domestic energy prices (gas and electricity) during 2022. A combination of factors such as a global increase of gas demand, reduced supply and low storage levels (Armstrong, 2021; BEIS, 2022) resulted in an increase in wholesale gas prices in the UK of almost 400% during 2022 (Trading Economics, 2023). This resulted in the closure of energy suppliers and an increase in the price of household gas and electricity, doubling home energy bills for UK residents by the end 2022 and pushing more households into fuel poverty (Department for Energy Security and Net Zero, 2023). This is highly relevant for social housing, who are the most financially vulnerable tenure group. Higher energy prices could result in lower indoor temperatures during winter, lower heating demand and potentially a proportion of household that do not use heating even higher than observed in the case studies. Future work could look at repeating the analysis of heating bills from the social housing tower blocks with data post 2022. Despite the potential changes in heating demand, the energy crisis context makes the findings of this research even more relevant, as energy efficiency and affordability of heat have become urgent matters.

In relation to the methodology, an important aspect to highlight is that this research fails to capture causality in occupant's behaviour. This is hypothesized from the available information, but it was not captured in the data collection. The study based on the care home (main publication 5) does include a commentary on residents' views and experiences, but this was captured informally and its subject to the authors own recollection. This lack of information limits the assumptions made on the reasons behind the heating patterns observed.

Finally, it should be noted that the nature of this candidature, as a member of staff, led to discontinuity in the analysis. This limited the flow of the research and time availability, which could have contributed to more efficient and thorough data processing in particular.

Chapter 9 Conclusions & recommendations

This research set out to reduce the energy performance gap in social housing buildings, by mapping the status of knowledge on heating and occupancy in domestic buildings, identifying determinants of heating demand, and comparing assumptions to observed behaviour. Despite the limitations mentioned in the previous section, this work succeeds to provide results for each of its objectives and serves as a starting point for future work in the fields of occupant behaviour and decarbonisation strategies for vulnerable populations.

The first objective of this work was **(i) to review the existing body of knowledge on the prediction of current and future heating demand in domestic buildings in the United Kingdom, to identify gaps and evidence needed**. The main areas identified were: the development and improvement of household energy models that needs to be supported by more and better quality evidence, the lack of standardized representative occupancy and heating patterns for UK households and adequate data collection to inform this, and the need for evidence on the impact of home energy efficiency measures, such as smart heating controls. These identified gaps build on previous studies in this area highlighted in the literature review (Huebner *et al.*, 2013; Kane, Firth and Lomas, 2015; Yan *et al.*, 2015; Gaetani, Hoes and Hensen, 2016) and more recent studies that reinforce the need for further evidence on occupant behaviour and heating demand (Marshall *et al.*, 2015; Delzendeh *et al.*, 2017; Sousa *et al.*, 2017; Bruce-Konuah, Jones and Fuertes, 2019; Hanmer *et al.*, 2019; Elsharkawy and Zahiri, 2020). Each of these areas formed the remaining objectives of the research and were further developed through a combination of literature reviews, examination of existing databases, and monitoring of social housing case studies in the UK.

One of the following objectives established consisted in **(iii) reviewing the main methodologies and assumptions used for estimating domestic heat demand and suggest improvements if needed**. Firstly, in relation to the data available and how it is collected, this work highlights the dependency of heating patterns on occupancy patterns and discovers multiple occupancy data collection methods that are available for research and commercial purposes. The findings suggest that to enhance the quality of evidence captured, it is necessary to collect sociodemographic information as well. Outlining the possible motivations behind the actions of occupants is essential to produce scalable results and forecasts, as well as for designing policies and technology.

Additionally, there seems to be a lack of consensus on fit-for-purpose large scale data collection. At a regional or national scale, Time Use Surveys are extensively used, though they are not focused on occupancy or energy consumption behaviour. There are no clear guidelines or methods for collecting representative data on occupancy in domestic buildings. The post covid-19 world will need replicable and scalable data collection, to understand the impact of the transition to hybrid and or home working on energy demand. The following recommendations can be made for the improving the efficiency and accuracy of future data collection on domestic occupancy and heating:

- Existing standardized sociodemographic surveys such as Population Census and Time Use Surveys could be reviewed to include fit for purpose data collection on occupant behaviour, energy usage, heating demand and perception of technologies.
- Continue to evaluate the use of existing datasets, such as metered electricity data, as this is a promising method to estimate occupancy and potentially heating patterns, in domestic and commercial buildings

Secondly, in relation to the evaluation of methodologies and assumptions, a review of existing literature and own evaluation shows that there is not enough diversity in the types of households used in energy modelling. Moreover, this work presents a mapping of household typologies using the English Housing Survey 2014-15 datasets which shows that the two typologies most used in modelling, (a) a family with dependent children where the parents work full time and (b) a retired elderly couple who spend most of their time indoors, combined amount to only 19% of England's households. Results also indicate which sectors are underrepresented. In particular, lone-parent households are shown to have significantly different occupancy patterns than other households, however they are not included in most modelling scenarios. This household type is more predominant in social housing and is particularly vulnerable. The following recommendation can be made from these findings:

- Domestic energy models are over reliant on household typologies (a) and (b) which limits the scope of their predictions. There are multiple typologies of similar or larger proportion, such as single person households and couples with no children, that should also be considered in domestic energy models.

