EVALUATING THE REAL ENERGY AND ENVIRONMENTAL PERFORMANCE OF AN ECO-HOUSING DEVELOPMENT IN ENGLAND

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Abstract

Reducing carbon emissions in new urban areas plays an important role in climate change mitigation. Over the last two decades, an increasing number of urban eco-developments addressing sustainability and environmental challenges have been planned and delivered worldwide. However, as evaluations of the achieved (in-use) performance are rare and tend to focus on a particular aspect of performance and small dwelling samples, the true potential of these developments in reducing urban emissions is still not well understood. In response, this study conducted a more holistic evaluation of in-use performance of a large case study eco-housing development in England (157 dwellings), capturing household behaviours (energy, transportation, waste and food) and dwelling use (energy, carbon, water, indoor conditions). The study findings were based on a rich dataset, comprised of one year monitoring data of dwelling energy and water performance and indoor environmental conditions, performance of the community heating system, as well as household interviews and a questionnaire survey. Based on the results of the data analysis, the case study development could be classified as a low energy housing development, rather than an exemplar of sustainable living, as intended. The mean dwelling energy use (76 kWh/m^2/year, n=74) achieved the design target. However, the targeted dwelling performance was not achieved in regard to the carbon emissions (20.2 kgCO_2e/m^2/year, n=74) and water use (96.2 l/p/day, n=46). In addition, adequate ventilation levels in bedrooms and cool indoor temperatures during the summer were not achieved in the majority of monitored dwellings (n=14). Reported energy- and water-saving behaviours were fairly common. The mean waste recycling rates (45% to 60%) were similar to local and national averages, and below the target of 80%. The mean rates of purchasing organic food (37%), growing food (31%) and meat consumption (in 36% of all meals) indicated that food behaviours were not more pro-environmental. Car-based modes of transportation were used for 70% of all the reported trips on average, which was higher than the national average and the target of 55%. The findings of this study support the argument that achieving more significant carbon reductions in new urban areas demands a dramatic change in the housing delivery culture. The study provided guidelines for policy makers, developers and practitioners to support the transition from delivering underperforming low carbon dwellings, to developments that make sustainable urban living a reality.

Declaration

I, Luka Oreskovic, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Published work

To date, findings of this thesis have been published in two scientific journals:

The first article ***In-use energy and carbon performance of a true zero carbon housing development in England*** was published in the *Science and Technology for the Built Environment* journal. The article is based on data presented in Chapter 6 of this thesis.

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Chapter 1: Introduction

1.1. Research Context

Society has been facing many environmental issues that are driven by human development, such as pollution, biodiversity loss and the depletion of natural resources (Meadows *et al.*, 1972; Meadows, Randers and Meadows, 2005). The abrupt climate change is currently though to be anthropogenic, and caused by a steep increase in the greenhouse gas (GHG) emissions from burning fossil fuels and industrial processes (Cook *et al.*, 2013). In 2019, the global average temperatures have increased by 1.1°C since the pre-industrial levels (WMO, 2019). An increase of 1.5°C at the end of this century seems to be already locked-in (WBG, 2014).

These findings imply that a range of dire negative consequences on the environment and the human society can be expected in the coming years. This includes more frequent extreme weather events, continuous rise of the sea level and loss of biodiversity. It is thought that the worst impacts of climate change might be avoided if the global temperature increase is kept below 2°C (IPCC, 2018). However, achieving this goal would require unprecedented strengthening of global agreements and national policies, which support dramatic technological, economic and lifestyle changes (UNEP, 2020).

By signing the Kyoto Protocol (UN, 1998), the 2008 Climate Change Act (UK Parliament, 2008), the Paris Agreement (UN, 2015) and the Glasgow Climate Pact (UNCC, 2021), the UK Government has progressively increased its national GHG reduction ambition. Given the climate urgency, in 2019 the Government committed to become a net zero economy in 2050 (DBEIS, 2019d). Meanwhile, more than two-thirds of the local districts have declared a state of climate emergency, and have developed local carbon action plans (Climate Emergency UK, 2022).

As illustrated in Figure 1, the big majority of the planned GHG reductions are expected to come from dramatic improvements in the demand-side sectors of the economy, such as buildings and transportation. This includes a widespread use of low zero carbon (LZC) technologies, and further increases in energy efficiency (CCC, 2020). Successful uptake of low carbon technologies such as heat pumps and electric cars is crucial, as this is hoped to deliver more than half of the needed reductions.

The building sector is a major energy user, related to about 40% of the national energy consumption (DECC, 2013a). Domestic buildings offer the biggest carbon reduction potential in the building sector. Dwellings accounted for about three-quarters of the building carbon emissions (CCC, 2017), and about a fifth of the national emissions (BEIS, 2021). the decarbonisation of buildings is expected to be driven by a strong transition from fossil fuelled to electric heating (mostly heat pumps) and heat network systems, complemented by significant improvements in energy efficiency. New dwellings are expected to be zero carbon from 2025 and move away from gas boilers from the mid-2030s (CCC, 2020).

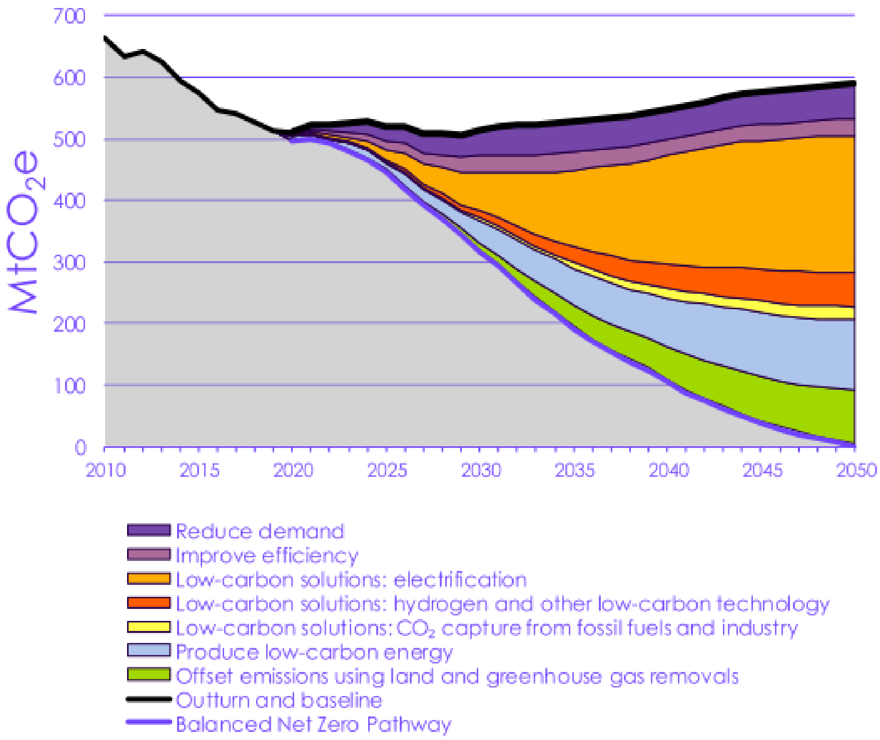

Figure 1 BEIS 2020 Provisional UK greenhouse gas emissions national statistics 2019; CCC analysis (CCC, 2020).

The majority of the proposed measures in the national pathway to net zero combined or were based on different societal/behavioural changes. In addition to an increase in energy saving behaviours and time-shifting of energy use in buildings, the envisioned decarbonisation process requires reducing demand for carbon-intensive household behaviours; between 10% and 40% reduction in demand in car use, intake of meat and dairy, and household residual waste (CCC, 2020).

When it comes to human settlements, new urbanising areas are thought to offer the largest carbon reduction potential, as their physical characteristics are not yet locked-in (IPCC, 2016). In addition to providing the latest LZC technologies, new physical setting carries a potential to enable or constrain environmental behaviours (Steg and Vlek, 2009). Hence, spatial and urban planning are regarded as one of the key demand-side pathways of reducing carbon emissions (Newton, 2014; Creutzig *et al.*, 2016).

Despite the rising climate emergency, the UK policy has been prioritising addressing the shortage of homes and other ongoing social and economic issues related to housing over environmental sustainability. This position was again demonstrated in the recent garden towns and villages housing scheme (DCLG, 2016), while the more sustainable planning policies such as the eco-towns supplement were short lived (DCLG, 2009). Recent climate policies focused on introducing gradual reductions of environmental impacts such as energy use and carbon emissions, side-lining other sustainability considerations (Pickerill, 2017).

Lacking robust policy drivers, first initiatives to deliver sustainable housing were community-based, driven by groups of eco-minded enthusiasts. Eco-village residents shared the same ethical and environmental values, translated into practice via growing ecological food, increasing biodiversity, communal sharing of goods and preservation and production energy and other resources (Tinsley and George, 2006). In line with such community ethos, eco-homes were affordable, self-built using low-impact materials and resource efficient (Pickerill, 2012).

Over the past few decades, an increasing number of developer-led eco-housing developments have been planned and delivered at different scales. The contemporary eco-housing developments have attempted to balance the contrasting principles of the deep-green rural eco-housing and the conventional housing industry, thus offering an effective pathway towards mainstreaming sustainable housing (Boyer, 2015). New eco-housing developments were also strongly shaped by sustainability-focused planning movements (Sharifi, 2016) such as New Urbanism (CNU, 1993, 2017) and urban village (Aldous, 1992), which favoured neighbourhood scale planning. Chapter 2 of the literature review elaborates how the development of technological measures, sustainable planning and behavioural measures shaped the phenomena of eco-housing developments (Figure 2).

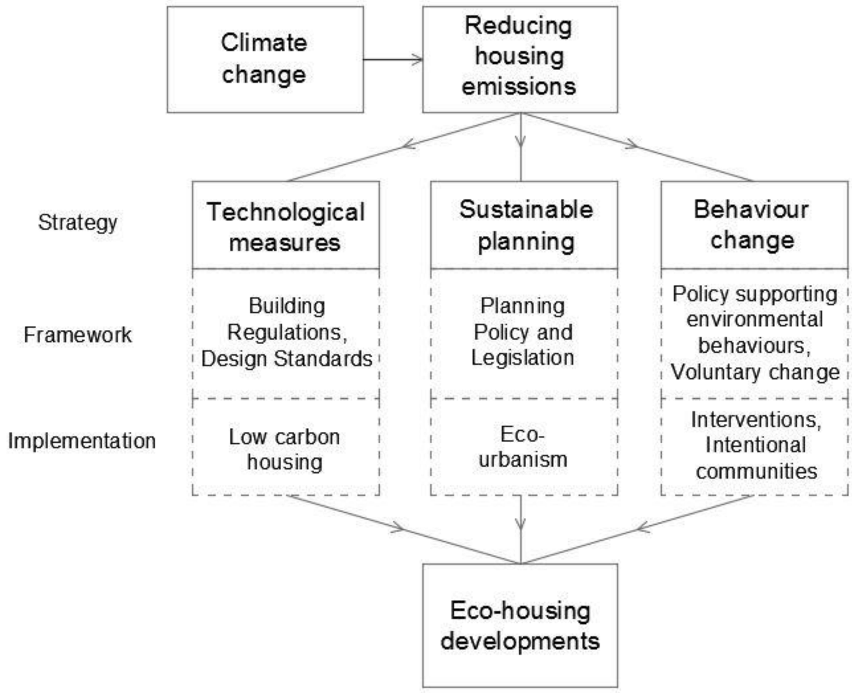

Figure 2 Schematic of the context shaping eco-housing developments.

Despite their growth in numbers, the potential of eco-housing developments in reducing urban emissions is still not well understood. Assessing the actual carbon emissions associated with new buildings and urban areas is not mandatory in the current policy. Hence, such assessments are rarely conducted. Moreover, the assessments tend to capture energy and carbon performance of a small number of case study dwellings, rather than development-wide performance based on household lifestyles. Chapter 3 of the literature review details how the environmental performance of eco-housing developments was assessed in the past studies, and shows key performance findings in regard to energy and carbon, ventilation, overheating, and environmental behaviours.

In response to this context, this thesis presents an in-use performance evaluation of a large case study eco-housing development, located in the UK. The case study consists of the initial two completed phases (157 dwellings) of the planned 4-phase development. The development was designed in compliance with the former Planning Policy Supplement 1 for new sustainable settlements called eco-towns, which makes the development unique in the UK. Consequently, the development has been designed to achieve a wide range of advanced sustainability targets, in regard to the dwelling performance and environmental behaviours.

1.2. Research Aims and Objectives

The aim of this study was to systematically and empirically evaluate the actual dwelling performance (energy, water and indoor environmental conditions) and residents' environmental behaviours (energy, transportation, waste and food) in the case study eco-housing development, against the design targets. To achieve this aim, the following six objectives were designed to:

1. Critically examine the environmental design of the case study development in terms of dwelling energy and water use, carbon emissions and the household energy, transportation, waste and food behaviours.
2. Assess the development-wide, time-series data on the dwelling energy use, energy generation, carbon emissions and water use for one year.
3. Conduct a development-wide survey to gather household responses about the experience and satisfaction with their home and indoor environmental conditions, and about the energy, waste, food and transportation behaviours.
4. Evaluate indoor environmental conditions of a subset of dwellings through in-situ monitoring during one year period of indoor temperature, relative humidity and CO_2 levels, with household interviews about heating, ventilation and cooling behaviours.
5. Compare the achieved environmental performance of the case study development with the design intent and the performance of similar eco-developments.
6. Produce performance-based guidelines for policy-makers and practitioners for designing the forthcoming eco-housing developments.

1.3. Thesis Structure

This section outlines the structure of the thesis and the content of its chapters.

Literature review is presented in Chapters 2 and 3.

Chapter 2: Context Shaping Eco-housing Developments

The intent of Chapter 2 is to provide some context to the phenomenon of eco-housing developments. It introduces the reader to sustainable urban initiatives and the important role they play in climate change mitigation. It explains how the design of new urban areas can impact household environmental behaviours and the associated carbon emissions. This chapter also explains how the historical context of sustainable housing policies, planning movements and community-led initiatives have shaped the development of eco-housing.

Chapter 3: In-use Performance Evaluations

The second chapter of the literature review identifies the gap in literature which justifies this study, and informs the design of the research methodology. This chapter introduces the common research methods used in housing performance evaluations, and their suitability for addressing the objectives of this study. The chapter continues by presenting the key findings from the available evaluation studies, using four themes; zero carbon performance, ventilation performance, occurrence of overheating, and environmental behaviours.

Chapter 4: Methodology

The first part of this chapter introduces the environmental design of the case study development. The text focuses on development's characteristics, design strategies and performance targets in regard to dwelling energy and carbon performance, and household environmental behaviours. The design of the development is compared to the designs of other eco-housing developments. The second part of the chapter describes the research methodology, which was designed to address the objectives of the study. Data collection methods used in the assessment process are presented in detail. This chapter also shows the results of the data cleaning and data validity assessment, the approach to the data analysis and the use of statistical tests; and the representativeness of the final sample.

The key results of the data analysis are presented in Chapters 5 to 7.

Chapter 5: Environmental Behaviours and Residents' Experience with the Indoor Conditions

Chapter 5 presents the results of the development-wide questionnaire survey. This chapter is divided into two parts. The first part presents the results of the questionnaire section which focused on the satisfaction and experience of residents with their home and indoor environmental conditions. This section also includes the questionnaire results in regard to household profile, perceived control over heating, cooling and ventilation, cost of utilities and noticed dwelling features. The second part of this chapter presents the results of the questionnaire section about environmental behaviours, in regard to energy use, waste recycling, food and transportation. The results are compared to the design intent, national averages, and the findings in similar studies.

Chapter 6: Dwelling Energy and Water Performance

This chapter presents the key results of the second part of the development-wide assessment; dwelling energy and water performance monitoring. Results of the data analysis are presented in regard to dwelling electricity and heat use, photovoltaic (PV) electricity generation, carbon emissions and water use. The achieved performance is compared to the design targets, national averages and the performance of similar housing developments.

Chapter 7: Energy Behaviours and Dwelling Indoor Environmental Conditions

The last chapter of the data analysis presents the key findings of the in-depth assessment focused on a subset of 12-14 dwellings. The assessment was based on the monitoring data, household interviews and thermal imaging of the dwelling envelope. The monitoring process conducted during one year period captured four parameters of indoor environmental conditions (air temperature, relative humidity and CO_2 concentrations), radiator temperature and window opening frequency. The interviews with households focused on energy behaviours, in regard to the heating, cooling and ventilation, and their experience with the home information display (named the Shimmy) and roof-mounted solar PV panels. Relating the monitored and self-reported data provided more insights about the impact of occupant behaviour on the indoor conditions.

Chapter 8: Discussion

This chapter discusses the significance and implications of the findings presented in Chapters 5 to 7. The discussion is divided into five key topics; dwelling performance, community heating performance, environmental behaviours, overall performance and holistic performance evaluations. Possible causes of the performance gap are also discussed.

Chapter 9: Conclusion

This chapter summarises the main findings of the thesis, identifies the contributions to the field of sustainable housing, and provides guidelines for policymakers and practitioners for designing the forthcoming eco-housing developments.

1.4. Limitations of the Study

This study focused on a single case study eco-housing development. On one hand, the case study approach is advantageous for studying highly contextualised and complex phenomenon such as eco-housing, as it allows going into more depth. On the other hand, this approach limits the generalizability of the study findings (see the section 4.3.1 for more details).

The study assessed only the two initial phases (157 dwellings) of the planned four-phase development, which were completed by the time of writing this thesis. The study excluded the school building, taking into account only the residential buildings within the development site.

The study managed to capture questionnaire responses from only 40% of households (n=64) within the case study development. This sample was representative of the households living in houses. Unfortunately, the sample included only one from 28 households living in flats. The energy performance was assessed in about half of the dwellings (n=74), due to the lack of complete and valid data sets. When compared to all 157 dwellings of the development, the 74 dwelling sample slightly underrepresented flats (-6.5%), 3-bed (-5.2%) dwellings and affordable dwellings (-5.1%). The monitored dwelling performance data was inspected for validity by taking meter readings. However, this was not possible in regard to the performance data of the community heating system, due to a lack of access to the plant.

Using a self-administered questionnaire and interviews in research is associated with limitations. Using the questionnaire for capturing household transportation behaviours is considered to yield less accurate responses compared to conducting interviews and trip diary methods in the national surveys. Participation in the survey and interviews for this study was voluntary, which is related to the self-selection bias. Residents living in such developments with green credentials might be hesitant to share their everyday practices, and being potentially judged for not behaving more sustainably. To try to mitigate this issue, this study complemented self-reported data with monitored data, where possible.

As the final limitation, this study only accounted for the emissions associated with the operational (in-use) building stage, excluding the emissions embodied in building materials and related to other stages of the building life cycle. Net zero and related definitions are explained in more detail in the following section.

1.5. Glossary

Nowadays, low or zero carbon, low or zero energy, sustainable, eco and other terms describing buildings, developments, towns and cities have entered the jargon about sustainable development. However, these terms are often not clearly defined, and can be associated with different meanings in the discussions around sustainable buildings. Most commonly used terminology is briefly explained in the text below.

Low energy or carbon building design aims to reduce energy use and/or carbon emissions beyond the minimum requirements of the Building Regulations of the time.

Zero carbon term is typically associated with the operational building stage. Operational emissions can be associated with regulated and unregulated energy use. The Building Regulations take into account only the regulated energy use. It includes the energy for space heating and cooling, hot water, ventilation, fans, pumps and lighting, and is estimated to capture only about half of the total electricity use in UK homes (DECC, 2013a). Hence, in order to estimate the total carbon emissions, unregulated energy use needs to be accounted for. This includes small (plug) loads such as IT equipment, lifts, escalators, external lighting, cooking and appliances. In addition to unregulated energy, industry is increasingly advocating taking into account the embodied carbon emissions (UKGBC, 2019; Arnold *et al.*, 2021).

Net zero energy implies that some fossil fuel energy can be used during the year as long as it is offset (balanced) with an equivalent export of zero-carbon energy. This definition has significantly changed over the past two decades, depending on which energy users are accounted for, and whether the use offsite renewables and carbon offsetting schemes is permitted (Torcellini *et al.*, 2006; Marszal *et al.*, 2011).

Carbon neutral in regard to buildings is used more rarely than the zero carbon term. The former can be used as a synonym for true zero carbon performance of dwellings and urban areas (Alexander, Hope and Degg, 2007).

Carbon negative implies that the building absorbs more carbon than it is emitted due to the use of fossil fuels. A development can aim to achieve this ambitious performance by producing even more renewable energy than is needed for offsetting carbon emissions (NEF, 2014), and by using carbon negative materials such as hempcrete (Jami, Karade and Singh, 2018).

Sustainable building (for e.g. CLG, 2006; Bergman, Whitmarsh and Köhler, 2007) often refers to buildings which aspire to contribute to sustainability, rather than to become fully sustainable. For example, green building design tends to prioritise improving certain environmental (energy, carbon and water) and social aspects (indoor health and comfort) (Crawley and Aho, 1999; Sinou and Kyvelou, 2006). The Brundtland Report deems human development sustainable, if it allows the pursuit of the current needs without compromising the needs of the future generations (WCED, 1987). It is apparent that ensuring sustainability requires action at a larger scale than a single building (Cole, 2004; Berardi, 2013).

In eco-housing, the prefix eco indicates the design's focus on reducing the ecological (environmental) impact. However, as eco-house designs tend to address other aspects of sustainability as well (Pickerill, 2012), the eco-housing term can be considered fairly similar to sustainable housing.

Eco-housing development term used in this thesis refers to housing developments designed with sustainability in mind. Dwellings in the UK are mostly delivered in the form of developer-led volume housing projects (Archer and Cole, 2016), easily identifiable by a characteristic dwelling design and layout. Depending on the context and project scale, new housing could be referred to as an estate, community, neighbourhood or a housing development. Housing estates can be often associated with social housing, while the term community is more often used when referring to social relations between residents. Neighbourhoods can be defined using two perceptions; the administrative/spatial[1] and in the subjective sense (The Young Foundation, 2010).

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[1] There is no clear definition of the neighbourhood in terms of population size, housing units or area. The smallest administrative unit in England representing an area of population is a *parish*, while Scotland and Wales use *communities*. A *ward* as an electoral area in England consists of 5,500 people on average. Office of National Statistics (2001), for instance, uses *Super Output Areas* (SOA) where the smallest area can contain between 400 and 1200 households.

Chapter 2: Context Shaping Eco-housing Developments

2.1. Introduction

The aim of this chapter is to introduce the reader to the key drivers, as well as the policy context that shaped the development of the eco-housing phenomenon. Three major pathways of reducing carbon emissions associated with housing development are presented; technological measures, behavioural change and planning. The section focused on technological measures, presents the key aspects of the recent Building Regulations and design standards, the transition to low carbon heating, and the importance of minimising the performance gap and overheating in dwellings. The following section presents household environmental behaviours, and the potential of shaping these behaviours with the physical setting. After this, the chapter focuses on sustainable planning, by providing a historic overview of the more prominent planning models, initiatives and policies. Lastly, a brief overview of different approaches to the design of eco-housing developments is presented.

2.2. Technological Measures

2.2.1. Building Regulations

Space heating makes about two thirds (65%) of the total energy use in dwellings (DBEIS, 2020b). The remaining use comes from water heating (17%), cooking (3%), lights and appliances (16%). Widespread energy-wastage in older dwellings has a major impact on the national energy demand, energy security, environment and occupant wellbeing. Using the current rate of housing delivery (MHCLG, 2020), it can be expected that the dwellings built after 2000 will make about a quarter of the UK housing stock by the year 2050. Hence, it is also vital to ensure that new housing is designed to high energy efficiency standards.

Progressively stringent Building Regulations in regard to conservation of fuel and power (Part L) in new housings are being introduced since the 1980s. Energy use reductions were driven by increasing the efficiency standard of the heating systems and by limiting the thermal properties of the building fabric. In addition to the Building Regulations, the Government and the industry have developed various building design standards over the years. Figure 3 shows a timeline of the Building Regulations and prominent design standards that were delivered since the 1990s.

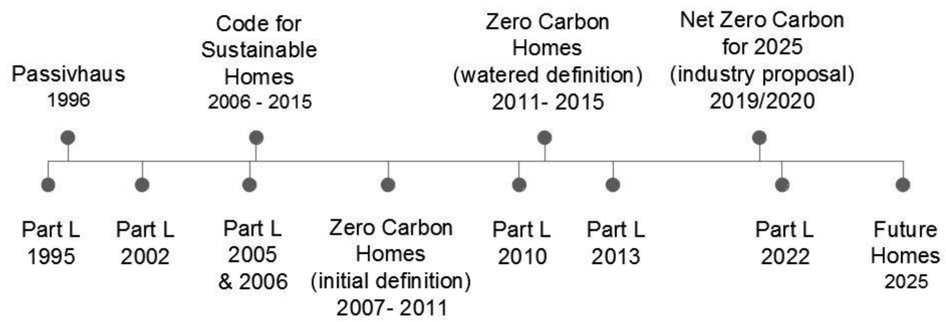

Figure 3 Timeline showing Building Regulations and the relevant building design standards delivered in the UK since the 1990s.

Since the 2000s, the Building Regulations have become more focused on reducing dwelling carbon emissions. The design compliance was proven by using *The Government's Standard Assessment Procedure for Energy Rating of Dwellings* (SAP) method (BRE, 2012). The SAP model can be used to estimate the annual energy consumption (kWh/m^2) of the proposed dwelling, and the resulting carbon emissions (kg CO_2/m^2). The calculation is based on dwelling performance parameters, which are constructed using available empirical evidence, and building design specifications. The design performance (named *Dwelling Emissions Rate)* is required to outperform the minimum performance of a notional building of the same size and shape as the proposed building (named *Target Emission Rate)*. The SAP is considered a relatively useful tool for limiting carbon emissions in new dwellings. However, it is inadequate in predicting the actual building performance due to a range of limitations (Reason and Clarke, 2008). To name just two; the SAP excludes plug loads and infrequently updates the prescribed fuel carbon factors. New SAP editions were issued only four times in the past two decades[2].

The Building Regulations introduced further requirements in order to minimise building heat loss. The 2013 Part L also introduced an additional energy standard for fabric performance called *Target Fabric Energy Efficiency Rate* (TFEE), measured in kWh/m^2/year (NBS, 2013). At the same time, the minimum dwelling airtightness levels in new buildings were limited to 10 $m^3/hr/m^2$@50Pa. Proving compliance by conducting airtightness tests in the

[2] Past SAP editions were issued in 2001, 2005, 2009 and 2012. SAP 10 has been announced for 2022.

post-construction stage was made mandatory. The Part F of the Building Regulations introduced minimum requirements for natural and mechanical ventilation strategies, to ensure the provision of fresh air and removal of excess moisture and indoor pollutants.

The Government has also delivered various programmes which supported energy efficient appliances and local renewable energy generation. It is estimated that energy efficient devices could save up to 20% of electricity use in UK dwellings (Zimmermann *et al.*, 2012). Given the continuous increase in the use of home electrical devices (DECC, 2013a), ensuring their high energy efficiency is becoming increasingly important. Introducing energy labelling for house appliances in the UK and Australia was estimated cost-effective, yielding significant energy savings (Lane, Harrington and Ryan, 2007). The national rollout of smart meters (DBEIS, 2013) was vital in making homes and the energy network smarter (HMG and Ofgem, 2017). Localised energy production via domestic solar PV installations was supported by the feed-in tariff and the subsequent Smart Export Guarantee (SEG) schemes (Ofgem, 2021a). The emerging dynamic energy pricing tariffs have been designed to reward energy flexible households with financial gains, while helping the energy network in balancing and reducing the peak demand (IRENA, 2019).

2.2.2. Building Standards

The Government has introduced Code for Sustainable Homes (CSH) in 2006, as a voluntary sustainability design standard for dwellings (CLG, 2006). The aim of the CHS was to further reduce dwelling environmental impacts, beyond the minimum requirements of the Building Regulations, and improve occupant wellbeing. In addition to energy and carbon emissions, the CSH stipulated design standards for other environmental criteria such as water, waste and ecology (CLG, 2010a). Reaching the highest two levels of the standard demanded zero carbon performance, excluding (Level 5) or including (Level 6) plug loads. In its more holistic approach to the building design, the CSH drew on environmental design rating tools such as BREEAM[3] in the UK, and LEED[4] in the US.

Passivhaus standard is a German voluntary energy performance standard delivered in the 1990s. With over 60,000 residential and non-residential certified buildings (iPHA, 2021) it

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[3] Building Research Establishment Environmental Assessment Method. https://www.breeam.com/

[4] Leadership in Energy and Environmental Design. https://www.usgbc.org/leed

has become a global standard for low energy dwellings. The standard requires reducing heating demand below 15 kWh/m^2/year, making conventional dwelling heating systems almost obsolete. This requires super-high levels of fabric efficiency, airtightness, and mechanical ventilation heat recovery (MVHR) to minimise heat loss from ventilation. The standard also limits primary energy use to 120 kWh/m^2/year. Primary energy takes into account all the losses of the energy production process, and is expected to be higher than the building energy use.

Zero carbon homes standard for 2016 was announced by the Government in 2007 (DCLG, 2007a), in line with the European near zero energy buildings directive for 2020 (EU, 2010)**.** The initial definition of zero carbon performance (sometimes called true zero carbon) included regulated and unregulated energy, and did not permit renewable energy production strategies that are disconnected from the site (DCLG, 2006, 2007a).

The announcement was followed-up by desktop-based modelling exercises, which explored the application of the standard across typical housing scenarios in the UK, using different LZC measures. Using the former SAP 2005 carbon factors (BRE, 2005), the standard seemed attainable (EST, 2008). However, other modelling studies (DCLG, 2008; UKGBC, 2008) highlighted technological limitations attributed to a narrow range of viable LCZ measures. Firstly, low carbon heat options were narrowed to systems with biomass, and gas combined heat and power (CHP) district heating. However, biomass fuel was associated with sourcing and operational issues, while the deployment of heat networks was limited to areas with higher load densities (DECC, 2013b). Secondly, in some housing scenarios, the size of the required solar photovoltaic (PV) and solar thermal systems appeared to be larger than the commonly available roof areas (Zero Carbon Hub, 2010). Thirdly, delivering high fabric efficiency levels called for a (too) steep advancement in building practices. Lastly, MVHR systems were associated with poor performance, often related to installation issues and occupant factors (Gupta, Kapsali and Howard, 2018).

In response to these concerning findings, the initial zero carbon definition was progressively watered down, to make the standard more viable. New definitions included only the emissions from regulated energy use (DBIS, 2011), and allowed off-site renewable energy production. New carbon offsetting scheme (named *Allowable Solutions*) allowed balancing the remaining emissions with investments in renewable energy generation projects, located off-site (DCLG, 2013). The hierarchy of design measures was based on the triad approach

(Entrop and Brouwers, 2010); prioritising the reduction in energy demand, followed by LZC measures and carbon offsetting. The proposed fabric efficiency range (39 - 46 kWh/m^2) was significantly weaker compared to the Passivhaus standard (Zero Carbon Hub, 2009). Due to the housing crisis (HM Treasury, 2015), the advancement of the minimum design requirements slowed down in the following years. Zero carbon standard, CSH and other low carbon policies were withdrawn (DCLG, 2017), while the decarbonisation of the building sector stalled (CCC, 2019a).

The next uplift of the Building Regulations is expected in June 2022. It will require 30% and 27% lower carbon emissions in new homes and other building types, respectively, compared to the 2013 Part L requirement. The Future Homes Standard announced by the Government for 2025 (MHCLG, 2019c), envisioned new dwellings as smart, climate-resilient, using low carbon heating and emitting 75-80% less carbon compared to 2013 Part L. It was suggested that the Standard will prioritise high energy efficiency and 'fabric first' approach, and make homes zero-carbon-ready (MHCLG, 2019b). In addition to carbon emissions, primary energy use was suggested as the metric of performance.

Industry reports (CCC, 2019b; LETI, 2020; RIBA, 2021) and briefing papers (CIBSE, 2019; UKGBC, 2020) regarded the proposed reductions of carbon emissions as inadequately ambitious, calling for a net zero carbon standard for 2025. The proposed net zero definition was stringent; taking into account all energy uses, excluding the use of fossil fuels, and introducing a performance target for embodied carbon. As the decarbonising electricity grid is on its own slowly reducing carbon emissions of buildings, minimising building energy demand is becoming increasingly important. In this context, tightening of fabric efficiency levels, introducing a space heating use standard and the energy use intensity (EUI) metric was also suggested. EUI refers to dwelling energy use measured at the meter, and excludes the contribution of renewable energy. Limiting the performance metrics to primary energy use and carbon emissions is suspected to potentially hide poor energy performance of buildings (Bordass, 2020). Table 1 compares the design requirements between the industry's net zero, the Future Homes standard and the 2013 Part L.

Subject		Design standards		
		Part L 2013 compliant	Future Homes Standard Part L option 1 (2019)	Net Zero Carbon for 2025 (industry proposal) (2020)
$W/m^2 K$	Walls	0.18	0.15	0.13 - 0.15
	Floor	0.13	0.11	0.08 - 0.10
	Roof	0.13	0.11	0.10 - 0.12
	Windows	1.4	0.8	0.8-1
	Air permeability ($m^3/hr/m^2@50Pa$)	5	5	1
	Ventilation	Natural	Natural	MVHR
	Heating system	Gas boilers allowed	Gas boilers probably to be excluded	No fossil fueles
	Carbon target	-	70-85% less carbon than Part L 2013 (regulated energy)	Zero carbon – all energy uses.
	Operational energy use target	-	Primary energy	EUI < 35 kWh/m^2 Space heating < 15 kWh/m^2

Table 1 Comparison of the design requirements between the 2013 Part L, the Future Homes Standard and the net zero carbon standard for dwellings that was recently proposed by the industry.

2.2.3. Toward Low Carbon Heating

Dwellings are associated with more than half of the UK's heat demand (BEIS, 2018). The transition to low carbon heat is one of the key strategies in the planned decarbonisation of the building sector (CCC, 2020) and the Government's Clean Growth Strategy (BEIS, 2017). Two key technologies that are expected to play a major role in this transition are the heat pump and district heating (DECC, 2013c; HM Government, 2020). The Renewable Heat Incentive (RHI) (EST, 2021) was delivered to support the installations of biomass boilers, solar water heating and heat pumps. Deployment of district heating systems was supported by the local authorities (DBEIS, 2018a), the RHI, and the Energy Company Obligation (ECO) schemes (Ofgem, 2021b).

The system is advantageous for delivering low carbon heat at the development and neighbourhood scale. The system consists of a centralised energy plant, and a network of underground pipes which circulate hot water between the plant and the buildings (users).

Some of its key advantages compared to the individual heating systems are higher energy efficiency and adaptability to the potential shifts in engine technology (Rezaie and Rosen, 2012). The last generation of district heating systems offers efficiency advancements via lower operating temperatures and use of low carbon fuels (Millar, Burnside and Yu, 2019).

Combined heat and power (CHP) technology using gas tends to be favoured in larger heat networks with both electricity and heat demands (Millar, Burnside and Yu, 2019). The CHP offers increased efficiencies due to the use of waste heat generated from the production of electricity. However, the rapid decarbonisation of the UK electricity network is increasingly diminishing the carbon reduction potentials in gas CHP systems (CIBSE, 2018), causing them to operate with a net increase in emissions already by the end of this decade (DECC, 2014a).

District heating systems in the UK cover only 2% of the national heat demand, which is significantly lower compared to the neighbouring countries (BEIS, 2018). Only a small fraction of district (community) heating systems have been deployed in housing developments[5] (DBEIS, 2020a). This is partly due to the their reduced feasibility in areas with low-density heat demand (Reidhav and Werner, 2008). Consequently, as a yet relatively "immature" technology in the UK, community heating systems have been associated with users' concerns about the monopoly of the heating supplier and high heating bills, which calls for more market regulation (Which?, 2015; Guijarro, 2017; Smith, 2017). In response, the Government has delivered regulations for metering and billing of heat (DBEIS and OPSS, 2014), and supported industry-led voluntary consumer protection schemes (Heat Trust, 2021) and technical standards (CIBSE and CHPA, 2015). In addition to the customer issues, in-use evaluations of community heating systems often revealed reduced operational efficiencies, which is elaborated in more detail in the section 3.3.1 of this thesis.

2.2.4. Performance Gap

When referring to the performance of buildings, it is important to distinguish between the designed performance and the actual performance. The designed performance is a projection of the building performance developed during the design stage, which can be used to prove compliance with the Building Regulations. The compliance method is based on building

[5] Excluding the micro-CHP systems.

design, selection of materials, and various projections in regard to climate, household behaviour, efficiency of the energy systems and the building fabric. The actual performance refers to the performance achieved during the building operation stage and normal occupation. The actual performance is expected to be higher than the designed performance, which is often named the *performance gap* (Zero Carbon Hub, 2014). This occurs as, firstly, the actual performance captures all building uses, not just the regulated energy. Secondly, building fabric and energy systems tend not to operate as expected due to various imperfections occurring during different stages of the building life cycle. Lastly, occupant factors have a major impact on building energy use, which can contribute to significant differences in total energy use among similar dwellings (see the section 2.3.2 for more details).

The performance gap has been noticed since the pioneering energy performance assessments of new energy efficient dwellings (Chapman, Lowe and Everett, 1985; Everet, Horton and Doggart, 1985). The reoccurrence of the gap in the following performance studies (Bell and Lowe, 1998; Wingfield *et al.*, 2011) initiated the Government to support research programmes focused on the in-use performance of new dwellings, which have revealed that the gap is a widespread issue (Tse and Colmer, 2014; Zero Carbon Hub, 2014; NEF, 2015).

The available meta-studies of low carbon building evaluations showed that the actual energy use increased 1.6 times on average (Gupta and Gregg, 2020), and carbon emissions 2.6 times (Innovate UK, 2016), compared to the design projections. All stages of the house building process can contribute to the loss of performance (Zero Carbon Hub, 2014; NEF, 2015; Innovate UK, 2016). This indicates wider systemic problems of design and construction in the UK (Bell *et al.*, 2010), and the lack of industry experience in achieving performances above the minimum requirements (Wingfield *et al.*, 2011).

The reoccurring factors of underperformance are the occupant behaviour (Chapman, Lowe and Everett, 1985; Bell *et al.*, 2010; Gram-Hanssen, 2010; Guerra-Santin and Itard, 2010; Gill *et al.*, 2011), and reduced energy efficiency of the fabric (Bell *et al.*, 2010; Wingfield *et al.*, 2011), heating (Bioregional, 2009; Lowe and Altamirano, 2014) and ventilation systems (Gupta and Kapsali, 2015). The issues with energy systems can be associated with unnecessary complex system controls, overlooked handover process and challenges with the installation and usage of novel low carbon systems such as the MVHR, solar thermal panels and community heating (NEF, 2015; Innovate UK, 2016).

The recurring performance gap can greatly hinder meeting the carbon reduction targets set for the building sector, and it needs to be narrowed. Hence, apart from uplifting the design standard, the industry also widely advocated that regulatory compliance based on the design intent, shifts towards ensuring ongoing compliance (CCC, 2019b; CIBSE, 2019; LETI, 2020; UKGBC, 2020).

2.2.5. Overheating

Apart from being energy efficient and low carbon, it is important that dwellings provide a comfortable and healthy living space (CCC, 2020). This is becoming increasingly important in the context of recent global trends, which are related to the changes in lifestyles and the environment. Firstly, the ageing population is more exposed to the health risks caused by poor indoor conditions (Age UK, 2019). Secondly, people are spending increasing amounts of time indoors and working from home (GWA and Flexjobs, 2017). Thirdly, progressively more airtight and insulated building envelopes reduce the infiltration of fresh air and trap solar gains, which increases indoor temperatures. Fourthly, climate change is increasing global temperatures and making heat waves (McCarthy, Armstrong and Armstrong, 2019) more frequent and severe (Chapman, Watkins and Stainforth, 2019). Lastly, due to the urbanisation trend (GOS, 2014; UN, 2018), an increasing number of people are exposed to the heat island effect (Oikonomou *et al.*, 2012).

Provision of comfortable indoor conditions can be measured by using thermal comfort standards. Thermal comfort can described as the state of satisfaction with the surrounding thermal environment. It can be affected by various environmental and personal factors. Taleghani *et al.* (2013) presented the development of the two main approaches to defining thermal comfort: the steady-state model developed by Fanger (1970), and the adaptive comfort model developed by Humphreys (1978). Steady state model seems to be more applicable for conditioned environments, as the comfortable indoor temperature range in naturally ventilated buildings is wider (De Dear and Brager, 2002). This notion suggested that thermal comfort is complexly linked with outdoor temperatures. Nowadays, ASHRAE-55 standard (ASHRAE, 2017) is widely used to specify indoor conditions in naturally ventilated spaces which would be regarded as comfortable by 80% or 90% of the occupants.

Overheating could be defined as "*the phenomenon of a person experiencing excessive or prolonged high temperatures within their home, resulting from internal and/or external heat* *gain and which leads to adverse effects on their comfort, health or productivity"* (ZCH, 2015b, p. 3). Exposure to higher temperatures impacts human health and the economy (ZCH, 2015c). Running mean outdoor temperatures above 25°C seem to be related to an increase in human mortality (Public Health England, 2012). Thermal discomfort is shown to impact the work productivity levels (Leaman and Bordass, 1999), and can lead to an increase in building energy demand due to the use of mechanical cooling (Peacock, Jenkins and Kane, 2010).

During the past decade, the Government backed research studies focused on understanding and mitigating overheating in dwellings. A considerable body of knowledge was produced by the Zero Carbon Hub[6] research programme. Planning, building design and occupant factors seem to play important roles in mitigation of overheating in dwellings (ZCH, 2016; Good Homes Alliance, 2019; MHCLG, 2019a).

Prevention of overheating in residential buildings was recently introduced in the new Part O of the Building Regulations (HM Government, 2021). Compliance with the requirements can be achieved by either using a prescriptive simplified method or dynamic energy modelling. Solar gain can be reduced with shading, reduced window area and improved shading specifications.

The occurrence of overheating in buildings can be assessed using a range of assessment methods (ZCH, 2015a). Environmental Design Guide A standard (CIBSE, 2006) outlines the static overheating criterion, while CIBSE TM52 standard (CIBSE, 2013) details the dynamic criterion. CIBSE TM59 standard (CIBSE, 2017) suggests that overheating in naturally ventilation dwellings should be assessed using the CIBSE TM52 *Criterion 1: Hours of exceedance* for living rooms, kitchens and bathrooms. Static criterion should be used for assessing bedrooms, which states that overheating occurs when the indoor air temperatures reach above 26°C for more than 1% of the occupied hours. The overheating analysis compares empirically measured indoor temperatures using in-situ monitoring to the temperature limits defined by the criteria. This appears more stringent than the Passivhaus compliance criterion, which requires not exceeding indoor temperatures above 25°C for more than 10% of the year. The dynamic standard defines overheating using three dynamic

[6] https://www.zerocarbonhub.org/full-lib

criteria. As an example, the first criterion defines the exceedance of the upper comfort limit by 1 K for more than 3% of the occupied hours.

2.3. Shaping Environmental Behaviours

2.3.1. Transportation, Waste and Food Behaviours

It is believed that human behaviour is shaped by external factors (such as physical settings) and personal factors (such as attitudes, norms and habits) (Stern, 2000). The impact of personal factors seems to dominate over the external factors in household consumption-based emissions, called footprints (Minx *et al.*, 2013). Personal factors also tend to dominate in personal mobility (Hanson and Hanson, 1981; Madanipour, 2001; Olaru, Smith and Taplin, 2011), car ownership (Aditjandra, Cao and Mulley, 2012), waste behaviours (Tonglet, Phillips and Read, 2004; Barr, 2015) and food choices (Furst *et al.*, 1996; Renner *et al.*, 2012). Although shaping environmental behaviours with external factors seems to have been less systematically examined (Steg and Vlek, 2009), this approach is still deemed more effective than altering personal values and attitudes (Geller, 2002).

Neighbourhood characteristics are suspected to have a stronger impact on household footprints when studying smaller spatial scales such as neighbourhoods (Baiocchi, Minx and Hubacek, 2010). Increased housing density and reduced dwelling size carried the greatest energy saving potential in regard to buildings, transportation and infrastructure in the studied US (Nichols and Kockelman, 2014) and Canadian neighbourhoods (Norman, MacLean and Kennedy, 2006).

Households are more likely to recycle in smaller neighbourhoods (Geiger *et al.*, 2019), when in proximity to recycling facilities (Barr, 2004). The literature review facilitated by WRAP[7] (2018) did not find clear evidence about how the improvements in recycling can be achieved, and which interventions seem to be more effective. International city-level schemes which appeared as the most effective provided proactive communication with the residents, frequent collection of recyclables, legislative drivers for recycling and separate charging of residual waste.

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[7] WRAP stands for "Wellness Recovery Action Plan". It was established as a not-for-profit company.

Altering transportation and food behaviours seems to be quite challenging. Reducing car use and adopting a low-impact diet are among the least favoured pro-environmental behaviours (DEFRA, 2008). Reduced car use was associated with higher neighbourhood density (Nichols and Kockelman, 2014), and good access to shopping, good public transportation services and social areas (Cervero, 1995; Aditjandra, Cao and Mulley, 2012).

Due to the lack of awareness about low-impact foods (Siegrist, Visschers and Hartmann, 2015), encouraging higher intake of healthy (local, seasonal, organic) foods is deemed an effective way of reducing food footprints (Owen, Seaman and Prince, 2007). Encouraging participation in urban gardens (Litt *et al.*, 2011; Garcia *et al.*, 2018) appears to be a more promising strategy compared to providing access to shops with healthy foods (Handy and Clifton, 2001; Wang *et al.*, 2007).

2.3.2. Dwelling Energy Use Behaviours

Household behaviour plays an important role in dwelling energy use (Chapman, Lowe and Everett, 1985; Bell et al., 2010; Gram-Hanssen, 2010; Guerra-Santin and Itard, 2010; Gill et al., 2011). As buildings are becoming more efficient, the significance of occupant behaviour is expected to increase. Expected energy use reductions can be hindered due to a variety of occupant factors, such as improper use of technologies (NEF, 2015; Gupta, Kapsali and Howard, 2018) and the rebound effect – when users increase energy use due to the notion of energy efficiency (Sorrell, Dimitropoulos and Sommerville, 2009; Chitnis and Sorrell, 2015).

Studies have suggested that energy behaviours accounted for about 50% of variance in dwelling heat use (Gill *et al.*, 2010; Van den Brom *et al.*, 2019). Ventilation behaviours (Sorgato, Melo and Lamberts, 2016), heating pattern and the household profile seem to be strong determinants of heat use (Guerra Santin, Itard and Visscher, 2009; Guerra-Santin and Itard, 2010; Do Carmo and Christensen, 2016).

Household behaviours accounted for 37% and 11% of variance in electricity use and water use (Gill *et al.*, 2010), respectively. Electricity use seems to be determined by the household profile, appliance ownership and occupancy patterns (Swan, Ugursal and Beausoleil-Morrison, 2011; McLoughlin, Duffy and Conlon, 2012). Provision of new technologies such as smart energy monitors and solar PV panels seem to carry a modest potential in motivating occupants to reduce energy use (Keirstead, 2007; Hargreaves, Nye and Burgess, 2013; Nachreiner *et al.*, 2015; Baborska-Narozny, Stevenson and Ziyad, 2016). Home batteries carry a potential in enabling energy load shifting and increasing the self-consumption of the generated PV energy (Luthander *et al.*, 2015).

2.4. Sustainable Planning

2.4.1. Recent Planning Models

The past planning models have strongly influenced the development of sustainable planning. Since the 20th century, various spatial and urban planning models have been developed in the attempt to address the emerging socio-economic problems of the time, which lowered the quality of urban life in rapidly growing cities. In addition to improving citizens' wellbeing, later post-modern (neo-traditional) movements aimed to address new issues, such as urban sprawl. After the 1970s, rising awareness about the environmental degradation associated with the human development shifted the focus of planners towards addressing the environmental impacts of cities.

One of the possible ways of improving the quality of urban life was developing new master-planned settlements. Ebenezer Howard's *Green City* was one of the earlier prominent utopian planning models, which influenced the development of the *New Town* and other housing programmes (Alexander, 2009). Some of the Green City's key design principles, such as merging nature with urban areas, self-sufficiency, inclusive community and the green belt (Parsons and Schuyler, 2002), were integrated in the later sustainable planning practices.

One of the key factors in achieving self-sufficiency (or self-containment) is the population size. It should be large enough to make basic services feasible, and to ensure that the number of jobs matches the expected number of housing units (Cervero, 1995). A population of 3,000-5,000 in urban villages was deemed sufficient to provide some retail facilities and a school (Aldous, 1992). Garden Cities with a population of ~ 30,000 were thought to ensure self-sufficiency in regard to energy, food, amenities and jobs. The principle of self-sufficiency is particularly interesting from the perspective of sustainable transportation, as it is expected to lead to reduced car use. However, it is argued smaller towns are unlikely to meet all the needs of households living in this modern era, with varying lifestyles, social networks and good access to mobility (Madanipour, 2001). A study of international New Town settlements found that the household commuter choices were determined by the quality of transit services and the proximity to major urban centres, rather than the job-to-home ratio and other known self-sufficiency parameters (Cervero, 1995). In fact, the same study showed that in the UK, remote location of New Towns and proximity to the major motorway networks increased the household car use.

These findings support the rationale behind the *transit-oriented development* (TOD) planning model, associated with the *smart growth* paradigm (Goetz, 2013). The TOD model proposes locating high density mixed use developments in proximity to good transit services (Calthorpe, 1993). It seems that the provision of high frequency transport services is essential for the success of a TOD (Hale, 2014; Knowles, Ferbrache and Nikitas, 2020). Further mainstreaming of TOD model is hindered by its dependence on the support of the Government and local councils in acquiring sizable site area, which is needed to ensure the viability of commercial spaces (Searle, Darchen and Huston, 2014).

Neighbourhood-scale planning appears to be recurrently favoured approach to expanding urban areas (Madanipour, 2001). It was popularised by Clarence Perry's semi-autonomous neighbourhoods (Patricios, 2002), *New Urbanism* (CNU, 2017) and the *urban-village* neo-traditional planning models (Aldous, 1992; Urban Villages Forum, 1997). The key design principles of neighbourhood-scale planning include medium-high density neighbourhoods, mixed land use, diversified housing options, strong community identity, high street connectivity, multi modal transportation, stakeholder engagement and vibrant street life attracting pedestrian movement.

Implementations of the mentioned neo-traditional planning movements demonstrated the challenges of bringing a theoretical model to reality. New Urbanist developments were associated with socio-economic elitism, insufficient density, favouring greenfield sites, and the false use of local history and traditions (Talen, 2013). High compactness was associated with social and economic challenges, and is through to offer questionable sustainability benefits (Jenks, Burton and Williams, 1996; Gordon and Richardson, 1997; Neuman, 2005). An assessment of three urban villages in the UK reported cases of low-density housing, low employment opportunities and mixing of private and social tenants (Biddulph, Franklin and

Tait, 2003). In the three villages, localisation seemed as an imperative of poverty, rather than preference.

2.4.2. Sustainable Planning Policies

The key sustainable planning policies and housing schemes delivered in the UK since the early 2000s are outlined in Figure 4. The UK's first sustainable development strategy recognised the pivotal role of spatial planning in sustainable development (HMG, 2005). The strategy supports the use of the neo-traditional planning principles, such as higher development density, wildlife protection, brownfield sites and giving preference to locations near urban centres to curb car dependency. In 2003, the Government delivered one of the first programmes supporting the delivery of more sustainable communities (ODPM, 2003). The programme prioritised addressing the ongoing social and economic issues related to housing, such as the housing shortage. The following *Planning and Climate Change* supplement to planning policy highlighted the importance of energy efficiency and carbon reductions in housing and transportation (DCLG, 2007b). The *Carbon Challenge*, *Low Carbon Communities Challenge* and similar programmes supported neighbourhood-scale sustainability strategies in new and existing housing developments (DECC, 2012).

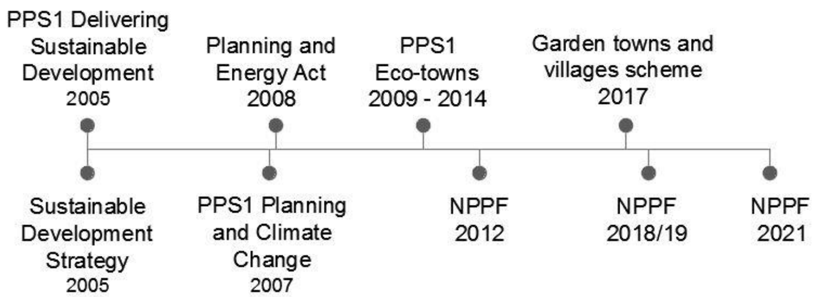

Figure 4 The key sustainable planning policies and housing schemes delivered in the UK since the early 2000s.

In 2007, the Government announced a programme for new sustainable settlements and urban extensions named *eco-towns* (CLG, 2007). Soon after, specific planning requirements were developed, reflecting the overall vision for the future eco-towns as *"...exemplars of good practice and a showcase of sustainable living"* (DCLG, 2009, p. 2). Environmental requirements prioritised achieving a drastic reduction in carbon emissions associated with dwelling use and household behaviours. Accordingly, the eco-towns were expected to; achieve zero carbon (all energy uses) at the development level and 70% advancement in dwelling energy efficiency compared to the 2006 Part L; provide of on-site renewables and low carbon heat; support on-site food growing and; reduce water use, generation of household waste and car use. Preference was given to planning proposals with sites in proximity to the existing urban centres, employment and public transportation links. Eco-towns were required to be of sufficiently large (> 5,000 dwellings), to ensure that the provision of basic on-site amenities is viable. In contrast to the Building Regulations, compliance with the design requirements needed to be continuously proven to the local authorities by conducting annual performance monitoring.

Although its ambition to support sustainable housing was commendable, the eco-towns programme was criticised for using a top-down approach to community building (Rose, 2009), which can be insensitive to the particularities of the local context (Willett, 2011). The size and density of the proposed eco-town developments was considered insufficient, which would result with more urban sprawl, increased car use and economic reliance on larger urban centres (Manns, 2008). It was also thought that the local authorities would lack the capacity to support and rigorously assess the results of performance evaluations (Morris, 2011).

In order to make planning more effective in tackling the housing crisis (DCLG, 2017), in 2012 the Government substituted the existing policies with an overarching *National Planning Policy Framework* (NPPF) (DCLG, 2012). The NPPF was deemed adequate in ensuring that the environmental damage from future housing is minimised. In line with this approach, the eco-town planning recruitments were considered overly challenging for housing developers, and the programme was soon after withdrawn (DCLG, 2014, 2015).

The subsequent garden towns and villages housing programme side-lined climate concerns, prioritising self-sufficiency, provision of local employment, green and public spaces, and speeded delivery of well-built homes (DCLG, 2016) Similarly to the eco-town programme, many of the planned garden towns and villages were envisioned as low-density greenfield developments, which would probably lead to increased car use and further expansion of the road network (Smart Growth UK, 2017; TNH, 2020).

The recent NPPF indicated a mild policy shift, outlining more clearly the contribution of planning to sustainable development (MHCLG, 2021). Nonetheless, the NPPF was deemed still insufficient in ensuring that the dramatic action needed to support the net-zero economy goal was demonstrated in local and neighbourhood plans (CSE, 2020; CSE and TCPA, 2021).

2.5. Eco-housing developments

2.5.1. Design approach

Over the last two decades, an increasing number of developer-led eco-housing developments addressing sustainability and environmental challenges have been planned and delivered worldwide (Joss, Tomozeiu and Cowley, 2011). Due to the lack of policy drivers and strong market demand for sustainable housing (Townshend, 2007; Williams and Dair, 2007), the developments have depended on the support of sporadic government programmes (Falk and Carley, 2012; Fraker, 2013) or/and the motivation of eco-minded stakeholders (Bioregional, 2009; Wingfield *et al.*, 2011). Given this context, they tend to be perceived as one-off demonstrations of advanced and innovative sustainability measures (Bayulken and Huisingh, 2015).

Eco-housing developments can vary in delivery mechanisms, spatial scale (from clusters of homes to whole neighbourhoods and cities) and typology (new settlements, urban expansions and redevelopments) (Joss, Tomozeiu and Cowley, 2011; Falk and Carley, 2012; Fraker, 2013; Thomson, Matan and Newman, 2013; Pullen *et al.*, 2015; Codispoti, 2021). The neighbourhood scale is deemed particularly suitable for combining urban design and new technologies (Newton, 2014), offering the potential to respond to and reinvent locality (Barton, 2000; Gibberd, 2013), benefiting from economies of scale (Codoban and Kennedy, 2008), and for generating new learning (Fitzgerald and Lenhart, 2015).

How sustainability is framed, and the selection of design principles in eco-housing developments is governed by different motivations, which are shaped by local contexts (Holden, Li and Molina, 2015). In addition to energy efficiency, urban systems, site ecology and low carbon technologies, eco-housing developments can adopt mixed land use, self-containment, compactness, proximity to services and other aforementioned design principles from neo-traditional planning models (Sharifi, 2016). Given the urgency of mitigating climate change, reducing carbon emissions tends to dominate over other sustainability objectives (Lovell, 2004; Chastenet *et al.*, 2016). The recurrent design approach prioritises implementing energy efficiency and low-carbon technologies, which reduce emissions intrinsically, minimise resident involvement and do not require changes in lifestyle or personal values (Lovell, 2004; Rutherford, 2020). Achieving further carbon reductions by providing bicycle lanes, urban gardens and other on-site measures that could enable or limit household environmental behaviours is considered far less certain (Williams, Dair and Lindsay, 2008).

2.5.2. Eco-housing Case Studies

More prominent examples of developer-led eco-housing developments which demonstrate different approaches to urban sustainability are presented in Table 2.
Pioneering developer-led eco-housing developments such as Slateford Green and BedZED shared the ambition to test innovative technologies and approaches to improving urban sustainability. In line with the rural origins of eco-housing (Pickerill, 2012), some eco-housing projects such as Thamesmead Ecopark and Triangle Eco Homes aimed to demonstrate that low-impact dwellings can be also affordable. Derwenthorpe and Stamford Brook are more prominent examples of low-density mass-housing eco-developments in the UK. However, both developments were still too small in scale to provide basic on-site amenities. Larger developments can be advantageous for achieving advanced environmental performance, as the economies of scale make design measures needed for achieving higher levels of urban sustainability (such as community heating and amenities) viable (Codoban and Kennedy, 2008). Vauban in Germany and Hammarby in Sweden are considered among the most advanced and well-known new eco-districts.

Study	**Development name, location and size**	**Key design features**
(EST, 2011)	Slateford Green UK 120 dwellings	Introduced a range of sustainability measures that will be recurrently used in the succeeding eco-developments; community heating, low-impact building materials, high fabric efficiency, passive solar design and limited parking spaces. The inclusion of other novel technological solutions such as the use of waste heat, grey water treatment system and biomass heating was either too costly or not practical.
(Bioregional, 2009)	BedZED UK 100 dwellings	Blocks of flats in an urban setting aiming to minimise the ecological impact of its residents. Ambitious design targets in regard to dwelling energy and water use, household waste recycling and car use. Novel sustainability measures included small-scale biomass CHP community heating and waste-water treatment system.

Study	Development name, location and size	Key design features
(Bioregional, 2014)	One Brighton UK 172 dwellings	Similarly to BedZED, the design team aimed to deliver truly sustainable zero-carbon community. Key features; urban location, low embodied carbon, no parking spaces offered, car club, on-site sustainability manager and green roofs.
(EST, 2005)	Thamesmead Ecopark UK 39 dwellings	One of the first affordable, low-impact social housing projects. Dwellings designed using robust and easily replicable low carbon measures, such as timber structure, solar thermal panels and rainwater harvesting system.
(HAB, 2011).	Triangle Eco Homes UK 42 dwellings	Mainstreaming certain low-cost design principles of the rural, self-built eco-housing in an urban context, such as hempcrete structural walls, stack ventilation and community gardens.
(Wingfield *et al.*, 2011).	Stamford Brook UK 700 dwellings	Envisioned as a sustainable housing neighbourhood exemplar. However, the selection of sustainability measures was limited to preserving the ecology of the existing river corridor and reducing dwelling energy use
(Quilgars *et al.*, 2015)	Derwenthorpe UK 500 dwellings	Planned as both socially and environmentally sustainable housing scheme*,* providing with a gas powered community heating system, energy efficient dwellings, a car club and other common sustainability measures.
(Foletta, 2008).	Millenium Village UK ~2800 dwellings planned	A rare example of a district-scale urban redevelopment in the UK. The key sustainability measures include CHP district heating, energy efficiency, passive building design and ecological regeneration of the brownfield site.
(Hunt *et al.*, 2012).	Adamstown Ireland ~3400 dwellings planned	One of the first new settlements in Ireland which aspired to be a sustainable development. However, this vision was not reflected in the implemented environmental design, which lacked water saving fixtures, on-site renewables, community heating and other essential measures.
(Scheurer and Newman, 2009; Freytag, Gössling and Mössner, 2014)	Vauban Germany ~5000 dwellings	High density eco-district, with highly energy efficient and low embodied carbon dwellings supported by large PV systems. Partly a car-free zone, with comprehensive network of open spaces. Participatory approach to planning; integrating the community and sustainable initiatives in shaping the design strategies from the onset.
(Mahzouni, 2015).	Hammarby Sweden ~11000 dwellings	Well-known eco-district for using innovative and sustainable urban systems. Household waste and the sludge from the wastewater treatment facility are used for the production of biogas.

Table 2 Eco-housing developments and their key features

2.6. Summary

Chapter 2 presented the key drivers and the policy context that shaped the phenomenon of eco-housing developments.

Given the urgency of climate change mitigation, the UK Government pledged to become a net zero economy in 2050. The decarbonisation of the building sector is expected to be mostly driven by low carbon heating technologies and improvements in energy efficiency. Apart from technological measures, achieving the net zero economy also requires reduction in demand in carbon-intensive household behaviours.

Progressively stringent Building Regulations in regard to conservation of fuel and power (Part L) in new housings are being introduced since the 1980s. In 2000s, the Building Regulations have incorporated design requirements to limit dwelling carbon emissions. Partly due to the pressures of the housing crisis, planned speeded tightening of the Part L requirements was eventually slowed down, and the zero carbon standard announced for 2016 was scraped. Prominent industry bodies deemed the forthcoming Future Homes Standard inadequate in supporting the national climate goal, and urged for introducing a stringent net zero carbon standard for 2025. The Government has also delivered different nation-wide programmes which supported local renewable energy generation and further reductions in dwelling energy demand, such as energy labelling for house appliances. Passivhaus and other voluntary building design standards have been developed over the years for achieving performances beyond the minimum requirements of the Building Regulations.

Heat networks play a vital role in the planned transition to low carbon heating. District heating system is advantageous for delivering low carbon heat at the development and neighbourhood scale. However, covering only 2% of the national heat demand, it is still considered a relatively “immature” technology in the UK, and is associated with different issues.

The gap between the designed and actual performance in new dwellings has been noticed since the first dwelling energy performance assessments. As the recurring gap hinders meeting the carbon reduction targets set for the building sector, and it needs to be narrowed. The key factors causing the gap are thought to be the occupant behaviour, reduced energy efficiency of the building fabric and the provided energy systems. Apart from being energy efficient and low carbon, is it important that new dwellings provide a comfortable and healthy living space. Preventing overheating in new dwellings is becoming increasingly important in the context of global warming and increasingly insulated and airtight buildings.

Shaping carbon-intensive behaviours with external factors such as the physical environment is deemed more effective than altering personal values and attitudes. Studies have shown that increased housing density and reduced dwelling size are important determinants in reducing energy use in new neighbourhoods. Measures that seem to increase household waste recycling rates include proactive communication with the residents, frequent collection of recyclables, legislative drivers for recycling and separate charging of residual waste. Studies have also found that reduced car use was associated with higher neighbourhood density, good access to shopping, good public transportation services and social areas. Encouraging higher intake of healthy foods is deemed an effective way of reducing food footprints. Provision of new technologies in dwellings such as smart energy monitors and solar PV panels, seem to carry a modest potential in supporting energy saving behaviours.

Planning new urban areas offers a great carbon reduction potential, by ensuring the provision of the latest technological measures and the physical environment which can support behavioural change. The past planning models tackling socio-economic problems of the time have strongly influenced the development of sustainable planning. Howard's Green City is well known for its underpinning design principles, such as merging nature with urban areas, self-sufficiency, inclusive community and the green belt. New Urbanism and the urban-village are prominent neighbourhood-scale planning models, popularising medium-high density, mixed land use, diversified housing options and other design principles. The Transit Oriented Development model proposed locating high density mixed use developments in proximity to good transit services. In 2000s, the Government delivered first sustainable planning policies and housing programmes. Eco-town programme for new sustainable settlements prioritised achieving a drastic reduction in carbon emissions associated with dwelling use and household behaviours. However, the programme was soon after withdrawn, while the subsequent garden towns and villages housing programme has side-lined climate concerns. The industry regarded the delivered National Planning Policy Frameworks inadequate in supporting the zero carbon economy commitment.

Over the last two decades, an increasing number of developer-led eco-housing developments addressing sustainability and environmental challenges have been planned and delivered worldwide. The recurrent design approach prioritises implementing energy efficiency and low-carbon technologies, which reduce emissions intrinsically, minimise resident involvement and do not require changes in lifestyle or personal values. Slateford Green and BedZED are well-known, pioneering eco-housing developments in the UK, which tested innovative technologies and approaches to improving urban sustainability. Thamesmead Ecopark and Triangle Eco Homes developments demonstrated the use of low-cost design principles to make eco-housing developments more affordable. Stamford Brook and Derwenthorpe are prominent examples of low-density mass-housing eco-developments in the UK. Millennium Village, Adamstown, Vauban and Hammarby are examples of larger eco-neighbourhoods and eco-districts. Larger spatial scale of developments can be advantageous for achieving advanced environmental performance, as the economies of scale can make the needed design measures more viable.

Chapter 3: In-use Performance Evaluations

3.1. Introduction

Chapter 2 introduced the reader to the eco-housing phenomenon and the context that has shaped its development. The first part of this chapter focuses on the common methodological approaches used for assessing the environmental performance of dwellings and urban areas. The methodologies' aims, methods, advantages and limitations in evaluating the in-use performance of housing developments will be presented. The second part of this chapter presents key performance findings from available evaluations of zero carbon housing and eco-housing case studies, in the following main themes: energy and carbon, ventilation, overheating, and environmental behaviours.

3.2. Performance Evaluation Methodologies

3.2.1. An Overview of Approaches

Increased awareness about the pivotal role of urban areas in sustainable development has driven the need to measure their environmental impact. Major world cities have pledged to reduce and monitor their carbon emissions (C40, 2021), and some have published their climate change action plans (Greater London Authority, 2018). However, there seems to be a lack of systematic evaluations of the implemented measures and the achieved carbon reductions in urban areas (IPCC, 2016).

Performance evaluations typically report on past and current environmental performance of an object of assessment. An evaluation relates to "*making of a judgement about the amount, number, or value of something"* (Oxford Living Dictionaires, 2017). Performance evaluations of the built environment sector can measure and quantify the achieved impacts, and potentially compare them against the design intent. The term performance can be defined as *"the fulfilment of a claim, promise, or request"* (Merriam-Webster Dictionary, 2017). Therefore, a performance evaluation could be understood as a judgment about the level of achievement against pre-defined criteria (value).

Due to their complexity, performance evaluations tend to be based on case studies. This approach can be seen as inferior to other scientific methods capturing large samples, as its context-specific findings cannot be generalised and used for theory development (Flyvbjerg, 2006). However, this approach is deemed beneficial for studying advanced housing, which demonstrates positive examples of highly contextualised phenomena (Yin, 2012). It is also seen as a necessary method in social sciences, which allows looking into a greater level of detail, using multi-method techniques and taking into account multiple aspects of a complex phenomenon, such as dwelling performance (Flyvbjerg, 2006). Leaman, Stevenson and Bordass (2010) noted that evaluation case studies can be criticised for being more anecdotal than producing new knowledge. The authors however argued that new findings from different case studies allow the build-up of the knowledge base, and communicating the lessons learned from vivid, real life examples.

Sub-national carbon accounting is typically conducted on the scale of cities and local councils. Measuring carbon emissions at smaller urban scales such as neighbourhoods and housing developments attracted less attention by the authorities, industry and academia. Without the necessary policy support, such performance assessments tend to be conducted rarely and mainly on a voluntary basis. The evaluation of the outcomes of neighbourhood-scale planning is not mandatory in current policy. In addition, the advantages of understanding the impacts of local planning can be overshadowed by concerns in regard to the time, costs, needed expertise and data availability (Seasons, 2003).

An increasing number of eco-housing developments delivered in the past two decades. Performance evaluations can demonstrate the benefits of sustainable urban design (Newton, 2014), and show the effectiveness of different design approaches and implemented measures (Bioregional, 2009; Quilgars *et al.*, 2019).

Without access to performance data, it is difficult to conduct a robust performance evaluation (RPS, 2008). Over the years, different evaluation methodologies and data collection techniques have been developed. Depending on their purpose, assessments can predict, rate or measure performance. They can also vary in selecting spatial or functional scope (from neighbourhoods to buildings and households), sustainability criteria, building stage of assessment, research approach (desktop-based, field work etc.) and data type (measurements, self-reported etc.).

The following text will briefly introduce the methodological approaches which can be used for evaluating the performance of eco-housing developments. Post Occupancy Evaluations and Building Performance Evaluations are commonly used in studies focused on the performance of buildings. Life cycle assessment, urban metabolism can be used in urban-scale assessments, while footprinting can be used also for assessing households.

3.2.2. Building Performance Evaluation

The first studies which evaluated the needs, experiences and behaviour of building occupants appeared during the 1960s, aimed at designing better social housing projects in Europe and North America (Preiser and Vischer, 2005). This marks the beginning of the Post Occupancy Evaluation (POE) methodology, from which the Building Performance Evaluation (BPE) evolved. Preiser *et al.* (2001) noted that there is no industry accepted definition or standardised method of POE, as the evaluation process needs to be adapted to the aims of a particular study. POE focuses on systematically evaluating a building during the occupation phase, which is nowadays viewed as a sub-process of BPE. The overall aim of POE is to systematically collect empirical evidence about user wellbeing and satisfaction with the building, identify recommendations for building improvement and provide feedback to building stakeholders.

Preiser and Vischer defined BPE as "*…the process of systematically comparing the actual performance of buildings, places and systems to explicitly documented criteria for their expected performance"* (2005, p. 10). Similarly to the POE, the BPE aims to systematically detect issues which hinder the designed building operation, share findings and build the knowledge base for future buildings. The BPE approach is, however, broader. It allows an assessment of all stages of the building delivery process, from the design stage to handover and building operation. In addition to capturing the user experience, it provides a detailed assessment of the building energy performance. Measurement of in-use performance is essential when aiming to narrow the recurring performance gap. As in urban-scale evaluations, monitoring and reporting the in-use performance of dwellings is rarely conducted. It is not mandatory under current regulations, while its many benefits for building stakeholders can be outweighed by concerns such as high costs and possible exposure of poor performance (Leaman, Stevenson and Bordass, 2010). The assessment typically involves the use of multiple techniques, gathering qualitative and quantitative data, which can be time consuming and requires interdisciplinary knowledge. Due to the multitude of variables which can hinder performance, a study can take a *drill down* approach to be more effective, taking a deeper assessment into certain aspects of interest (Leaman, Stevenson and Bordass, 2010).

Over the years, the industry has started to recognise the benefits of the BPE in delivering buildings which perform as expected (UBT and BSRIA, 2009). In the last decade, more attention is being given to improving performance of the domestic sector, with the development of first guides about the assessment process (TSB, 2012; BSRIA, 2016). In order to provide much needed consistency in the BPE method, a British Standard for BPE is expected to be delivered in 2022 (BSI, 2022).

3.2.3. BPE Data Collection Methods

BPE methodology can capture different project delivery phases, depending on the purpose of the study, and when the study enters the project delivery process. Key building assessment elements and performance metrics are presented in Table 3.

	Study element	Performance metrics
As-built performance	Building fabric thermal performance	Airtightness
		Heat loss
		Thermal transmittance of measured unit
		Moisture content in measured material
	Services and systems performance	Heating systems
		Ventilation systems
In-use performance	Energy performance	Energy consumption / generation and GHG implications
	Energy end uses	Water consuming appliances
		Heating and hot water
		Cooling
		Ventilation systems
		Electricity consuming appliances
	Indoor environment	Thermal environment Heat
		Indoor air quality (IAQ)
	Resident experience / perception	Long-range resident perception
		Time of evaluation resident perception and environmental relationship

Table 3 Key performance metrics used in BPE studies. Source: State of the Nation Review (Gupta and Gregg, 2020).

As-built Performance Assessment

The as-built performance assessment is mostly conducted at the end of the construction stage and before building occupation, aiming to evaluate the building fabric and energy systems. Common building fabric testing techniques used in BPE studies are the airtightness test, thermographic survey, fabric U-value test, co-heating and various qualitative observations.

Airtightness measures the rate of air infiltration through the whole building fabric. Type-testing is mandatory for new dwellings in England and Wales upon whole building completion, for proving compliance with the airtightness level limit (10 $m^3/hr/m^2$@50Pa, which is set by the 2006 Building Regulations (ODPM, 2006).

The thermographic survey is a qualitative visual assessment based on thermal camera images. The survey can help in the detection of possible fabric efficiency issues such as thermal bridges, discontinuity of insulation, air leakage paths, moisture and damp surfaces.

U-value ($W/m^2.K$) test measures the heat transfer through the key fabric elements, typically the external wall, floor and ceiling. The test results are compared to the designed thermal specifications of the installed fabric materials. Using different methods (Butler and Dengel, 2013), the co-heating test aims to calculate the rate of heat loss across the whole building, including building fabric and ventilation losses (Wingfield *et al.*, 2010).

An assessment of the installed ventilation, heating and renewable energy systems aims to ensure that the energy systems are operating effectively (TSB, 2012). This can include energy monitoring of the system's operation and verifying if the installation and commissioning were done in accordance with related standards and guidelines.

In-use Performance Assessment

The post-occupancy (also called in-use) assessment in new dwellings is usually conducted at least one year after the occupants have moved in. This helps avoid the impact of possible teething problems on dwelling operational performance. The assessment can capture qualitative and qualitative data. BSRIA (2016) distinguishes the collection of *soft* data based on the user feedback the *hard* data based on the measurements of energy and environmental performance.

Practice has shown that the use of survey questionnaires seem to be more practical and cost effective compared to other POE techniques such as semi-structured interviews, occupant diaries or focus groups (Leaman, 2011). The increased use of POE and BPE methods led to the development of standardised questionnaires such as the *Building Use Studies* (BUS) (Leaman, 2011). Using multiple variables mainly based on Likert scale questions, the BUS method can effectively gather occupant feedback about air temperatures, ventilation, lighting, noise, control of heating and cooling and other important aspects of the indoor environmental conditions. Integrating the BUS into the Government-backed, *Building Performance Evaluation Programme* (TSB, 2012), led to building a user feedback database, against which the results of future studies can be benchmarked.

Monitoring can include measurement of water and energy performance and different indoor environmental parameters which directly impact the wellbeing and comfort of occupants. Depending on the purpose of the study, data logging processes can vary in regard to the conditions measured (temperatures (°C), relative humidity (RH) etc.), water and energy data type (heat use, electricity generation etc.), logging frequencies (1 second and above) and the length of the monitoring process (from on-spot measurements to on-going monitoring). To reduce occupant disturbance, ongoing monitoring is typically conducted by installing remote data logging equipment, which allows off-site data assessment and analysis. To better understand monitoring results, data can be assessed in relation to occupant feedback about indoor conditions, energy use behaviours, dwelling handover, occupancy and dwelling characteristics. Key challenges of the monitoring process include gaining access to the property and data loss caused by malfunctioning, lost or poorly installed logging equipment (BSRIA, 2016).

Gaining access to the dwellings in the focus of the study can be challenging, and often leads to lower than expected response rates, possible communication issues with the occupants and drop out of participants. To overcome this, disturbing users should be minimised (Leaman, Stevenson and Bordass, 2010), and studies should aim for large sample sizes (BSRIA, 2016). Studies can also face challenges when conducting monitoring and analysis of energy performance, mostly related to the design, installation and management of the monitoring system. Common reported issues include incorrect labelling of meters; unreliable meters; communication issues between meters and data storing systems; and the lack of contextual data needed to explain the results (Gupta and Gregg, 2020; LETI, 2020). This can result in a need for labour intensive data cleaning and analysis, data loss and poor data quality.

3.2.4. Life-cycle Assessments

ISO (2006) describes Life Cycle Assessment (LCA) as an accounting method for addressing various quantifiable environmental impacts of an activity, processes or products, with the capacity to provide assessment through the whole life cycle (from the cradle to the grave).

In the building sector, LCA is commonly applied to assist the decision making process for identifying environmentally preferred products, and optimization of project delivery processes. It can be also used for exercising impact of different design scenarios or setting environmental targets. Building-based LCA studies tend to capture impacts of whole buildings (Scheuer, Keoleian and Reppe, 2003; Basbagill *et al.*, 2013) or building elements (Papadopoulos and Giama, 2007) and materials (Harris, 1999). Lotteau *et al.* (2015) reviewed 21 LCA case studies from 14 papers focused on residential and mixed-use neighbourhoods. The studies aimed to assist in the decision-making process or to generate knowledge for urban policy making, mainly focusing on energy and GHG impacts. Examples include studying existing eco-districts to identify best practices for future reference (Gregory and Bruno, 2010) or energy intensities of neighbourhoods with different building densities (Norman, MacLean and Kennedy, 2006; Nichols and Kockelman, 2014).

Neighbourhood-scale LCA can be limited by the lack of site-specific data and issues related to temporal aspects of the LCA study (Lotteau *et al.*, 2015). To achieve higher accuracy, technical design documents and building energy modelling results can be used. Chau, Leung and Ng (2015) noted that while solely focusing on environmental impacts, the LCA approach fails to capture social aspects, which can lead to negative effects on human health and wellbeing (Jönsson, 2000; Hellweg *et al.*, 2009). Due to the complexity and its wide scope, LCA studies can also be considered costly and time consuming (Khasreen, Banfill and Menzies, 2009).

3.2.5. Urban Metabolism

Urban Metabolism can be described as "…*inflows of material and energy resources, the outflows of wastes and emissions and the retention of materials as stock in the built* *environment and infrastructure"* (Clift *et al.*, 2015, p. 4). The assessment is generally broad, aiming to measure all complex processes in an urban system in relation to all three aspects of sustainability (Kennedy, Cuddihy and Engel-Yan, 2007).

Urban Metabolism tends to be used for assessing ecological impacts of cities (Barrett *et al.*, 2002). Hence, studies of smaller urban scales are less common. Assessments seem to favour the environmental aspect of sustainability. For instance, Oliver-Solà *et al.* (2007) studied the energy metabolism of an urban park. Two studies compared the metabolic differences between different case study neighbourhoods. Codoban and Kennedy (2008) was interested in the flows of energy, water, food and transportation. Hall (2011) estimated the biological (photosynthesis), industrial (home and car energy usage), and socio-economic (unemployment, education, income) metabolic profile of the neighbourhoods.

Similar to the LCA studies, the key limitation of Urban Metabolism studies is their lack of site-specific data, which results in a reduced accuracy of the results. The mentioned studies estimated the performance by supplementing the available national and municipal statistics with field observations and measurements. The statistical data was also not always sufficiently granulated to show variation in metabolism results between neighbourhoods.

3.2.6. Footprinting

Ecological Footprint was conceived in 1990 by Wackernagel and Rees. According to the Global Footprint Network website (2017) this approach measures both the demand side: "*… the ecological assets that a given population requires to produce the natural resources it consumes… and to absorb its waste*" and the bio-capacity as the supply side or: "*…the productivity of its ecological asset …*". The main advantages of the Ecological Footprint method are thought to be the aggregation of a population's ecological impact into a single unit of land area, illustrating a sense of over-consumption, and communicating the message to the wider public (Wiedmann and Barrett, 2010). However, the method received a fair amount of academic criticism (Galli *et al.*, 2016), questioning its validity for the development of sustainability polices (Blomqvist *et al.*, 2013).

Ecological Footprint is predominantly used for visualising the impact of populations, on the scale of nations (Lenzen *et al.*, 2007), municipalities (Wilson and Grant, 2009) and cities (Barrett *et al.*, 2002). Studies assessing smaller spatial scopes, such as developments and settlements, are less common. For instance, Kuzyk (2012) compared the estimated energy consumption and material use in two case study homes, differentiated by age and urban locations. As another example, Li *et al*. (2010) adapted the environmental (eco)-efficacy (EE) concept (WBCSD, 2000), to estimate the resource use and waste production of a case study residential development. Similar to the previously mentioned approaches, use of top-down statistical data can lead to the use of significant assumptions (Wilson and Grant, 2009), and reduction of the study's scope (Li *et al.*, 2010).

Carbon Footprint assessment was widely popularised in the recent decades, lacking a clear definition in the literature (Minx *et al.*, 2009). Wiedmann and Minx (2008, p. 4) defined Carbon Footprint as "*... a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*". Similarly to the aforementioned methods, carbon footprinting at the urban-scale has attracted less academic attention (Peters, 2010). Carbon Footprint assessments have been typically used to study impacts of nations (Druckman and Jackson, 2010), municipalities (Petsch *et al.*, 2012), cities (Jones and Kammen, 2011), in comparisons between urban and rural areas (Heinonen and Junnila, 2011), different socio-economic population groups and in geographical mapping of household intensities (Petsch *et al.*, 2012; Minx *et al.*, 2013). Such studies can use different input-output analysis methods and household consumption data (Kok, Benders and Moll, 2006).

3.2.7. Bottom-up Data Collection Approaches

In order to understand household footprints at finer urban scales such as neighbourhoods, it is essential to study the links between the local infrastructure and lifestyles (Minx *et al.*, 2013). Site-specific data can be more effectively captured using different bottom-up data collection approaches, compared to using national and local statistics. Collecting household responses can provide more insight about the household profile, environmental behaviours and their satisfaction and experience with the surrounding environment: design features, on-site infrastructure, technologies and amenities. Responses are typically collected by conducting questionnaire surveys, focus groups and household interviews.

Household responses can be used to estimate their footprints. Various footprinting calculator tools have been developed over the past two decades, like the *REAP Petite* (SEI, 2017) for UK households. Easily accessible online, these tools simplify the footprinting calculation process, allow comparison between different households and communities, and are thought to increase consumer awareness about the environmental impacts of products (Weidema *et al.*, 2008). The calculation can be based on household responses about dwelling characteristics and annual energy use, household profile and expenditure, transportation and food behaviours. Output inconsistency is thought to be one of the key limitations of footprinting tools, as they can be based on different databases and estimates (Padgett *et al.*, 2008).

Gathering reported household environmental behaviours is valuable. It can indicate the sustainability potentials of eco-villages (Tinsley and George, 2006) and eco-housing developments (Williams, Dair and Lindsay, 2008; Bioregional, 2009; Quilgars *et al.*, 2019). To detect potential behavioural change, collected responses can be compared to responses from conventional households (Quilgars *et al.*, 2019), located in adjacent neighbourhoods (Bioregional, 2009), to national statistics (Williams, Dair and Lindsay, 2008) or to behaviours in former accommodation (Flynn *et al.*, 2016). Studies focused on the effects of different sustainable measures in existing urban areas can use household responses to identify the effectiveness of the measures (Davidson, Theobald and Walker, 2011), and behavioural change opportunities (Alexander, Hope and Degg, 2007; Haq, Cambridge and Owen, 2011).

Some performance studies were designed to capture an even broader number of environmental aspects, including, for instance, the carbon balance of soil and vegetation (Lomas *et al.*, 2010) or have assessed social aspects of sustainability (Quilgars *et al.*, 2019). Assessing resident experience and other social aspects in eco-development is often side-lined by environmental aspects. Yet it is considered essential for understanding personal factors that shape consumption (Moloney, Horne and Fien, 2010) and whether the residents have accepted the provided sustainability measures of dwellings (Butler, 2004; Freytag, Gössling and Mössner, 2014). Methods such as *New Ecological Paradigm* can be used to analyse environmental attitude of surveyed residents using 15 questions based on five-point Likert scale. A resulting score of 45 indicates neutral environmental attitude, while the higher and lower scores indicate positive and negative attitude, respectively (Dunlap *et al.*, 2000).

Using household responses in research is associated with different limitations (Wilson and Grant, 2009). To mention a few, voluntary participation (self-selection) can result with a more eco-minded household sample (West *et al.*, 2015). Household responses can also be biased, due to social desirability and other social factors (Gatersleben, Steg and Vlek, 2002). Collecting responses in new developments, soon after families have moved in, can result in an inflated household expenditure and associated emissions, due to furnishing activities (Quilgars *et al.*, 2015). Studies have also demonstrated that it can be challenging to acquire data such as energy bills (Haq, Cambridge and Owen, 2011) and dietary habits (Bioregional, 2009). Lastly, approaching residents by surveys and other methods can be time-consuming, costly and face issues with accessing households. Acquiring sufficiently large participant sample is challenging. Good recruitment strategies include approaching community groups (Haq, Cambridge and Owen, 2013) and resident representatives (Davidson, Theobald and Walker, 2011).

For evaluating household waste, weight-based monitoring and collecting household responses are thought to be the most valuable data collection methods (Read, Gregory and Phillips, 2009). Household responses are commonly used to gain insight into the perceived waste behaviour, awareness and attitudes (Giordano *et al.*, 2018). Weight-based monitoring conducted over consecutive years (limiting seasonal effects) can offer more robust rates of recycled waste (Parfitt, 2002). However, measuring waste arisings in specific developments is challenging. It requires monitoring and evaluation plan developed with the local authority, resources and weighing equipment (WRAP, 2018).

3.3. Findings of Evaluation Studies

This section presents key findings of in-use performance evaluations of advanced housing developments in regard to energy, carbon, ventilation, overheating and household environmental behaviours.

3.3.1. Energy and Carbon Performance

The performance gap in new housing (section 2.2.4), makes achieving the ambitious net zero carbon performance during in-use even more challenging. Evaluations of case study dwellings aiming for the weakened zero carbon standard (Gupta and Kapsali, 2014; Sodagar and Starkey, 2016) and true zero carbon (Ridley *et al.*, 2014), showed that the carbon target was not achieved, due to increased energy use. Similarly, net zero energy target was not achieved in housing development case studies in the UK (Young, 2015), Australia (Berry *et al.*, 2014) and in two-thirds of dwellings in a US study (Thomas and Duffy, 2013). The Passivhaus standard seems to quite reliable in meeting the space heating target (Mitchell and Natarajan, 2020), and in delivering low energy homes (Mahdavi and Doppelbauer, 2010; Ridley *et al.*, 2013; Mutani *et al.*, 2017).

Due to occupant factors, studies have shown that electricity use differed from 1.9 (Sodagar and Starkey, 2016) to five times (Lee, Whaley and Saman, 2014). Heating use differed about three times in dwellings with equivalent occupancy (Gill *et al.*, 2011) and same typology (Gram-Hanssen, 2010). Evaluating larger housing developments is beneficial for demonstrating whether the performance target is achieved at the development level, rather than by individual dwellings. However, larger dwelling sample makes collecting the household profile and other contextual data more challenging, which can limit gaining a deeper understanding of performance results.

Larger zero carbon housing developments have being delivered internationally, using different design approaches adapted to local contexts (NHBC Foundation, 2009; Williams, 2012). However, reports on their actual performance were found only for a small number of UK developments, briefly presented in Table 4; Birchway Eco Community (SCI, 2013), Hanham Hall (BSRIA, 2015), One Brighton (Lowe and Altamirano, 2014), BedZED (Young, 2015), Sinclair Meadows Carbon Negative Community Village (NEF, 2014) and Lancaster Cohousing (Wrigley, no date; Ecoarc, 2013). As the Lancaster Cohousing project seems to lack a more detailed energy performance report, a single Welsh Passivhaus dwelling aiming for true zero carbon was added to showcase this design approach (Ridley *et al.*, 2014).