A further objective of this work was **(ii) to evaluate the state of knowledge on occupant behaviour and characteristics that impact heating demand**. To begin with, several common characteristics were found across literature. Heating and occupancy patterns in domestic buildings depend on the same set of sociodemographic characteristics, such as age and number of occupants, and employment status. However, they do no not always coincide. For example, financial limitations in social housing homes can result in a mismatch between occupancy and heating patterns. Additionally, space heating demand also depends on the type of heating system and controls. This includes features like programmable characteristics, and users' perception and understanding. Further research is required to determine how each parameter affect heating and occupancy separately.

The biggest predictor of household's occupancy seems to be employment status, which is evidenced in the mapping of English household typologies. Social housing hosts the largest proportion of 'inactive' residents and is hence expected to have higher occupancy than other types of tenure. This, combined with limited financial availability, puts social housing at distinct risk. In relation to employment status, a factor that was not considered in this research but has become highly important recently, is home working. Proposed future work could look at: (a) repeating the household mapping exercise with data collected post pandemic, as a direct comparison is possible using the datasets from the most recent English housing Survey (DLUHC, 2021) which includes data from Apr 2021 to March 2022, and (b) analyzing new heat billing records from the case study tower blocks as well as performing interviews to a sample of residents on their employment and work conditions.

The final objective of this work consisted in **(iv) contributing empiric evidence on the aspects of occupant behaviour and heating demand previously evaluated, within the context of social housing**. Two main case studies in the South of England were explored: a group of tower blocks and a care home. Results from an additional case study in the same location, corresponding to supporting work, are also discussed. Looking at the evidence from the case studies, both similarities and differences were found between common assumptions and actual behavior.

Regarding thermal comfort, indoor temperatures in the care home case study were higher than the mean for English households (between 22 and 24 degrees). Though high comfort thresholds are expected for elderly it should be pointed out that heating in the care home is unmetered and residents only pay a fix tariff. In addition, living rooms showed the highest daytime occupancy, which was evidenced by the level of interaction with heating controls. The flats evaluated in the retrofit study (supporting publication one) also evidenced higher than average indoor temperatures. However, this was not attributed to the age of the residents, but to the payment and tariff system. Unmetered electric heating resulted in almost unlimited heating demand and hence temperatures over 23 degrees during winter. These findings bring to light how the absence of financial limitations can influence resident's comfort, and the potential risk of distress for residents if they are transition to metered billing systems.

In relation to heating patterns, the types of heating strategies found were similar to what shown in literature, distinguishing between regular and irregular households and those which do not use heating. However, the observed proportion of households that do not use heating was higher (11% in the case study compared to 2% in the Energy Follow up Survey) and the variability in terms of level of demand and regularity within time was an unexpected result. Additionally, characteristics of seasonality, including start of the heating season and duration, proved to be irregular. Modelling heating demand as a binary product is a big oversimplification of reality. One of the main conclusions of this study is the high level of variability of the heat demand in social housing sites, which can also be evidenced in other social housing case studies (Jones *et al.*, 2016; Gupta, Kapsali and Howard, 2018). The variability observed in the monitored social housing towers is attributed mostly to occupant behaviour, including occupancy schedules, temperature setpoints, and ventilation strategies, which can be influenced by residents cultural and economic background.

Furthermore, this work also adds new empirical evidence on heating control usage and understanding. In the context of a care home, engagement with controls seems to be related to users' understanding of the system and the technology they are accustomed to use. In the case study, a quarter of residents did not understand how the new controls worked and continued to operate them as they did the previous system. This coincides with findings from literature which show that elderly residents are unlikely to change their heating behaviour and or adopt new technologies (Day and Hitchings, 2009; Cleary et al., 2019). Similar behaviour was evidenced in the tower retrofit study, where users did not understand how storage heaters worked, and the protocol of night charging at lower tariffs, resulting in higher energy demand and costs. Building and housing stock models assume that residents use their systems and controls perfectly, whereas reality shows that this is not the case.

Predicting the success of controls is particularly complex. First, there is the issue of whether users have the cognitive capacity to understand a system, then whether they understand it (this can depend on their preconceptions or information they've received), and finally whether they choose to interact with it or not (particularly relevant in care homes, where a third person might operate the controls for the resident). Furthermore, their potential success in terms of reducing energy consumption in domestic buildings, is still unknown. A recent evidence review on the energy saving capacity of heating controls (Lomas *et al.*, 2018) suggests that there is moderate evidence of energy savings from zonal controls and smart thermostats, but very little to none on other systems (smart and traditional), and that people find them difficult to use.

Overall, literature (Hong *et al.*, 2016, 2017; Delzendeh *et al.*, 2017) and this work agree that there are knowledge gaps in occupant behavior and prediction of heating demand in domestic buildings. It is clear that one model does not fit all, and that occupant behavior is a major source of discrepancy between predicted & actual performance that requires further research. The findings of this research work highlight the importance to move towards a more disaggregated approach in energy modelling and have a direct application in bottom-up models, and thermal comfort. As a result, the following recommendation can be made:

- A more disaggregated approach that considers the critical elements that shape consumption is necessary in energy modelling, starting with differentiating households by tenure.
- Future research should look at enhancing these results through incorporating qualitative data collection, including sociodemographic information and motivations behind behaviors.

Additionally, the variability in heating demand as well as the mismatch between intended and actual use of technology found in this work, have implications on forecasting the impact of home energy saving measures and interventions. For example, results and literature show that there is a high risk of overestimating current energy demand and potential reductions when analysing social housing. In reality, heating demand can be much lower than expected, and there is a high risk of the ‘rebound effect’ after a retrofit, when residents can afford to heat their homes (Bakaloglou and Roubaud, 2018; Flower, Bao and Li, 2020, Hawker and Bell, 2020). However, an improvement of indoor conditions and thermal comfort, though it may not achieve reduction in energy demand and carbon emissions it can do so in health costs. Improving warmth in residential buildings is a cost-effective measure when considering health in the picture, in particular for elderly populations (Bray et al., 2017). The same applies to future proofing buildings to risks of climate change, such as overheating. Resilient measures in the context of climate change should consider the dimension of health and potential cost savings (Vardoulakis *et al.*, 2015; Flower, Hawker and Bell, 2020; van Daalen *et al.*, 2022). In summary:

- Evaluations and forecasts of the potential impact of energy saving measures should include aspects beyond energy, such as comfort and health. The same applies to the design of behavioral interventions for reducing energy demand; a more holistic analysis is needed.

Finally, in the current context of decarbonization and devolution this work is highly relevant for local authorities, who play a key role in assuring buildings are livable, and in preventing fuel poverty. What is more, the present-day energy crisis makes understanding social housing even more pertinent. Local authorities face the challenge of defining the strategies for both upgrading their own building stock as well as motivating residents. Studies show that the correct match between energy efficiency measure and occupants is a key element of ensuring savings (Marshall *et al.*, 2015) and highlight the importance of involving and engaging residents in selecting technologies (McCabe, Pojani and van Groenou, 2018). Tailoring interventions and generating efficient ‘nudges’ to promote energy efficiency in homes is an urgent problem that requires understanding households and their behaviour. Future work will aim to evaluate the impact of quality of information and handover strategies, on the understanding and use of controls. Recommendations derived from this body of work include:

- Housing associations and local authorities have the opportunity to do large scale consultations and outreach, which could contribute to more effective selection and use of technology.
- Final users need to be kept in the loop when designing and selecting equipment.
- There is a clear need to better inform users and improve handover processes.

As the UK government must define its pathways towards net zero, it needs to understand their building stock, their residents, what measures perform best, and what the consequences of each are in terms of energy, comfort and health. This work brings to light gaps in data and methodologies to obtain it and provides evidence that can contribute to the development of standards and guidelines, be applied directly in bottom-up modelling, and contribute to policy making for reducing demand, maintaining comfort & decarbonizing heat.

Chapter 10 References

Anderson, B. *et al.* (2002) *BREDEM-12 Model Description 2001 update*.

Armstrong, H. (2021) *What is behind the rising gas prices?* Available at: https://www.bayes.city.ac.uk/news-and-events/news/2021/september/what-is-behind-the-rising-gas-prices.

Bao, H. and Li, S. (2020) 'Housing wealth and residential energy consumption', *Energy Policy*, 143. doi: https://doi.org/10.1016/j.enpol.2020.111581.

BEIS (2021a) 'Energy Consumption in the UK (ECUK): Final Energy Consumption Tables'. Available at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2021.

BEIS (2021b) *Heat and buildings strategy*. London, UK. doi: ISBN 978-1-5286-2459-6.

BEIS (2021c) *Sustainable warmth: protecting vulnerable households in England*. doi: ISBN 978-1-5286-2412-1.

BEIS (2022) *British energy security strategy*. Available at: https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy.

BEIS (2023) *Social Housing Decarbonisation Fund statistics: February 2023*, *Official Statistics*. Available at: https://www.gov.uk/government/statistics/social-housing-decarbonisation-fund-statistics-february-2023 (Accessed: 15 April 2023).