Study	Project name	Completion year and size	Design target and key specifications	Actual performance findings
SCI (SCI, 2013)	Birchway Eco Community	2009 24 flats	Zero carbon-regulated energy Biomass community heating PV 0.9 kWp/unit, MVHR 6 $m^3/hr/m^2$@50Pa	Procurement, operation and maintenance issues with the heating system. Use of backup oil boilers and electric heaters during the initial two years. MVHR issues.
BSRIA (BSRIA, 2015)	Hanham Hall	2015 185 flats and houses	Zero carbon -regulated energy Gas boiler PV 1.5 kWp/unit, MVHR 1.5 $m^3/hr/m^2$@50Pa	Project design switched from true zero to zero carbon and provision of individual gas boilers. Brief interim report informs that energy use is in line with design projections.
Lowe and Altamirano (Lowe and Altamirano, 2014)	One Brighton	2010 172 flats	Zero carbon -offsetting Biomass community heating PV 0.1 kWp/unit, MVHR 5 $m^3/hr/m^2$@50Pa	High distribution loss of the heating system resulted in 10 times higher carbon intensity of heat, and reduced usage of received heat. High MVHR electricity use due to issues.
Young (Young, 2015)	BedZED	2002 100 flats	Zero energy Biomass CHP 1.9 kWp/unit, Natural v. 3 $m^3/hr/m^2$@50Pa	Passive design approach. Ongoing issues with biomass CHP led to replacing the system with a community gas boiler and increased carbon intensity of heat. High heat usage.
NEF (NEF, 2014)	Sinclair Meadows	2012 21 flats and houses	Carbon negative Biomass community heating PV 4 kWp/unit, MVHR 2.5 $m^3/hr/m^2$@50Pa	Very low overall efficiency of the heating system (~20%) due to boiler failure causing seven times higher carbon intensity of heat. Fabric first approach resulted in low space heating use.
Wrigley (Wrigley, no date) Ecoarc (Ecoarc, 2013)	Lancaster Cohousing	2012 41 houses	True zero carbon Passivhaus Biomass community heating PV 2.2 kWp/unit, 160kW hydro, 0.6 ach	Credible performance report lacking. Community heating and hydro turbine performance not disclosed. Low electricity usage probably due to cohousing lifestyle.
Ridley et al. (Ridley *et al.*, 2014)	Welsh Passivhaus	2010 1 house	True zero carbon Passivhaus, Gas boiler PV 4.7 kWp 0.6 ach	Lack of energy efficient appliances and lights and occupant factors resulted in high electricity usage. True zero carbon target missed.

Table 4 Basic project information and key performance findings of zero carbon/energy housing developments in the UK.

The comparative analysis of designs indicated that reaching true zero carbon in housing developments demanded highly efficient LZC design measures. Taking the 'fabric first' approach, designed fabric efficiency was close to or at Passivhaus levels. The use of mechanical ventilation heat recovery (MVHR) systems seems to be widespread, as it is considered essential for delivering adequate ventilation levels in very airtight dwellings. The majority of developments relied on community heating systems, offering advanced energy efficiencies and a very low carbon intensity of heat. Despite concerns regarding its reliability (UKGBC, 2008), biomass fuel seems to be favoured. Net zero design also required large PV systems, above 4 kWp per dwelling. Alternative net zero design pathways combined Passivhaus level of fabric efficiency with a gas boiler in the Welsh Passivhaus, and an off-site measure of purchasing green electricity in bulk in One Brighton development. In the recently planned Salt Cross Village and Springfield Meadows developments, reaching net zero on site using electric heating (heat pumps) demanded even larger PV sizes, close to 5 kWp per dwelling (OCC, University of Oxford and Energy, 2020).

Although some developments from the Table 4 achieved their energy use targets, zero carbon performance was recurrently not achieved at the development level. In four of seven developments, operational issues of the community heating system resulted in significantly (up to 10 times) higher carbon intensity of heat. This underperformance could be partly attributed to the modest scale of the developments (20-200 dwellings) which could have led to insufficient heat load (DECC, 2013b). In some cases, recurring operational issues led to the replacement of the installed biomass heating systems with fossil-fuelled heating systems (Bioregional, 2009; SCI, 2013). Evaluations of other developments which used gas powered CHP community heating (UCL Energy Institute and Crest Nicholson, 2014) and heat pumps (Bell *et al.*, 2010) also showed significant underperformance of the heating systems. Despite not achieving their carbon targets, the developments aiming for true zero carbon emitted substantially less carbon (< 10 $kgCO_2/m^2/year$) compared to developments aiming for the weakened zero carbon standard (20 - 40 kg $CO_2/m^2/year$), using SAP 2005 and 2009 fuel carbon factors.

3.3.2. Ventilation Performance

Building evaluations commonly use measured CO_2 concentrations as a proxy of indoor air quality (Ramalho *et al.*, 2015). Keeping the concentrations under a 1,000 ppm (parts per million) threshold is commonly advised, in order to avoid possible reduction in cognitive performance, respiratory problems in children and other health risks (Azuma *et al.*, 2018). Special attention should be given to indoor air quality in bedrooms, as the risk of exposure to high CO_2 concentrations is six times higher there compared to living rooms (Laverge, Delghust and Janssens, 2015).

Comparison of dwelling indoor air quality studies is difficult due to the lack of standardization in the way data is collected and reported (Aganovic *et al.*, 2017). Results can refer to different time periods (all hours, occupied hours), spaces (all habitable space, particular rooms) and concentration thresholds (1,000 ppm, 1200 ppm etc.). In addition, some studies shared little information about occupant behaviour, dwelling characteristics and other contextual factors which would help in understanding the results. Given these limitations, inadequate ventilation levels have been repeatedly reported across the housing stock. This is worrying, considering that new dwellings are becoming increasingly airtight.

Provision of mechanical ventilation is suggested in dwellings with airtightness levels between 3 and 4 $m^3/hr/m^2$@50Pa, or less (CLG, 2010b; Howieson, Sharpe and Farren, 2014). Mechanical ventilation seems to provide more stable CO_2 levels compared to naturally ventilated dwellings, which in the latter strategy depend on occupant behaviour (Van Holsteijn and Li, 2014; Van Holsteijn et al., 2016). MVHR systems seem to provide lower average and peak CO_2 levels compared to other mechanical ventilation systems (Sharpe *et al.*, 2016).

A study of 39 naturally ventilated dwelling case studies in Scotland found that no dwelling provided adequate ventilation rates (Sharpe *et al.*, 2015). Such poor results can be associated with poor ventilation design, insufficient trickle vent areas, too small door undercut and the lack of cross ventilation in flats (CLG, 2010b). A study of 20 airtight dwellings using natural, MEV and MVHR ventilation strategies measured inadequate ventilation levels during the night across the sample (McGill *et al.*, 2015). Insufficient air flow rates were also found in about half of case study dwellings with MVHR systems (Sharpe *et al.*, 2016) and in two-thirds of dwellings with MEV systems (Balvers *et al.*, 2012). CO_2 concentrations above 1,000 ppm were predominant during the occupancy hours in case study dwellings with MVHR systems (Gupta and Kapsali, 2015), and at least 40% of the time in dwellings with different ventilation strategies (Staepels *et al.*, 2013).

Operational issues with mechanical ventilation are associated with all system delivery stages: design, installation, commissioning, maintenance and use (Balvers *et al.*, 2012; NEF, 2015). Increased noise or complex controls can result in improper usage and reliance on natural ventilation strategies (Sharpe *et al.*, 2016). Ventilation design can also be based on unrealistic assumptions rather than real world situations where air flow is often obstructed by doors and in other ways (Sharpe *et al.*, 2015). A more widespread monitoring of the actual ventilation performance in dwellings is required (Van Holsteijn and Li, 2014). Demand-controlled and other innovative ventilation systems show some potential in reducing energy use and in increasing indoor air quality (Pollet, Vens and Losfeld, 2013; Guyot, Sherman and Walker, 2018; De Maré *et al.*, 2019).

3.3.3. Occurrence of Overheating

Difficulty to keep one or more rooms cool also seems to be a widespread issue, reported across the housing stock (DECC and BRE, 2015). Climate and dwelling characteristics are regarded as important factors of overheating. Risk of overheating across England in the future is significant, especially in the South (MHCLG, 2012; Liu and Coley, 2015). Dwellings which are more prone to overheating tend to; be small, highly insulated, lack shading measures, achieve poor cross ventilation (NHBC and ZCH, 2012); be built with light construction systems (Lomas and Kane, 2013; McGill *et al.*, 2017) and; have rooms oriented to the west, east and south (Gupta, Gregg and Bruce-Konuah, 2017).

Using the static overheating criterion (see section 2.2.5) shows significantly higher occurrence of overheating in dwelling case studies, compared to using the more stringent dynamic criterion (Gupta and Kapsali, 2015; Gupta, Gregg and Bruce-Konuah, 2017; Gupta, Gregg and Irving, 2019). Using the static criterion, overheating in bedrooms seems to be commonly detected, while overheating in living rooms was less frequent. In different studies of low carbon dwellings, overheating was reported in all bedrooms and the majority of living rooms (Gupta and Kapsali, 2015); in all bedrooms, but not the living rooms (Gupta, Gregg and Bruce-Konuah, 2017); in about two-thirds of bedrooms and a third of living rooms (McGill *et al.*, 2017) and lastly; in 71% of bedrooms and 23% of living rooms (Young, 2015). Similar rates of overheating in living rooms and bedrooms were also found in studies of conventional dwellings (Lomas and Kane, 2013; Gupta, Gregg and Irving, 2019).

3.3.4. Environmental Behaviours

As mentioned earlier, eco-housing developments tend to be designed with the intent to enable its residents to live in a more sustainable way. Consequently, new developments can be associated with various narratives generated by design teams and media (Freytag, Gössling and Mössner, 2014), promoting them as places of sustainable living[8] [9]. However, the significance of such developments really depends on the extent to which this intent has been achieved during the occupation (in-use) stage (Joss, 2011).

The actual household lifestyles are rarely evaluated against the design aspirations in new developments, due to the lack of policy drivers and other challenges (see section 3.2). A small number of studies that evaluated actual environmental behaviours, and the impact of the implemented design measures in eco-housing developments, are briefly presented in Table 5. The selection captured developments and neighbourhoods, excluding evaluations of city-scale eco-developments, such as Tianjin in China (Flynn *et al.*, 2016). Evidence from the selected studies should be interpreted with caution, due to the possible biases associated with the self-selection of the participants, social desirability, stakeholder's involvement in the study and non-academic sources (Gatersleben, Steg and Vlek, 2002; Femenias, Kadefors and Eden, 2009).

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[8] https://www.hill.co.uk/about-hill/sustainability/knights-park-cambridge

[9] https://www.bioregional.com/projects-and-services/case-studies/springfield-meadows-zero-carbon-homes-immersed-in-nature

Study	Development name, location and size	Key findings
(Bioregional, 2009)	BedZED UK 100 dwellings	About 10% lower ecological footprint due to more energy-efficient dwellings. Compared to those in conventional housing, residents seem to drive and compost less, and grow less food. Proximity to the subway station and discouragement of on-site parking probably contributed to the reduced car use.
(Williams, Dair and Lindsay, 2008)	13 case studies UK 27–303 dwellings	Responses suggested that energy- and water-saving behaviours were more frequent. However, households owned more cars and composted less compared to national averages.
(Quilgars *et al.*, 2019)	Derwenthorpe UK 500 dwellings	About 10% lower carbon footprint due to more energy-efficient dwellings. Higher car usage was associated with the end-of-town location of the site. Waste facilities appear insufficient. Provided measures had a marginal impact on food behaviours.
(Amarach Research, 2009; Hunt *et al.*, 2012)	Adamstown Ireland 1126 dwellings	Many design measures commonly found in eco-developments were lacking. Resident dissatisfaction with the lack of basic on-site facilities. Two-thirds of residents used a car for commuting, despite the good public transportation links in the vicinity.
(Nobis, 2003; Freytag, Gössling and Mössner, 2014)	Vauban Germany 2000 dwellings	Parking being limited to only one communal zone and multiple public transportation options contributed to the significant increase in car-free households and bicycle use. Other on-site measures were welcomed, but residents continued with fairly common everyday practices.
(Green, 2006; Vestbro, 2007; Pandis Iverot and Brandt, 2011; Mahzouni, 2015; Rutherford, 2020)	Hammarby Sweden 11,000 dwellings	Multiple on-site amenities and public transportation options contributed to achieving the 20% car-use-rate target. Households opposed proposals for limited parking and did not behave more pro-environmentally in regard to waste, water and dwelling energy use compared to households in other areas of the city.

Table 5 An overview of key findings about actual environmental behaviours and the impact of the implemented measures in the evaluated eco-housing development case studies.

Differences in local contexts, scope and research methods made it difficult to effectively compare the findings of the presented studies. Although some developments achieved the set targets for car-use reduction, most of the studies reported that the actual household behaviours were not more sustainable, as anticipated.

Despite a range of provided sustainability measures, households in Vauban eco-neighbourhood seem to have carried on with common everyday practices. Similarly, households living in Hammarby appreciated its environmental credentials, but were not keen to sacrifice their personal comfort to help achieve the environmental objectives of the development. Households opposed proposals for limiting the available car parking spaces, and did not behave more pro-environmentally in regard to waste, water and dwelling energy use, compared to households living in other areas of the city. Households in 13 UK eco-housing developments seem to act more pro-environmentally compared to the wider population in regard to water and energy efficiency, and less environmentally in behaviours such as encouraging wildlife, car use and waste composting. Studies of BedZED and Derwenthorpe eco-housing developments suggested that the actual household lifestyles were far from the aspired sustainability, achieving only about 10% lower footprints in comparison to households in conventional homes. Importantly, this slight reduction in footprints was mainly attributed to the intrinsic dwelling energy efficiency measures, and not to significant changes in household behaviours.

The lack of lifestyle changes in Vauban and Hammarby developments was attributed to the top-down planning approach, which excluded residents from the planning process, assuming that the provided design measures would be accepted and used as envisioned. Such over-optimistic assumptions in eco-developments are related to physical determinism (Sharifi, 2016). In the BedZED and Derwenthorpe studies, it was argued that a more significant reduction in household footprints would require broader sustainability measures, which would reduce the environmental impacts of household behaviours occurring beyond the small sites of eco-developments. In Derwenthorpe, limited behavioural change was also attributed to the selection of MVHR, energy efficient appliances, outside drying facilities and other measures which were unattractive to households, and/or were not used as intended.

Intentional, eco-minded housing communities achieved significantly lower household footprints (Daly, 2017), compared to developer-led eco-housing developments. This finding supports the argument that without a fundamental social change, delivering more sustainable housing will remain challenging (Smith, 2007). Otherwise, novel technologies and designs can be imposed on people who just transfer old consumptive lifestyles to the new environment (Newman, 2010). In addition, intrinsic measures such as dwelling energy efficiency can be associated with having a sustainable lifestyle (Quilgars *et al.*, 2015), which could make households feel absolved of acting pro-environmentally (Marres, 2008).

Transportation behaviours

The recurring approach to reducing car use in eco-housing developments is based on the provision of infrastructure which supports modal shift to more eco-friendly transportation alternatives. Developments can offer public transportation links to local urban centres, basic on-site amenities, car clubs, bicycle facilities, and limited number of available car parking spaces.

In new settlements, reduced car use was attributed to the high quality of public transportation and the proximity to urban centres (Cervero, 1995; Hale, 2014). Increased car use in was related to the edge-of-town location with weak public transportation links in Derwenthorpe development, and the lack of on-site amenities in Adamstown. In contrast, car-free neighbourhood design in Vauban, proximity to multiple public transportation options in Hammarby, and the subway network in BedZED, contributed to significantly reduced car use. Expectedly, strategies which discourage on-site parking were generally not well accepted by residents. High charges for a small number of parking spaces in BedZED led to parking off-site. In Derwenthorpe, lack of parking spaces led to ongoing conflicts between neighbours. In the same two developments, uptake of the car club service was low. Car clubs are recommended for more high density, mixed development areas, with good public transport links, limited parking (Bonsall, 2002) and low vehicle ownership (TRB, 2005).

Food and waste behaviours

Sustainability design of eco-housing developments rarely includes measures which improve access to low impact foods, and reduce household food footprints. In high-density developments such as BedZED, on-site food growing potentials were diminished due to space constraints. In the same development, increased purchasing of organic food and reduced intake of meat were attributed to more eco-minded households, rather than to some particular design measure. Expectedly, households associated their gardens with socialising, rather than with significant production of food. The impact of a community garden and a pop-up shop on food behaviours in Derwenthorpe development was also considered marginal.

Impact of the provided waste facilities on household waste behaviours in eco-housing developments is not well understood. Actual waste arisings are normally not monitored at such small spatial scales, due to methodological challenges (see section 3.2.7.). Based on resident responses, the study that captured 13 UK eco-housing developments showed that households recycled and composted even less frequently compared to national averages (Williams, Dair and Lindsay, 2008).

Combining informational measures and new waste facilities, Government-backed interventions had mixed success in increasing household recycling rates in existing urban areas (Phillips *et al.*, 2011; WRAP, 2018). Good results have been reported in a pay-as-you-throw waste program (Van Der Werf *et al.*, 2020), and when supporting community-led measures in rural areas (Maycox, 2003), cities (Barton, 2000), and in cohousing case studies (Hendrickson and Wittman, 2010). Findings of these studies highlighted the important role of local authorities, community governance and social capital in waste behaviours.

3.4. Summary

This chapter presented an overview of methodologies that can be used in evaluations of housing developments, and outlined key findings from the available evaluations of zero carbon and eco-housing developments.

Evaluations quantify the performance that was achieved over a certain time period. The actual performance can be compared to the design intent and performance of similar developments. Evaluations can vary in spatial scope, sustainability criteria, stage of assessment, research approach and type of data collected. Performance evaluations tend to be case study based. This allows studying complex and contextualised phenomena in greater depth and from multiple perspectives. Evaluations of eco-housing developments are scarce but valuable, as they can show their effectiveness in reducing environmental impacts, and share the lessons learned.

Building Performance Evaluation was identified as the most prominent methodology for assessing energy, carbon and indoor environmental performance at the building level. It aims to systematically evaluate the whole building process in order to detect possible performance issues, identify the causes, propose optimization measures and improve performance. Life Cycle Assessment (LCA), Urban Metabolism and footprinting methodologies can be used to assess the performance at the urban scale. LCA assesses life cycle impacts, Urban Metabolism the material and energy flows, while footprinting estimates the environmental impacts associated with household consumption. These three methodologies are associated with different limitations. For example, difficulties with sourcing site-specific data often has often led to higher inaccuracy of findings. An alternative, bottom-up data collection approach shows some potential in addressing this issue. Collecting resident responses can provide more specific data about the household profile, behaviours and experiences.

Evaluations of large zero carbon housing developments showed that reaching the carbon target was not achieved during building operation. The recurring determining factor of underperformance was the community heating system, resulting in significantly higher carbon intensity of delivered heat. The existing evidence suggests that occurrence of overheating and poor ventilation levels in new dwellings seems to be widespread, especially in bedrooms. Dwellings which are small, highly insulated, lack shading measures, achieve poor cross ventilation and are built with light construction systems tend to be prone to overheating. Issues causing inadequate ventilation levels in dwellings can occur during all stages of the building process: design, installation, commissioning, maintenance and use.

A small number of evaluations of eco-housing developments indicated their limited potential in enabling more sustainable lifestyles. Slight reduction of household footprints in eco-housing developments was caused by the intrinsic efficiency measures, rather than behavioural changes. Households living in eco-housing also seem to be of higher socio-economic class, but not more eco-minded. Findings from intentional housing communities indicate that more significant reductions in footprints might demand social change and more community-based models of housing delivery. Providing good public transportation links and proximity to urban centres seems to be determining factors in reducing car use. The impact of different design measures on waste and food behaviours is still not well understood. Measures such as pop-up shops and community gardens in eco-housing developments seem insufficient. Evaluations of Government-backed waste-reduction initiatives indicated the importance of local authorities and community action in household waste behaviours.

Chapter 4: Methodology

4.1. Introduction

The previous chapters presented the context that shaped the development of the eco-housing, different methodological approaches to evaluating the in-use performance of housing developments and the key results of available evaluation studies. Drawing on these findings, this chapter introduces the case study development's design and the research methodology developed to address the objectives of this thesis. The design concept, environmental features and performance targets of the case study development are contextualised against the characteristics of similar developments. The research approach is elaborated in regard to the research framework, epistemological stance, sustainability criteria of interest, methods and data collection and analysis processes.

4.2. Case study

4.2.1. Overall Design Approach

The case study development is comprised of the initial two phases of a 4-phase urban extension of a town in England. The 4-phase development was envisioned as the first step of a larger master-planned low-density neighbourhood, consisting of ~6,000 dwellings with supporting non-residential buildings.

The two phases in the focus of this study consisted of 157 dwellings, a dwelling converted into a community house for residents, a primary school, a small office building with rental space and a community heating plant. Such scale places it among other eco-housing developments like One Brighton and BedZED. Once all four phases are completed (~400 dwellings) the development will be comparable in scale to Derwenthorpe and Stamford Brook developments. The scale of the four phases was deemed sufficiently large to make the basic on-site facilities and a community heating system viable, and to create new jobs for the households. However, even with the fourth building phase underway at the time of writing this study, the planned grocery shop and a pub were still not provided. Due to its larger scale, the future neighbourhood stemming from the case study development was planned on greenfield land at the edge of town.

The performance evaluation is focused on 157 dwellings of the case study development. When the study commenced, 86 dwellings (Phase 1) had been occupied for two years and 71 dwellings (Phase 2) for one year, or less. In terms of dwelling typology, the assortment of 129 two-storey houses consists of 2- and 3-bed mostly terraced houses and 4- and 5-bed mostly detached houses. 28 Flats (1- and 2-bed) are situated in three-storey blocks of flats. Across the development, dwellings with the same number of beds vary in orientation and in total floor area (TFA). Dwellings are built using a light-weight structural insulated panel (SIPs) system. An example of plans of terraced houses can be seen in Figure 5.

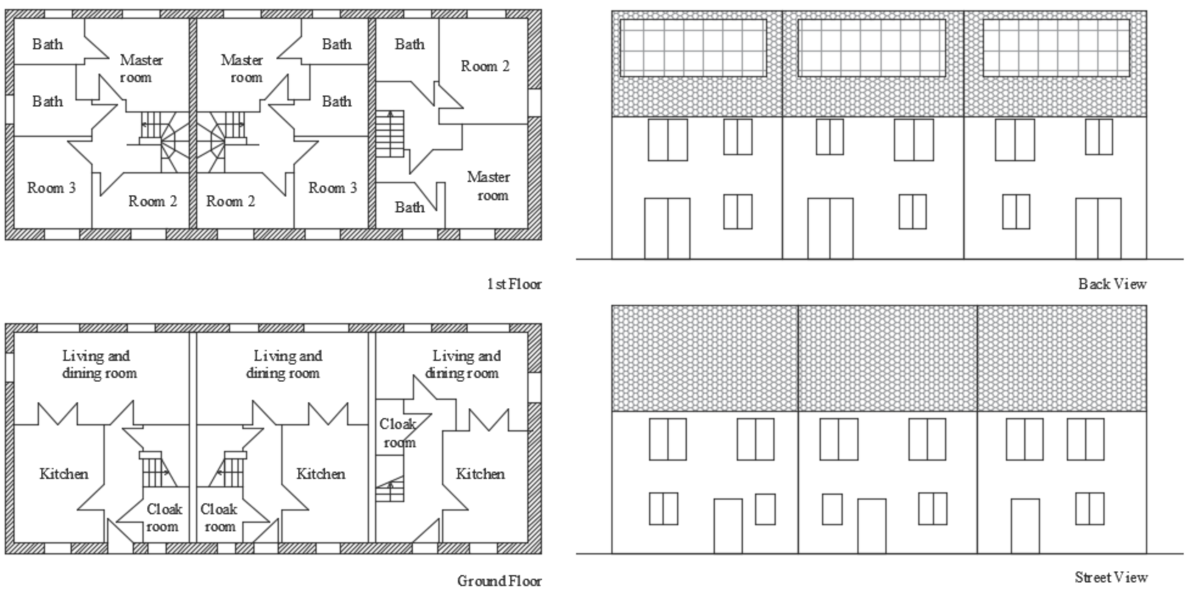

Figure 5 Architectural drawings of a terraced house sample.

Following the requirements of the local planning authority, the neighbourhood was planned in compliance with the ambitious planning policy for eco-towns (DCLG, 2009), which made it unique in the UK. Consequently, the initial 4-phase development was designed to become an exemplar of sustainable housing and achieve a wide range of environmental performance design targets. Table 6 presents the key criteria and design targets against which the actual energy and environmental performance of the case study development will be evaluated.

Criterion	Eco-town requirements	Case study design targets
Carbon and energy	True zero carbon from dwelling energy use at the development level.	True zero carbon, Mean energy use of 75.4 kWh/m2/year energy use per dwelling.
Water	90 litres/person/day (Code of Sustainable Homes Level 5).	80 litres/person/day.
Waste	At least 50% of household waste diverted from landfill and 225kg of residual waste in 2020 by means of re-using, recycling or composting.	80% household waste diverted (recycling/composting) from landfill.
Transportation	50% of trips by non-car means, increase over time to 60%.	45% of trips by non-car means by 2016 and 50% by 2026.
Food	Allow local production of food from community, allotment and or commercial gardens.	0.5ha for allotments, edible landscaping, 30% of food available site sourced within 30 miles.
Wellbeing	Improving health and wellbeing of people, resilient to climate change,	Global warming proofed, achieving good ventilation levels and indoor air quality.

Table 6 Design targets of the eco-town policy and the case study development.

By complying with the eco-town policy, the design of the development appears to capture broader environmental criteria and aims for significantly more stringent performance compared to similar mainstream eco-housing. The design targets in other eco-housing developments can be undisclosed or missing (Slateford Green), follow less stringent design standard like the Code for Sustainable Homes (Derwenthorpe), or have design targets only for energy and/or carbon performance (BedZED, One Brighton), omitting performance aspirations in regard to household environmental behaviours.

The design characteristics of the development were similar to Derwenthorpe, with its semi-rural setting, edge-of-town location, low-density housing and larger spatial scale. This physical context, however, can be associated with certain environmental challenges. Unlike the brownfield and/or urban infill sites selected for BedZED or One Brighton, greenfield development reduces farmland. An edge-of-town location could lead to higher car dependency. Low-density housing appears to suit the morphology of the local town, but it is often associated with urban sprawl. In the development’s design brief it is argued that the sustainability design will outbalance these shortcomings. Potential increase in car use will be tackled by providing new jobs, amenities and green infrastructure. Loss of farmland will be balanced by supporting on-site food growing at a large scale. Lastly, large roof area and green plot due to low density housing will be exploited by maximising rainwater harvesting, solar PV systems and food growing.

In order to meet the design intent, the sustainability design brief proposed combining a wide range of informational and physical design measures. However, similarly to other eco-housing, the suggested informational measures were largely omitted in the actual delivery, relying on energy efficiency, new technologies and green infrastructure.

4.2.2. Dwelling Design and Community Heating

Aiming for the ambitious true zero carbon target placed the case study among the few least carbon-intensive housing developments: Sinclair Meadows, Park Dale, and Lancaster Co-housing. The selected zero carbon design approach was relatively common; combining high energy efficiency, large PV systems and very low carbon intensity of heat from the community heating system.

The key design specifications of the case study development are presented in Table 7. In line with the true zero carbon definition, the 4-phase development was designed to balance annual carbon emissions (from used grid electricity) with energy exports from the on-site solar PV's and the CHP community heating. Design calculations estimated a mean net carbon emission of -0.14 $kgCO_2/m^2$/year per dwelling. This was based on SAP 2009 carbon factors, projected carbon intensity of delivered heat (0.014 $kgCO_2$/kWh), solar generation (807.3 kWh/kWp), PV system size (3.7 kWp), and energy use (75.4 kWh/m^2/year) as a sum of mean electricity usage per dwelling (30.8 kWh/m^2/year) (based on the former APEE standard[10]) and the heat requirement[11] (44.6 kWh/m^2/year). Energy efficient inbuilt lights and white goods were provided in all non-rented dwellings (74% of all case study dwellings).

The community heating system was designed to supply heat to all four building phases, and achieve an overall efficiency of 67%. The plant consists of a CHP engine, thermal storage and supporting gas boilers. A gas-fuelled CHP engine and thermal storage were expected to

[10] UK Energy Saving Trust's Advanced Practice Energy Efficiency (APEE) standard

[11] This is calculated as a sum of the space heating requirement and water heating requirement found in SAP spreadsheets, where the latter is defined as *0.85 x Energy content of hot water + 15% distribution loss* (occurring within the home) but excluding the primary circuit, tank and combi losses occurring within the plant.

deliver 90% of heat, while the remaining 10% would be provided by gas boilers. With the designed supply temperature of 85°C, the system can be regarded as a 3rd generation district heating (Werner, 2017). In the application for low energy dwellings, new 4th generation systems with lower supply temperatures seem to offer higher energy efficiency (Nord *et al.*, 2018).

Unlike in similar net zero carbon developments, fabric efficiency of the case study dwellings was distinctively weaker compared the Passivhaus standard. Designed fabric specifications (as U-values in $W/m^2.K$) were 0.15 for walls, 0.15 for floor, 0.13 for roof and 0.8 for windows, with a targeted air permeability of 3 $m^3/h.m^2$@50Pa. MVHR systems were provided in rented dwellings (26%), while all other dwellings were provided with a continuous mechanical extract ventilation (MEV) system with fans located in wet rooms.

Designed performance per dwelling			**Fabric thermal properties**	
Carbon emissions	-0.14 $kgCO_2/m^2$/year	$W/m^2.K$	Walls	0.15
Solar generation	807.3 kWh/kWp		Floor	0.15
Solar PV system	3.7 kWp		Roof	0.13
Energy use	75.4 kWh/m^2/year		Windows	0.8
Electricity use	30.8 kWh/ m^2/year		Air permeability ($m^3/hr/m^2$@50Pa)	3
Heat demand	44.6 kWh/ m^2/year		Thermal bridging (y-value)	0.04
Energy efficient appliances	In private and shared ownership (74%).		Ventilation system	MEV (74%) MVHR (26%)
Heating system	Community heating for 4 phases; Plant; gas fuelled CHP engine, thermal storage and gas boilers.			

Table 7 Design specifications of the case study development.

Third-party in-situ fabric testing conducted on a small sample of case study dwellings indicated poorer as-built fabric performance compared to the design intent. Compared to the mean result of a large sample of tested low carbon dwellings (Gupta and Gregg, 2020), a 1.2 times mean increase in Heat Loss Coefficient was similar, while a mean increase in as-built U-values of tested external walls (2 times) and ceilings (2.2 times) was more pronounced. The mean airtightness of 3.3 m^3/m^2h@50Pa was close to achieving the design target.

Dwellings were designed to be cool in summer and warm in winter. Hence, computer simulations were conducted to adapt the design of the dwellings to future climate, and develop recommendations (Gupta, Harker and Young, 2013). However, external shading and other suggested measures were not included in the final design.

The water usage design target of 80 litres/day/person was adopted from the highest Level 6 requirement of the Code for Sustainable Homes standard. Water efficiency measures included low flush toilets, aerated taps and shower heads, and rainwater harvesting used for flushing and garden irrigation.

4.2.3. Enabling Environmental Behaviours

Considering the shortcomings of the site's location, achieving the car use target was considered challenging by the design team. Some of the provided measures supporting sustainable transportation were common in eco-housing (bus line, discounted bus tickets, car club), while other were more novel (folding bike rental, electric cars in the car club, home electric car chargers). A designated bus line linking the development with the town's centre was also provided in the Derwenthorpe development, and appears to be necessary for edge-of-town sites. Each household was provided with a home information display named Shimmy, which provided news about bus timetables and car club availability. Electric charges were provided to households which proved ownership of an electric or hybrid vehicle. Unlike in other eco-housing developments which provided no or very limited parking spaces for all households, in the case study development parking space was limited only for households in flats and especially for visitors. The existing road infrastructure offers bicycle lanes separated from the road for only about half of the distance to the town centre, which makes frequent cycling less convenient.

Targeted rate of recycled and composted waste of 80% can be regarded as very ambitious, considering that the average rate in the UK is stagnating around 45% (DEFRA, 2021b). The waste management plan for the development was developed in conjunction with local authorities. Apart from the conventional kerbside bins and communal recycling bins, households were provided with bins fitted in kitchens and garden compost bins. In addition, the proposed informational measures included info-stands about local waste recycling at community events, door-knocking visits and other means of communication with households.

The strategy to reduce household food footprints was based on providing better access to low-impact foods via public edible landscape, large areas for gardening and the food sold in shops. It was aspired that 30% of all the food provided on-site was either organic, sourced locally or from Fairtrade sources. Planned large, vegetated area covering 40% of the site would offer ample space for allocating edible landscape, including 0.5 hectares for community allotments, two community orchards, and a fruit tree in private gardens. In addition, the sustainability brief also proposed cookery classes, edible landscape tours and other informational measures to promote intake of low-impact foods.

4.3. Methodology

4.3.1. Approach to Research Design

A wider application of the zero carbon performance standard has been anticipated for over a decade. However, the conducted literature review suggested that achieving even less ambitious standards was already quite challenging for the industry. Prior to mainstreaming zero carbon dwellings, it is essential to acquire more understanding about how to deliver such advanced performance in larger housing developments and effectively utilize the needed LCZ technologies.

In addition, given the urbanisation trend and the vital role of behavioural change in meeting climate objectives, more empirical evidence about actual behaviours and achieved carbon emission reductions in expanding urban areas is urgently needed. Presently, due to the small number of robust evaluations often focused on particular aspects of performance, the potential of new urban areas in encouraging pro-environmental behaviours is still not well understood.

The aims and objectives of this study were developed as a response to these aforementioned challenges. The study aimed to evaluate the actual environmental performance of a large eco-housing development aiming for true zero carbon, using a more systematic analysis of a broad range of behaviours regarding energy, water, waste, food and transportation.

The choice of the methodological approach and data collection methods used in this study was guided by the study's specific context and findings of the literature review. Study context entails research aims and objectives, available resources for conducting the research (time limitations, access to equipment etc.) and the ability to access accurate performance data. Literature review has provided good insights into the available research methodologies, but also the research approaches used by similar housing performance studies. Evaluation studies of similar case study developments and performance benchmarks are essential to contextualise the results of this study.

This study took the case study approach, focusing on a particular housing development. As presented earlier in section 3.2 of this thesis, in-use performance evaluations of buildings and urban areas tend to be focused on one or a small number of case studies. This approach was found suitable, as the phenomenon of interest is highly contextualised and complex (development performance), and seen as a strong, positive example (an eco-housing exemplar) (Yin, 2012). The case study approach also allows studying the complexities in a greater depth and using a multitude of methods (Flyvbjerg, 2006). It also allows assessing housing performance from multiple of perspectives, which is important given the multi-scalar context (Carr and Affolderbach, 2014). The particular cast study development was chosen for the study due to its ambitious sustainable design targets and the acquired access to the development's design team and to the highly valuable development-wide energy, water and waste data.

In order to achieve the study aim, a pragmatic worldview was taken, based on the case study framework. Chapter 2 demonstrated the dual nature of eco-housing developments, shaped by both technological (energy efficiency, technology, infrastructure etc.) and social systems (household characteristics and behaviours), which are interconnected. It is argued that, from an epistemological perspective, pragmatism could balance the potential conflicts of both technical and social disciplines in studies of building performance (Lowe, Chiu and Oreszczyn, 2018). The pragmatic worldview in research is concerned with usefulness and practicality of new knowledge, rather than with building abstract theories (Bacon, 2012). As such, it supports the use of different methods in order to more effectively investigate a phenomenon and find solutions for problems such as the widespread underperformance of new buildings.

Using mixed methods research is suitable for addressing the socio-technical nature of building and urban performance. Understanding the development performance as complex socio-technical phenomenon. Using mixed methods is advantageous in this specific context. It allows capturing environmental and social aspects of sustainability, gathering empirical evidence from multiple sources, generating qualitative and quantitative data and providing more insights about the links between the performance results and the residents' responses to the provided sustainably measures. Quantitative data can suggest to *what* extent the performance targets were achieved. Qualitative data can cast more light on *why* such performance results were achieved.

The suitability of using different performance evaluation methodologies presented in the literature review for the purposes of this study was carefully examined, considering their advantages and limitations. Summary of the assessment is presented in Table 8.

Advantages	Limitations	Application in the study
Building Performance Evaluation		
Most widely used methodology for assessing building performance. Captures qualitative and qualitative data. Methods are standardized. Offers performance benchmarks for conventional and advanced housing. Allows drill down approach.	Provides most benefits when the performance is assessed during all building stages, not only the in-use stage. Time-intensive. Requires technical expertise, costly equipment and close collaboration with the building delivery team.	Certain in-use data collection methods used: building energy and water monitoring, indoor environmental monitoring, thermographic survey, household questionnaires and semi-structured interviews.
Life cycle assessment		
Shows the impact of buildings more holistically by capturing embodied carbon in addition to operational carbon, which is important in low carbon/energy buildings.	Lack of access to development's cost plan and material data needed for modelling. Time-consuming at neighbourhood scale.	Methodology not used in the study.
Urban Metabolism		
Good potential to generate a more holistic energy profile of the	Lack of site-specific data to generate the full energy profile,	Methodology not used in the study.

Advantages	Limitations	Application in the study
development by capturing inputs and outputs of all materials, stocks and processes.	such as mass of purchased food. Use of assumptions would reduce accuracy of findings.	
Footprinting		
Bottom-up data collection allows estimating site-specific impacts from a wider range of household behaviours, not only dwelling energy use. Ecological Footprinting can be beneficial for illustrating a sense of over-consumption and visualising the impact.	Requires an extensive questionnaire which can reduce residents' response rates and leave little room for additional questions which would benefit the study more. Demands details about flights, goods purchasing and other household behaviours which are not usually affected by the site context and design.	Methodology not used in the study. However, transportation behaviour questions from a standardized questionnaire were adopted to benchmark the results.

Table 8 Examining the potential application of the prominent performance evaluation methodologies for the proposes of this study

Among the examined methodologies, Building Performance Evaluation (BPE) was considered the most fitting for this study. Common BPE approach used during the building in-use stage was slightly adapted to accommodate the specific aims and objectives of this study. Compared to the typical BPE, the scope of this study is wider; both in terms of environmental aspects of interest (household behaviours) and spatial scale (large housing development). Rather than conducting an in-depth assessment of energy performance focused on a small number of dwellings (typical for BPE), this study aimed to understand multiple aspects of environmental performance at the development-level, but still using dwellings and households as functional units of analysis. Further expansion the assessment scope to show embodied emissions (LCA), metabolic profile (Urban Metabolism) and ecological/carbon footprint of the development was associated with various limitations and would not help to address study's objectives.

The choice to use BPE data collection methods was also encouraged by the provided access to data collection equipment and resources. Energy and water performance of all development's dwellings was already monitored by the developer. The Researcher was granted the permission to use indoor environmental monitoring kit, thermographic camera, and the licenced BUS questionnaire. In line with Leaman's suggestions (2011), questionnaire survey was considered a more effective method for collecting development-wide household responses compared to semi-structured interviews, occupant diaries or focus groups. As a strategy of explanatory sequential design (Creswell and Plano Clark, 2011), conducting interviews can be advantageous, as they can help deepen the understanding of results obtained through quantitative methods. In line with this stance and the BPE's 'drill-down' approach, semi-structured interviews were used for conducting in-depth investigations focused on specific topic of interest in a small dwelling sample.

4.3.2. Research Design

The study used four research methods, with key characteristics presented in Table 9.

	Development-level Assessment		**Dwelling subset Assessment**	
Method	In-situ monitoring	Questionnaire survey	In-situ monitoring	Semi-structured interviews
Functional scope	Dwellings	Households	Dwellings (rooms)	Households
Subject / Criterion	Energy and water performance	Experience with the dwelling, and environmental behaviours	Indoor environmental conditions	Energy use behaviours
Parameters / topics	Electricity use, solar PV generation and export, heat use, water use	Comfort, energy, waste, food and transportation behaviours	Air temperature, relative humidity, CO_2 levels, window opening frequency, radiator temperature	Heating, ventilation and cooling behaviours
Data source	Secondary data sourced from an existing monitoring system	Primary data collected by conducting a door-knocking survey	Primary data collected via in-situ monitoring	Primary data collected by conducting interviews
Data type	Quantitative	Quantitative	Quantitative	Qualitative

Table 9 Characteristics of the utilised research methods.

The assessment was conducted on two spatial levels: development-wide and on a subset of households. The first assessment aimed to capture a broad range of environmental aspects and to answer *what* performance was achieved at the development level. The secondary assessment was conducted on a subset of households. A smaller study sample allowed performing a more detailed assessment of dwelling indoor environmental conditions and heating, ventilation and cooling behaviours, to provide more understanding about *why* such indoor conditions and energy performance was achieved.

Design of eco-housing developments often aims to address all three aspects of sustainability. This thesis was primarily focused on evaluating environmental performance. More specifically, it focused on the energy, water, carbon emissions from dwelling use and household environmental behaviours. In addition, it aimed to understand social impacts of the development, capturing household satisfaction and experience regarding the provided environmental features and indoor environmental conditions.

Hence, the study took a bottom-up data collection approach, practiced in POE, BPE and footprinting methodologies. As the design intent of the development was to enable more sustainable lifestyles, the building-focused BPE approach was expanded to capture household environmental behaviours shaped by the urban setting, namely the transportation, waste and food behaviours. Vale and Vale (2010) similarly argued that the focus of in-use assessments needs to expand from buildings to household lifestyles, as building energy efficiency alone is not sufficient to achieve reductions in total dwelling energy use and household footprints.

The assessment used mixed methods. Development-wide assessment relied on quantitative data collection methods. Energy, water and carbon performance was based on measured data sourced from a monitoring system that was already installed by the developer. A questionnaire survey was used to collect household responses about their environmental behaviours, background, and satisfaction and experience with the dwelling. SPSS software was used for statistical analysis of the quantitative data. Detailed assessment of the dwelling subset used both qualitative and quantitative methods. Monitoring was conducted to assess indoor environmental conditions. Semi-structured interviews were conducted to acquire household responses about their heating, cooling and ventilation behaviours. Figure 6 illustrates how the research design addresses the objectives of this thesis.

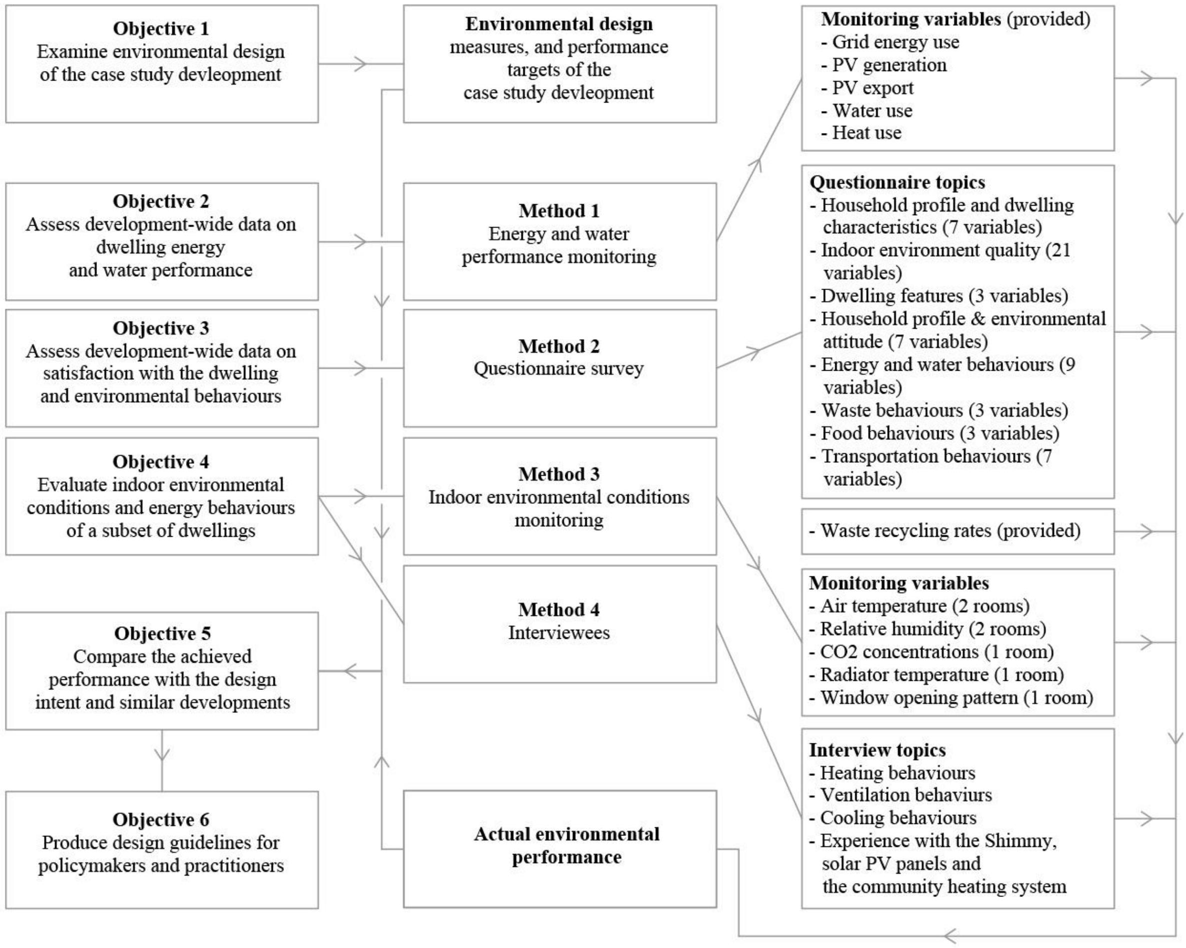

Figure 6 Diagram linking the objectives of this thesis, research methods used to address these objectives, and captured variables grouped under different topics.