Belaïd, F., Bakaloglou, S. and Roubaud, D. (2018) 'Direct rebound effect of residential gas demand: Empirical evidence from France', *Energy Policy*, 115, pp. 23–31. doi: https://doi.org/10.1016/j.enpol.2017.12.040.

Bray, N. *et al.* (2017) 'Costs and outcomes of improving population health through better social housing: a cohort study and economic analysis.', *International journal of public health*, 62(9), pp. 1039–1050. doi: 10.1007/s00038-017-0989-y.

Broad, O., Hawker, G. and Dodds, P. E. (2020) 'Decarbonising the UK residential sector: The dependence of national abatement on flexible and local views of the future', *Energy Policy*, 140, p. 111321. doi: https://doi.org/10.1016/j.enpol.2020.111321.

Brown, P., Swan, W. and Chahal, S. (2014) 'Retrofitting social housing: reflections by tenants on adopting and living with retrofit technology', *Energy Efficiency*, 7(4), pp. 641–653. doi: 10.1007/s12053-013-9245-3.

Bruce-Konuah, A., Jones, R. V. and Fuertes, A. (2019) 'Physical environmental and contextual drivers of occupants' manual space heating override behaviour in UK residential buildings', *Energy and Buildings*. Elsevier, 183, pp. 129–138. doi: 10.1016/J.ENBUILD.2018.10.043.

Buttitta, G. and Finn, D. P. (2020) 'A high-temporal resolution residential building occupancy model to generate high-temporal resolution heating load profiles of occupancy-integrated archetypes', *Energy and Buildings*, 206, p. 109577. doi: https://doi.org/10.1016/j.enbuild.2019.109577.

Cheng, V. and Steemers, K. (2011) 'Modelling domestic energy consumption at district scale: A tool to support national and local energy policies', *Environmental Modelling & Software*, 26(10), pp. 1186–1198. doi: 10.1016/j.envsoft.2011.04.005.

Ciancio, V. *et al.* (2020) 'Energy demands of buildings in the framework of climate change: An investigation across Europe', *Sustainable Cities and Society*. Elsevier, 60, p. 102213. doi: 10.1016/J.SCS.2020.102213.

CIBSE (2006) *CIBSE Guide A: Environmental design*. 7th edn, *Building*. 7th edn. CIBSE Publications. doi: 10.1016/B978-0-240-81224-3.00016-9.

Cleary, M. *et al.* (2019) 'The environmental temperature of the residential care home: Role in thermal comfort and mental health?', *Contemporary Nurse*. Routledge, 55(1), pp. 38–46. doi: 10.1080/10376178.2019.1583068.

Climate Change Committee (2020) *The Sixth Carbon Budget Buildings*. London, UK. Available at: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Buildings.pdf.

Crawley, D. B. (2008) 'Estimating the impacts of climate change and urbanization on building performance', *Journal of Building Performance Simulation*. Taylor & Francis, 1(2), pp. 91–115. doi: 10.1080/19401490802182079.

van Daalen, K. R. *et al.* (2022) 'The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future', *The Lancet Public Health*. Elsevier, 7(11), pp. e942–e965. doi: 10.1016/S2468-2667(22)00197-9.

Dar, U. I. *et al.* (2015) 'Influence of occupant's behavior on heating needs and energy system performance: A case of well-insulated detached houses in cold climates', *Building Simulation*, 8(5), pp. 499–513. doi: 10.1007/s12273-015-0230-y.

Day, R. and Hitchings, R. (2009) *Older people and their winter warmth behaviours: understanding the contextual dynamics*. Available at: https://research.birmingham.ac.uk/portal/en/publications/older-people-and-their-winter-warmth-behaviours(1bd54821-4707-43b2-9370-7d62bb327c54).html.

DEFRA (2022) 'UK Climate Change Risk Assessment 2022'. London, UK: HMG, p. 49. doi: ISBN 978-1-5286-3136-5.

Delzendeh, E. *et al.* (2017) *The impact of occupants' behaviours on building energy analysis: A research review*, *Renewable and Sustainable Energy Reviews*. Pergamon.

Department for Business Energy & Industrial Strategy (2021) *Energy Follow Up Survey : Heating patterns and occupancy Final report*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018727/efus-heating-patterns-occupancy.pdf.

Department for Business Energy and Industrial Strategy (2019) *The Climate Change Act 2008 (2050 Target Amendment) Order 2019*, *STATUTORY INSTRUMENTS 2019 No. 1056*. Available at: https://www.legislation.gov.uk/uksi/2019/1056/made (Accessed: 6 October 2021).

Department for Communities and Local Government (2017) 'English Housing Survey, 2014: Housing Stock Data. 4th Edition'. UK Data Service. doi: SN: 8010.

Department for Energy Security and Net Zero (2023) *Annual fuel poverty statistics report: 2023 Fuel poverty statistics report for 2023 (2021 and 2022 data).* Available at: https://www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2023.