The large scale of the study is indicated in the richness of the data base. The energy and water monitoring and indoor environmental monitoring provided 410 and 98 valid data channels, respectively. The survey (90 residents) provided 6,373 responses (data points) to 77 quantitative questions and 1,010 responses to 26 qualitative questions. Lastly, the interviews with 12 households provided 228 responses in total to 19 questions.

4.3.3. Ethical Considerations, Data Security and Dissemination

The utilised research methods were developed in accordance with the ethical considerations of Oxford Brookes University. The study was given full approval by the University Research Ethics Committee (Registration No: 181178). Adult residents living in the case study development were invited to voluntarily participate in the study, and to sign a consent form (opt-in). There are no possible negative effects on the participants.

Anonymity/confidentiality of participant identity was ensured. All of the information collected during the field work activities were confidential and fully anonymised. Data collected in the course of the research was kept securely at all times. Data was stored in electronic form for a period of ten years after the completion of this study. Laptops and other devices were password protected and additionally encrypted. Data generated by the study was retained in accordance with the Oxford Brookes University's policy on Academic Integrity. The key findings of the thesis will be disseminated to the development's stakeholders.

4.3.4. Energy and Water Performance Monitoring

The second objective of the thesis was to assess the development-wide, time-series data on the dwelling energy use, energy generation, carbon emissions and water use for one year

Dwelling energy and water data were sourced from the existing monitoring system developed by Carnego Systems, installed as part of the ongoing monitoring programme. Each dwelling was provided with meters recording high frequency (1 minute) data. In each house, five data channels collected grid energy use, PV generation and export, water use and heat use. Each flat is associated with only three data channels (electricity, heat and water) as solar PV panels installed on roofs of blocks of flats were not wired to the flats below. Meters from all dwellings provided a total of 729 data channels. Electricity usage, PV generation and export data were recorded in Wh units, heat flow was recorded in kWh and water in 10 litre units. Specifications of provided meters can be seen in Table 10.

Meter Type	**Connection Method**	**Granularity**	**Accuracy**
Import & Export Electricity	Pulse	0.001 kWh / pulse	Class 2
PV Generation	Pulse	0.001 kWh/ pulse	Class 1 & MID
Water	Pulse	10 L / pulse	Not known
Heat	Pulse	1 kWh / pulse	MID certified

Table 10 Sensor specifications used for monitoring of the case study.

The provided high frequency data was used to generate 30-minute, hourly, daily, monthly and annual values. Half-minute readings for one summer (July) and winter (February) month were used to generate daily energy usage and generation profiles. This was done only for electricity data (Watts), as heat (m^3) and water (10 litres) data units were not sufficiency granulated. Detailed assessment of daily values allowed the detection of possible data loss due to faulty equipment. Monthly values were generated to show seasonal changes in energy use and production. Annual values were used to analyse the variation of performance across the development sample occurring due to differences in household profile and dwelling characteristics. Annual values were also used to compare the mean performance of the development against the design intent. The community heating system's annual energy performance data provided by the developer was used to estimate dwelling carbon emissions.

As it is illustrated in Figure 7, meter readings were automatically sent via wire to the Meter Concentration Unit (MCU), and then uploaded via ethernet and optical fibre cables to the online database. The Researcher was granted access to the internet website designed for viewing and downloading the collected data. Data were downloaded in the form of excel sheets, focusing on one year monitoring period from 1 June 2018 to 31 May 2019.

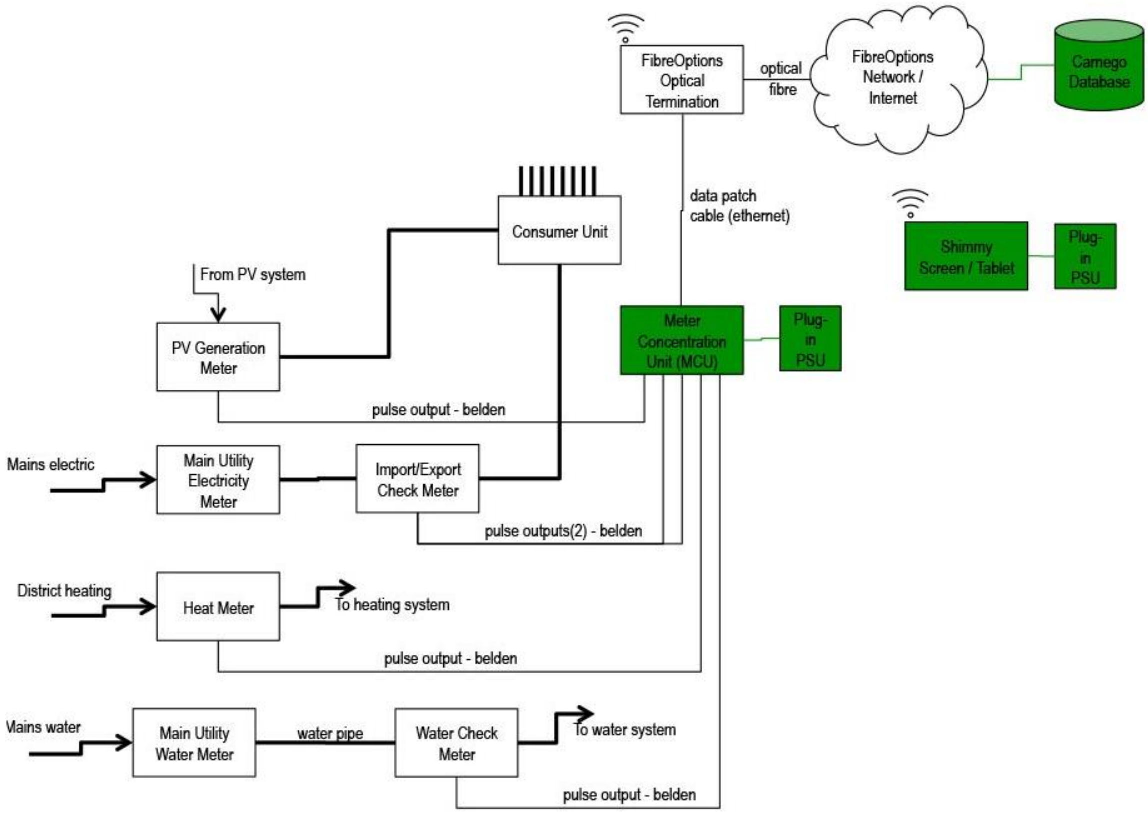

Figure 7 Schematic of the monitoring system (Source: Carnego Systems, William Box).

4.3.5. Questionnaire Survey

In order to meet the third objective of the thesis, a development-wide questionnaire survey was conducted to gather household responses about the experience and satisfaction with their home and indoor environmental conditions, and about the energy, waste, food and transportation behaviours.

The questionnaire used in this study consists of two parts; the *Housing Evaluation* and the *Lifestyle Evaluation*. A sample of the whole questionnaire is presented in the Appendix. The *Housing Evaluation* is a standardised questionnaire, focused on the households' experience with their home. The *Lifestyle Evaluation* is a bespoke questionnaire developed by the Researcher for the purposes of this thesis. It expands the first part of the questionnaire by capturing households' environmental behaviours. Both questionnaires were designed to be concise, counting four A4 pages in total. This was expected to make the whole questionnaire seem less time consuming for the residents, and help achieve higher participation rate. The questionnaire's brevity and its aim to cover a broad range of environmental and social aspects allowed designating only a few questions per each topic. Hence, the intent of the questionnaire was not to go into great depth, but rather to provide an overview of the achieved performance across multiple aspects, and to identify the topics which could be further investigated in the later stage of the assessment. Table 11 and Table 12 show the variables from the questionnaire, related data type and its objective.

	Data type*				
Variable	**NU**	**OR**	**NO**	**QL**	**Objective**
Age	X				Household and dwelling profile
Sex			X		
Time of moving-in			X		
Occupancy	X				
Typical time of occupancy			X		
Dwelling typology			X		
Tenure			X		
Winter/Summer temperature; comfort		X			Indoor environment quality
Winter/Summer temperature; sensation		X			
Winter/Summer temperature; stability		X			
Winter/Summer air; stillness		X			
Winter/Summer air; dryness		X			
Winter/Summer air; freshness		X			
Winter/Summer air; smell		X			
Winter/Summer conditions; satisfaction		X			
Overall comfort; satisfaction		X			
Health		X			
Personal control; heating		X			
Personal control; cooling		X			
Personal control; ventilation		X			
Dwelling features; satisfaction				X	Dwelling features
Environmental design features				X	
Utilities cost comparison		X			

*Table 11 Description of key variables from the Housing Evaluation questionnaire. *Data types; NU=Numerical, OR=Ordinal, NO=Nominal, QL=Qualitative.*

Variable	NU	OR	NO	QL	Objective
	Data type				
Education			X		Household profile & environmental attitude
Frequency of eco-friendly behaviour		X			
Information about eco-friendly lifestyle		X			
Lifestyle and climate change		X			
Lifestyle has changed		X			
Lifestyle became more eco-friendly		X			
Reasons for choosing the home			X		
Living lights on		X			Energy and water behaviours
Washing clothes on 40°C		X			
Cutting water use		X			
Using solar energy with appliances		X			
Cautiousness energy use; due to dwelling			X		
Cautiousness energy use; due to monitor			X		
Thermostat temperature			X		
Air-conditioning ownership/openness			X		
Open to - energy and water savings			X		
Use of waste facilities			X		Waste behaviours
Encouraged recycling due to facilities			X		
Open to - additional recycling			X		
Frequent low-impact food behaviours			X		Food behaviours
Meat consumption in meals	X				
Open to - adopting eco-friendly diet			X		
Mode of transport for 10 different purposes			X		Transportation behaviours
Destination per transportation mode			X		
Weekly frequency per transportation mode	X				
Importance of eco-friendly facilities			X		
Vehicle ownership	X				
Mileage per vehicle	X				
Open to - more eco-friendly transportation			X		

*Table 12 Description of key variables from the Lifestyle Evaluation questionnaire. *Data types; NU=Numerical, OR=Ordinal, NO=Nominal, QL=Qualitative*

<u>Questionnaire Part 1: Housing Evaluation</u>

The Housing Evaluation questionnaire captured the social impacts of dwellings on their occupants. It collected household feedback about the dwelling occupancy and the experience and satisfaction with the dwelling design, environmental features and indoor conditions. The questionnaire was developed for domestic POE applications, and is based on the Building Use Studies (BUS) method of occupant data reporting and analysis (Leaman, 2011). Using this method is advantageous, as it helps to contextualise the assessment results. The final report based on the collected data presented the mean results of each variable alongside the results of other housing evaluation studies within the BUS database, serving as a performance benchmark.

The questions are divided into different topics: household background, satisfaction with the dwelling design, air temperatures, air quality, noise, lighting and environmental features, impacts on health, the ability to control the indoor conditions and costs of energy and water. The big majority of questions were designed using a seven-point Likert scale for rating household experience. In addition, some space was offered for providing additional comments for each topic.

Three questions of this standardised questionnaire were expanded or altered for this study to generate more detailed feedback. The answer to the question *What is your age?* was expanded from two to five age categories which are commonly used in national statistics. An additional answer *I work from home* was added to the question *Are you normally at home?*. Existing answers to the question *Are you in a…?* were expanded with *Mid-terrace* and *End of terrace* answers to more accurately capture the typology of dwellings.

Questionnaire Part 2: Lifestyle Evaluation

The Lifestyle Evaluation questionnaire aimed to capture to what extent the development's design shaped household environmental behaviours. The questionnaire was divided into five main topics: household background, energy and water use, waste recycling, food choices and transportation behaviours. The design of the questionnaire combined multiple choice questions, six and seven point Likert scales, matrix questions and offered the provision of additional qualitative comments for each topic.

The background section aimed to bring more insights about the personal factors which can shape environmental behaviours. Collecting responses about household education levels can serve as indicator of their socio-economic status. Studies have indicated that environmental attitudes were not associated with household consumption (Newton and Meyer, 2013) or carbon footprints (Quilgars *et al.*, 2019). However, gathering insights about environmental attitudes in eco-developments could indicate if such locations attract more eco-minded households. Established assessment methods for assessing environmental attitude such as the *New Ecological Paradigm* tend to use multiple questions to generate more robust findings (Dunlap *et al.*, 2000). Hence, only three questions dedicated to environmental attitudes in this questionnaire served only as its indicators. After the background section, the remaining questions focused on household environmental behaviours. Each environmental behaviour contained questions about the frequency of the behaviour, usage of the provided infrastructure and other design measures, perceived impact of these measures on behaviour, and lastly openness to further behavioural change.

In order to contextualise the results, the majority of the questions were adopted from questionnaires used in national surveys, and in studies of other eco-housing developments. Questions in regard to environmental attitude, energy and water saving behaviours and thermostat settings were adopted from DEFRA's national survey (2009). The question on education is used in the national census (ONS, 2014). Questions regarding the perceived impact of provided measures on behaviours were adopted from a study of 13 eco-housing developments (Williams, Dair and Lindsay, 2008). Different answers regarding the openness to further behaviour change were adopted from a study by Semenza et al. (2008) and DEFRA's survey (2009). The question about the meat consumption was adopted from the *REAP Petite* carbon footprinting calculator (SEI, 2017), which was used in other eco-housing studies (Bioregional, 2009; Quilgars *et al.*, 2019).

Where available, reported transportation behaviours were compared to national or local statistics. Terminology for trip mode and purpose categories were adopted from the national transportation survey (DT, 2018). In addition, two trip purpose categories from the national survey were expanded to collect more detailed responses. The *Shopping* category was divided into *Groceries shopping* and *Other shopping*, while *Leisure* category was divided into *Leisure visiting friends/relatives* and *Leisure other* categories. Comparison of the questionnaire results with the national statistics were limited in two ways. Firstly, the national survey used trip diaries and interviews to collect data. Due to time constraints, this study used self-administered questionnaires which yield less accurate responses. The second limitation refers to the difference in age of the surveyed residents. The national survey included all age groups, while this study underrepresents the non-working population. It excluded minors from participation, while the 65+ age group makes only 3% of the captured resident sample.

4.3.6. Indoor Environmental Conditions Monitoring

The fourth objective of the thesis required evaluating indoor environmental conditions of a subset of dwellings in the case study development. Households which participated in the questionnaire survey were asked if they were interested in participating in the further stage of the study, which involved monitoring of indoor environmental conditions of their home and taking part in household interviews. After the questionnaire survey was completed, 14 subset households signed the consent forms and agreed to participate in the monitoring study.

The one year monitoring period from 1 October 2018 to 30 September 2019 matched the energy performance monitoring period. The Researcher installed data logging equipment in each of the subset homes to remotely monitor air temperature, relative humidity, CO_2 concentrations, window opening frequency and radiator temperature. CO_2 concentrations were used as indicators of indoor ventilation levels. Monitoring of radiator temperature served to capture heating patterns. The specifications of the installed data loggers can be seen in Table 13. All devices were commercially available and provided for the purposes of this study by Oxford Brookes University.

Space	Monitoring parameters	Data logger	Reading frequency (minutes)	Specifications
Living room	Temperature and relative humidity	HOBO UX100-003	15	Temperature: Range: -20°C - +70°C, Accuracy: ± 0.53°C from 0° to 50°C, Resolution: 0.14°C at 25°C. RH : Range: 25% to 95% RH Accuracy: ±3.5% from 25% to 85% Resolution: 0.07% @ 25°C and 30% RH
	Temperature (radiator)	iButton DS1922L	30	Range: -40 and +85°C, Accuracy: ± 0.5 from -10°C to + 65°C, Resolution: 0.5°C (8-Bit resolution) or 0.0625°C (11-Bit resolution)
Bedroom	Temperature and relative humidity	HOBO U12-012 (option B)	15	Temperature: Range: -20°C to 70°C, Accuracy: ±0.35°C @ 0°C to 50°C, Resolution: 0.03°C @

Space	Monitoring parameters	Data logger	Reading frequency (minutes)	Specifications
				25°C. RH: Range: 5% to 95% RH, Accuracy: ±2.5% (10% to 90% RH), Resolution: 0.03%
	CO2 levels	TinyTag CO2-TGE-0011	15	Range: 0 – 5000ppm, Accuracy: ± 50ppm, Resolution: 0.1ppm
	Window opening	HOBO U9 – 001 State datalogger	-	Time accuracy: Approximately ± 1 minute per month at 25°C, Operating temperature: -20° to 70°C, Humidity range: 0 to 95% RH
Outdoor	Temperature and relative humidity	HOBO MX2301	15	Temperature: Range: -40°C to +70°C, Accuracy: ±0.2°C from 0 to 70°C, Resolution: 0.04°C. RH: Range: 0% - 100%, Accuracy: ±2.5% from 10% to 90%, Resolution: 0.05% RH

Table 13 Specifications of the data logging instruments.

The monitoring focused on two commonly used spaces: the living room and the main bedroom. Air temperature and relative humidity were monitored in both rooms. The loggers were positioned on the top of the room door frame, to minimise possible interference with the occupants. Temperature of one radiator was monitored in living rooms to capture heating patterns. The logger was attached on the back of the radiators, close to its top. CO_2 concentrations and opening of one casement window were recorded in main bedrooms, in order to gather more insight about the air quality and the use of windows for ventilation. CO_2 concentrations in bedrooms are of greater concern compared to other rooms due to reduced occupants' ability to improve the conditions during the night. The CO_2 logger was placed near an available electricity socket for necessary charging. Examples of data logger positions can be seen in Figure 8.

Figure 8 Data loggers positions presented on floor plans of two subset dwellings.

With 14 monitored dwellings and seven monitored parameters, the data set consisted of 98 data channels. Radiator temperatures were recorded every 30 minutes, while all other loggers were taking readings every 15 minutes. Between the deployment of the loggers and their removal at the end of the one year monitoring period, the households were needed to be re-visited two more times, due to limited battery size and internal memory storage.

4.3.7. Interviews

Apart from evaluating the indoor environmental conditions, meeting the fourth objective of the thesis required conducting household interviews about the heating, ventilation and cooling behaviours in their homes.

The interview was designed to be semi-structured, containing mostly open-end questions. A sample of the interview can be seen in the Appendix. Interview questions (19 in total) were divided into background, heating season, non-heating season, ventilation and miscellaneous sections. In the background section, interviewees shared typical hours of occupancy in the two rooms that were monitored. In regard to heating, the interviewees were asked about the preferred heating schedule, use of the thermostat and possible issues with the heating system. The ventilation section aimed to capture in detail how the households preferred to position the windows, curtains, doors and window trickle vents at different times of the day, week and seasons. Households were also asked to explain how they kept their home cool during the hot weather. Lastly, expanding on the Housing Evaluation questionnaire, households shared their experience with the Shimmy device, solar PV panels and the community heating system, as the more prominent environmental features of the development. The feedback from the interviews will then be related to (and possibly explain) the measured indoor environmental conditions.

4.4. Data Validity Analysis, Recruitment and the Final Sample

4.4.1. Energy and Water Performance Monitoring

As the dwellings' energy and water performance findings were going to be based on the data provided by the 3rd party monitoring system, it was crucial to first assess the data validity. As the initial step of the assessment, the following datasets collected over five consecutive days for one Phase 1 dwelling was compared (Table 14): Carnego daily data; Carnego daily data aggregated from hourly data; manual meter readings; and daily data from emonPi monitoring system[12] installed by one resident. Small discrepancies are marked in yellow and larger ones in red in the same Table. This comparison demonstrated that the daily data from Carnego was not valid, but when generated from hourly data it tallied well with the meter reading. As a result, hourly data was used to generate daily, monthly and yearly values for Phase 1 dwellings.

[12] https://guide.openenergymonitor.org/applications/home-energy/

	Date	Manual reading	Difference to manual reading		
			emonPi daily data	Carnego daily data	Carnego daily from hourly data
Grid electricity use (kWh)	11-Mar-19	3.5	-0.2	0.7	0.1
	12-Mar-19	11.7	-0.6	-0.1	0.0
	13-Mar-19	2.9	-0.3	8.8	-0.1
	14-Mar-19	7.8	-0.6	0.0	0.1
	15-Mar-19	8.4	-0.6	-0.2	-0.1
Solar generation (kWh)	11-Mar-19	14.0	0.2	0.0	0.0
	12-Mar-19	3.4	0.1	10.6	0.0
	13-Mar-19	9.9	0.2	0.0	0.0
	14-Mar-19	8.5	0.3	1.4	0.0
	15-Mar-19	4.6	0.1	4.0	0.0
Solar export (kWh)	11-Mar-19	13.2	0.0	0.0	0.0
	12-Mar-19	0.3	0.0	12.9	0.0
	13-Mar-19	7.7	0.1	0.1	0.1
	14-Mar-19	1.8	0.1	6.0	0.0
	15-Mar-19	1.8	0.2	0.1	0.1

Table 14 Comparing the readings between the emonPi, Carnego monitoring system and manual readings.

For the second data validity test, the Carnego data for grid electricity, heat and water use, and solar PV generation were compared to manual utility meter readings obtained in a sample of ten Phase 1 and 2 dwellings (Table 15). The comparison results showed that Carnego data and manual readings tallied in regard to grid electricity usage, heat usage and solar generation, but not for water use. Analysis of water bills provided by residents confirmed that the Carnego water data for Phase 1 dwellings is not valid. As a result, dwelling water performance was based solely on the data from Phase 2 dwellings.

	Dwelling	Manual readings Elec-tricity (kWh)	Heat (kWh)	Solar gen. (kWh)	Water (m3)	Carnego data Elec-tricity (kWh)	Heat (kWh)	Solar gen. (kWh)	Water (m3)	Factor of difference Eelec-tricity	Heat	Solar gen.	Water
Phase 1	HPI7	5,631	4,286	3,118	56.0	5,620	4,344	3,135	79.1	*1.00*	*0.99*	*0.99*	*0.71*
	HPI12	2,215	4,878	3,454	106.0	2,194	4,810	3,483	106.6	*1.01*	*1.01*	*0.99*	*0.99*
	HPI16	1,484	3,154	3,987	36.0	1,453	3,533	4,024	58.9	*1.02*	*0.89*	*0.99*	*0.61*
	HPI11	1,505	3,350	3,277	46.0	1,436	3,249	3,154	63.9	*1.05*	*1.03*	*1.04*	*0.72*
	HPI8	2,680	-	-	64.0	2,657	-	-	87.0	*1.01*	-	-	*0.74*
	HPI21	2,054	7,526	5,351	60.0	1,929	7,283	4,717	46.3	*1.07*	*1.03*	*1.13*	*1.30*
Phase 2	HPII33	835	5,329	3,078	73.0	828	5,332	3,085	74.2	*1.01*	*1.00*	*1.00*	*0.98*
	HPII46	1,888	6,367	5,075	52.0	1,879	6,372	5,093	51.5	*1.00*	*1.00*	*1.00*	*1.01*
	HPII25	1,180	4,547	1,762	61.0	1,169	4,554	1,766	60.8	*1.01*	*1.00*	*1.00*	*1.00*
	HPII15	1,093	4,575	2,450	-	1,088	4,583	2,455	-	*1.00*	*1.00*	*1.00*	-

Table 15 Comparing manual readings with Carnego data for Phase 1 and 2 dwellings.

Downloaded Carnego daily data values were carefully analysed in order to detect possible loss of data or unreliable values occurring throughout the monitoring year. Data channels which contained more than 95% of the valid daily data readings during the one year monitoring period were included in the further analysis. Loss of up to 5% of the data (up to 18 days) was not considered to significantly deteriorate the accuracy and validity of a data channel. The remaining daily values were extrapolated in order to estimate total annual usage/generation. This was done by firstly aggregating valid daily values to generate an annual sum. This was then divided by the number of days in order to calculate the average daily value. Lastly, the number of missing days was multiplied by the average daily value and added to the collected data.

Analysis of the data set detected positive, zero and N/A (not applicable) daily data values. A careful analysis was conducted for each data channel in order to detect whether a zero entry signified that there was no recorded energy or water flow, or the meter was faulty. About half (55%) of the Phase 1 meters experienced loss of data on the same 15 days, which was extrapolated (< 5% of missing days). Dwellings which were vacant, recently occupied, with highly intermittent occupancy or prolonged periods with no occupancy were excluded from further analysis. Data channels with less than 95% of yearly data and channels recording nonsensical values were also excluded. It was also detected that in six Phase 2 dwellings heat meters were measuring water use while water meters were measuring heat use. The results of this analysis suggested that only 56% of data channels from a total of 729 meters can be regarded as valid. As seen in Figure 9, sufficient water use data (> 95% of daily data) was collected in 93 dwellings (59%), heat use data in 94 dwellings (60%), grid electricity usage in 97 dwellings (62%), solar PV export in 66 houses (51%) and finally PV generation in 60 houses (47%).

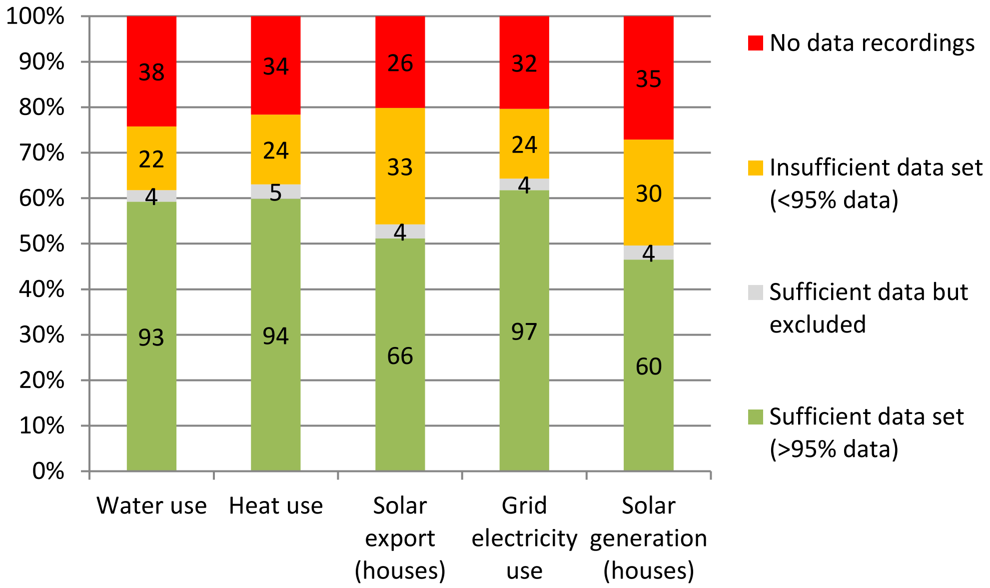

Figure 9 Status of monitoring data channels (energy and water) after the data validity analysis.

Based on the data validity analysis, only 98 dwellings (62% of all 157 dwellings) were associated with at least one type of valid (> 95% of daily data) data channel. This dwelling set consisted of 52 Phase 1 homes (abbreviated as HPI) and 46 Phase 2 homes (HPII). Within these 98 dwellings, valid heat use data was available for 94 dwellings, while total energy use could be calculated for 74 dwellings. The dwelling sample with available heat and energy data is presented in a schematic of the development site in Figure 10. Total energy use was calculated by adding up heat use, grid electricity and self-consumed electricity use (subtracting solar PV export from generation). Also, it was possible to relate energy use data with questionnaire responses for 35 households within this 74-dwelling subset.

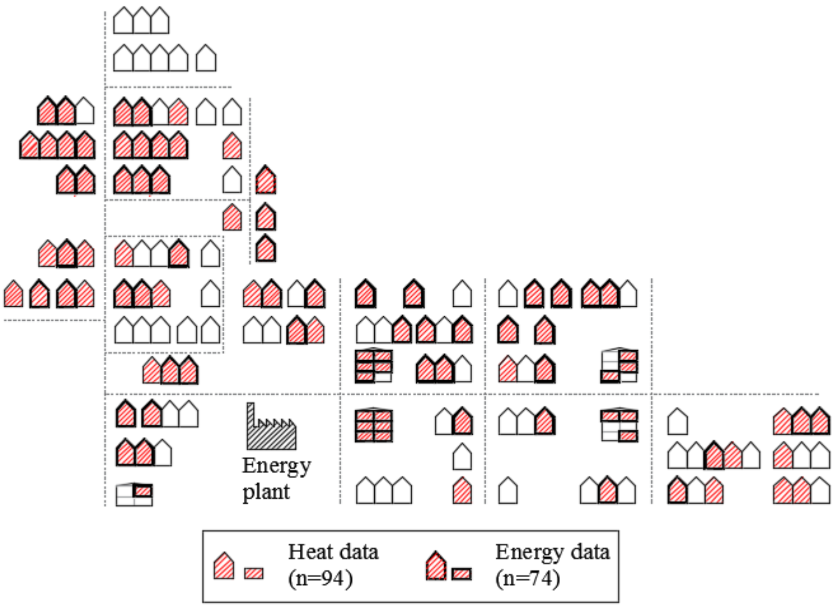

Figure 10 Schematic of the development site showing the dwelling sample with sufficient heat data and energy data.

Comparing the dwelling sample with energy data (n=74) to all 157 dwellings in regard to key dwelling characteristics, it can be noticed that the sample underrepresented flats (-6.5%), 3-bed (-5.2%) dwellings and affordable dwellings (-5.1%), as presented in Table 16.

	n=74	Difference to all 157 dwellings
1-Bed	4	+0.3%
2-Bed	36	+3.4%
3-Bed	23	-5.2%
4-Bed	1	+0.1%
5-Bed	10	+1.4%
Private owned	50	+5.1%
Affordable rent	14	-7.2%
Affordable shared ownership	10	+2.0%
Flats	18	+6.5%
Houses	56	-6.5%
Phase 1	41	+0.6%
Phase 2	33	-0.6%
TFA (m2)	92.1	+0.7
Number of beds	2.7	0.0

Table 16 Descriptive statistics of the dwelling sample with energy data (n=74).

4.4.2. Questionnaire Survey

In advance of conducting the questionnaire survey, case study developments' households were invited to voluntarily participate in this study after a regular community meeting and on the community's Facebook page.

The survey was conducted in the period from 25 August 2018 to 16 December 2018 (~3.5 months) by the Researcher. Due to small development size (157 dwellings), it was important to maximise household participation rate. Throughout the survey period, households were approached multiple times via door-knocking visits taken in different times of the day and week. Absent households were revisited up to five times in order to make contact, which made the survey quite time intensive. Residents who expressed interest to participate in the study completed the consent form. After this they were provided with an information sheet, and up to two self-administered questionnaires for two adults in the household. In POE and BPE studies, each household is usually given only one questionnaire, which is considered to represent that household. Offering up to two questionnaires in this study can be considered a more rigorous approach to data collection.

Door-knocking method proved to be ineffective for approaching households in flats, yielding only one successful questionnaire completion. The households were mostly not responsive to the buzzer located at the main building entrance. To address this issue, additional method of distributing questionnaire packages (sheets, return envelopes with a small chocolate as an act of gratitude) to flats' postal boxes also proved unsuccessful, resulting in no completed questionnaires.

Survey participation results are presented in Figure 11. Questionnaires were completed by 64 households, amounting to 41% of all households in the development. About a quarter (26%) of households were not responsive to the repeated door-knocking attempts or questionnaire packages sent by post. An additional completed questionnaire was collected in 26 households, aggregating a total of 90 completed questionnaires.

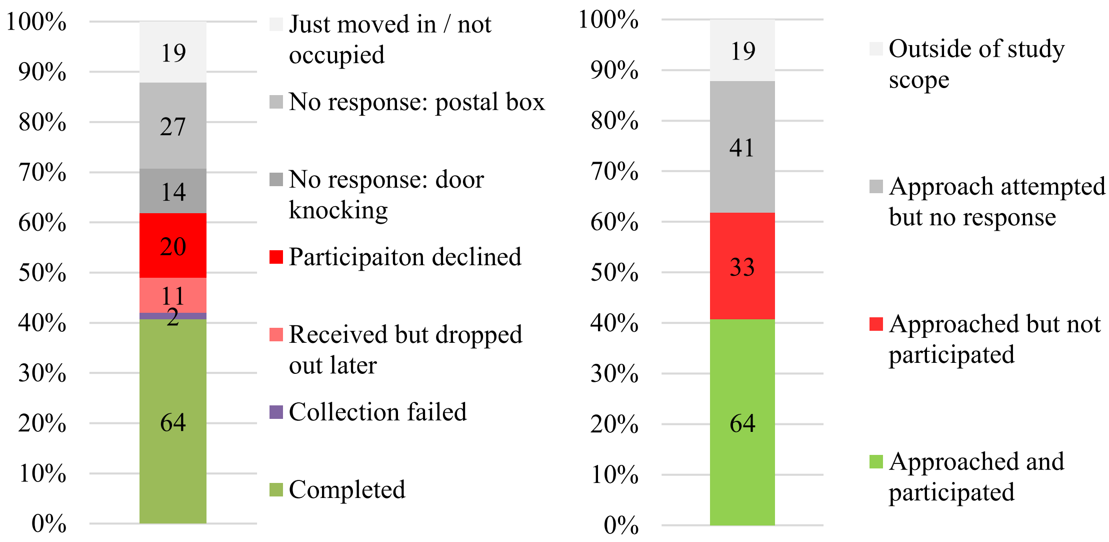

Figure 11 Results of the questionnaire survey and final household sample.

As seen in Table 17, the final sample fails to represent households living in flats. It represents the development well in terms of house typology, with somewhat more private properties (11% more) and slightly more responses (7% more) from Phase 1 households. In conclusion, due to small differences in dwelling characteristics, the collected sample can be considered representative of households living in houses.

Category	All dwellings (n=157)	Sample dwellings (n=64)	Difference to all
Dwelling type			
Houses	82%	98%	16%
Flats	18%	2%	-16%
Tenure			
Private owned	62%	73%	11%
Affordable rent	26%	19%	-7%
Affordable shared ownership	11%	8%	-4%
House type			
Detached house	20%	16%	-4%
Semi- D house	12%	13%	1%
End-terrace house	41%	41%	0%
Mid-terrace house	27%	30%	3%
2-bed house	40%	37%	3%

Category	All dwellings (n=157)	Sample dwellings (n=64)	Difference to all
3-bed house	44%	49%	-5%
4-bed house	2%	3%	-2%
5-bed house	15%	11%	4%
Households per phase			
Phase 1	55%	52%	3%
Phase 2	45%	48%	-3%
Total responses per phase			
Phase 1	48%	55%	7%
Phase 2	52%	45%	-7%

Table 17 Representativeness of the household sample participating in the questionnaire.

4.4.3. Indoor Environmental Conditions Monitoring

From 64 households which completed the questionnaire, 14 households agreed to participate in the subsequent part of the study: indoor environmental conditions monitoring of their home.

Before they were installed in the dwellings, monitoring instruments (data loggers) were calibrated (taking one-minute readings over three days) to assess the accuracy of readings. The assessment showed that the difference in readings between the reference logger and other loggers was negligible, hence the readings were valid. Temperature data differed between 0.2°C and 0.1°C per logger, and less than 0.1°C, as a group average. RH data differed only 0.3%.

Monitoring of outdoor air temperatures and RH was also conducted during the same monitoring period. An outdoor logger was placed in the garden of the dwelling H0. As the logger was not successfully protected from the sun, the collected 15-minute temperature data was often too high and needed to be excluded from further analysis. Instead, hourly data from the nearby weather station were used (Met Office, 2020; The Weather Company, 2020).

As observed in Table 18, air temperature and RH measurements were successfully collected for all but two subset dwellings. Due to occupant factors, the monitoring period in dwellings

H11 and H13 was shortened for about three months, collecting from 80% to 85% of annual data. Half of the loggers which were measuring radiator temperatures ended their lifetime at some point during the monitoring, capturing from 37% to 85% of annual data. CO_2 loggers were not available during the whole monitoring year. Hence, CO_2 concentrations were monitored from February to September 2019 (eight months). In dwellings H4, H6 and H11, major loss of CO_2 data (27% to 68% data collected) was caused by occupants, who unplugged the logger from the electricity socket several times during the monitoring period. In the majority of other dwellings, minor data loss (89% to 96% data collected) was related to the late start of monitoring in some dwellings during February 2019.

	Living room			Bedroom			
Case	Temperature	RH	Radiator temperature	Temperature	RH	CO2 (Feb - Sept)	Window opening
H0	100%	100%	52%	100%	100%	100%	100%
H1	100%	100%	35%	100%	100%	93%	100%
H2	100%	100%	100%	100%	100%	93%	100%
H3	100%	100%	100%	100%	100%	96%	100%
H4	100%	100%	37%	100%	100%	27%	100%
H5	100%	100%	100%	100%	100%	95%	100%
H6	100%	100%	100%	100%	100%	68%	100%
H7	100%	100%	77%	100%	100%	93%	100%
H8	100%	100%	62%	100%	100%	92%	100%
H9	100%	100%	100%	100%	100%	89%	100%
H10	100%	100%	100%	100%	100%	96%	100%
H11	85%	85%	85%	85%	85%	54%	85%
H12	100%	100%	100%	100%	100%	96%	100%
H13	80%	80%	69%	80%	80%	100%	80%

Table 18 Ratio of data readings collected during the monitoring period. Light grey and darker grey shade mark less and more significant data loss, respectively.

4.4.4. Interviews

From 14 subset households that participated in the indoor monitoring process, all but two subset households (H9 and H11) also agreed to partake in an semi-structured interview with the Researcher.

In seven households a single adult was interviewed, while in the remaining five households two adults preferred to answer most of the questions together. Interviews lasted about one hour and took place in January 2020, about one year after the questionnaire survey and about six months after the monitoring period. The household H13 was interviewed using a telephone, while all other interviews were conducted face-to-face in residents' homes.

Basic information about 12 interviewed households is presented in Table 19. The households' dwellings represented both building phases. All dwellings were privately owned, apart from one shared ownership dwelling. All house types were represented: mid-terrace, end-terrace, semi-detached and detached. The interviewed households can be considered already well settled in their home. At the time of the interview, Phase 1 households had already lived at the property for about three and a half years, while Phase 2 households had lived there for about two years.

Case	Phase	Tenure	Type	Occupancy	Participating residents	Moved in
H0	1	Private	Mid Terrace	2	1	Apr-16
H1	2	Private	End Terrace	2	1	Nov-17
H2	2	Private	Detached	2	2	Mar-18
H3	2	Private	Mid Terrace	3	2	Oct-17
H4	1	Private	End Terrace	2	2	May-16
H5	1	Private	End Terrace	2	1	Jun-16
H6	1	Shared ownership	Semi-Detached	2	2	Jul-16
H7	2	Private	Mid Terrace	4	1	Feb-18
H8	1	Private	Detached	3	1	Sep-16
H9	1	Private	Mid Terrace	2	NA	NA
H10	2	Private	Mid Terrace	2	2	Oct-17
H11	1	Private	Detached	4	NA	NA
H12	2	Private	End Terrace	2	1	Apr-18
H13	1	Private	End Terrace	2	1	May-16

Table 19 Main characteristics of the interviewed household sample.

4.5. Approach to Data Analysis

Using the licenced Housing Evaluation questionnaire allowed comparing the mean score (vote) for each variable to the score of a sample of 58 surveyed new-build housing developments in the UK[13]. The results of the monitoring process and the mean results of the Lifestyle Evaluation questionnaire and were compared to the local and national averages, and results from similar studies of low-carbon and eco-housing developments, where available. It was possible to relate the collected energy data from 35 dwellings (47% from all dwellings with energy data) to the questionnaire responses of residents residing in these dwellings. For this analysis each dwelling was represented by one response from the questionnaire.

Using the SPSS software, the collected data was statistically analysed for associations. The data was firstly assessed using descriptive statistics. Continuous data from water and energy monitoring, and from the questionnaire were assessed for normality (Shapiro-Wilk test) and tested using Pearson r, ANOVA and other parametric tests. Categorical data and ordinal data from Likert scale questions were assessed using different nonparametric tests. Spearman's rho was used to measure associations between two ordinal variables, and between an ordinal and a categorical variable. Chi-Square test was used to determine associations between two categorical variables. Fisher Exact test was used for small samples, when 20% of cells in a contingency table had small frequencies (< 5). Cramer's V test was used in cases when contingency tables were larger than two by two. Mann-Whitney U test was used to determine differences between two independent groups, and the Kruskal-Wallis H test for differences between three or more groups. To identify exactly which groups differed, Dunn's test with Bonferroni correction was used. Cronbach's alpha test was used to measure the level of internal consistency between three Likert-scale questions about environmental attitude. Lastly, regression analysis was also used to explain the variance in electricity, heat and total energy use with variables in regard to dwelling characteristics, household background and behaviours.

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[13] Information provided via email correspondence from the BUS database manager A. Leaman

4.6. Summary

This chapter presented the design of the case study eco-housing development, the research approach and methods used to address the objectives of this thesis.

The case study consists of 157 dwellings forming the initial two phases of a 4-phase eco-housing development, located in England. The development is considered unique, as it was designed in compliance with the withdrawn planning policy for eco-towns. Consequently, the development was required to achieve exemplary performance in a broad range of sustainability aspects and enable more sustainable lifestyles. The key environmental performance targets were ambitious: true net zero carbon from dwelling use, potable water use of 80 litres/day/person of, waste recycling/composting rate of 80%, and car use rate of 45%. These targets place the case study among the most ambitiously designed eco-housing developments. The zero carbon design approach was fairly common. It combined high energy efficiency, large solar PV systems and very low carbon intensity of heat from the community heating system. The designed fabric efficiency was slightly weaker compared to other developments aiming for true zero carbon. With regard to car use, it was hoped that the provided infrastructure (a bus line to town, car club, electric car chargers etc.) would outbalance the drawbacks of the development's semi-rural, edge of town location. The household waste strategy was developed with the local authorities, combining good waste facilities and educational measures. On-site gardening options and shops would provide good access to low-impact foods.

The research approach was based on the case study framework. Acknowledging the socio-technical nature of housing performance, mixed methods were used to gather empirical evidence from multiple sources. The assessment was conducted on two spatial levels: the development-wide and on a subset of households. Development wide assessment aims to answer *what* performance was achieved on a wide range of aspects in regard to dwellings (energy, water, carbon emissions) and households (satisfaction and experience with the home, environmental behaviours). This assessment was based on two quantitative methods; energy and water performance monitoring and a questionnaire survey. The following assessment focused on a subset of dwellings aims to go into greater depth, and offer some explanation about *why* such performance in regard to energy and indoor environmental conditions was achieved. Accordingly, it used both quantitative (indoor environmental conditions monitoring) and qualitative methods (household interviews).

The actual energy and water performance was based on monitoring data collected over one year period: from 1 June 2018 to 31 May 2019. The high frequency (1-minute) data was sourced from an existing monitoring system provided by the developer. The analysis of the sourced dataset showed that out of all 157 dwellings, valid heat use data was available for 94 dwellings, water data for 93 dwellings and total energy use was possible to calculate for 74 dwellings (47%). The sample with available energy data was considered representative in regard to the dwelling typology when compared to all 157 dwellings.

The questionnaire survey was conducted development-wide. The self-administered questionnaire consisted of two parts. The first part called Housing Evaluation focused on collecting household feedback about dwelling occupancy, the satisfaction and experience with the dwelling design, indoor environmental conditions and environmental features. The second part named Lifestyle Evaluation focused on collecting the feedback about household background and environmental behaviours, in regard to energy and water, waste, food and transportation. The survey successfully collected 90 completed questionnaires from 64 households (41% of all dwellings), as up to two questionnaires were offered to adults in each household. The final household sample can be regarded as representative for households living in houses, but under-representative for households living in flats.

Out of 64 households which participated in the survey, 14 accepted to take part in the monitoring of indoor environmental conditions of their home. Installed data loggers monitored indoor conditions in living rooms and in one bedroom during one year. In the living rooms, loggers monitored air temperature and relative humidity and the temperature of one radiator. In the bedrooms, in addition to air temperature and relative humidity, loggers monitored window opening frequency and CO_2 concentrations as a proxy for ventilation levels. From the same subset, 12 households were interviewed by the Researcher in regard to ventilation, cooling and heating behaviours, and their experience with the Shimmy device, solar PV panels and the community heating system.