DLUHC (2013) *Housing finance and household expenditure: notes and definitions*, *National and official statistics*. Available at: https://www.gov.uk/guidance/housing-finance-and-household-expenditure-notes-and-definitions (Accessed: 17 April 2023).

DLUHC (2021) *English Housing Survey Headline Report, 2020-21*. London, UK. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060141/2020-21_EHS_Headline_Report_revised.pdf.

DLUHC (2022a) *English Housing Survey, 2020 to 2021: housing quality and condition*. London, UK. Available at: https://www.gov.uk/government/statistics/english-housing-survey-2020-to-2021-housing-quality-and-condition.

DLUHC (2022b) *English Housing Survey, 2020 to 2021: owner occupier leaseholders*. London, UK. Available at: https://www.gov.uk/government/statistics/english-housing-survey-2020-to-2021-owner-occupier-leaseholders.

DLUHC (2022c) *English Housing Survey, 2020 to 2021: private rented sector*. London, UK. Available at: https://www.gov.uk/government/statistics/english-housing-survey-2020-to-2021-private-rented-sector.

DLUHC (2022d) *English Housing Survey, 2020 to 2021: social rented sector*. London, UK. Available at: https://www.gov.uk/government/statistics/english-housing-survey-2020-to-2021-social-rented-sector.

DWP (2023) *Technical report: assessment of the impact of the coronavirus (COVID-19) pandemic on the FRS statistics, 2020 to 2021*. Available at: https://www.gov.uk/government/statistics/family-resources-survey-financial-year-2020-to-2021/technical-report-assessment-of-the-impact-of-the-coronavirus-covid-19-pandemic-on-the-frs-statistics-2020-to-2021.

Elsharkawy, H. and Rutherford, P. (2018) ‘Energy-efficient retrofit of social housing in the UK: Lessons learned from a Community Energy Saving Programme (CESP) in Nottingham’, *Energy and Buildings*. Elsevier, 172, pp. 295–306. doi: https://doi.org/10.1016/j.enbuild.2018.04.067.

Elsharkawy, H. and Zahiri, S. (2020) ‘The significance of occupancy profiles in determining post retrofit indoor thermal comfort, overheating risk and building energy performance’, *Building and Environment*. Pergamon, 172, p. 106676. doi: https://doi.org/10.1016/j.buildenv.2020.106676.

European Comission (2020) *Building and district thermal retrofit and management solutions*. Available at: https://cordis.europa.eu/project/id/723562 (Accessed: 30 August 2022).

Flower, J., Hawker, G. and Bell, K. (2020) ‘Heterogeneity of UK residential heat demand and its impact on the value case for heat pumps’, *Energy Policy*, 144, p. 111593. doi: https://doi.org/10.1016/j.enpol.2020.111593.

Gaetani, I., Hoes, P.-J. and Hensen, J. L. M. (2016) ‘Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy’, *Energy and Buildings*, 121(ISSN 0378-7788), pp. 188–204. doi: https://doi.org/10.1016/j.enbuild.2016.03.038.

Galvin, R. (2014) ‘Making the “rebound effect” more useful for performance evaluation of thermal retrofits of existing homes: Defining the “energy savings deficit” and the “energy performance gap”’, *Energy and Buildings*, 69, pp. 515–524. doi: https://doi.org/10.1016/j.enbuild.2013.11.004.

Gaterell, M. R. and McEvoy, M. E. (2005) ‘The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings’, *Energy and Buildings*. Elsevier, 37(9), pp. 982–995. doi: 10.1016/J.ENBUILD.2004.12.015.

Gershuny, J. and Sullivan, O. (2017) ‘United Kingdom Time Use Survey, 2014-2015. [data collection]’. UK Data Service. doi: 10.5255/UKDA-SN-8128-1.

Gram-Hanssen, K. (2010) ‘Residential heat comfort practices: understanding users’, *Building Research & Information*, 38(2), pp. 175–186. doi: 10.1080/09613210903541527.

Greening, L. A., Greene, D. L. and Difiglio, C. (2000) ‘Energy efficiency and consumption — the rebound effect — a survey’, *Energy Policy*, 28(6), pp. 389–401. doi: https://doi.org/10.1016/S0301-4215(00)00021-5.

Guerra-santin, O. and Tweed, C. (2013) ‘Summer post occupancy evaluation of a Passivhaus care home in the UK’, *PLEA 2013: Sustainable Architecture for a Renewable Future*.

Guerra Santin, O. (2011) 'Behavioural Patterns and User Profiles related to energy consumption for heating', *Energy and Buildings*, 43(10), pp. 2662–2672. doi: 10.1016/j.enbuild.2011.06.024.

Gupta, R. *et al.* (2021) 'Examining the magnitude and perception of summertime overheating in London care homes', *Building Services Engineering Research and Technology*. SAGE Publications Ltd STM, 42(6), pp. 653–675. doi: 10.1177/01436244211013645.

Gupta, R. and Gregg, M. (2012) 'Using UK climate change projections to adapt existing English homes for a warming climate', *Building and Environment*. Pergamon, 55, pp. 20–42. doi: https://doi.org/10.1016/j.buildenv.2012.01.014.

Gupta, R. and Gregg, M. (2013) 'Preventing the overheating of English suburban homes in a warming climate', *Building Research & Information*, 41(3), pp. 281–300. doi: 10.1080/09613218.2013.772043.

Gupta, R., Gregg, M. and Williams, K. (2015) 'Cooling the UK housing stock post-2050s', *Building Services Engineering Research and Technology*, 36(2), pp. 196–220. doi: 10.1177/0143624414566242.

Gupta, R., Kapsali, M. and Howard, A. (2018) 'Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK', *Energy and Buildings*. Elsevier, 174, pp. 548–562. doi: 10.1016/J.ENBUILD.2018.06.057.

Hajat, S. *et al.* (2014) 'Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s', *Journal of Epidemiology \& Community Health*. BMJ Publishing Group Ltd, 68(7), pp. 641–648. doi: 10.1136/jech-2013-202449.

Hanmer, C. *et al.* (2019) 'How household thermal routines shape UK home heating demand patterns', *Energy Efficiency*, 12(1), pp. 5–17. doi: 10.1007/s12053-018-9632-x.

De Haro, M. T. and Koslowski, A. (2013) 'Fuel poverty and high-rise living: Using community-based interviewers to investigate tenants' inability to keep warm in their homes', *Journal of Poverty and Social Justice*, 21(2), pp. 109–121. doi: 10.1332/175982713X668917.

HM Department for Communities and Local Government and Department for Communities and local government (2017) *English Housing Survey - Headline Report 2013-14*, *NATIONAL STATISTICS*. Available at: https://www.gov.uk/government/collections/english-housing-survey.

HMG (2018) *The Clean Growth Strategy Leading the way to a low carbon future*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf.

HMG (2020) *The Ten Point Plan for a Green Industrial Revolution*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.

Holmes, M. J. and Hacker, J. N. (2007) 'Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century', *Energy and Buildings*. Elsevier, 39(7), pp. 802–814. doi: https://doi.org/10.1016/j.enbuild.2007.02.009.

Hong, T. *et al.* (2016) 'Advances in research and applications of energy-related occupant behavior in buildings', *Energy and Buildings*. Elsevier, 116, pp. 694–702. doi: 10.1016/j.enbuild.2015.11.052.

Hong, T. *et al.* (2017) 'Ten questions concerning occupant behavior in buildings: The big picture', *Building and Environment*. Pergamon, 114, pp. 518–530.

HPA (Heat Pump Association) (2019) *DELIVERING NET ZERO: A ROADMAP FOR THE ROLE OF HEAT PUMPS*. Available at: https://www.heatpumps.org.uk/wp-content/uploads/2019/11/A-Roadmap-for-the-Role-of-Heat-Pumps.pdf.

Huebner, G. M. *et al.* (2013) 'Heating patterns in English homes: Comparing results from a national survey against common model assumptions', *Building and Environment*. Pergamon, 70, pp. 298–305. doi: 10.1016/j.buildenv.2013.08.028.

Huebner, Gesche M. *et al.* (2015) 'Explaining domestic energy consumption – The comparative contribution of building factors, socio-demographics, behaviours and attitudes', *Applied Energy*, 159, pp. 589–600. doi: 10.1016/j.apenergy.2015.09.028.

Huebner, Gesche M *et al.* (2015) 'The shape of warmth: temperature profiles in living rooms', *Building Research & Information*, 43(2), pp. 185–196. doi: 10.1080/09613218.2014.922339.

Hulme, J., Beaumont, A. and Summers, C. (2013) 'Energy Follow-up Survey 2011 Report 4 : Main heating systems', (286733), pp. 1–77. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/274772/4_Main_heating_systems.pdf.

Jones, R. V. *et al.* (2016) 'Space heating preferences in UK social housing: A socio-technical household survey combined with building audits', *Energy and Buildings*. Elsevier B.V., 127, pp. 382–398. doi: https://doi.org/10.1016/j.enbuild.2016.06.006.

Kane, T., Firth, S. K. and Lomas, K. J. (2015) 'How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling', *Energy and Buildings*, 86, pp. 817–832. doi: 10.1016/j.enbuild.2014.10.011.

Kavgic, M. *et al.* (2010) 'A review of bottom-up building stock models for energy consumption in the residential sector', *Building and Environment*. Pergamon, 45(7), pp. 1683–1697. doi: https://doi.org/10.1016/j.buildenv.2010.01.021.