Chapter 5: Environmental Behaviours and Residents' Experience with the Indoor Conditions

5.1. Introduction

After the data collection process was completed, data analysis was conducted using the SPSS statistical software. The results of the data analysis are presented in this and the two following chapters. This chapter presents the results of the questionnaire survey conducted development-wide. The first part of the questionnaire named *Housing Evaluation* is standardized, and frequently used in BPE and POE studies. It is designed to collect household responses about their experience and satisfaction with the dwelling design, eco-features and indoor environmental conditions. The bespoke *Lifestyle Evaluation* part of the questionnaire was designed by the Researcher, to collect household responses about their environmental attitude, environmental behaviours and their experiences with the provided eco-features and on-site facilities. For contextualisation, the results of the questionnaire were compared to national averages and results from similar studies, where available. From now on, the resident sample (n=90) that completed the questionnaire will be referred to in this chapter as the 'residents'.

5.2. Housing Evaluation Questionnaire

5.2.1. Household Demographics

The data analysis suggests that the residents were equally distributed in terms of sex (50:50). Residents were noticeably younger on average compared to the national averages (ONS, 2011b) (Figure 12).

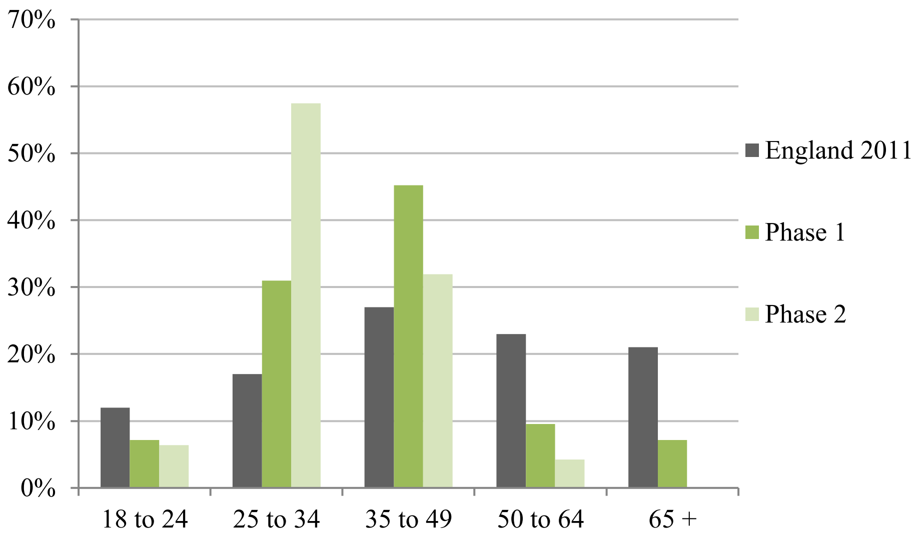


Figure 12 Histogram comparing responses to the question "What is your age?" between the resident responses and national averages (ONS, 2011b).

With regard to the length of occupation, half of the households (48%) (mostly from Phase 2) occupied their homes less than one year. This implies that they did not fully experience both winter and summer conditions, which is typically required in POE studies.

The analysis showed that on average, households consisted of 0.6 of minors (younger than 18 years old) and two adults. The resulting mean household size of 2.6 (*SD* = .97) was slightly higher compared to the national average size of 2.3. Figure 13 shows that the mean occupancy per number of bedrooms increased gradually with each additional bedroom. Using a polynomial trend line ($R^2 = 1$), estimated mean occupancy of 1-bed flats would be 1.95.

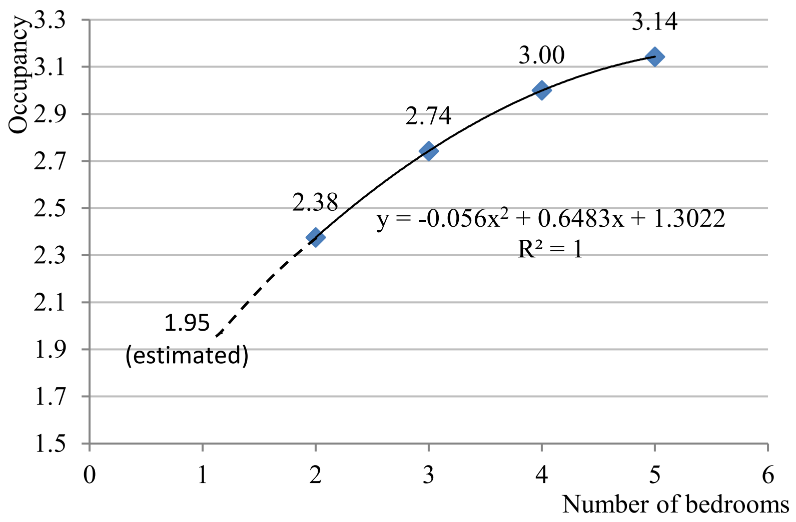


Figure 13 Scatter plot relating the mean number of occupants and the mean number of bedrooms.

The majority of the residents (61%) reported to be mostly at home in the evenings and weekends. A quarter of the residents tended to be at home most of the time, 2% worked from home, while 13% had a varying work schedule. Statistical analysis using Fisher's Exact Test suggested that owners were more likely to occupy the dwelling mostly in the weekends and evenings compared to other tenures, with marginal significance level (p = .063) (Figure 14).

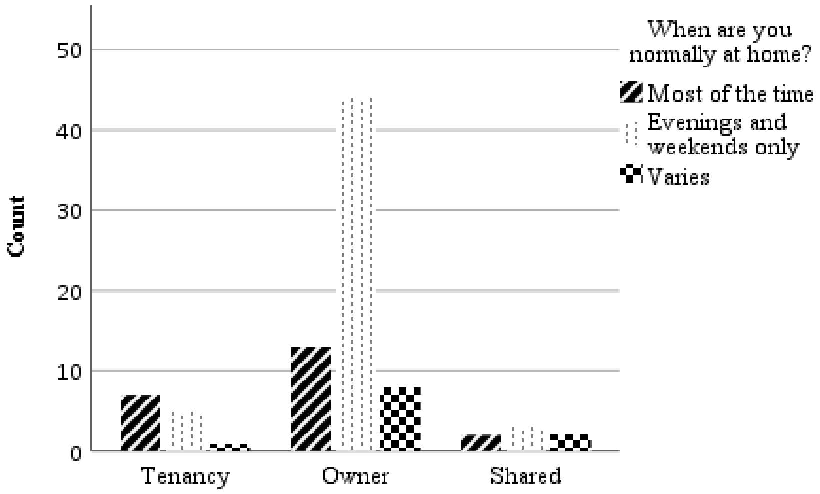


Figure 14 Comparing the frequency of responses regarding typical dwelling use pattern across tenure.

5.2.2. Overview of Results

The mean response rate of 90 residents to all 48 quantitative questions was 94%. As seen in Figure 15, the responses per topic varied. At the time of the survey, some households did not yet experience winter conditions in their new home, which was reflected in reduced number of responses. Also, 12 residents were not able to compare the costs of energy and water use (bills) between their current and previous accommodation.

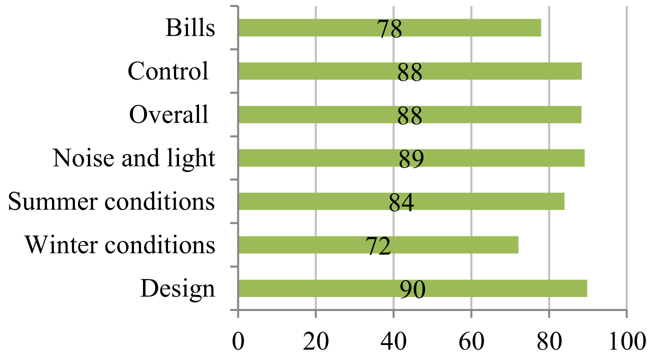


Figure 15 Mean number of responses per questionnaire topic (n=90).

The overview of the questionnaire results can be seen in Figure 16. As mentioned before, the mean score (vote) for each variable was compared to the score of a sample of 58 surveyed new-build housing developments in the UK, as a benchmark dataset. The 'slider' graphic plots in Figure 16 show the residents' mean vote (marked in colour), in relation to three ticks on the top of the slider, which indicate the mean and the standard error of the mean (SEM) of the benchmark. The mean score marked in yellow, green and red colour indicate similar, better and worse score, respectively, compared to the benchmark.

The summary index plot in the same Figure compares the overall mean score to the dataset, capturing the following variables; impact on health, satisfaction with indoor air conditions, air temperatures, noise, lighting, design and with how well dwelling features meet the needs of the household. The results suggested that the overall satisfaction with case study dwellings was average compared to the benchmark.

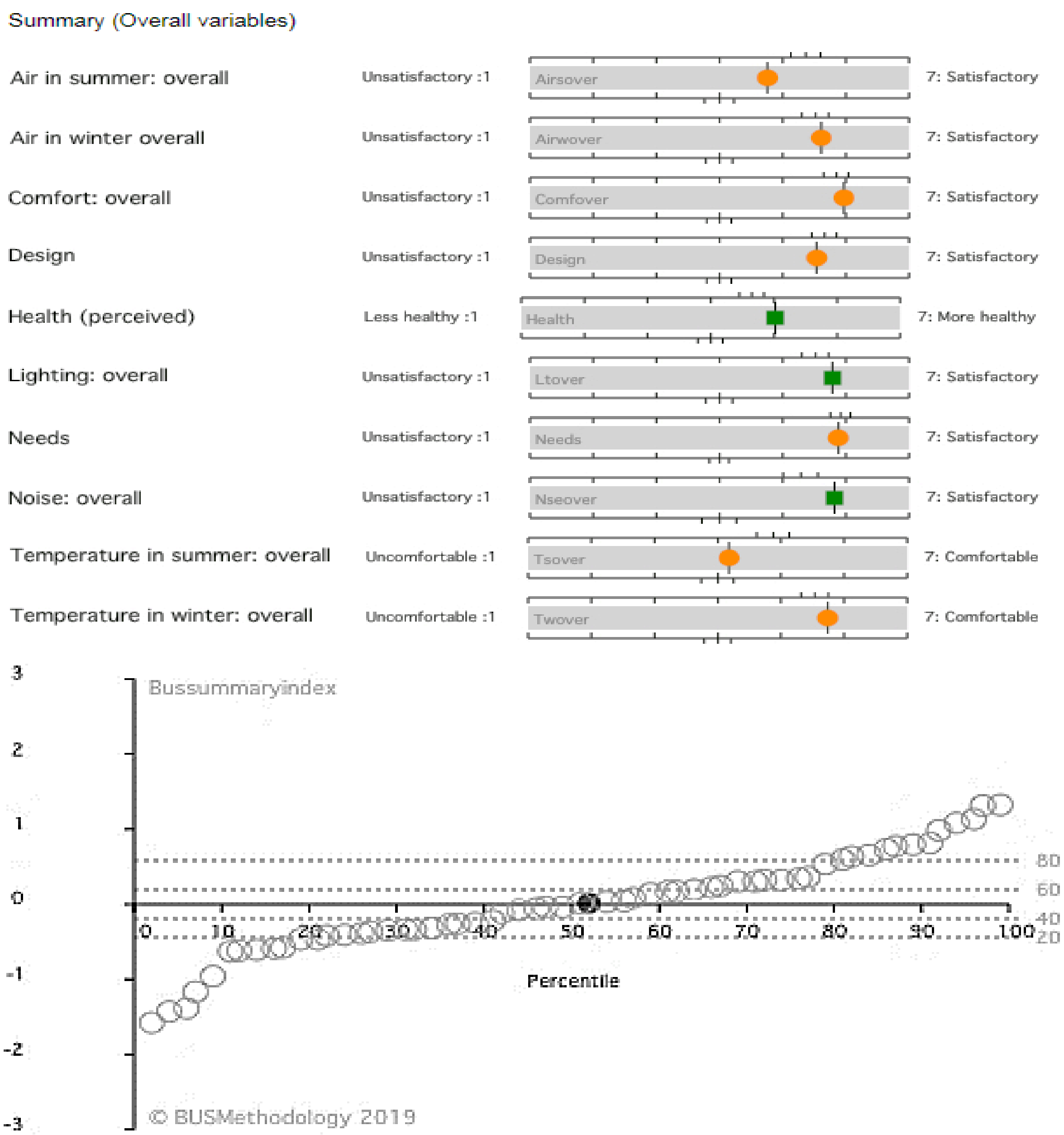


Figure 16 Above: Slider bars comparing the mean results to the benchmark for key variables. Below; Comparing the summary index of the case study development to the index of other 58 housing studied. Source: Adrian Leaman [14].

Table 20 summarises the variables with a mean score placed outside of the SEM of the benchmark, which indicates a more pronounced difference. In the winter season, in some aspects the development has performed better, while in other aspects it has performed worse.

[14] Received from Adrian Leaman (adrianleaman@usablebuildings.co.uk), http://www.usablebuildings.co.uk

Poorer performance during the summer season is apparent. With regard to three other variables, the score was better compared to the benchmark dataset.

Season	Lower score compared to the benchmark	Better score compared to the benchmark
Winter	• Drier air • Higher heating costs	• More odourless air • Better control over heating
Summer	• Air more still and less satisfactory • Overall temperature hotter and more uncomfortable • Lower control over cooling	• Temperatures more stable
Other		• Higher satisfaction with noise • Slightly higher satisfaction with lighting • Residents felt healthier

Table 20 Variables with a mean score that was significantly different compared to the benchmark dataset.

5.2.3. The Residence Overall

Over 80% of the residents reported satisfaction with the location of their home, provision of space, layout, appearance, design, and how their home met their needs. Figure 17 presents a summary of the qualitative comments regarding the development's location, provided by 32 participants (36%). The most common positive comments include the proximity to the town, transportation links, green areas and the quietness. In contrast, a few residents felt isolated living on the edge of town. Also, two residents would have preferred having more on-site amenities and activities in town.

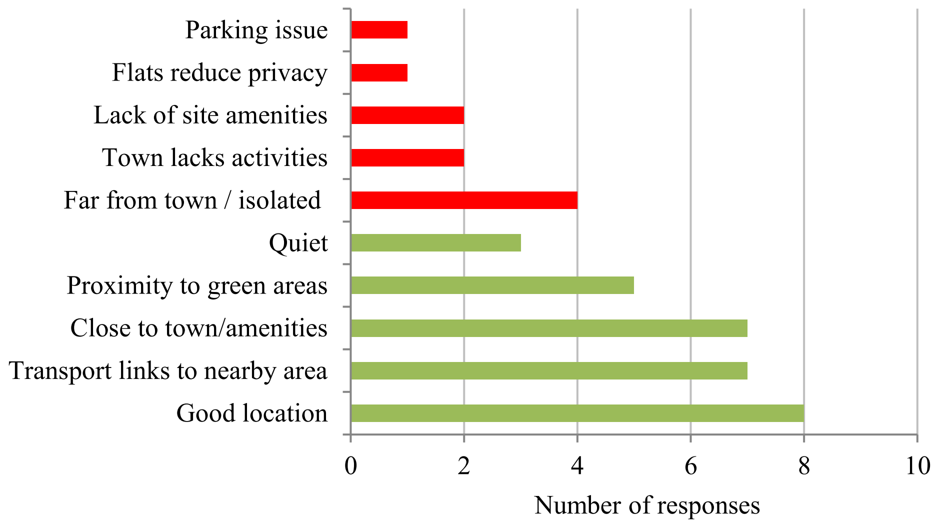


Figure 17 Frequencies of qualitative responses about the site's location.

5.2.4. Conditions in the Heating Season

The mean score in regard to the winter season were similar to the benchmark in all but two aspects; the air was considered drier, and had less odour (Figure 18). Although the great majority of the residents were comfortable and satisfied with the indoor conditions, a quarter of the residents still felt cold. The majority of the residents felt that the indoor air was dry, fresh and odourless, while some felt that the air was humid, stale, and with odours. Less than half (43%) of the residents also thought that the air temperature was not stable. This could be related to the common home heating regime; boosting the heating when necessary (see section 7.4.2 for more details).

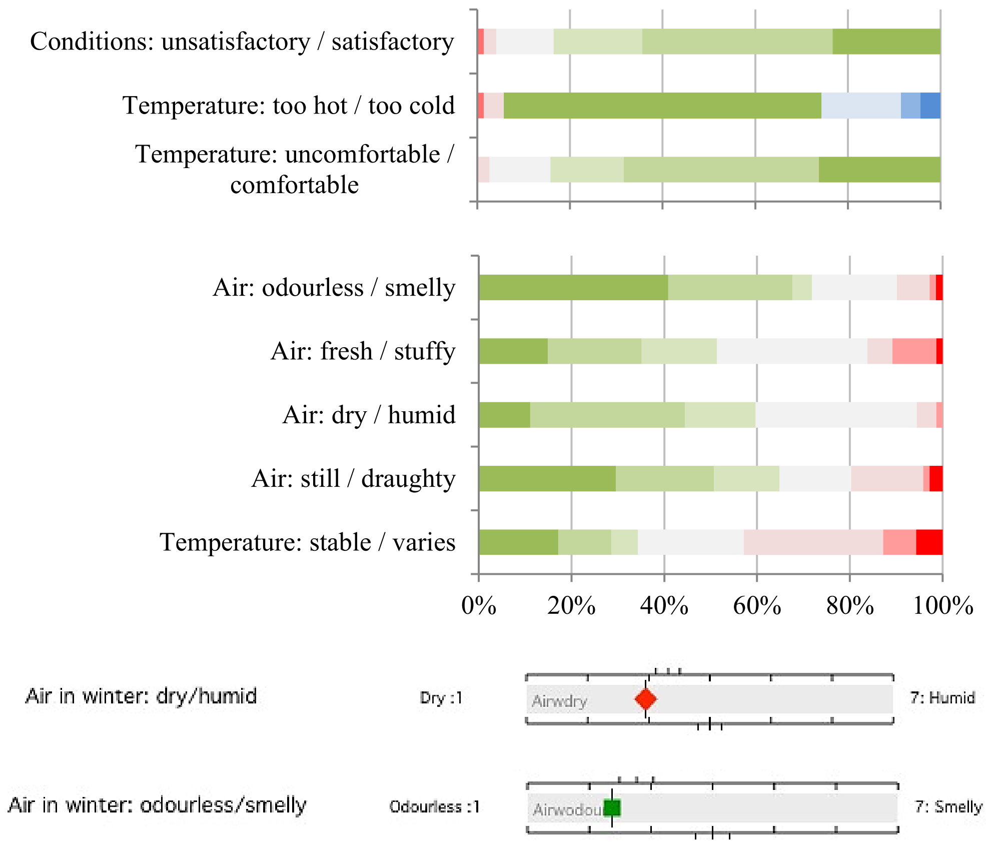


Figure 18 Above: Distribution of responses to questions about the dwelling indoor conditions during the winter season. Below: Slider bars comparing the mean score to the benchmark in regard air dryness and odour.

Fisher's Exact test suggested that the distribution was not equal across all dwelling types ($p < .001$). Figure 19 indicates that the households living in detached and semi-detached dwellings were more likely to have felt cold. This could be attributed to higher fabric heat loss due to larger façade area that is exposed to the outside air.

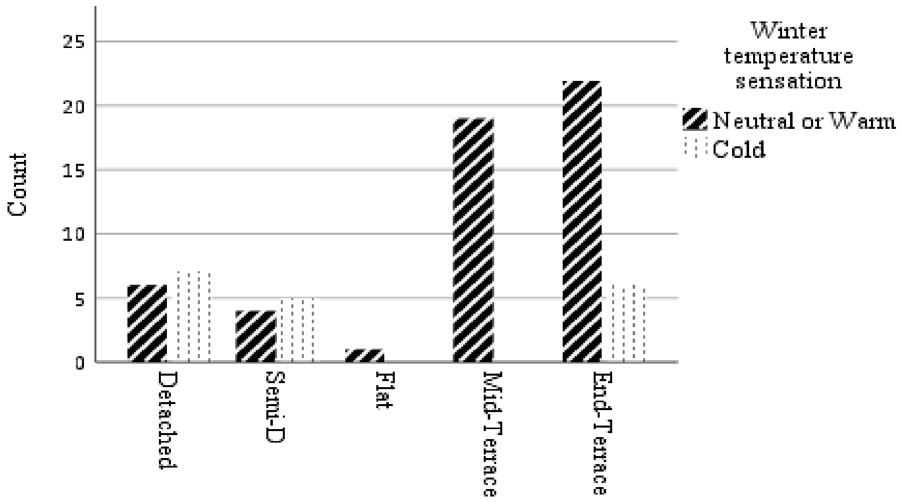


Figure 19 Comparing frequencies of responses about the winter temperature sensation (too hot / too cold) across dwelling typology.

Qualitative comments about heating their home provided by almost half of the residents (44%), offered more insight into the possible causes of the thermal discomfort (Figure 20). Heating issues were mostly reported by households from Phase 1. The most frequently mentioned issues were the slow-heat up of the house, drafts, inability to heat their home above a certain temperature limit, cold bathroom and the lounge. Household interviews reveal more details about the reported heating issues (section 7.4.5).

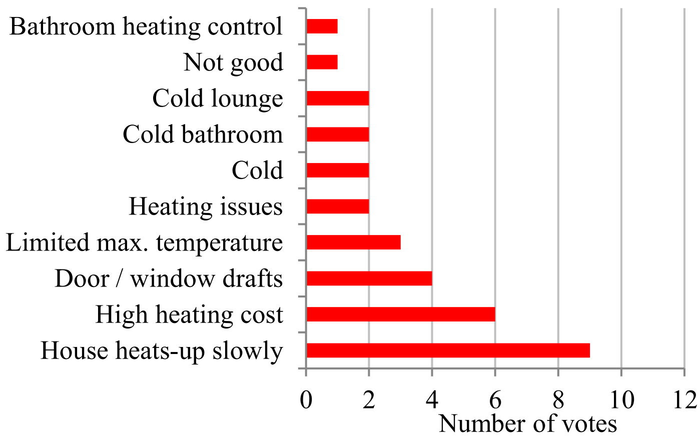


Figure 20 Frequencies of qualitative comments about heating.

5.2.5. Conditions in the Non-heating Season

Although 40% of the residents reported feeling uncomfortable and two-thirds (64%) felt hot, only a quarter (23%) of the residents were unsatisfied with these conditions (Figure 21), which suggests a fair level of tolerance. The mean scores for temperature sensation and satisfaction with the conditions were more negative compared to the benchmark Also, the air was regarded as more still and less satisfactory. Overall about three-quarters of the case studies within the dataset provided more comfortable and satisfactory conditions during the summer, compared to the case study dwellings.

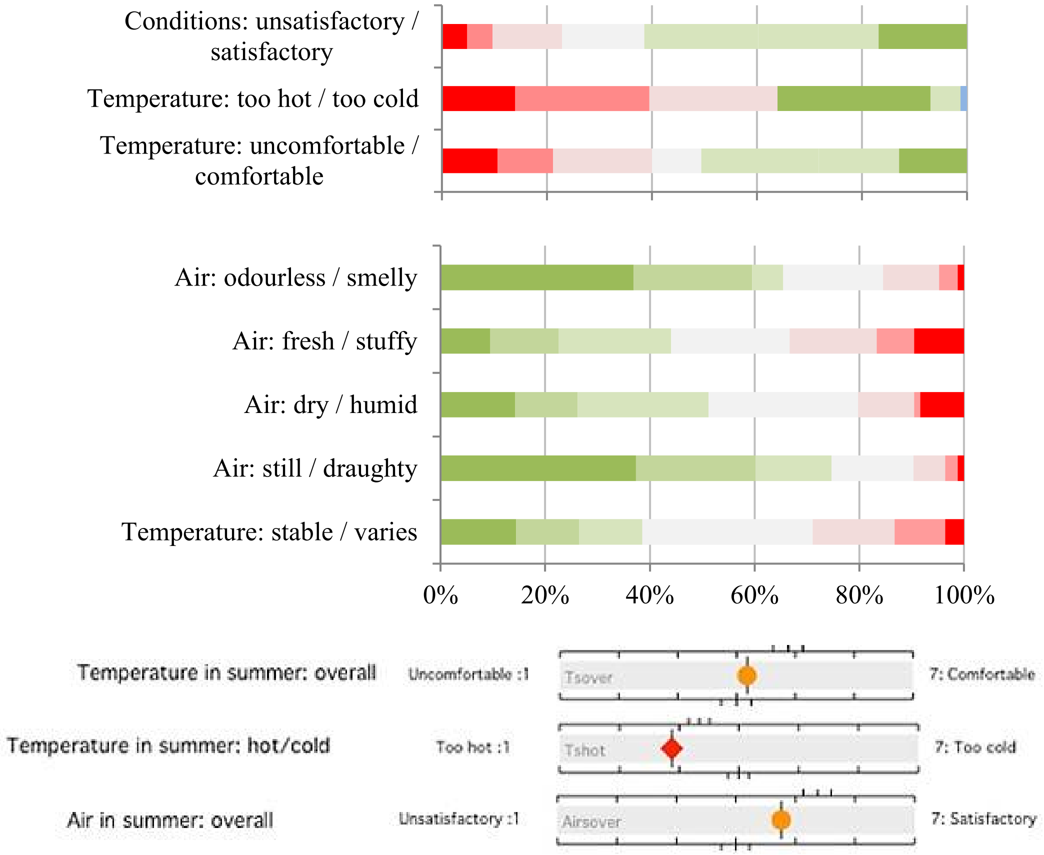


Figure 21 Above: Distribution of responses to questions about the dwelling indoor conditions during the summer season. Below: Slider bars comparing the mean score to the benchmark in regard to thermal comfort, thermal sensation and satisfaction with the air.

Spearmen's rho correlation suggested that the thermal comfort responses were positively and strongly corelated with the temperature sensation (r_s = .68, p < .001), and moderately corelated with the air freshness (r_s = 0.46, p < 0.001) variable. The temperature sensation differed in relation to orientation of living rooms (U = 650.50, p = .027). Residents with living rooms exposed to the noon and/or afternoon solar radiation (S, SW, SE and W orientations) reported feeling more hot (M = 3.2, SD = 1.13) compared to the residents with living rooms in other orientations (M = 2.6, SD = 1.19).

Figure 22 presents a summary of qualitative comments about the indoor conditions during the summer season, provided by half of the residents (51%). Residents most often complained about feeling hot and the inability to cool their home.

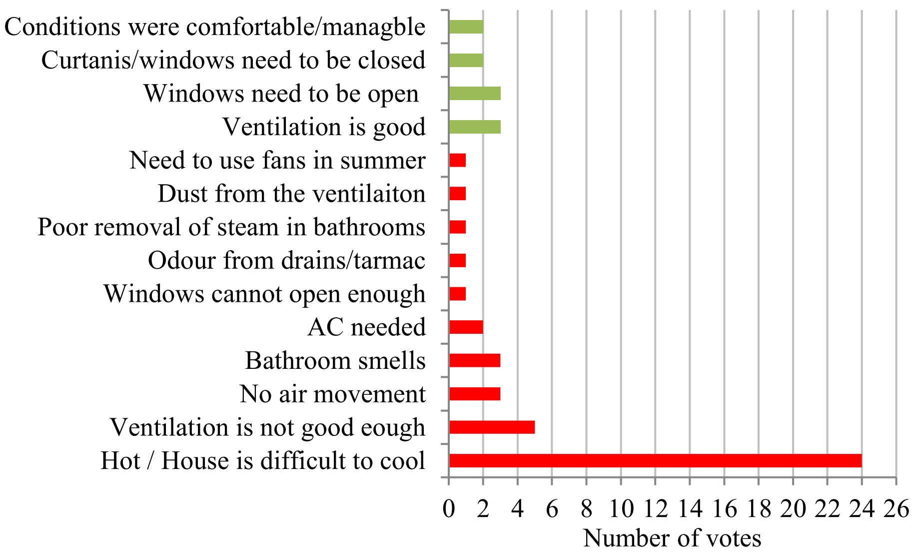


Figure 22 Frequencies of qualitative comments about the indoor conditions during the summer season.

5.2.6. Control Over Heating, Cooling, Ventilation and Noise

Residents felt like they have had the highest level of control over heating (80%) and the lighting levels (78%), following by ventilation (57%), noise levels (43%) and cooling (31%) (Figure 23). Residents had significantly lower control over cooling compared to the benchmark. Expectedly, Spearmen's correlation suggested that the summer thermal comfort was weakly correlated with the control over cooling (r_s = .39, p < .01) and ventilation (r_s = .27, p = .013) variables.

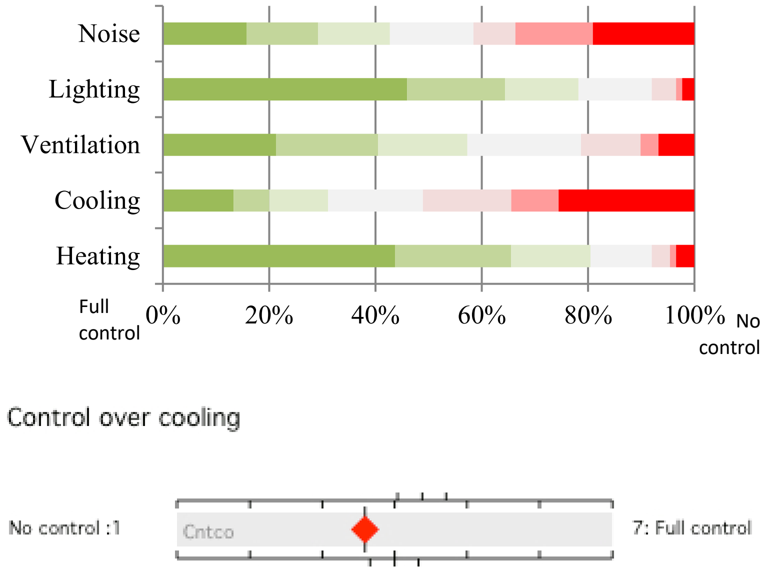


Figure 23 Above: Distribution of responses to questions; "How much control do you personally have over … noise, lighting, ventilation, cooling and heating?". Below: Slider bar comparing the mean score to the benchmark in regard to the control over cooling.

5.2.7. Overall Comfort and Health

Overall, almost all of the residents (94%) felt generally comfortable in their new homes. Also, more residents felt that their health improved since they have moved-in, compared to the benchmark (Figure 24). Qualitative comments from a quarter of the residents (27%) stated that the proximity to green spaces (fresh air, ability to walk) and comfortable indoor conditions during the winter (warm and less damp) had a positive effect on their health.

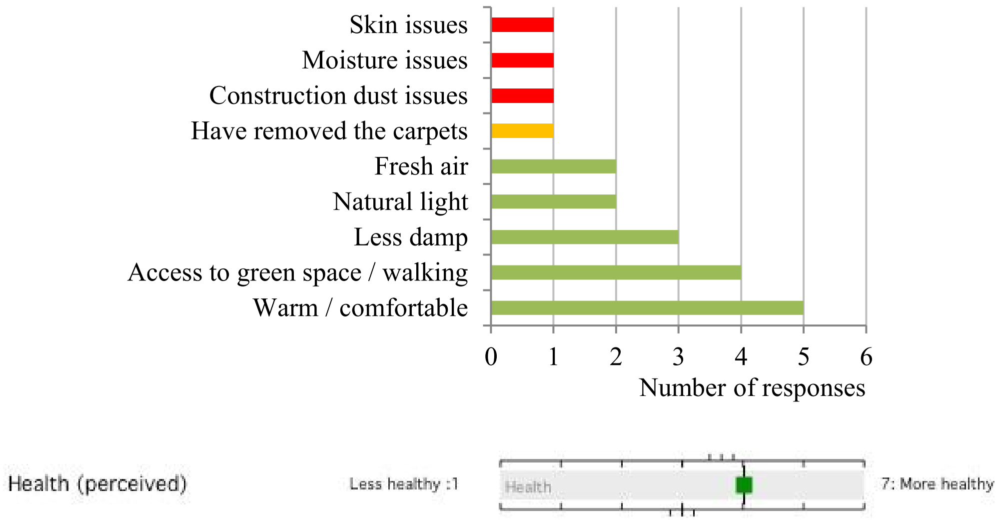


Figure 24 Above: Frequencies of qualitative comments about the personal health. Below: Slider bar showing the mean score of the responses to the question: "Do you feel that the building affects your health by making you feel less healthy or more healthy?", compared to the benchmark.

Responses about health were moderately correlated with the summer thermal comfort (r_s = .43, p < .001), and weakly with the winter thermal comfort (r_s = .32, p < .001), and the satisfaction with the indoor conditions during summer (r_s = .36, p < .001) and winter (r_s = .29, p = 0.012) variables. Responses about health were also weakly correlated with the air freshness during the summer (r_s = 0.378, p < .001), and winter (r_s = .263, p = .024) and the control over ventilation (r_s = .25, p = .016) variables. As indicated in Figure 25, Phase 1 residents felt less healthy compared to ones in Phase 2 (p = .39). The perceived change in health was not associated with age.

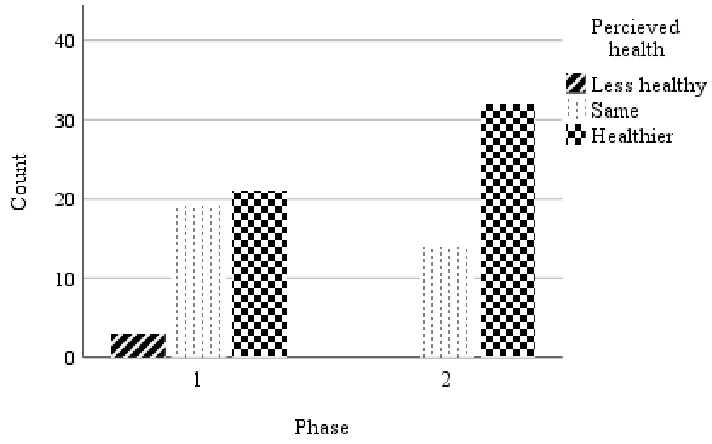
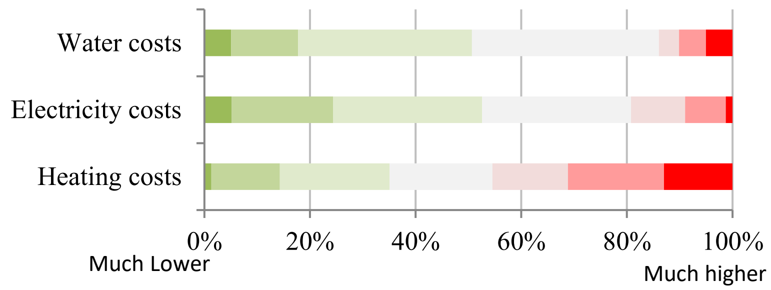


Figure 25 Comparing the frequencies of responses about the personal health between the two building Phases.

5.2.8. Utilities Costs

Less than a quarter of the residents (20%) thought that their current costs of using electricity and water were higher compared to same costs in their previous accommodation (Figure 26). However, two times more residents (45%) regarded their heating costs as higher than before, with a notably higher mean score compared to the benchmark. Household interviews presented later in section 7.4.4 showed that the notion of higher heating costs is related to high standing charge of the community heating system.



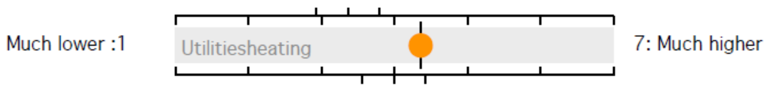


Figure 26 Above: Distribution of responses to the question; "How do your utilities costs compare with your previous accommodation?". Below: Slider bar comparing the mean score to the benchmark in regard to the costs of heating.

The electricity costs variable was negatively and weakly correlated with the frequency of use of solar PV electricity (r_s = - .29, p = .014) and washing clothes on 40°C (r_s = - .24, p = 0.04) variables. These associations are in line with the expectation that energy saving behaviours can reduce grid electricity usage.

Figure 27 shows a comparison between the current and previous heating costs, across different dwelling types. The Kruskal–Wallis test (H (4) = 19.51, p = 0.01), followed by a pairwise post-hoc Dunn test (with Bonferroni adjustments) suggested that households in end-terrace dwellings reported higher heating costs compared to ones in mid-terrace dwellings only (p = .001). A more detailed follow-up BPE study would be needed to investigate the potential causes of this difference.

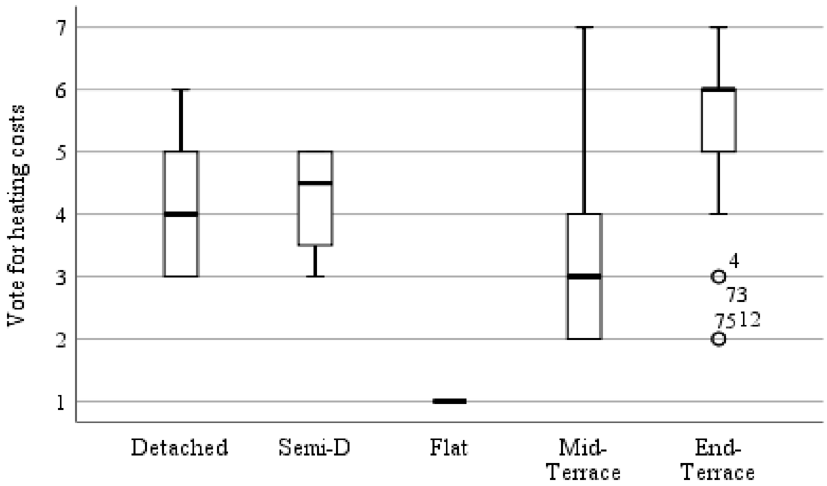


Figure 27 Boxplots of responses to the question; "How do your utilities costs compare with your previous accommodation?" across different dwelling types. Reponses (vertical axis) span from *Much lower than before* (1), *to Much higher than before* (7).

Residents who were attracted to the development partly due to potential energy and water savings reported having higher heating costs (Mdn = 5) compared to the residents who moved-in for other reasons (Mdn = 4) (U = 472.50, p = .009). This indicates that the residents who looked forward living in an energy efficient home were more likely to regard the new costs of heating as high.

5.2.9. Design Features, Noise and Light Levels

Less than half of the residents (47%) provided qualitative responses about their experience with environmental design features of their home (Figure 28). Rainwater harvesting and solar PV panels captured most attention, causing mixed feelings.

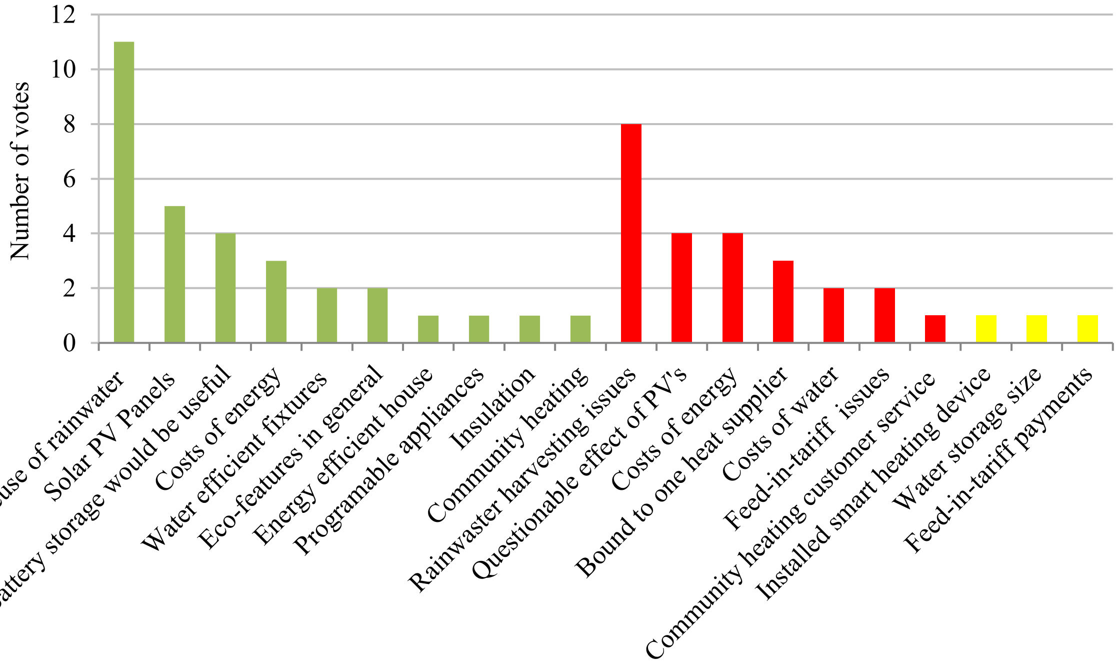


Figure 28 Frequencies of qualitative responses about energy or water saving features. Green, red and yellow colour mark responses that were regarded as positive, negative and neutral, respectively.

The majority of the residents were satisfied with noise and light levels in their home. The mean score in regard to outdoor noise was better compared to the benchmark, probably due to more airtight fabric and triple glazing. Only 12% and 22% of the residents reported hearing too much noise from their neighbours and the street, respectively.

5.3. Lifestyle Evaluation Questionnaire

5.3.1. Response Rates

The second part of the questionnaire containing 29 questions achieved a slightly lower number of responses per topic (Figure 29), compared to its first part. This probably occurred due to response fatigue.

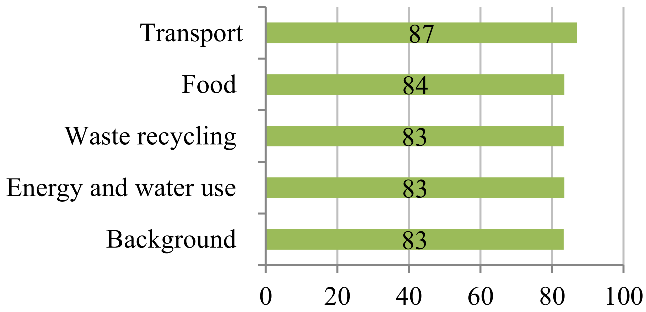


Figure 29 Mean number of responses per each topic of the Lifestyle Evaluation questionnaire part (n=90).

5.3.2. Household Socio-demographics

The data analysis showed that the majority (63%) of the residents reported holding a degree or higher qualification, which was significantly higher than the average for the local town (OCC, 2014) and England and Wales (ONS, 2011a), and similar to the population of the City of London district (68%) (Figure 30). It should be noted that the resident sample was slightly skewed socio-economically, as the survey captured responses from only one from 28 household that live in flats, and from 11% more privately owned dwellings. The higher levels of education found in this study, and higher levels of occupation (Williams, Dair and Lindsay, 2008) and income (Quilgars *et al.*, 2019) reported in other eco-developments, indicated higher socio economic backgrounds for the households in the eco-developments.

Figure 30 Histogram comparing responses to the question: "What is your highest formal qualification level?" between the case study development and averages for the City of London district, England and Wales and the local town.

Residents were asked about the most important reasons for choosing their home in the case study development. Six possible answers were offered (see the Appendix), with an opportunity to name other reasons. As seen in Figure 31, residents have chosen to move to the development primarily due to the characteristics of the dwellings (78%), followed by the development's eco-credentials (46%), potential energy and water savings (43%), and, lastly, the access to work (37%) and family or friends (23%). In other eco-developments, the architectural characteristics of the development were similarly regarded as most important by the households (Vestbro, 2007; Williams, Dair and Lindsay, 2008; Freytag, Gössling and Mössner, 2014; Quilgars *et al.*, 2015).

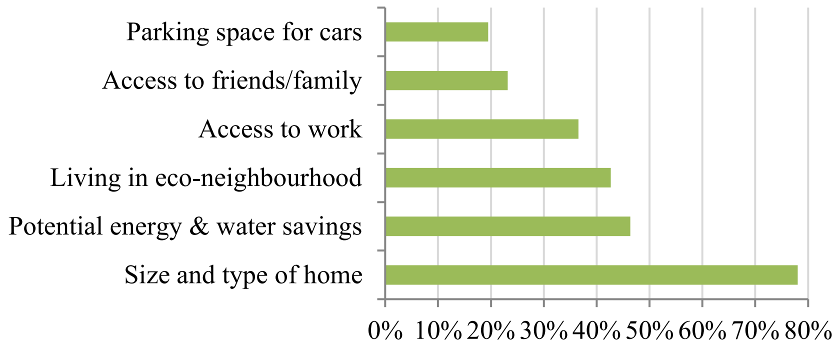


Figure 31 Ratios of responses to the question: "Which were the most important reasons for choosing your home?"

Three questions about household environmental attitudes and energy- and water-saving behaviours from DEFRA's national survey (2009) were used in this questionnaire. As presented in Table 21, the residents who were attracted to live in an eco-neighbourhood had significantly ($p < .05$) higher scores (compared to the rest of the sample) of responses to three questions regarding environmental attitude and to one question regarding energy- and water-saving behaviours.