Kelly, J. A., Fu, M. and Clinch, J. P. (2016) 'Residential home heating: The potential for air source heat pump technologies as an alternative to solid and liquid fuels', *Energy Policy*, 98, pp. 431–442. doi: https://doi.org/10.1016/j.enpol.2016.09.016.

Kennedy-Asser, A. T. *et al.* (2022) 'Projected risks associated with heat stress in the UK Climate Projections (UKCP18)', *Environmental Research Letters*. IOP Publishing, 17(3), p. 34024. doi: 10.1088/1748-9326/ac541a.

Khosravi, F., Lowes, R. and Ugalde-Loo, C. E. (2023) 'Cooling is hotting up in the UK', *Energy Policy*. Elsevier, 174, p. 113456. doi: 10.1016/J.ENPOL.2023.113456.

Kozarcanin, S. *et al.* (2020) 'Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe', *Energy Policy*. Elsevier, 140, p. 111386. doi: 10.1016/J.ENPOL.2020.111386.

Lewis, A. (2015) 'Designing for an imagined user: Provision for thermal comfort in energy-efficient extra-care housing', *Energy Policy*, 84, pp. 204–212. doi: 10.1016/j.enpol.2015.04.003.

Lomas, K. J. *et al.* (2018) 'Do domestic heating controls save energy? A review of the evidence', *Renewable and Sustainable Energy Reviews*. Pergamon, 93, pp. 52–75. doi: 10.1016/J.RSER.2018.05.002.

Lowe, R. *et al.* (2017) *FINAL REPORT ON ANALYSIS OF HEAT PUMP DATA FROM THE RENEWABLE HEAT PREMIUM PAYMENT (RHPP) SCHEME*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/606818/DECC_RHPP_161214_Final_Report_v1-13.pdf.

Marshall, E. *et al.* (2015) 'Combining Energy Efficiency Measure Approaches and Occupancy Patterns in Building Modelling in the UK Residential Context', *Energy and Buildings*, 111, pp. 98–108. doi: 10.1016/j.enbuild.2015.11.039.

Martiskainen, M. and Kivimaa, P. (2019) ‘Role of knowledge and policies as drivers for low-energy housing: Case studies from the United Kingdom’, *Journal of Cleaner Production*, 215, pp. 1402–1414. doi: https://doi.org/10.1016/j.jclepro.2019.01.104.

McCabe, A., Pojani, D. and van Groenou, A. B. (2018) ‘The application of renewable energy to social housing: A systematic review’, *Energy Policy*. Elsevier, 114, pp. 549–557. doi: 10.1016/J.ENPOL.2017.12.031.

Met Office (2022) *UK Climate Projections: Headline Findings August 2022*. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_headline_findings_v4_aug22.pdf.

Ministry of Housing Comunities & Local Government (2020) *The Charter for Social Housing Residents Social Housing White Paper*. Available at: https://www.gov.uk/government/publications/the-charter-for-social-housing-residents-social-housing-white-paper.

Moore, N. *et al.* (2016) *Improving the installation of renewable heating technology in UK social housing properties through user centred design*, *Indoor and Built Environment*. doi: 10.1177/1420326X15598819.

Nicol, F. (2017) ‘Temperature and adaptive comfort in heated, cooled and free-running dwellings’, *Building Research & Information*, 45(7), pp. 730–744. doi: DOI: 10.1080/09613218.2017.1283922.

Nicol, F. and Spires, B. (2013) ‘The limits of thermal comfort : avoiding overheating in European buildings TM52: 2013’.

NoRodger, D., Callaghan, N. and Thomson, C. (2021) ‘Exploring collaboration within social housing retrofit practice for an ageing population: a single case study in the West of Scotland.’, *Journal of Financial Management of Property and Construction*, 26(1), pp. 126-140. doi: https://doi.org/10.1108/JFMPC-04-2020-0020.

Office Statistics Regulation (2020) *Adult Social Care Statistics in England*. Available at: https://osr.statisticsauthority.gov.uk/wp-content/uploads/2020/01/19_11_15_SocialCare_SRv3.pdf.

Piddington, J. *et al.* (2020) *The Housing Stock of the United Kingdom*. Available at: https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf.

Roberts, S. (2008) ‘Altering existing buildings in the UK’, *Energy Policy*. Elsevier, 36(12), pp. 4482–4486. doi: 10.1016/J.ENPOL.2008.09.023.

Scott, F. (2014) *Greening the skyline The challenges and opportunities of tower block retrofit*. London.

Shi, Y., Sorrell, S. and Foxon, T. (2023) ‘The impact of teleworking on domestic energy use and carbon emissions: An assessment for England’, *Energy and Buildings*. Elsevier, 287, p. 112996. doi: https://doi.org/10.1016/j.enbuild.2023.112996.

Shipworth, M. *et al.* (2010) *Central heating thermostat settings and timing: building demographics*, *Building Research & Information*. Routledge. doi: 10.1080/09613210903263007.