Grouping Variable: Living in an eco-neighbourhood was one of important reasons for choosing your home.	Environmental attitude			Energy and water saving behaviour		
	Need more info on eco-behaviour	Perceived eco-behaviour	Behaviour contributes to climate change	Cutting down on water use	Living room lights on	Washing clothes at 40 degrees
Mann-Whitney U	612.50	503.00	628.00	629.00	748.00	857.50
Wilcoxon W	1837.50	1679.00	1853.00	1854.00	1378.00	2082.50
Z	-2.37	-3.17	-2.18	-2.13	-1.06	0.00
Asymp. Sig. (2-tailed)	**0.018**	**0.002**	**0.029**	**0.033**	0.289	1.000

Table 21 Results of the Mann-Whitney U Test, comparing the difference between the residents who were attracted to live in an eco-neighbourhood, and the rest of the resident sample in regard to environmental attitude and energy and water saving behaviour variables.

Considering that only three questions about environmental attitude were included in the questionnaire due to its brevity, their low internal consistency indicated by the Cronbach's alpha ($\alpha = 0.12$) was not surprising. Statistical analysis showed that all three environmental attitude variables were weakly correlated only with the number of waste bins that residents reported to use frequently ($r_s = .30$ to $r_s = .33$, $p < .05$).

When compared to national averages, the responses to three questions about environmental attitudes demonstrated only an increase in the awareness about the personal impact on climate change (Table 22, Figure 32 to Figure 34), which was weakly associated with higher education levels (r_s = .30, p = .009). In a similar notion, in two other eco-development studies, households appeared to be slightly more knowledgeable but not more concerned about the environment (Williams, Dair and Lindsay, 2008; Hostetler and Noiseux, 2010).

	Perceived eco-behaviour	Need more info on eco-behaviour	Behaviour contributes to climate change
Mann-Whitney U	3,917.5	3,719.0	3,162.0
Wilcoxon W	8,768.5	8,669.0	6,732.0
Z	-0.311	-1.298	-2.801
Asymp. Sig. (2-tailed)	0.756	0.194	**0.005**

Table 22 Results of the Mann-Whitney U Test, comparing the responses to three questions regarding the environmental-attitude between the case study development and averages for England (DEFRA, 2009).

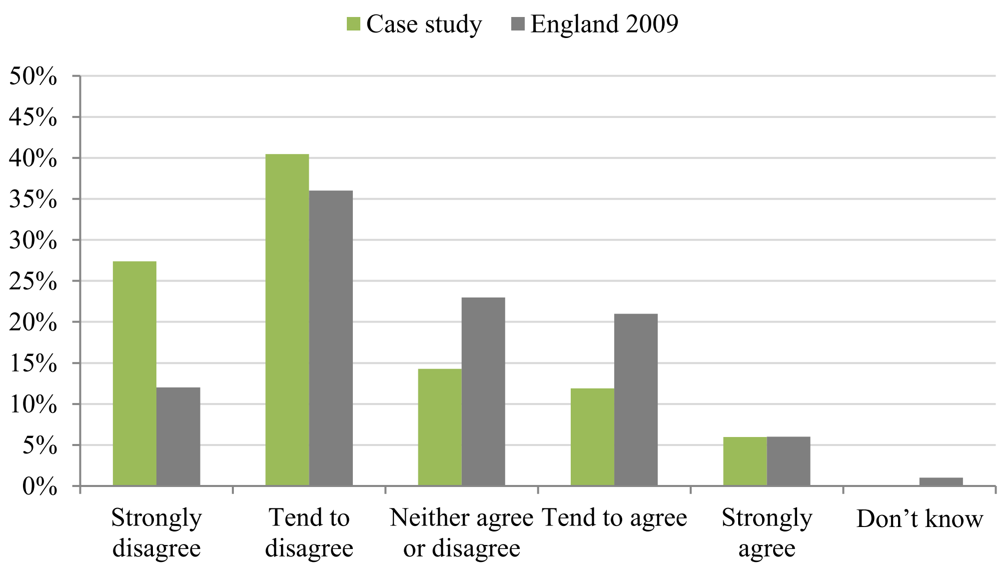


Figure 32 Histogram showing responses to the question: “I don’t believe my everyday behaviour and lifestyle contribute to climate change.”

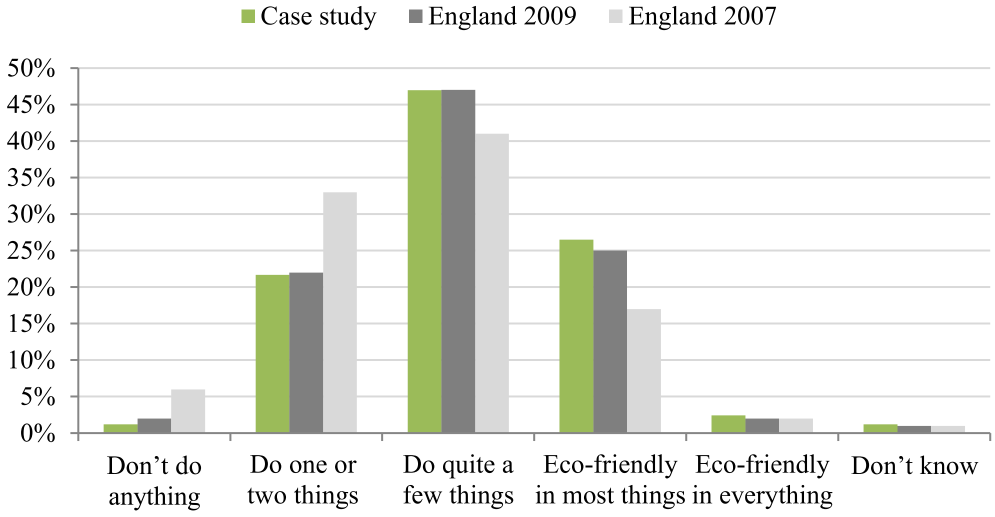


Figure 33 Histogram showing responses to the question: “Which of these would you say best describes your current lifestyle?”

As seen in Figure 34, about two-thirds (64%) of the residents thought that they could benefit from additional information about how to behave in a more eco-friendly way. In this light, sideling the proposed informational measures in the actual delivery could be perceived as a lost opportunity for enabling behavioural change.

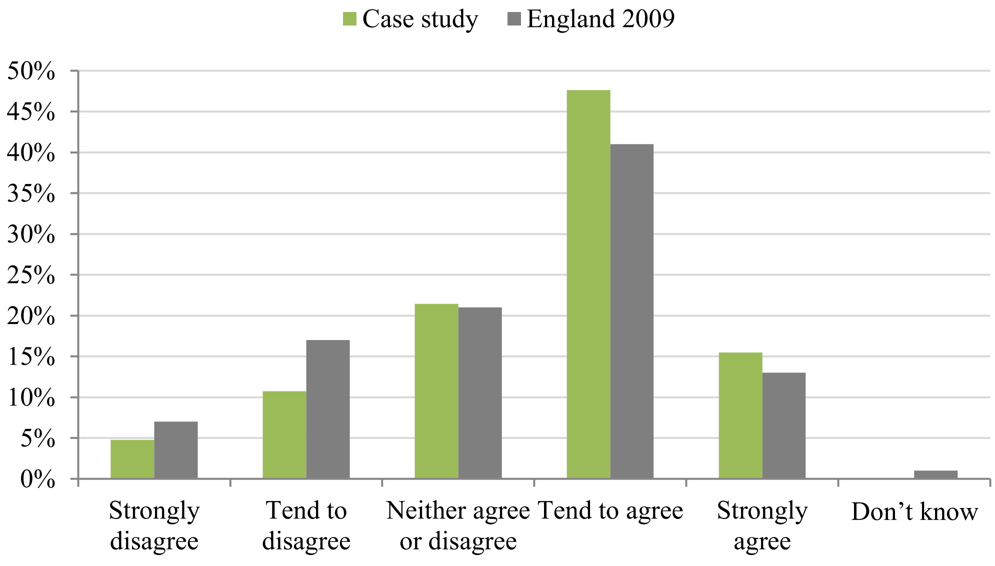


Figure 34 Histogram showing responses to the question: “I need more information on what I could do to be more environmentally (eco) friendly.”

As observed in Figure 33 and Table 22, the residents' perceived occurrence of eco-friendly behaviours did not significantly differ from the national averages. Contrastingly, more than two-thirds (70%) of the residents saw their new lifestyles as more eco-friendly than before (Figure 35). The perception of having a more eco-friendly lifestyle was weakly associated with feeling more cautious in using energy (τ_c = .36, p < .001) and in recycling waste (τ_c = .34, p = .002), with noticing lower electricity bills (r_s = -.24, p = .038), and with the use of major appliances in order to exploit the PV electricity (r_s = -.22, p = .045).

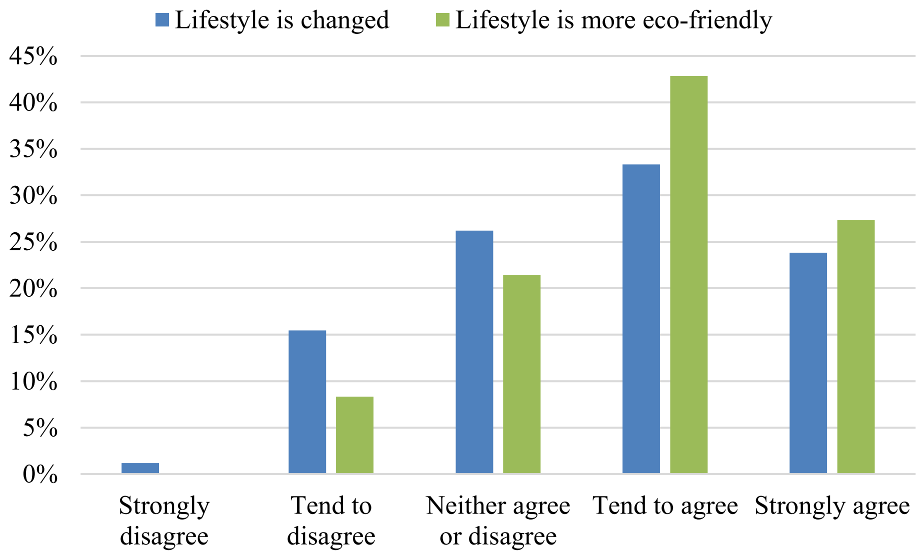


Figure 35 Histogram showing responses to questions "Living in the new development has changed my lifestyle" and "Since living in the new development my lifestyle has been more eco-friendly".

5.3.3. Energy and Water Use Behaviours

The statistical analysis suggested that the responses to three questions about common energy- and water-saving behaviours adopted from the same DEFRA's survey (2009) were not significantly different compared to the national averages (Table 23).

	Cutting down on water use	Living room lights on	Washing clothes at 40 degrees
Mann-Whitney U	3,868.5	4,173.0	3,662.5
Wilcoxon W	7,438.5	9,223.0	7,232.5
Z	-0.714	-0.079	-0.537
Asymp. Sig. (2-tailed)	0.475	0.937	0.591

Table 23 Results from Mann–Whitney U test comparing scores for three questions about energy- and water-saving behaviours between case study development and the averages for England.

As observed in Figure 36 and Figure 38, the responses suggest that the households might be perhaps even less conscientious when it comes to saving energy and water. Compared to the national averages, residents seem to be less vigilant to *always* close the light in empty rooms (10% less votes) and cut water use (18% less votes). A slightly lower motivation to energy and water saving could indicate of a rebound effect, due to the provision of energy and water efficient dwelling features.

Three energy- and water-saving behaviour variables were weakly correlated with the environmental attitude variables in only two out of nine possible cases. To name one, leaving the room light on variable was weakly correlated with the belief in personal contribution to climate change ($r_s = .29$, $p = .007$).

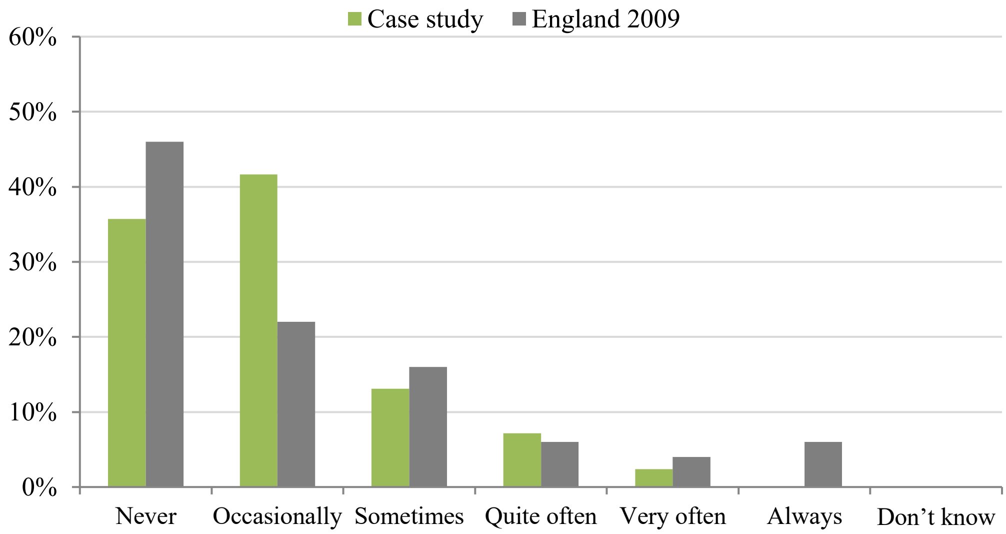


Figure 36 Histogram showing responses to the question: "How frequently you personally leave the lights on when you are not in the room?"

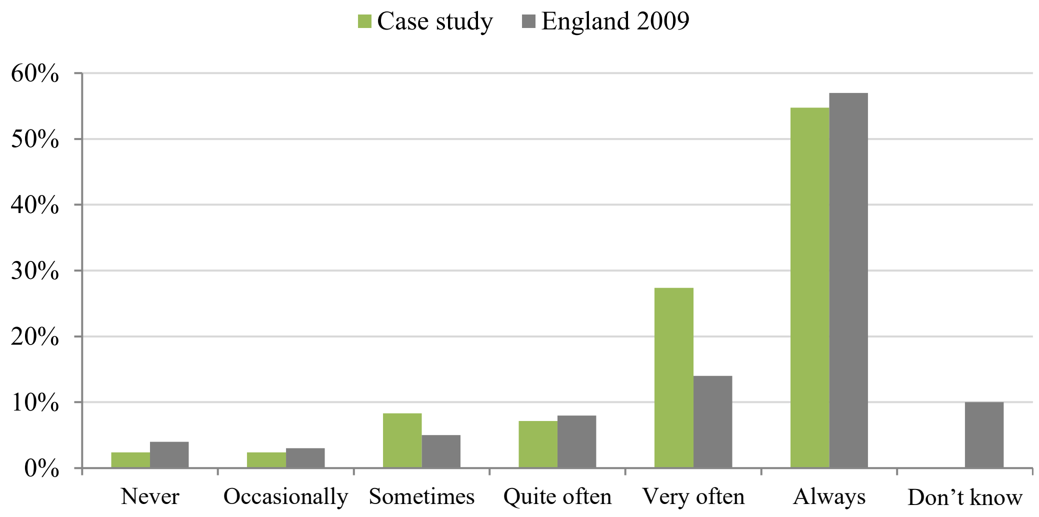


Figure 37 Histogram showing responses to the question: “How frequently you wash clothes at 40 degrees or less?”

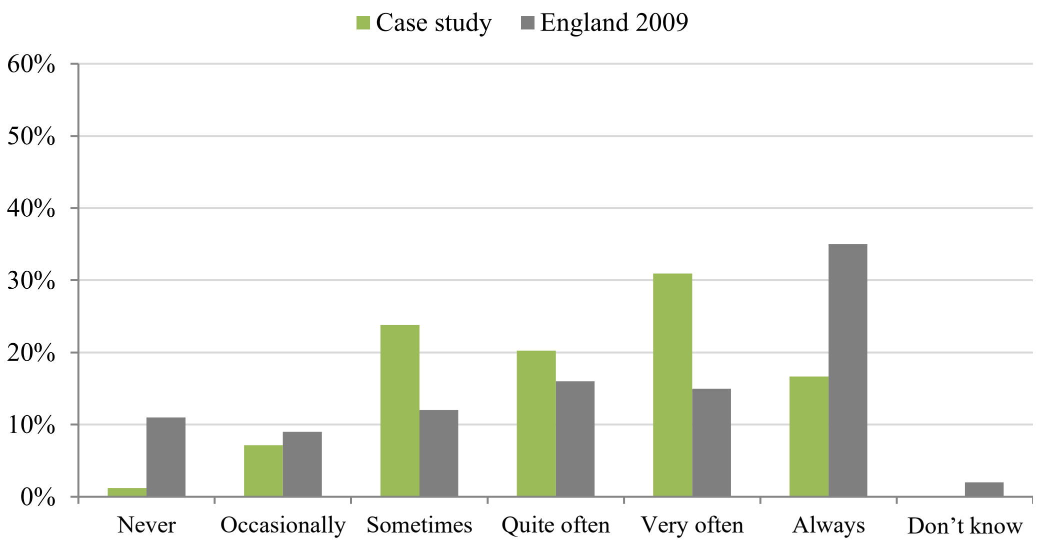


Figure 38 Histogram showing responses to the question: “How frequently you make an effort to cut down on water usage at home?”

More than two-thirds of the residents (72%) reported that living in their new home made them feel more cautious in using energy. As seen in Figure 39, this was slightly higher than the rate reported in 13 eco-developments (Williams, Dair and Lindsay, 2008). This difference was attributed to a more widespread provision of energy-efficient features in the case study dwellings. About a third (36%) of the residents felt more cautious in using energy due to the provided home information display (Shimmy). For 10% of the residents the device did not work or had not yet been installed. Most of the residents (83%) reported frequently using the washing machine, dishwasher and tumble dryer when PV electricity was generated (Figure 41).

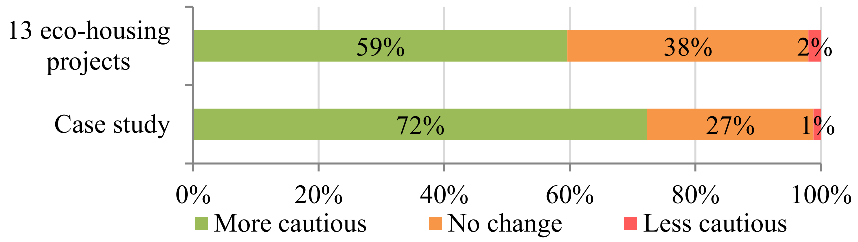


Figure 39 Comparing the ratios of responses to the question: "Has living in your energy efficient home encouraged you to be ...?" between the case study development and 13 other eco-housing developments.

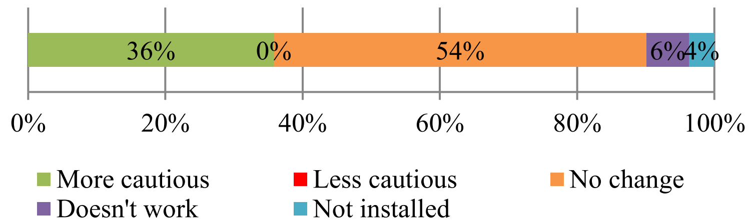


Figure 40 Ratios of responses to the question: "Does having information about home energy usage on Shimmy encourage you to be...?"

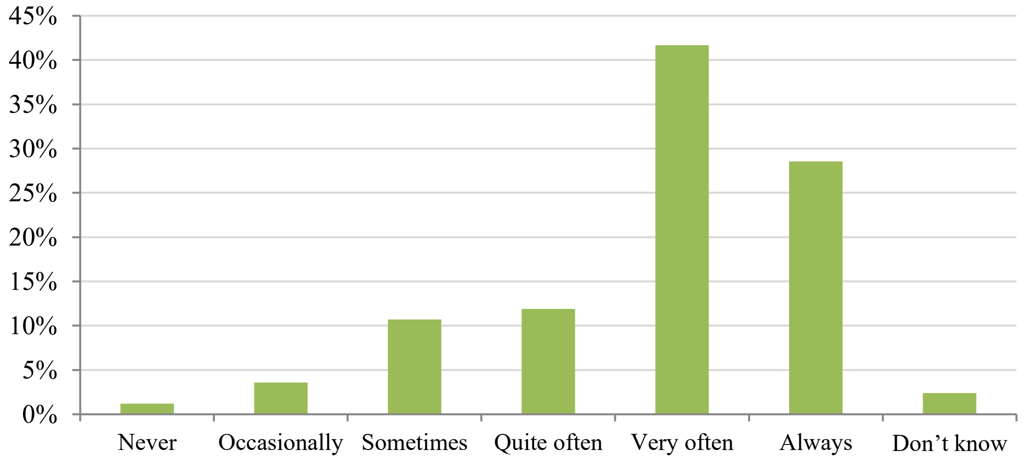


Figure 41 Histogram showing responses to the question: "How frequently you personally use some appliances like the washing machine and dishwasher during sunny weather when solar energy is available?"

Figure 42 shows that five households had already installed an air conditioning (AC) system, and about a third of households were considering installing the system in the future. The responses were not significantly different between the two building phases (p > .05). Expectedly, the statistical analysis showed that these responses associated with responses in regard to indoor conditions (Table 24). Residents who already have or were considering installing the AC (responses *Yes* and *No, but considering it*) have reported stuffier air, felt more uncomfortable, hot, and with lower control over cooling and ventilation, compared to the residents who were not considering the AC.

Grouping Variable: Did you install air conditioning in your home due to hot weather?	Summer temperature comfort	Summer temperature sensation	Summer air freshness	Control of cooling	Control of ventilation
Mann-Whitney U	370.5	268	489	463.5	553.5
Wilcoxon W	1036.5	898	1479	1129.5	1219.5
Z	-4.026	-5.108	-2.651	-3.347	-2.479
Asymp. Sig. (2-tailed)	0.000	0.000	0.008	0.001	0.013

Table 24 Results from Mann–Whitney U test comparing scores for five variables about indoor conditions between the residents who already have or were considering installing the AC and the rest of the resident sample.

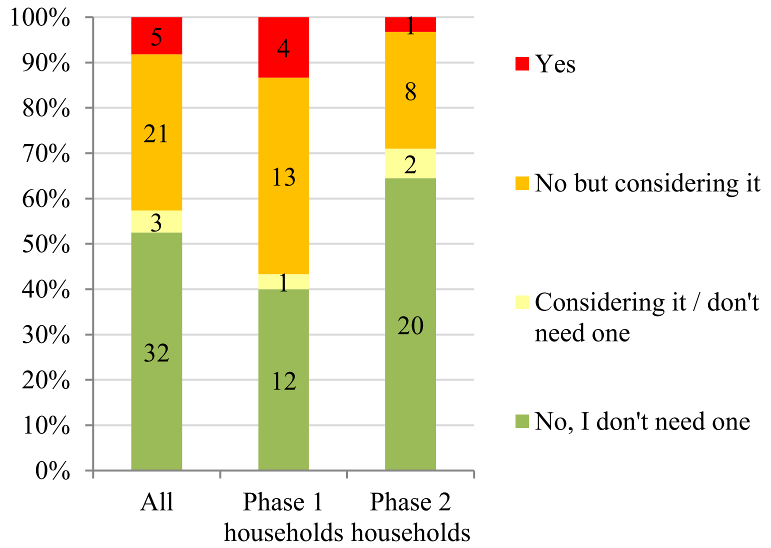


Figure 42 Frequencies of responses to the question: "Did you install air conditioning in your home due to hot weather?", presented per building Phase, and in aggregate.

Figure 43 shows that two-thirds of the residents preferred setting the thermostat temperatures within a 20 - 24°C range, while about a quarter (23%) preferred temperatures within a 15 - 19°C range. The results suggested that households preferred higher temperatures compared to national averages (DEFRA, 2009), which was expected due to high dwelling fabric efficiency. The mean score in regard to temperature (20-21°C range) was in line with the suggested living room temperature of 21°C in SAP ((BRE, 2012). The difference in the reported temperature setting between building phases, tenure and typology was not statistically significant ($p > .05$).

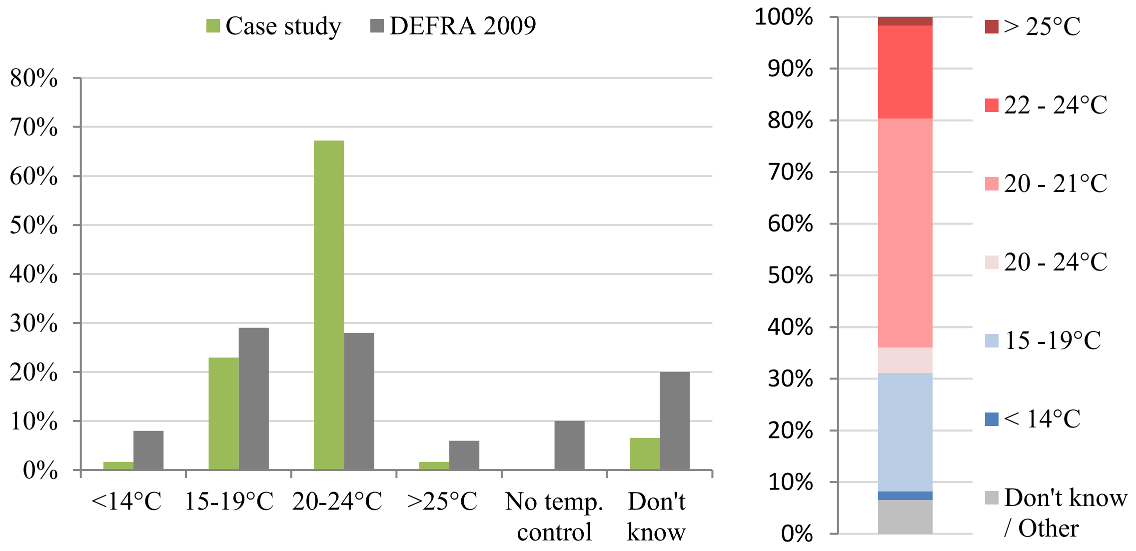


Figure 43 Left: Histogram comparing the responses to the question: "Usual temperature setup of your thermostat?" between the case study development and the national averages. Right: Distribution of the responses on a stacked bar graph.

5.3.4. Waste Recycling

Most of the residents (88%) reported frequently using general recycling, glass recycling and food waste bins. The garden compost bin and kitchen bins were frequently used by significantly fewer residents (57%) (Figure 44). As seen in Figure 45, more residents reported regularly recycling and composting compared to the national averages (DEFRA, 2009), and to households in 13 eco-developments (Williams, Dair and Lindsay, 2008). In DEFRA's report, "always", "very often" and "often" votes were aggregated to represent behaviour that can be considered as regular.

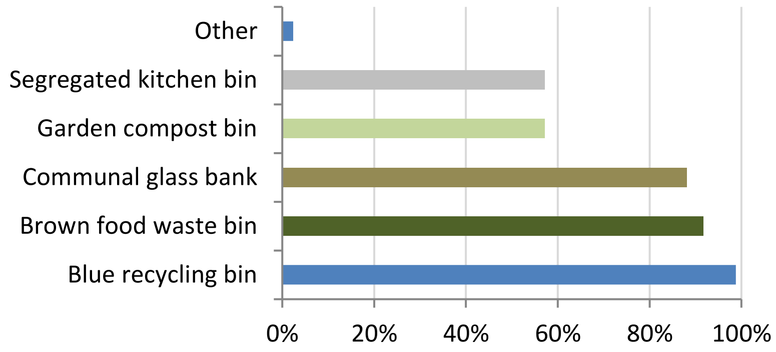


Figure 44 Ratio of residents that reported to regularly use different on-site waste facilities.

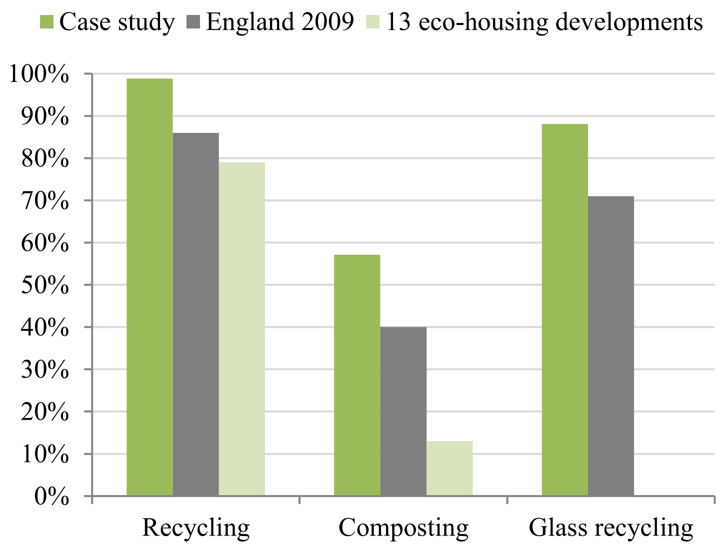


Figure 45 Comparing the reported waste recycling and composting rates between the case study development, the national averages and 13 eco-housing developments.

More than two-thirds of the residents (70%) felt that the on-site waste facilities encouraged them to recycle (Figure 46). It can be argued that households who regularly used more types of recycling bins showed higher attentiveness to recycling. Statistical analysis showed that the number of different recycling bin types used was weakly associated with all three environmental attitude variables ($r_s = .3$, $p < .05$).

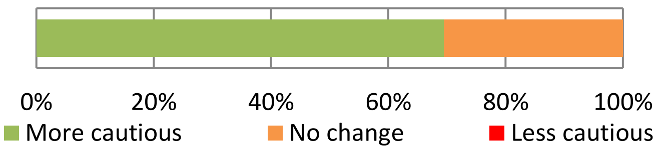


Figure 46 Ratios of responses to the question: "Do available recycling facilities make you more cautious in the way you recycle?"

To complement the results of the questionnaire, annual results for weight-based waste monitoring focused on the development site were sourced from the local authorities. As observed in Table 25, the annual results over a three-year period did not demonstrate a clear trend. However, in contrast to reported behaviours, the results did indicate that the actual rates were relatively similar to the national (45%) and district averages (55%) (DEFRA, 2021a), and significantly lower than the set target of 80%.

Period	Organic waste (kg)	Dry Recycling (kg)	Residual Waste (kg)	Total waste (kg)	Organic waste	Dry recycling	Total organic/ dry
2017/18	16790	13190	36660	66640	25%	20%	45%
2018/19	19190	22020	50280	91490	21%	24%	45%
2019/20	33600	39035	48060	120695	28%	32%	60%

Table 25 Annual waste arising for the eco-development from measurements taken over three consecutive years. Data provided by the local authorities.

5.3.5. Food Behaviours

As observed in Figure 47, about a third of the residents reported regularly buying organic food (37%) and growing food in their gardens (31%), which were similar rates compared to the national averages (DEFRA, 2009; OTB, 2015) and averages for Ireland (DAFM, 2014). Only 15% of the residents reported regularly visiting farmers' markets. The number of different low-impact food behaviours in which residents had engaged was weakly associated with higher education levels (r_s = .23, p = .48), and with eating less meat (r_s = .22, p = .47).

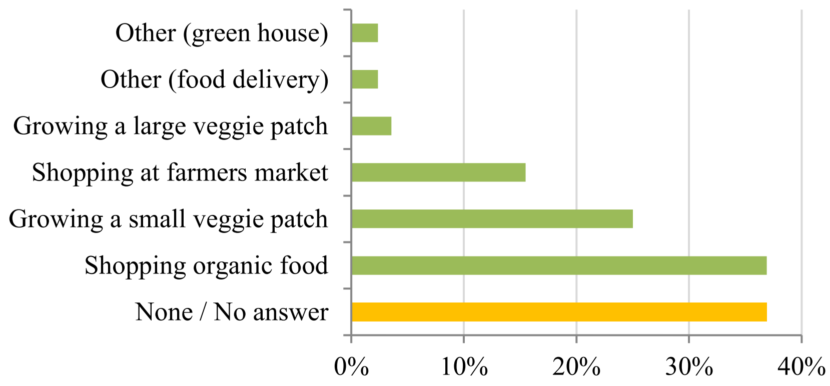


Figure 47 Frequencies of responses to the question: "Which of these actions you perform regularly?"

Residents have included meat in 36% of all weekly meals on average; in 0.4 breakfasts, 2.8 lunches and 4.3 dinners per week. This was similar to the mean rates reported by households living in conventional housing and in the Derwenthorpe eco-development, and higher than the rates in the BedZED and Lancaster Cohousing eco-developments (Quilgars *et al.*, 2019) (Figure 48). Also, the rate of vegetarians in the resident sample (2% did not include any meat) seems to be lower compared to the national averages (5%) (Waitrose and Partners, 2019).

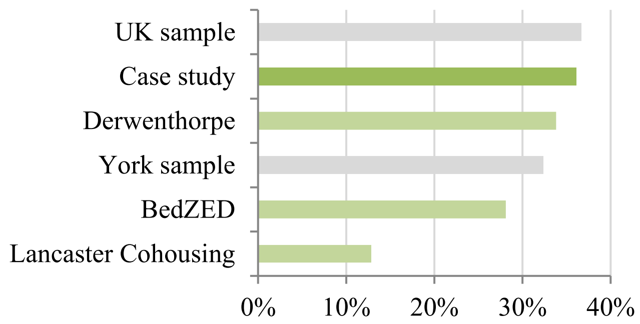


Figure 48 Comparing the mean rate of meat-free meals per week between the case study development, other eco-housing developments and households in living in the UK and the city of York (Quilgars *et al.*, 2019).

5.3.6. Transportation Behaviours

In the last section of the Lifestyle Evaluation questionnaire, residents needed to complete a matrix of their weekly travel pattern. For a) each purpose of a trip taken they had to select

b) preferred mode of transportation followed by c) three offered destination ranges and lastly d) number of trips per week they usually take for that purpose.

The data analysis showed that there were significantly more reported commuting and business trips in favour of other purposes, compared to national averages (DT, 2017a) (Figure 49). This was not surprising, as using questionnaires for collecting household transportation behaviours is expected to yield less accurate results compared to using trip diaries and conducting interviews (see section 4.3.5).

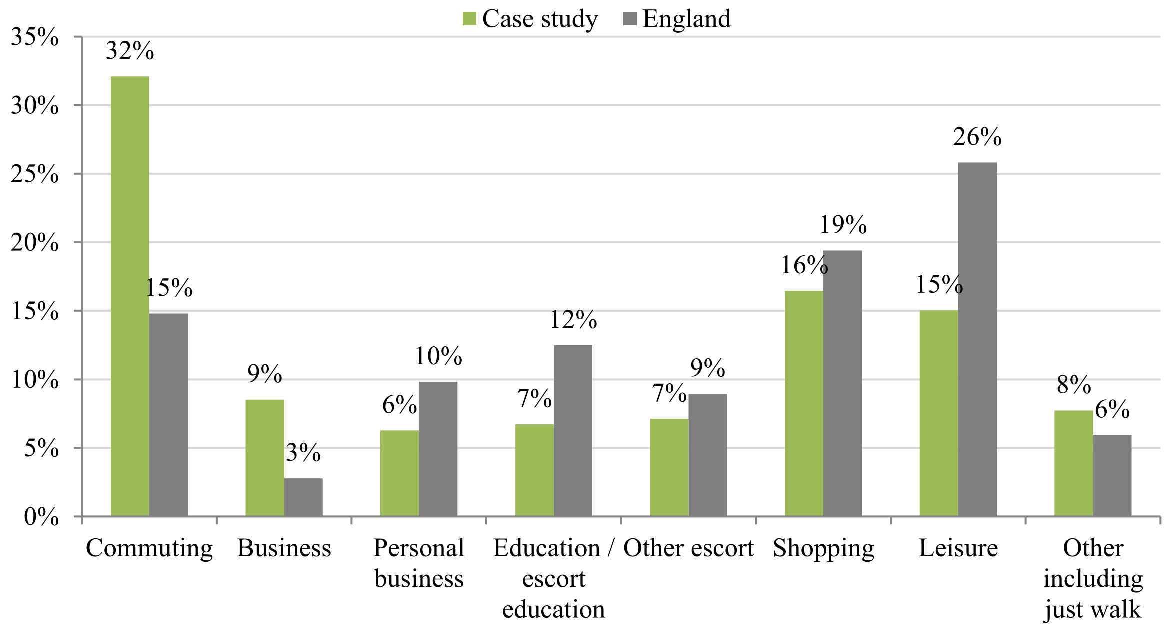


Figure 49 Comparing the ratios of trips between the case study development and national averages, per different purposes.

Figure 50 shows that commuting was by far the most frequently reported purpose of a trip (five times per week on average), performed by most of the residents (91%). Transportation modes were grouped according to their carbon intensity. *Car-based modes* group included all the reported car/van driver or passenger and motorcycle trips. *Eco modes* included walking, bicycle, public transportation, and other private transportation trips. *Car and/or eco modes* represented cases when car-based and more eco-friendly modes were combined during the same trip.

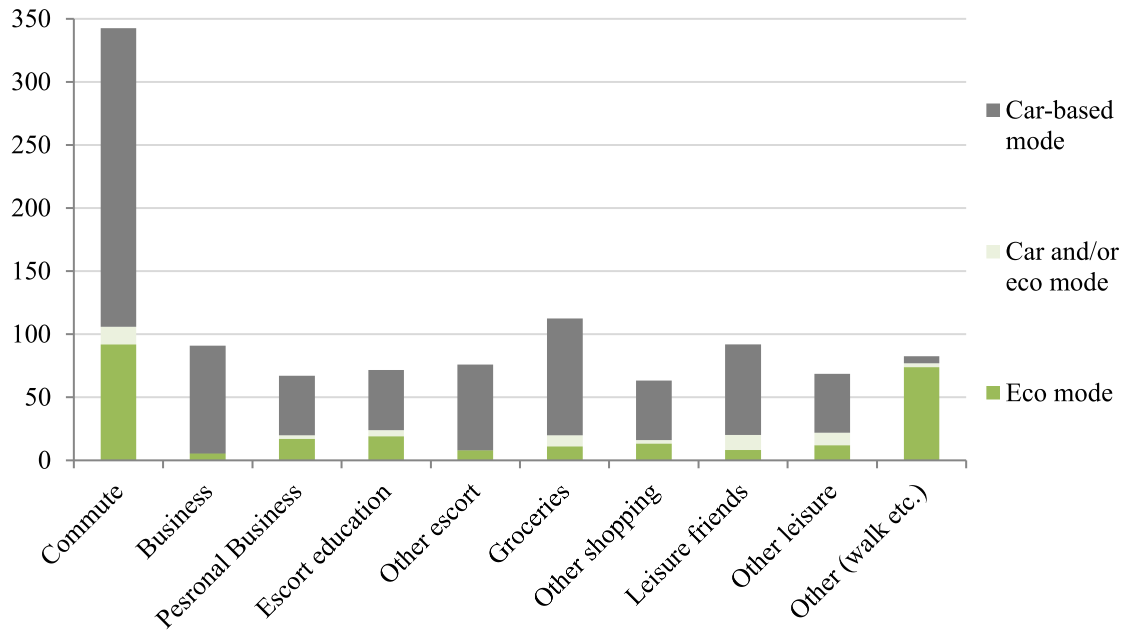


Figure 50 Frequencies of reported trips per modes, by trip purpose.

Overall, 70% of all reported trips were car-based, 24% of the trips were taken by more eco-friendly modes, and for the remaining 6 % of the trips the residents combined the two. This was higher than the national average (62%) (DT, 2017a), the averages for the same ward (65%) (ONS, 2011c; DEFRA, 2014), and the set target for 2016 (55%) (Figure 51).

As observed in Figure 52, business and non-education escort trips were the most car-dependent (around 90%), followed by grocery shopping and trips for visiting friends (around 80%). It could be argued that the skewed resident sample (due to excluding minors and notably younger residents) is expected to increase the ratio of car-based trips. However, the age groups below 16 and above 70 seem to have a similar ratio of car-based trips compared to the rest of the population (DT, 2017b).

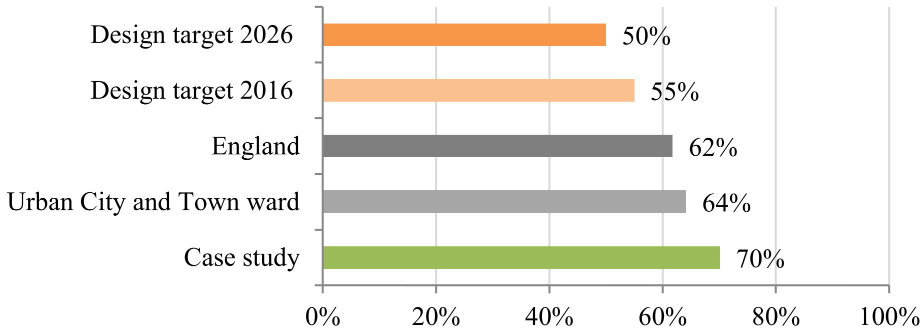


Figure 51 Comparing the overall rate of car-based modes between the case study development, design targets and averages for England and the same ward.

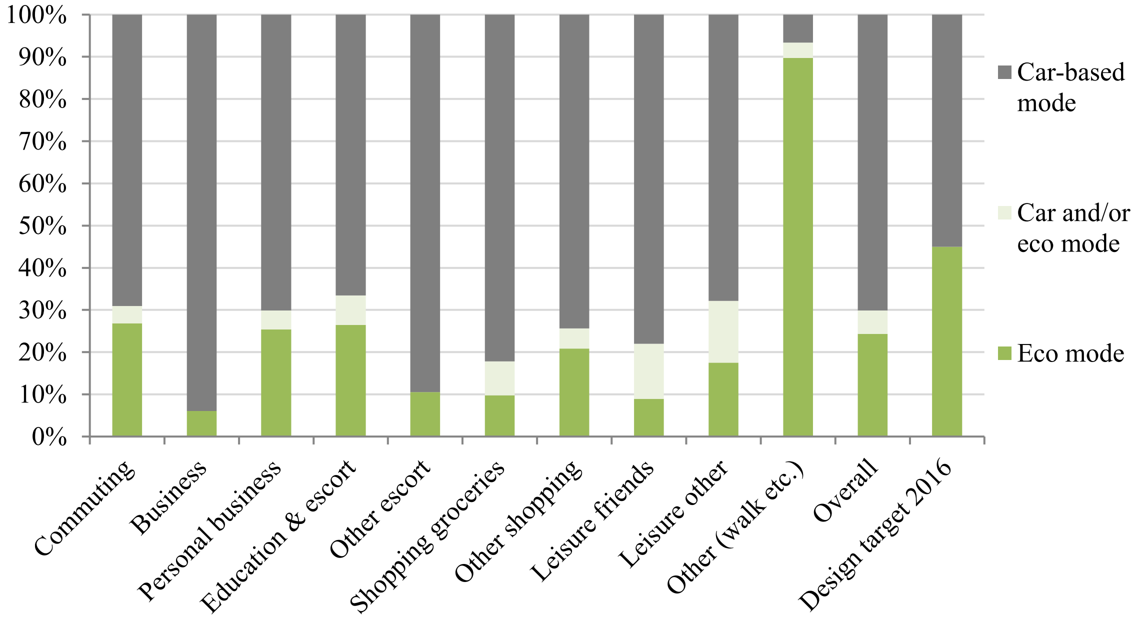


Figure 52 Ratios of three transportation modes, by trip purpose.

Figure 53 shows that the residents were slightly more car-dependent than the wider population for every category of trip purpose apart from trips for leisure. This particularly applied to grocery shopping and education-escort trips, where a 1.3 and 1.6 times higher car-use rate was reported, respectively. Free parking for visitors provided by the large local supermarket probably contributed to preferring to use the car for groceries shopping.

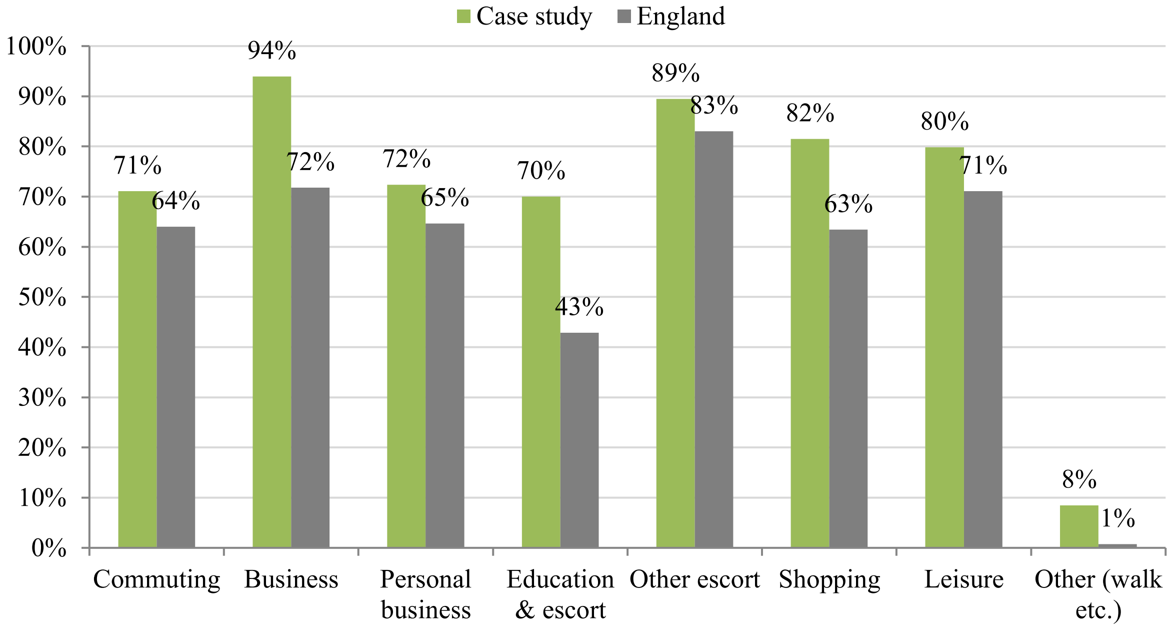


Figure 53 Comparison of car-based trip ratios, by trip purpose.

As observed in Figure 54, data analysis suggested that the residents tend to walk less and use cars and public transportation more, compared to households living in the local town (OCC, 2011) and to the national averages (DT, 2017a). This result was expected, due to the development's edge-of-town location. Considering that the majority of walking trips are under 1 mile long (DT, 2018), walking 1.5 mile to reach the town centre seems inconvenient. Compared to households in 13 eco-developments (Williams, Dair and Lindsay, 2008), 10% more residents in the case study development preferred using cars for commuting over greener alternatives.

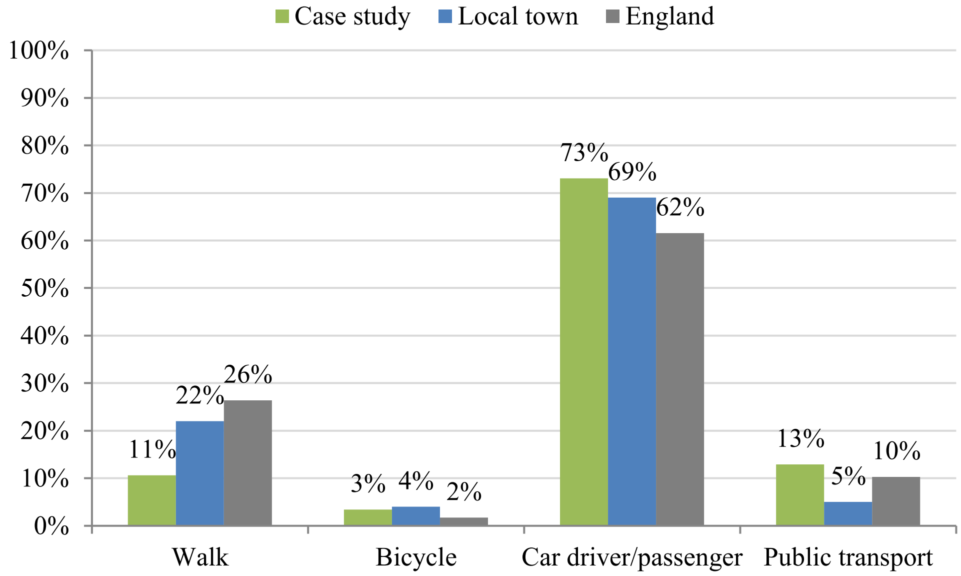


Figure 54 Comparing ratios of different trip modes between the case study development, national averages and the averages for the local town.

Figure 55 shows the residents' preference for different eco-modes of transportation. For commuting trips, the most popular types of eco-mode were public transportation (51%), followed by combining public transportation with cycling (20%), walking (21%) and just cycling (9%). Walking was the preferred eco-mode for escorting trips, probably due to the site's proximity to several schools and preschools. Public transportation was deemed most practical for grocery shopping. About 20% of all trips using eco-modes were taken by the bicycle only or combining the bicycle with other eco modes. The bicycle seems to be the favoured mode for leisure activities.

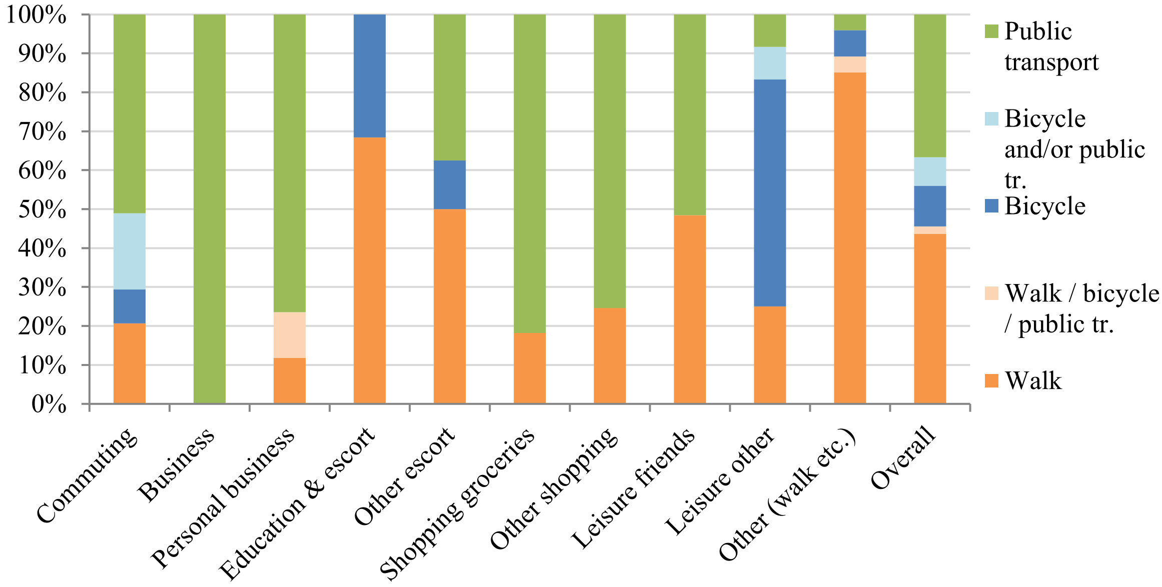


Figure 55 Ratios of different eco-modes of transportation, by trip purpose.

Survey participants who do not own a car or do not regularly use a car were asked whether some on-site facilities were important in making this decision. For residents who regularly used eco-modes of transportation (30%), the local bus to town was considered the most important measure (89%), followed by train and bus services located in the town centre (56%), and walking routes (44%) (Figure 56). Bicycle routes, e-car club, electric car chargers and bike rental facilities were deemed the least important measures (< 22%). Compared to the household responses in 13 other eco-housing developments (Williams, Dair and Lindsay, 2008), the local bus was given much higher importance in the present case study, while convenient walking and bicycle routes were regarded as similarly important.

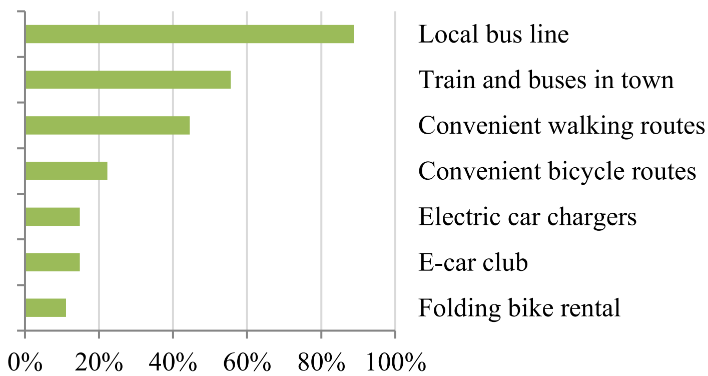


Figure 56 Frequencies of responses to the question: "If you do not own or regularly use a standard car/van, were any of these facilities important to you in taking this decision?"

Analysis of the responses regarding the final trip destinations showed that the local town (< 3-mile radius) was the final destination for about a bit more than a third of all the reported trips (37%). Close to half of the trips (45%) ended in the wider region (4- to 50-mile radius), while 12% of the trips were taken to destinations further than 50 miles away (Figure 57). The results also suggest that the town was the most attractive destination for grocery shopping (~90% of all trips), and the least attractive destination for work, business and other leisure activities (< 25% of all trips). As indicated in Figure 58, the Chi-square test suggested that, for commuting trips, residents favoured car-based modes for reaching destinations located in the wider region (4- to 50-mile radius) but not for longer or shorter trips (X^2 (2, N = 68) = 10.61, p = .005).

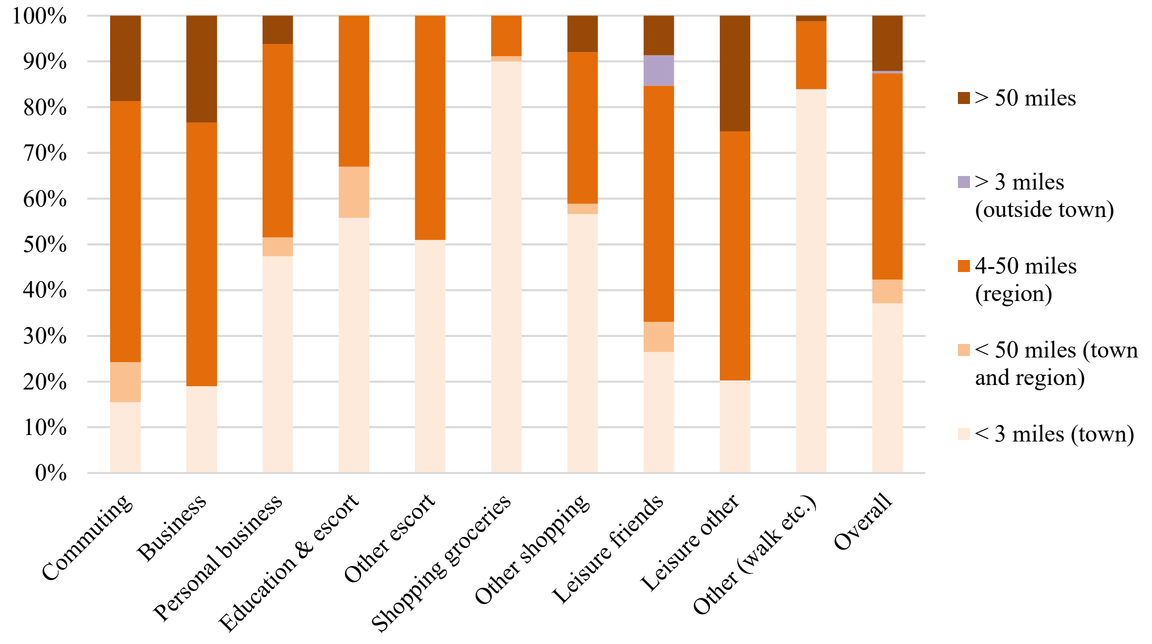


Figure 57 Ratios of different trip destination ranges, by trip purpose.

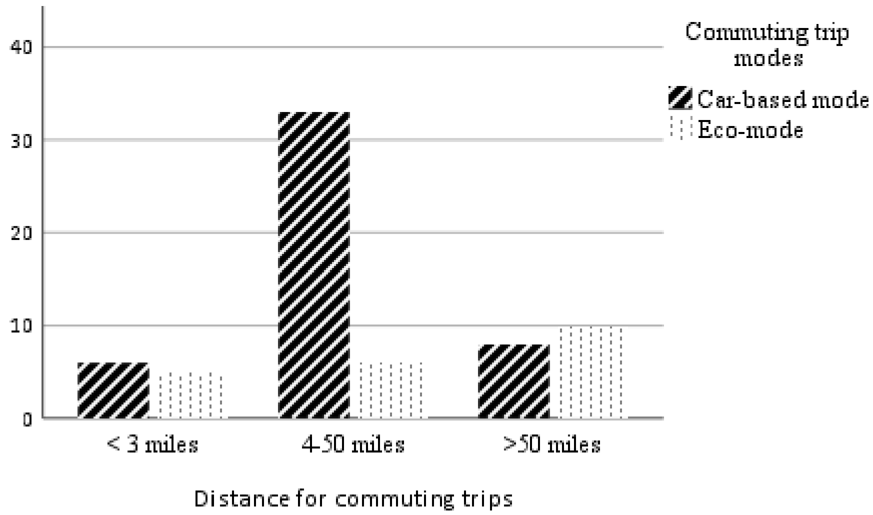


Figure 58 Ratios of transportation modes for commuting trips, according to the destination ranges.

As observed in Figure 59, the local town was more than two times less attractive for work and leisure activities for the case study residents, compared to the households living in the town itself (OCC, 2011). This significant difference was partly attributed to the inclusion of minors in the town's survey, and the higher share of older adults living in the town (OCC, 2014).

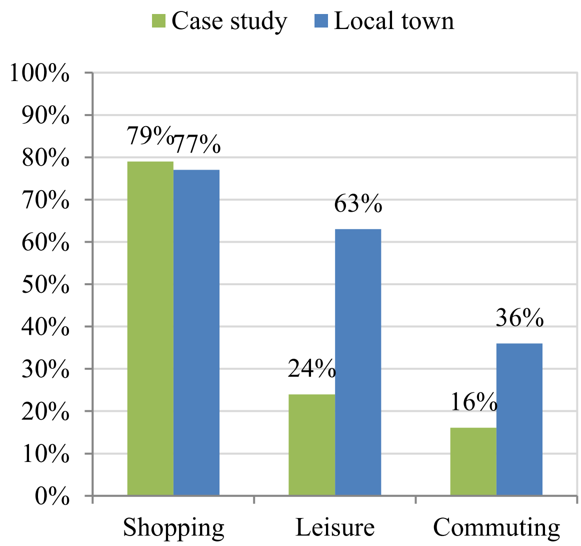


Figure 59 Comparing the ratio of shopping, leisure and commuting trips taken to the town area between the case study development and households living in the town.

As observed in Figure 60, the households owned 1.4 cars on average, similarly to the households living in the town, the averages for the ward, and slightly more than the national averages. It was surprising to find that only one surveyed household (2%) was car-free. This could be attributed to the higher socio-economic status of the households. However, 14% of English households in the highest earning quintile did not own a car (DT, 2017c). Also, according to the national statistics (ONS, 2018), half of captured households in social rent (n=11) would have been car-less. These findings indicate that that owning a car in the case study development might be seen as necessary due its detached location.

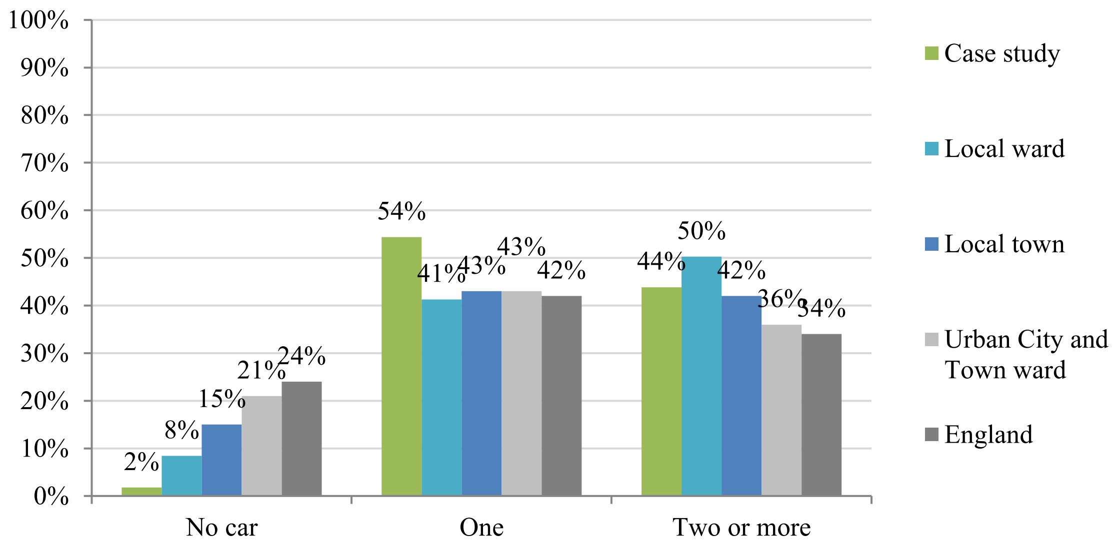


Figure 60 Comparing the car ownership ratios in the case study development to local and national statistics.

The households seemed to own more cars and drive more miles per occupant (5,410 miles/year) on average, compared to households living in other new eco-developments[15] (Quilgars *et al.*, 2019) (Figure 61). A strong correlation ($R^2 = .91$) between the reported miles driven per occupant and the car ownership per household indicated that the case study and Derwenthorpe developments were more car-dependant the national averages. This is probably related to their edge-of-town locations.

[15] Ashton Hayes is an existing rural village aiming to become carbon neutral.

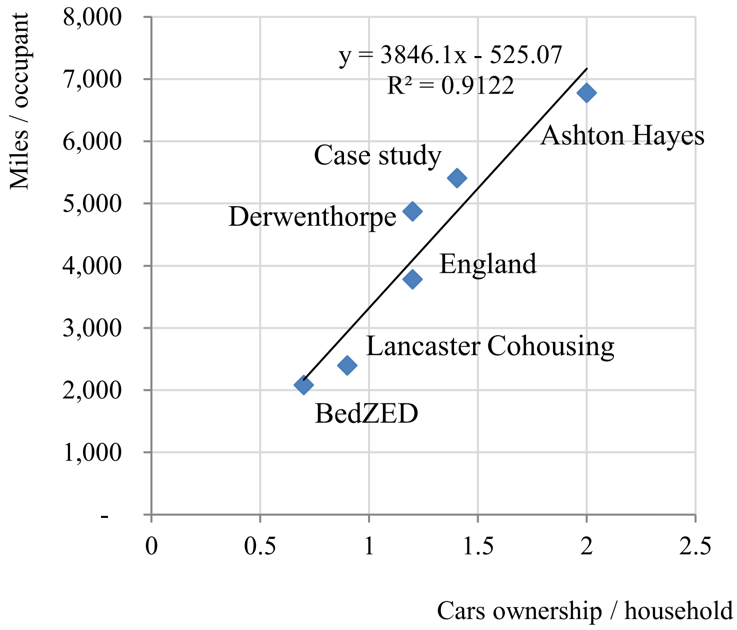


Figure 61 Scatter plot, relating the means of car miles/year/occupant and the means of car ownership/household in the case study development, other eco-housing and data for England (Quilgars et al.*, 2019).*

Higher ownership of electric cars (5%) and hybrid cars (8%) in the development compared to the UK market share in 2019 (0.9% electric and 4.7% hybrid) (SMMT, 2019) was attributed to economic status households and the provision of the personal electric car chargers (Patt *et al.*, 2019).

5.3.7. Openness to further environmental behaviours

Figure 62 shows that the residents were more hesitant to adopt an eco-friendlier diet (43%) than to recycle more (29%) or to save more energy and water in their home (24%). This result is in line with the finding that adopting a low-impact diet is among the least favoured pro-environmental behaviours (DEFRA, 2008). Expectedly, these residents were also more open to further save energy and water ($\varphi_{Cramer} = .27$, $p = .04$) compared to the rest of the sample (Figure 63). Residents that were open to further savings also showed higher awareness about the contribution of their everyday behaviour to climate change ($U = 494.50$, $p = .01$).

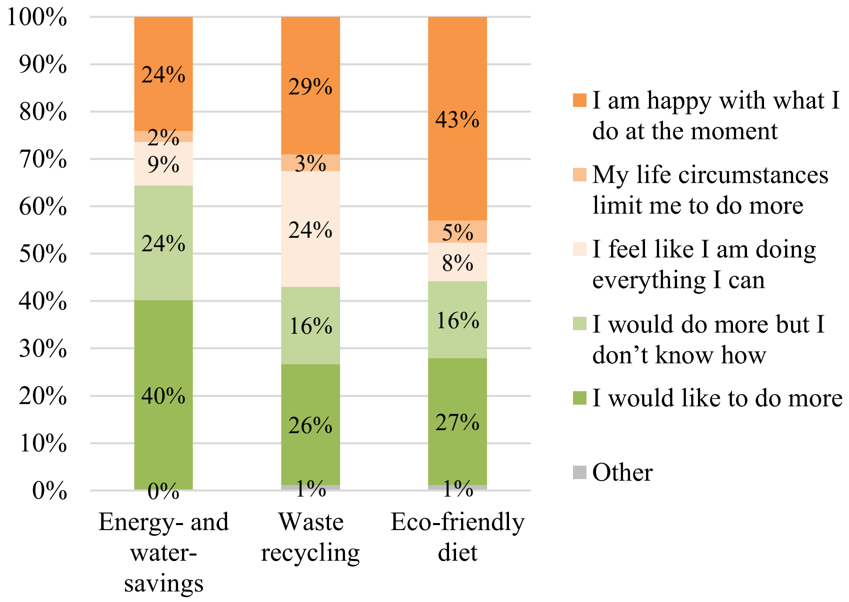


Figure 62 Comparing the rates of responses to the questions: "Would you consider; ... making additional energy and water savings?; ...recycling more?; ...adopting a more eco-friendly diet?".

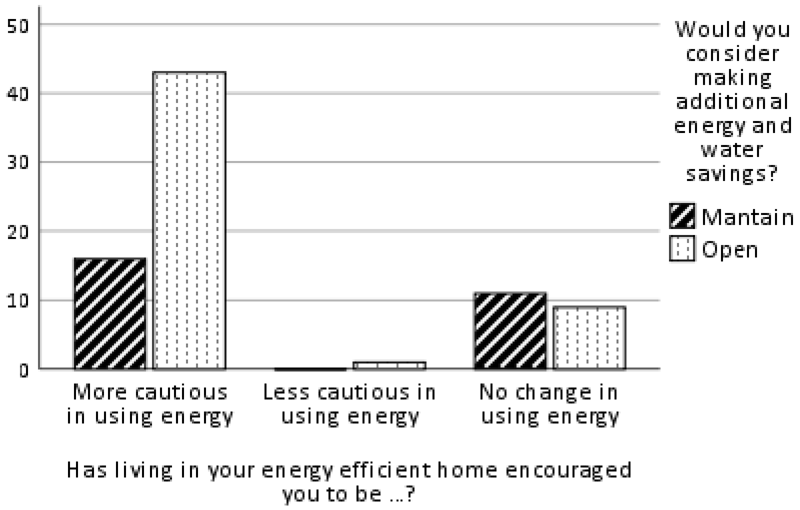


Figure 63 Comparing the number of responses of the residents that are open to further behavioural change to the rest of the sample, across the responses about the cautiousness in using energy.

From all the residents who do not already use eco-modes, more than half (55%) felt constrained to do so, 13% frequently used their car out of choice and lastly, a third (32%) thought that an adequate alternative to driving was not yet offered (Figure 64). It was apparent that more residents (34%) use life circumstances as a justification for frequent car use, compared to the households in the local town (6%) (OCC, 2011). Also, fewer residents felt like an adequate alternative to car was offered (8%), compared to responses from the local town (29%).

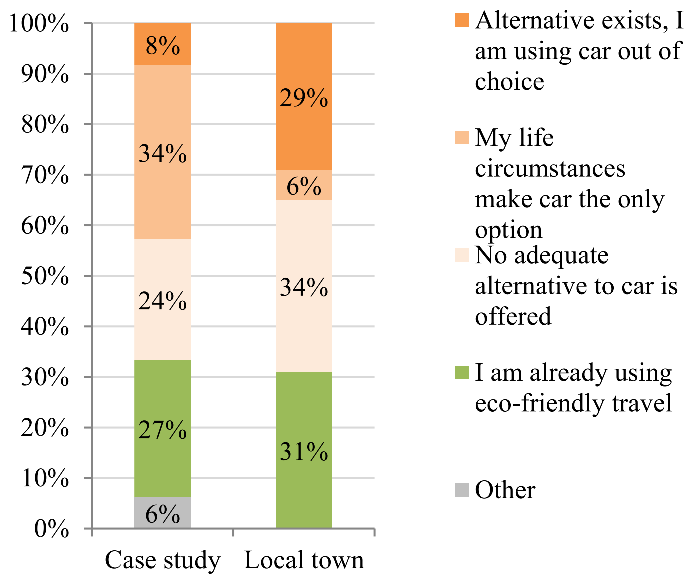


Figure 64 Comparing the ratio of responses to the question: "Would you consider using choosing a more eco-friendly travel?" between the case study development and the local town (OCC, 2011).

5.4. Summary

This chapter presented the key results of the questionnaire survey, as the first part of the development-wide assessment. The survey captured responses from 90 participants from 64 dwellings, or 41% of all 157 dwellings in the case study development. The captured sample well represents the households living in houses, but has captured only one of the 28 households living in flats. Hence it slightly underrepresented social dwellings (-11%), while the difference in regard to other dwelling typology was small, below 7%. Mean results per each variable was compared to the provided benchmark consisting of responses from 58 other housing studies.

The surveyed residents regarded the indoor conditions of their homes during the winter season as comfortable in general. However, about half of the Phase 1 households reported different issues, such as uncomfortable drafts, cold rooms and the home warming-up too slowly. Responses about the indoor conditions during the summer season suggest that the dwellings did perform as it was aspired. The majority of residents felt hot and were unable to keep their home cool. This pertains especially to dwellings with living rooms exposed to the south and west orientations. Dwellings seem to be hotter and more uncomfortable to occupants during the summer than the majority of housing developments captured in the benchmark dataset. Due to the experienced discomfort, about half of the households were considering purchasing an air-conditioning system in the future, which would increase the dwelling energy demand. The majority of the residents felt healthier than in their previous accommodation. Compared to the benchmark, more residents thought that their current cost of heating was higher than in their previous accommodation.

High education levels of residents confirmed the notion that eco-housing households belong to a higher socio-economic class. About two-thirds of residents thought that their new lifestyle is more eco-friendly than before. This perception was partly related to feeling more cautious in using energy, recycling and benefiting from eco-features like solar panels. In contrast, the common energy- and water-saving behaviours were similar to the national averages. Responses to three questions in regard to the environmental attitude suggested that the residents might be more knowledgeable but not more concerned about the environment.

More residents reported to frequently recycle waste compared to the national averages and households in other eco-housing. In contrast to this, actual waste recycling rates measured over three consecutive years (45%, 45% and 60%) were similar to the national and local averages, and significantly lower compared to the design target (80%).

Reported rates of organic food purchasing, growing vegetables and eating meat suggested that residents' low-impact food behaviours were similar to the national averages. Noteworthy, residents seem to include meat more often in their diet compared to households in three other eco-housing developments.

The reported transportation behaviours suggested that the car-based modes of transportation were used in 70% of the reported trips. This was more compared to local and national averages, and the design target set for 2016 (55%). Cars were more preferred than eco-friendlier alternatives only for reaching destinations in the nearby area surrounding the town. Unlike the town's residents, a big majority (~80%) of the residents reported to work and take leisure trips away from the town. Responses about the car ownership suggested that owning at least one car seems a necessity in the case study development. Residents reported to drive more miles per occupant compared to the wider population and residents in other eco-housing.

Considering all four captured environmental behaviours, the data analysis suggested that the residents were most open to further engage in energy- and water-saving behaviours. Such finding is confirmed in other studies. Further recycling and adopting an eco-friendlier diet were considered by only about half of residents. Two-thirds of car-dependant residents either felt constrained to switch to eco-friendlier alternatives or were content with using the car.

Chapter 6: Dwelling Energy and Water Performance

6.1. Introduction

This chapter presents the key results of the second part of the development-wide assessment, focused on energy and carbon performance of all dwellings in the case study development. Data analysis was based on time-series data collected during a one year period via the pre-installed remote monitoring system, and the provided annual energy performance data of the community heating plant. The time-series data captured dwelling water use, heat use, grid electricity use, and solar PV electricity generation and export. Daily data were used to generate monthly and yearly values, while 30-minute electricity data were used to generate daily profiles. The energy performance data of the district heating system were used to estimate the annual dwelling carbon emissions. Performance results were compared to the design intent, and the performance of conventional and advanced housing developments, where available.

6.2. Energy performance

6.2.1. Total energy use

Based on a 74 dwelling sample, mean net energy use (annual grid energy use) is found to be 70.5 kWh/m^2/year. By adding the mean self-consumed PV electricity of 5.5 kWh/m^2/year, the resulting mean energy use achieved is 76 kWh/m^2/year per dwelling (Table 26 and Figure 66). The achieved energy usage almost matched the designed usage of 75.4 kWh/m^2/year. Achieved mean energy use was low; equal to the mean use reported for a Passivhaus dwelling sample (Gupta and Gregg, 2020). On the other hand, achieved energy use was outperformed by two zero carbon housing developments; Lancaster Cohousing and Sinclair Meadows (Figure 65).

Annual energy use (kWh/m²)	1-Bed	2-Bed	3-Bed	4-Bed	5-Bed	All
Minimum	25.8	42.9	55.5	74.5	31.2	25.8
Maximum	114.0	115.8	139.0	74.5	93.6	139.0
Median	60.1	71.6	85.6	74.5	69.6	76.3
Mean	65.0	72.4	85.4	74.5	65.7	76.0
Sample size	4	36	23	1	10	74

Table 26 Descriptive statistics of annual energy use per dwelling, by number of rooms.

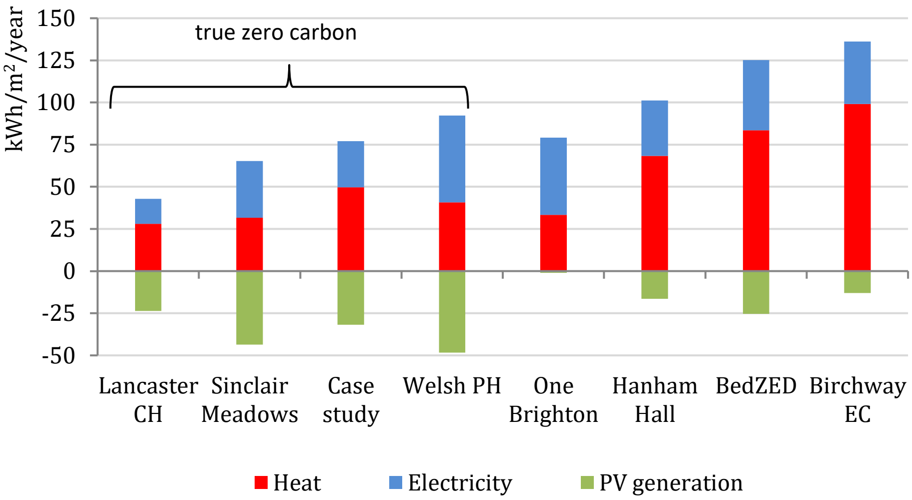
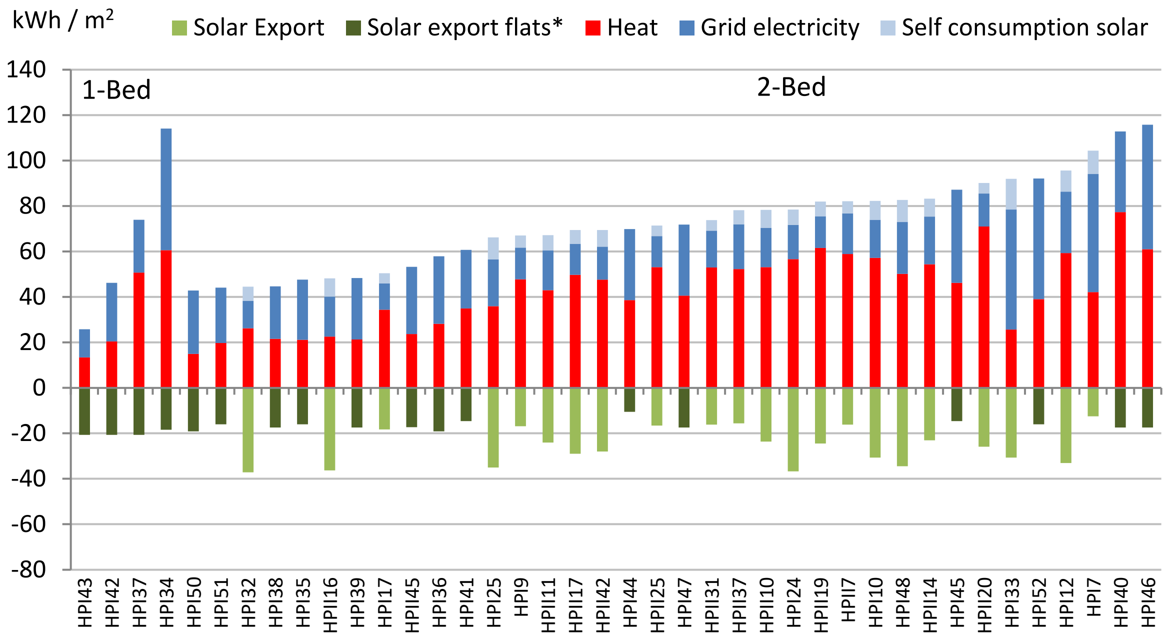


Figure 65 Comparison of mean energy performance of dwellings from different zero carbon housing developments. Performance is sourced from reported data where available[16].

[16] PV yields are estimated for BedZED, Lancaster Cohousing and Hanham Hall using 850 kWh/kWp generation standard and reported PV system sizes. 85% boiler efficiency and 1.5 kWp/dwelling PV system is assumed for Hanham Hall.



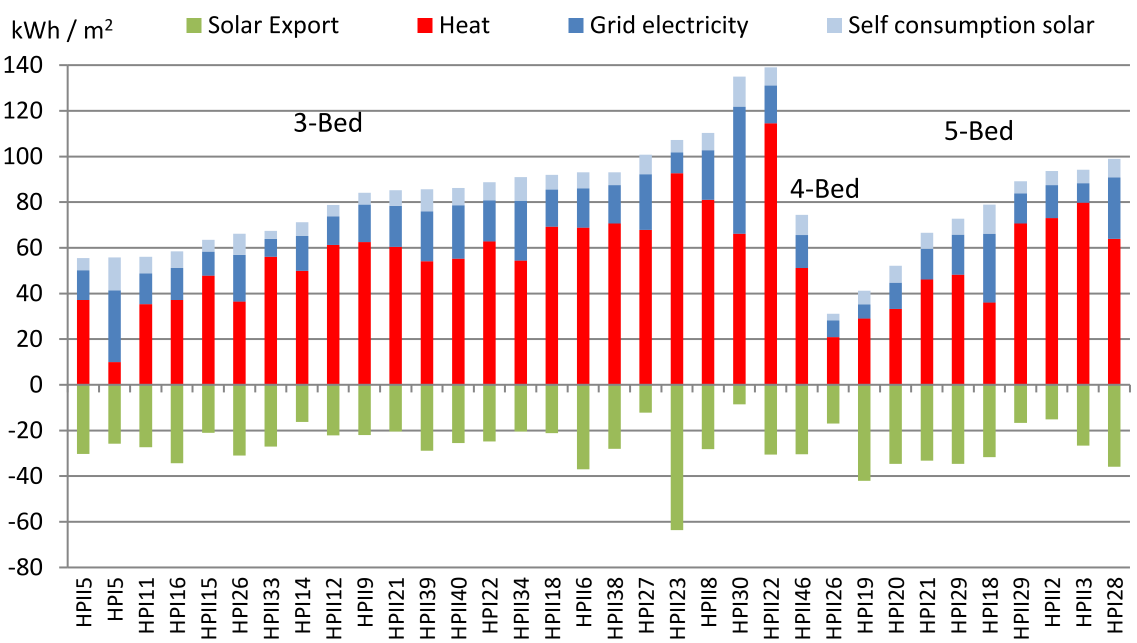


Figure 66 Annual dwelling grid electricity, heat and self-consumed solar energy usage, and solar energy export, by number of bedrooms (n=74). Abbreviations HPI and HPII in the names of captured dwellings stand for House Phase 1 and House Phase 2, respectively.

Total energy use per floor area was not significantly associated with dwelling typology, occupant factors (dwelling use pattern, tenure, occupancy), household environmental attitude and reported environmental behaviours. Dwellings occupied during evenings and weekends used similar amount of energy per floor area compared to dwellings with residents that were at home most of the time. As indicated in Figure 67, heat use per floor area (n=29) was moderately and positively correlated with the preferred thermostat settings (r_s = .51, p = .005).

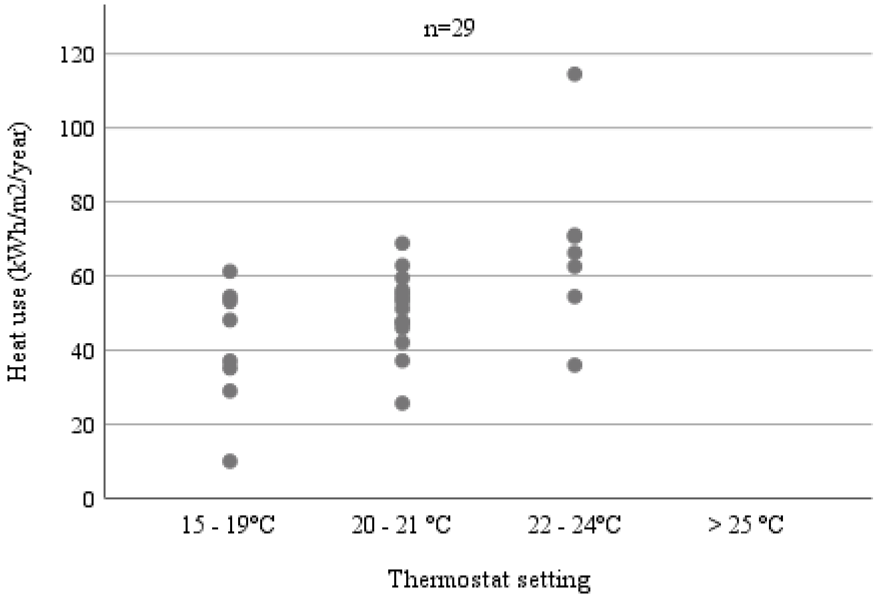


Figure 67 Scatter plot of the thermostat setting and dwelling annual heat usage.

Statistical analysis indicated links between housing, transportation and food as the most environmentally-intensive household categories (Tukker and Jansen, 2006). Annual electricity use per floor area was negatively correlated with the belief that own behaviour contributes to climate change variable (r_s = - .44, p = .011), and was positively correlated with the frequency of leaving the room lights on (r_s = .37, p = .036) and eating meat (r_s = .51, p = .003) variables. More than half of variance in energy use was explained with four variables; annual mileage per vehicle, meat-eating frequency and thermostat setting; F (3, 22) = 10.66, $p < .001$, $R^2 = 0.59$. Estimated annual car mileage and frequency of eating meat variables were positively and weakly corelated with dwelling energy use per floor area, as indicated in Figure 68 and Figure 69.

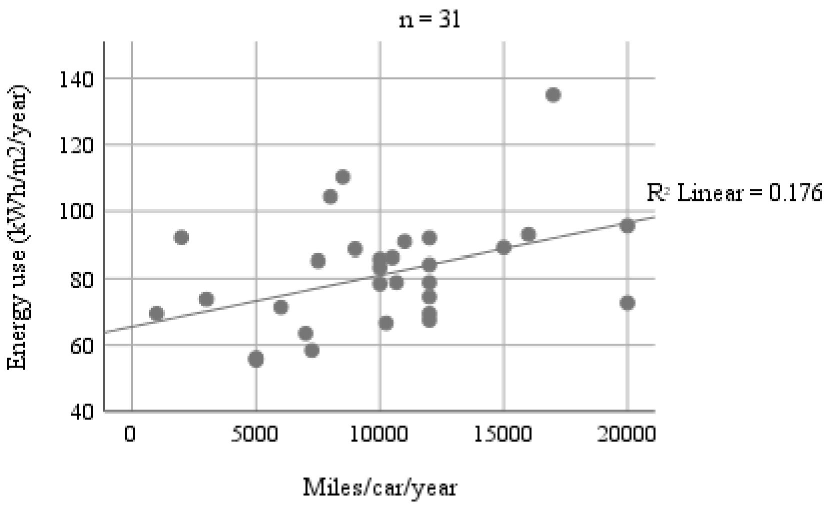


Figure 68 Scatter plot of the monitored annual dwelling energy use and reported annual mileage driven per car.

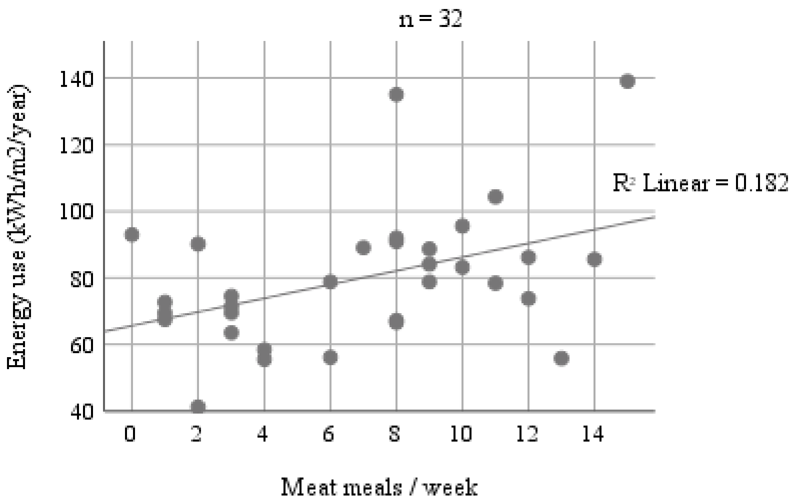


Figure 69 Scatter plot of the monitored annual dwelling energy use and number of meals with meat per week of households.

Dwelling annual heat and electricity use data per total floor area were analysed among dwelling groups that share the same building characteristics. The difference between the minimum and maximum energy use ranged from 2.1 to 8.1 for heat use, and from 2.4 to 4.2 for electricity use (Table 27). The difference in electricity use across the dwellings with the same occupancy was slightly higher; up to 6.7 times when including a strong data outlier[17],

[17] Data value more than three times above the interquartile range

and up to 5.1 times when it was excluded (Table 28). The resulting difference in heat use per floor area among low energy dwellings with same building characteristics was more pronounced compared to what was reported elsewhere (Gill *et al.*, 2011). The variance in heat use (M = 4,830, SD = 3,014, CV[18] = 0.62) of the dwelling sample with heat data (n=94) was also more prominent compared to the findings in Dutch and Danish households (Guerra Santin, Itard and Visscher, 2009; Van den Brom *et al.*, 2019).

	Annual energy use per dwelling kWh/m²	2-Bed flats	2-Bed Mid-terrace	3-Bed End-terrace	5 Bed
Heat use	Minimum	21.3	34.4	10.0	20.8
	Maximum	77.3	71.0	81.0	96.2
	Factor of difference	3.6	2.1	8.1	4.6
	Sample size	9	17	23	12
Electricity use	Minimum	23.1	16.1	11.3	10.3
	Maximum	54.7	62.2	45.8	42.9
	Factor of difference	2.4	3.9	4.0	4.2
	Sample size	9	15	19	10

Table 27 Descriptive statistics of energy use variance in four dwelling archetype groups.

Annual electricity use per dwelling kWh	Number of occupants per dwelling				
	1	2	3	4	5
Minimum	1,620	1,053	2,273	2,028	3,379
Maximum	5,104	7,077	4,048	6,356	3,392
Factor of difference	3.2	6.7	1.8	3.1	1.0
Sample size	2	23	5	3	2

Table 28 Descriptive statistics of electricity use variance per number of occupants.

The data analysis showed that the 3-bed houses in Phase 1 (n=12) used almost a third less heat on average, compared to similar dwellings in Phase 2 (n=19). Also, 5-bed dwellings in Phase 1 (n=6) used nearly 90% less heat on average, compared to similar dwellings in Phase 2 (n=6). Based on the dwelling sample with occupancy data (n=35), the energy use per floor area was not significantly associated with occupant factors (dwelling use pattern, tenure and

[18] Coefficient of variance (CV) was calculated as the ratio of the standard deviation (SD) to the mean heat use (M).

occupancy), dwelling orientation or typology. In contrast to the results, smaller household size in Phase 2 (*M* = 2.2) compared to Phase 1 (*M* = 2.8) is expected to result with lower heating use, due to more childless households (Do Carmo and Christensen, 2016) and reduced heating in the additional bedrooms (Guerra Santin, Itard and Visscher, 2009). It should be noted that the two building Phases were built by different contractors, which might result in some differences in the as-built fabric performance. A more detailed BPE study would be needed to explain the difference in heat use.