Sorrell, S. (2007) *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. doi: ISBN 1-903144-0-35.

Sousa, G. *et al.* (2017) ‘A review and critique of UK housing stock energy models, modelling approaches and data sources’, *Energy and Buildings*, 151, pp. 66–80. doi: https://doi.org/10.1016/j.enbuild.2017.06.043.

Swan, L. G. and Ugursal, V. I. (2009) ‘Modeling of end-use energy consumption in the residential sector: A review of modeling techniques’, *Renewable and Sustainable Energy Reviews*, 13(8), pp. 1819–1835. doi: https://doi.org/10.1016/j.rser.2008.09.033.

Tartarini, F., Cooper, P. and Fleming, R. (2018) 'Thermal perceptions, preferences and adaptive behaviours of occupants of nursing homes', *Building and Environment*. Pergamon, 132, pp. 57–69. doi: 10.1016/J.BUILDENV.2018.01.018.

Teli, D. *et al.* (2015) 'Fuel poverty-induced 'prebound effect in achieving the anticipated carbon savings from social housing retrofit', *Building Services Engineering Research and Technology*, pp. 0143624415621028--. doi: 10.1177/0143624415621028.

Trading Economics (2023) *United Kingdom Natural Gas Price, 2023 Data - 2013-2022 Historical - 2024 Forecast*. Available at: https://tradingeconomics.com/united-kingdom/electricity-price#:~:text=Electricity Price in the United,the United Kingdom Electricity Price (Accessed: 24 May 2023).

University of Southampton (2022) 'Regulations for Members of Staff in Candidature for the Degree of Doctor of Philosophy'. Southampton, UK: University of Southampton. Available at: https://www.southampton.ac.uk/~assets/doc/calendar/RegulationsforStaffCandidature.pdf.

Vardoulakis, S. *et al.* (2015) 'Impact of climate change on the domestic indoor environment and associated health risks in the UK', *Environment International*. Pergamon, 85, pp. 299–313. doi: 10.1016/J.ENVINT.2015.09.010.

Walker, S. L., Lowery, D. and Theobald, K. (2014) 'Low-carbon retrofits in social housing: Interaction with occupant behaviour', *Energy Research & Social Science*, 2, pp. 102–114. doi: 10.1016/j.erss.2014.04.004.

Wang, Y. and He, W. (2021) 'Temporospatial techno-economic analysis of heat pumps for decarbonising heating in Great Britain', *Energy and Buildings*, 250, p. 111198. doi: https://doi.org/10.1016/j.enbuild.2021.111198.

Watson, S. D., Lomas, K. J. and Buswell, R. A. (2019) 'Decarbonising domestic heating: What is the peak GB demand?', *Energy Policy*, 126, pp. 533–544. doi: https://doi.org/10.1016/j.enpol.2018.11.001.

De Wilde, P. (2014) 'The gap between predicted and measured energy performance of buildings: A framework for investigation', *Automation in Construction*, 41. doi: 10.1016/j.autcon.2014.02.009.

Yan, D. *et al.* (2015) 'Occupant behavior modeling for building performance simulation: Current state and future challenges', *Energy and Buildings*, 107. doi: 10.1016/j.enbuild.2015.08.032.

Yi, C. yoon *et al.* (2022) 'Thermal comfort modelling of older people living in care homes: An evaluation of heat balance, adaptive comfort, and thermographic methods', *Building and Environment*. Pergamon, 207, p. 108550. doi: 10.1016/J.BUILDENV.2021.108550.

Zhang, C. and Jia, Q. (2016) 'A review of occupant behavior models in residential building: Sensing, modeling, and prediction', in *2016 Chinese Control and Decision Conference (CCDC)*, pp. 2032–2037. doi: 10.1109/CCDC.2016.7531318.

Zhang, T., Siebers, P.-O. and Aickelin, U. (2012) 'A three-dimensional model of residential energy consumer archetypes for local energy policy design in the UK', *Energy Policy*, 47, pp. 102–110. doi: 10.1016/j.enpol.2012.04.027.

Chapter 11 Appendix

11.1 Dataset

Please refer to the following repository entry

- Aragon, V., Gauthier, S., James, P., Anderson, B., & Warren, P.(2017). England's domestic occupancy patterns. Southampton: University of Southampton. doi:10.5258/SOTON/D0142 [Data set].

11.2 Supporting publications

Please see the following publications

- Aragon V. et al (2018), Evaluation of Retrofit Approaches for Two Social Housing Tower Blocks in Portsmouth, UK. Future Cities and Environment, 4(1), p.4, DOI: http://doi.org/10.5334/fce.8

- Ornaghi C. et al (2018), The effect of behavioural interventions on energy conservation in naturally ventilated offices, Energy Economics, 74, pp582-591, https://doi.org/10.1016/j.eneco.2018.07.008.