6.2.2. Heat use

Based on dwelling sample with available heat data (n=94) the mean heat usage achieved was 49.7 kWh/m^2/year per dwelling (Figure 70). Similarly, 48.5 kWh/m^2/year of heat was used in dwellings with available total energy use data (n=74). This is 11% and 9% more heat used, respectively, compared to the design projections and higher than the mean usage reported in mentioned zero carbon housing developments (~28 – 41 kWh/m^2/year). With a similar mean total floor area (TFA) compared to UK dwellings (MHCLG, 2018), the mean heat usage of 4,830 kWh/year per dwelling is low compared to 11,400 kWh (51 - 100 m^2 TFA group) gas use from the NEED database (DBEIS, 2018b) and 12,000 kWh of gas usage for a medium UK user (Ofgem, 2017).

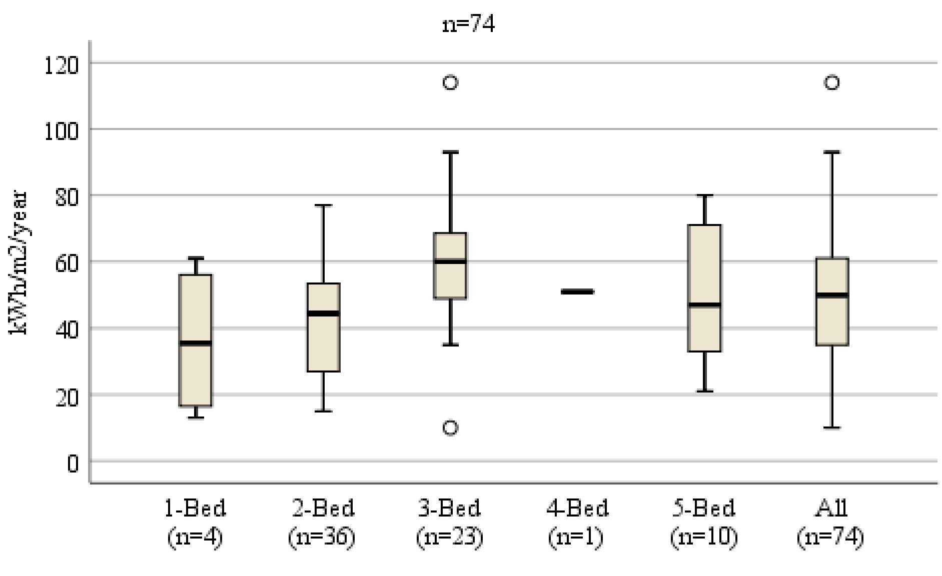


Figure 70 Box plots of annual dwelling heat usage, by number of rooms.

Strong correlation (R2=0.96) (Figure 71) between the monthly heat usage of the dwelling sample and degree day data (Monthly Degree Day Data, no date) from the nearby weather station, indicated the hot water usage over the summer months. The lowest monthly heat usage of the sample that occurred in July, was regarded as an equivalent to the mean monthly hot water usage. On this basis, hot water and space heating usage ratios for the development were estimated as 23% and 77%, respectively, which was similar to the national averages (DECC, 2014b). Consequently, the estimated mean space heating use would be 38.3 kWh/m^2/year per dwelling, significantly higher than the Passivhaus standard.

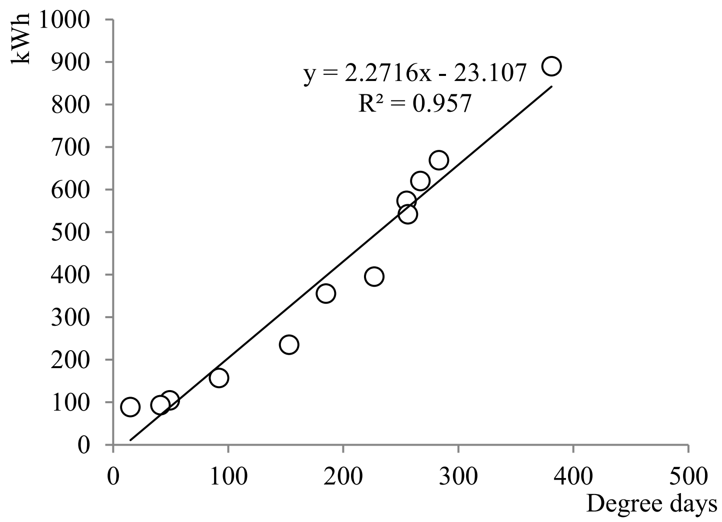


Figure 71 Scatter plot of degree days and mean heat usage per month (n = 94).

From the dwelling sample with heat usage data (n=94), four archetype groups (common dwelling types) were selected, to inspect the potential differences between the designed and actual heat use. The results of the data analysis suggested that the actual heat usage was higher in three of four dwelling groups, compared to the design predictions (Figure 72). The estimated space heating usage fraction was 1.3 to 2.2 times higher compared to the predictions. Conversely, the design overestimated the hot water usage between factors of 1.3 and 1.9. It seems that lower as-built fabric efficiency outdid the reduced heat demand due to warmer and sunnier weather. During the monitoring period, there were 13% fewer degree days recorded compared to long-term means (DBEIS, 2019b), 14% higher monthly temperatures (Met Office, 2019a) compared to SAP 2009 figures (BRE, 2010), and 8% more sun hours during the heating period (DBEIS, 2019a) compared to the 10-year mean. Lower hot water usage was probably attributed to the reduced actual water usage of 96.2 litres/person/year on average. This is 34% lower compared to the national averages (AC, 2018), and lower than the hot water requirement used in SAP.

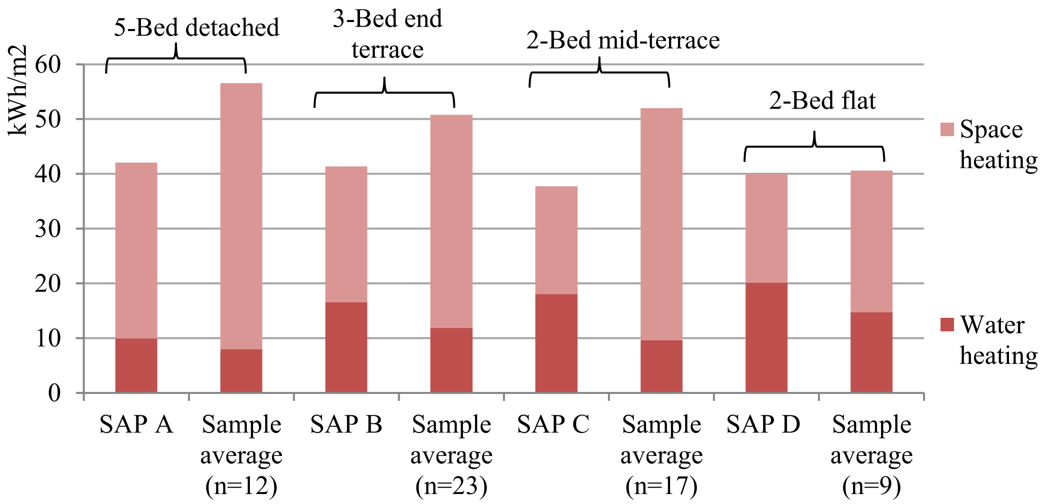


Figure 72 Comparing space heating and hot water fractions between achieved and designed annual dwelling heat usage for four dwelling groups.

6.2.3. Electricity use

The mean electricity use per dwelling was 27.4 kWh/m^2/year (n=74) (Figure 73). The resulting usage is one of the lowest reported in housing developments. It is lower compared to the mean usage of the aforementioned (Table 4) zero carbon housing developments (~33 - 46 kWh/m^2/year[19]), and the samples of low carbon (~55 kWh/m^2/year) and Passivhaus dwellings (~47 kWh/m^2/year) (Gupta and Gregg, 2020). The mean usage of 2,527 kWh/year per dwelling is 18% lower compared to the Ofgem's mid user's electricity usage of 3,100 kWh/year, and by 26% compared to 3,400 kWh/year usage from the NEED database (52 - 100m^2 TFA).

[19] Excluding the result from the non-conventional cohousing project

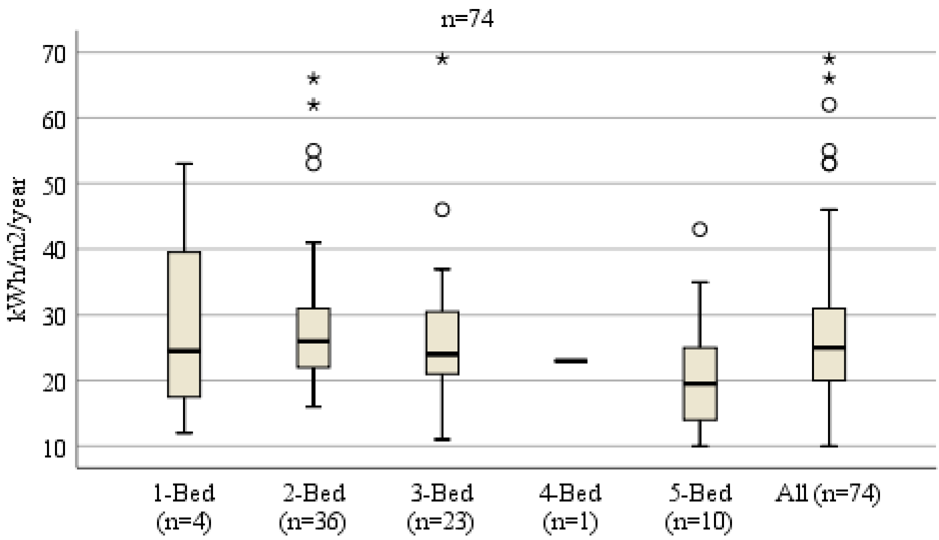


*Figure 73 Box plot of annual dwelling electricity usage, by number of rooms. Strong data outliers are marked with * symbol.*

6.2.4. PV energy generation, export and self-consumption

The mean energy output per solar PV system reached the design projections. This was achieved as a balance of slightly smaller system size (2.9 kWp), and 1.2 times higher mean solar generation (991.7 kWh/kWp) than predicted. Due to the lack of monitoring data, the solar generation of systems located on blocks of flats was estimated using the mean output from houses. As seen in Table 29, the mean self-consumed solar energy accounted for 23% of total solar generation in houses (n=56), ranging from 8% to 61%. The mean self-sufficiency rate (self-consumption of solar energy in relation to total electricity use) achieved was 30%.

	Grid use (kWh)	Self-consumption solar (kWh)	Solar export (kWh)	Solar generation (kWh)	Self-consumption / generation	Self-consumption / electricity use
Minimum	717.3	335.5	792.6	1725.5	8%	16%
Maximum	5137.5	2099.0	6955.7	7959.9	61%	50%
Median	1526.0	670.1	2487.5	3173.6	21%	29%
Average	1834.3	736.1	2727.7	3463.7	23%	30%

Table 29 Descriptive statistics of dwelling annual grid electricity use, solar generation, export and self-consumed electricity fraction. House sample (n=56).

6.2.5. Daily electricity profiles

The 30-minute data readings were used to generate 24-hour profiles for electricity use and generation (n=74). The assessment was based on the data from July 2018 and January 2019, which represented the non-heating and heating months of the monitoring period.

A Hierarchical cluster analysis (Ward method) was used to differentiate four key user groups; low-user, mid-user and two high-user groups. The high-use group was differentiated to the high-day and high-evening users. The former use electricity evenly throughout the day, and probably stay at home. The latter, as the name says, use electricity more intensely in the evening hours.

Average hourly electricity usage during the day, evening and night-time, between different user groups was presented in Table 30. The analysis showed that households used 1.2 times more electricity per day on average in January (7.1 kWh) compared to July (6 kWh). This was expected due to the shorter days. The high-evening user used more than 2.5 times more electricity compared to the low user during both months. For all but the high-day users, the evening hours (5 pm – 9 pm) were up to two times more energy intensive than the day-time hours (10 am – 4 pm). The contribution of the provided energy efficient appliances is apparent when comparing the sample's mean parasitic base load (1 am - 6 am) of ~150 Wh to the ~250h of the sample of UK homes (DECC and DEFRA, 2014).

January	Hourly means during parts of day (kWh)					
User type group	Day 10am-4pm	Evening 5pm-9pm	Night 1am-6am	Total daily use (kWh)	Sample size	From total (%)
Low	0.19	0.31	0.10	4.3	21	28%
Mid	0.26	0.46	0.11	5.9	28	38%
High evening	0.37	0.65	0.19	8.8	16	22%
High day	0.63	0.75	0.17	11.5	5	7%
Other	-	-	-	-	4	5%
All	0.31	0.55	0.15	7.1	74	100%

July	Hourly means during parts of day (kWh)					
User type group	Day 10am-4pm	Evening 5pm-9pm	Night 1am-6am	Total daily use (kWh)	Sample size	From total (%)
Low	0.16	0.22	0.10	3.7	27	36%
Mid	0.22	0.38	0.13	5.5	25	34%
High evening	0.31	0.50	0.20	8.0	12	16%
High day	0.45	0.50	0.21	9.0	8	11%
Other	-	-	-	-	2	3%
All	0.25	0.38	0.15	6.0	74	100%

Table 30 Clustering results; electricity use levels during different parts of the day, months of January and July.

Figure 74 shows the daily profiles of a low-user, a high-evening-user, and the mean profile of the 74-dwellings sample. A discrepancy can be noted in regard to the availability of the generated electricity and the energy demand. In January, when the energy demand is higher, solar electricity was generated only during a short time window (8 am to 4 pm), missing the evening electricity usage peak (~6:30 pm). In contrast, more than two times (factor of ~2.2) of surplus electricity was exported in July, compared to the amount of electricity used. As a result, self-consumed solar energy in January met only 10% of the daily electricity needs, on average. In July, self-consumed energy met 37% of the daily electricity needs.

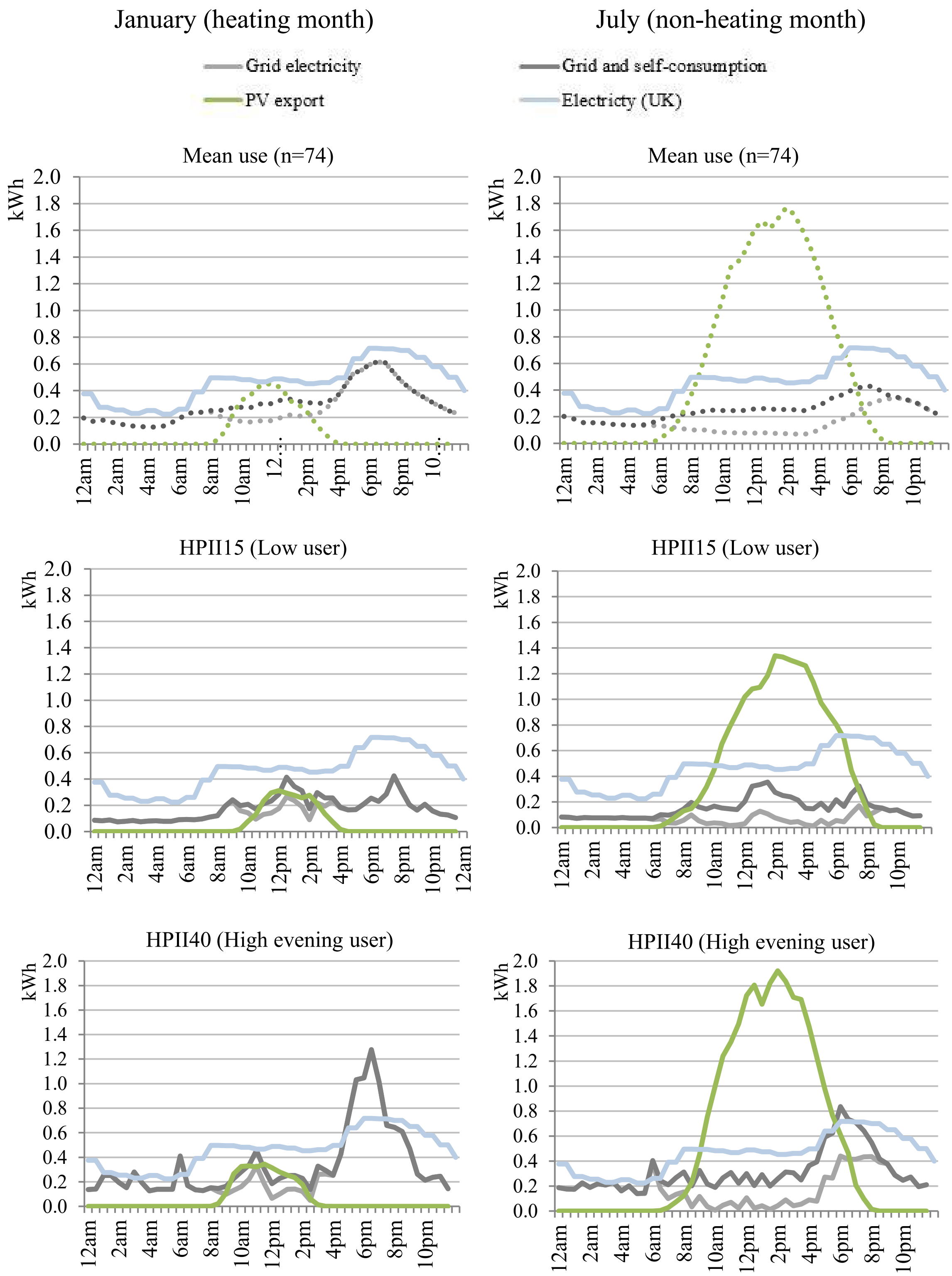


Figure 74 Daily profile of electricity use, grid electricity use and export of the sample mean, a low- and a high-evening-user, January and July mean hourly data. The hourly electricity use values for UK are based on one year data (DECC and DEFRA, 2014).

6.3. Carbon emissions

6.3.1. Community heating performance

The energy performance assessment of the community heating system was based on the two-year data, between 1 April 2017 to 31 March 2019. The gas and grid electricity factors for 2017/2018 and 2018/2019 period were calculated by averaging the reported annual factors (DBEIS and DEFRA, 2017, 2018, 2019) (see the Appendix for details).

Comparison of the actual to the designed performance presented in the Table 31 shows the underperformance of the community heating system. The actual carbon factor of the received heat during the 2018 - 2019 monitoring period was estimated as 0.432 $kgCO_2/kWh$, similar to the previous year. Although the plant's energy efficiency was at the level of the design projections, the contribution of the CHP engine in heat production was only 46% in the 2018/2019 period, about half of what was projected. Consequently, this resulted in reduced production of electricity, greatly increasing the carbon factor of produced heat.

CHP system annual performance		Design SAP 2009 (2013)	Design strategy (2013)	Actual (2017 -2018)	Actual (2018 - 2019)
Fraction of heat supplied by CHP		90%	90%	26%	46%
Heat distribution loss factor		1.05	1.39	2.00*	2.00*
Energy efficiency	CHP engine	78%	78%	66%	75%
	Boiler	87%	87%	88%	87%
	Plant	84%	78%	77%	79%
	System	82%	67%	46%	51%
CHP engine factor	Heat to gas	0.45	0.42	0.62	0.56
	Electricity to gas	0.39	0.37	0.15	0.23
CO2 factors (kg/kWh)	Mains gas	0.198	0.198	0.184	0.184
	Grid electricity	0.529	0.529	0.317	0.269
	Produced heat	-0.019	0.014	0.436	0.432

Table 31 Comparison of community heating performance between design projections and actual data based on empirical measurements and estimated distribution loss factor (marked with symbol).*

Actual distribution loss data was not available. Therefore, a scatter plot based on empirical data from six housing developments (BRE, 2016) was used for its estimation. Applying the mean heat use per case study dwelling (4,830 kWh/year, n=94) to the formula, the resulting factor was 2 (50%) (Figure 75). This estimation also seemed sensible for district heating systems not complying with *"Heat Networks: Code of Practice for the UK"* (CIBSE and CHPA, 2015), as suggested in forthcoming SAP 10 (BRE, 2019). Taking this into account and the plant efficiency of 79%, the resulting overall efficiency of the community heating system was 51% for the 2018/2019 period. A study of a housing development with similar characteristics reported even lower actual performance; plant efficiency of 61%, distribution loss of 57%, and overall system efficiency of only 37% (UCL Energy Institute and Crest Nicholson, 2014).

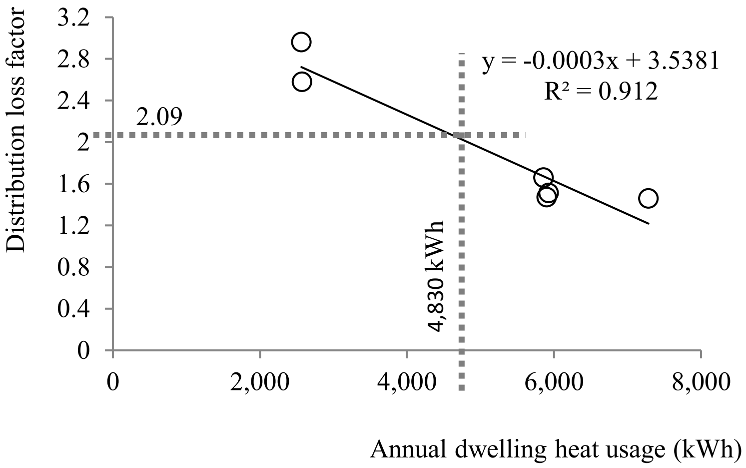


Figure 75 Estimating the distribution loss factor with the scatter plot, adopted from BRE report (BRE, 2016).

A theoretical exercise was performed in order to inspect the rationale behind the selection of this particular heat system. The resulting carbon factor of heat was projected over the plant's expected 20-year technical lifetime (IEA, 2013) from 2015 to 2035, and compared to individual gas boilers (87% efficiency) as the alternative (Figure 76). The calculation used designed system efficiencies, keeping the 2015 gas carbon factor constant (DBEIS and DEFRA, 2015) and using the expected carbon factor of electricity for 2025 and 2035 (DBEIS, 2019e). The results of this exercise suggested that, even if operating efficiently as designed, the case study's plant is estimated to produce more carbon intensive heat compared to individual gas boilers, already by the first quarter of the engine's life-cycle.

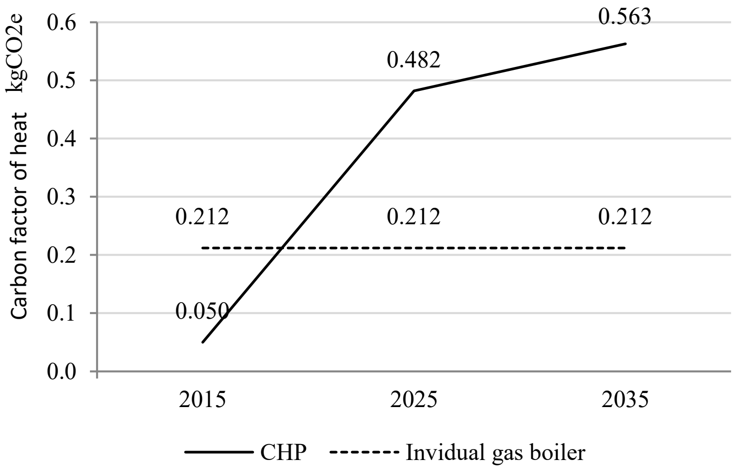


Figure 76 Estimating the carbon coefficient of heat from gas-fuelled district heating with individual gas boilers; 20-year projection.

6.3.2. Dwelling carbon emissions

The estimated carbon performance of dwellings for the 1 April 2018 - 31 March 2019 period was based on the actual dwelling energy usage data (n=74), community heating's performance data and the 2018/2019 fuel carbon factors. Mean carbon emissions per dwelling were estimated as 20.2 $kgCO_2e/m^2$/year, ranging from 2.8 to 45.7 $kgCO_2e/m^2$/year (Figure 77). These results suggested that the net zero carbon target was neither achieved individually, nor at the development level. The achieved emissions were still significantly lower compared to the projected emissions of 38.1 $kgCO_2e/m^2$/year for an average UK dwelling in 2017 (ESC, 2019).

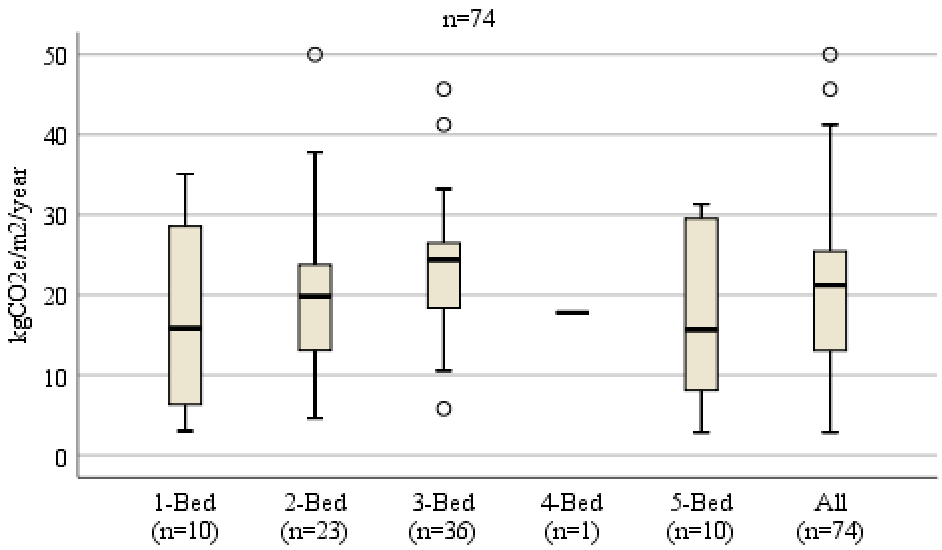


Figure 77 Box plots of annual dwelling carbon emissions, by number of rooms.

6.4. Water use

Potable water use results were based on the data collected in 43 dwellings from Phase 2. As it was already elaborated in the section 4.4.1 of this thesis, water use data from Phase 1 dwellings was not valid.

The results show that the mean annual water use per dwelling was 80.5 m^3, or 220 litres/day (n=43) (Table 32). The most water intensive Phase 2 household used over 13 times more water than the most water saving one. Based on the occupancy data for Phase 2 households, mean water use per person was 96.2 litres/day. Although the water usage was 34% lower compared to the mean usage in SE England (AC, 2018), it was still slightly (1.2 times) higher compared to the design target of 80 litres/day/person. Water usage reported in other low carbon or eco-housing was in some cases similar (Gill et al., 2011), while in other cases it was lower (Bioregional, 2009; BSRIA, 2015) or even higher (SCI, 2013). Figure 78 demonstrates similar water usage levels throughout the year, with slightly increased usage in July.

Annual water consumption (m3)	1-Bed	2-Bed	3-Bed	4-Bed	5-Bed	All
Minimum	69.7	22.8	12.6	81.3	65.8	12.6
Maximum	69.7	97.0	166.1	81.3	161.3	166.1
Median	69.7	61.2	84.4	81.3	132.0	77.3
Average	69.7	57.5	85.0	81.3	124.4	80.5
Sample size	1	15	20	1	6	43

Table 32 Descriptive statistics of annual water consumption per dwelling (n=43).

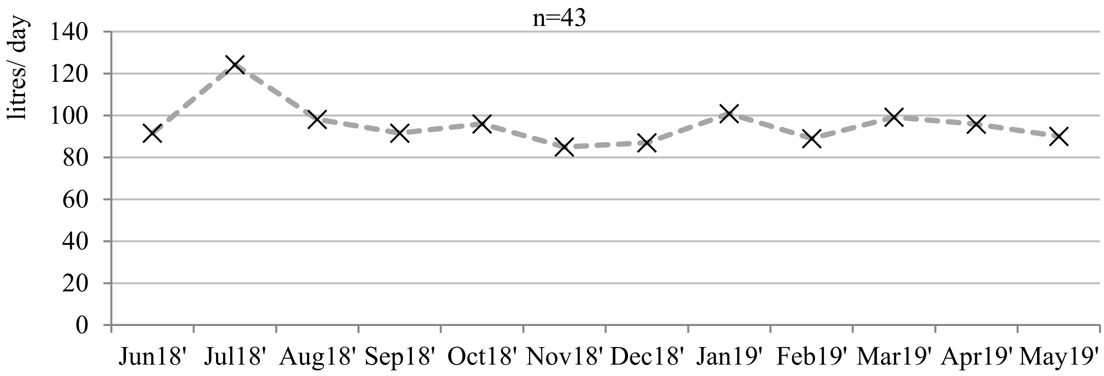


Figure 78 Mean daily water consumption per person in Phase 2 dwellings, by month.

6.5. Summary

An assessment of actual energy and carbon performance was conducted on a large case study housing development in England, designed to achieve the ambitious net true zero carbon target. During the one year monitoring period, the mean energy use was 76 kWh/m^2/year per dwelling (n=74), achieving the design target. The achieved heat use (48.5 kWh/m^2/year) and the designed fabric efficiency fell short compared to other true zero carbon housing. Despite the warmer weather conditions, a performance gap in terms of the space heating usage was noted. This was partly attributed to the reduced as-built fabric efficiency. Dwellings used 11% less electricity than expected, achieving one of the lowest reported usage in housing developments (27.4 kWh/m^2/year). Annual heat usage variance seemed more prominent than what was reported in other studies. Roof PV systems (2.9 kWp on average) achieved the projected solar generation levels. However, due to substantial system size and low electricity use, only 23% of generated energy was self-consumed, calling for the usage of home batteries. It is estimated that 20.2 $kgCO_2e/m^2$/year was emitted on average per dwelling, missing the aspired zero carbon performance. The resulting carbon intensity of heat (0.432 $kgCO_2$/kWh) based on 2018/2019 carbon factors, was significantly higher compared to the design projections. The underperformance of the community heating system was attributed to the changes in the electricity grid and reduced system efficiency probably caused by the insufficient heat load. Lastly, based on the data from 43 Phase 2 dwellings, the mean daily potable water consumption was 220 litres per dwelling, or 96.2 litres per person, missing the design target of 80 litres/person/day.

Chapter 7: Energy Behaviours and Dwelling Indoor Environmental Conditions

7.1. Introduction

This chapter presents an in-depth assessment focused on 12 to 14 dwellings, as a subset of the wider dwelling sample captured in the development-wide assessment presented in the previous two chapters. Monitoring of the indoor environmental conditions was conducted on 14 dwellings over the one year period. Within this dwelling sample, 12 households were interviewed about their experiences and behaviours related to heating, ventilating and keeping their home cool. This chapter aims to bring together these objective measurements with subjective responses of the households.

The findings are divided into four main topics: heating season, non-heating season, ventilation and home energy use behaviours. With regard to the heating season, the text presents measured temperatures, households responses about the preferred heating regime, their understanding and experience with the heating system, thermostat, noted heating issues and lastly, the results of indoor and outdoor thermal imaging. The study findings about the non-heating season capture temperature measurements, an assessment of potential occurrences of overheating during the warmer days, and household responses about the actions they take to keep their homes cool. Measured CO_2 concentrations are used as indicators of the ventilation levels. These results are related to the reported household ventilation behaviours. Finally, the households are asked about their experience with the Shimmy and the solar PV panels, as the two important dwelling environmental features.

7.2. Dwelling Occupancy Pattern

Figure 79 shows the dwelling occupancy pattern of a typical week, as reported by the interviewed households. During the weekdays, all households apart from H6 and H8 tend to leave for work. Typical use of the bedroom (marked in green) varied. Most households would use the bedroom between 10 pm and 7 am. Typical use of living rooms (marked in blue) was in the period from 4 pm to 8 pm. During the weekend, the usage pattern expectedly altered. Occupants stayed slightly longer in their bedrooms, often using living rooms throughout the day. Despite slight changes in room use, the indoor conditions in the subset households were compared using the most common occupancy pattern; 10 pm to 7 am for bedrooms, and 7 am to 10 pm for living rooms.

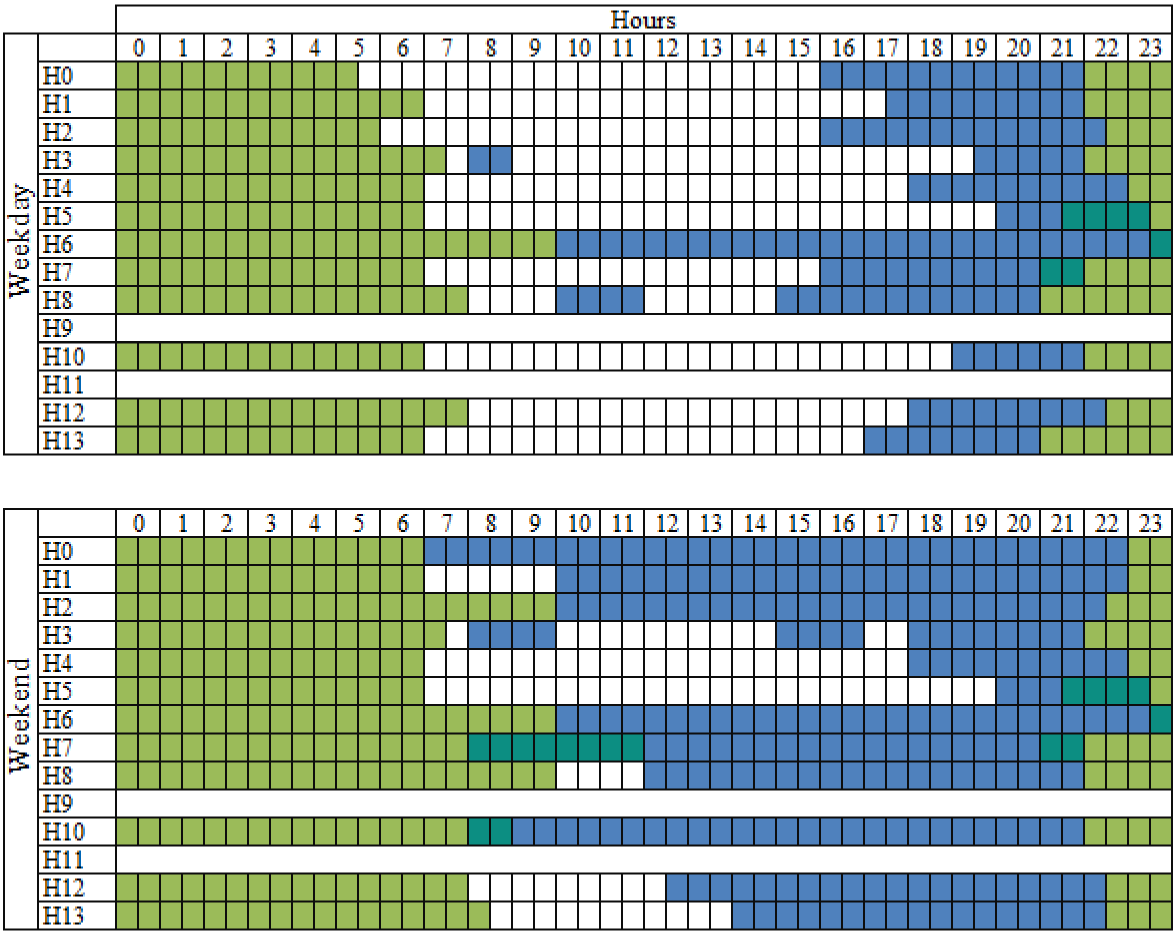


Figure 79 Reported typical weekday and weekend occupancy of living rooms (marked blue) and bedrooms (marked green).

7.3. Relative Humidity

Over the course of the monitoring year, the mean relative humidity (RH) levels measured during the typical occupancy hours ranged between 45% and 54% in the living rooms, and similarly from 45% to 58% in the bedrooms (Figure 80). The measured monthly humidity values are not at odds with the reported measurements in a sample of low carbon and Passivhaus dwellings (Gupta and Gregg, 2020).

Higher humidity levels in buildings are thought to increase exposure to fungi, mites and other air-borne hazards (Arundel *et al.*, 1986). The percentage of the time with RH levels above the recommended level of 70% was negligible; at below 0.2% in all the monitored rooms. Low humidity levels are thought to increase the risk of respiratory infections (Metz and Finn, 2015). In bedrooms, RH levels under the recommended threshold of 40% were recorded only 2% of the time, apart from the bedrooms in dwellings H9 and H11 (14% and 17% of the time, respectively). Living rooms were notably drier. In 11 living rooms, RH levels below 40% were recorded between 2% and 13% of the time, and just above 20% in the living rooms of dwellings H6 and H8. Lower humidity levels in the living rooms can be partly explained by the preference for slightly higher air temperatures (section 7.4.1), compared to bedroom temperatures. The dwellings with notably low humidity (H6 and H8) were mostly stay-at-home households, who preferred to manually control the heating system (see section 7.4.2 for more details).

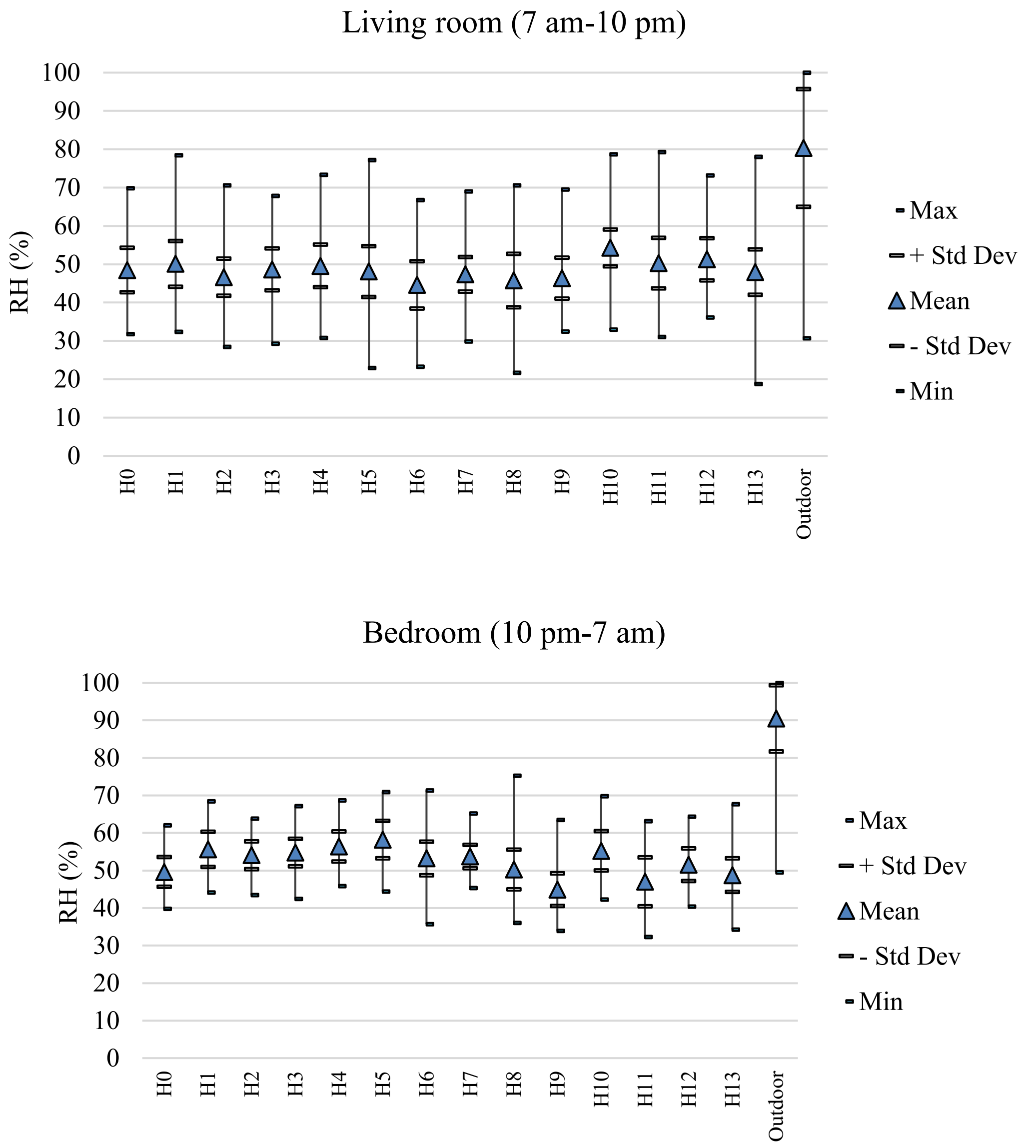


Figure 80 Mean, minimal, maximal and standard deviation of relative humidity levels in living rooms and bedrooms, during typical occupancy hours.

7.4. Heating Season; Temperatures, Household Behaviour and Experience with the Heating System

7.4.1. Temperatures

As seen in Figure 81, the mean living room temperatures during the typical occupancy hours ranged from 19.7°C to 23.2°C in the heating season (October to April). The mean living room temperature of the dwelling sample was of 20.8°C. This is about 3°C higher compared to mean temperatures in a sample of UK dwellings (Kane *et al.*, 2011), and similar to the temperature in SAP 2009. The bedrooms were heated to slightly lower temperatures. Time-weighted average bedroom temperature of the dwelling sample during night hours was 20°C. The mean temperatures during the night hours ranged from 19°C to 21.7°C. Overall, the monthly living room and bedroom temperatures of the whole sample were similar to the results of a larger low carbon dwelling sample (Gupta and Gregg, 2020).

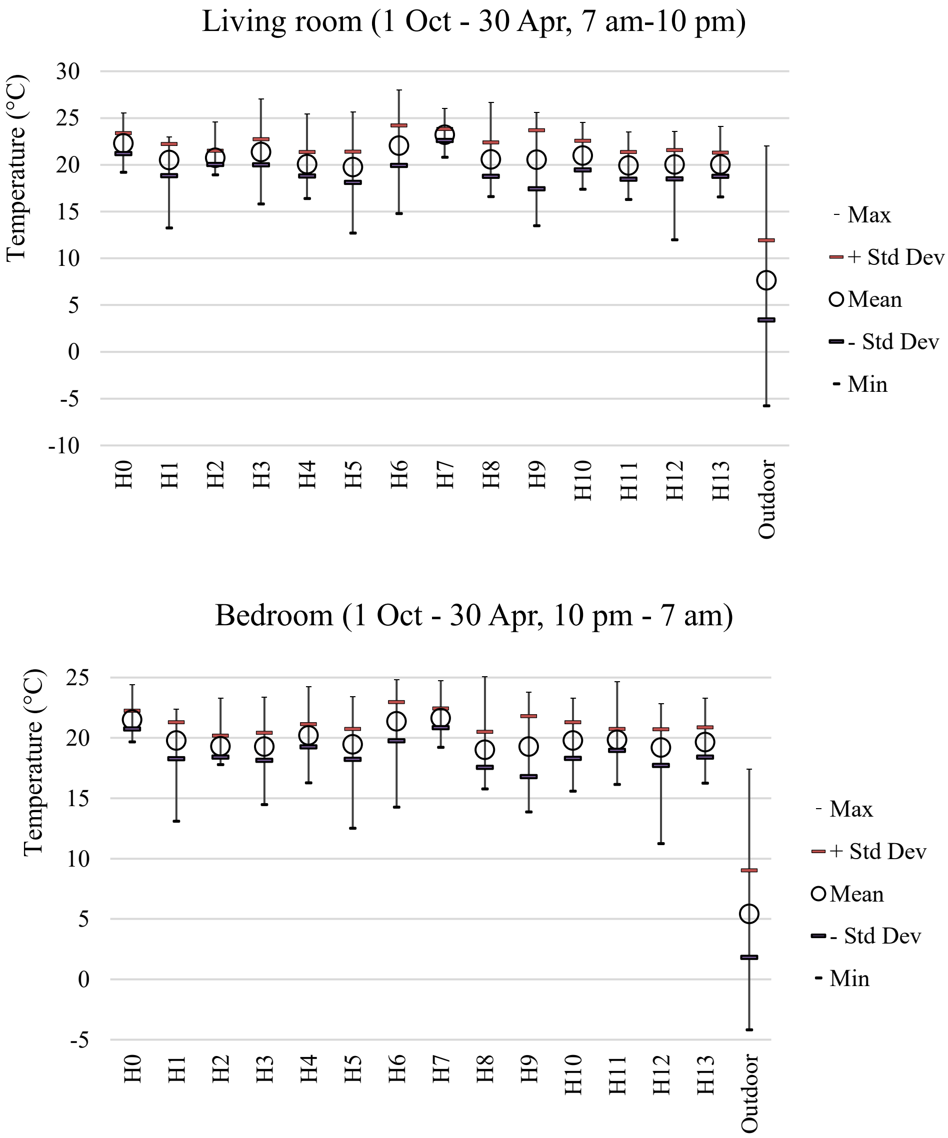


Figure 81 Maximum, minimum, mean and standard deviation of living room and bedroom temperatures during the heating season.

The lowest recorded temperatures seen in the same Figure indicate the conditions occurring during the times of longer absence and holidays. It can be noted that only three out of the 14 monitored households preferred to keep the house warm during the absent days, not allowing the temperature to drop below 19°C. The majority of the households were probably keen to save energy and keep the house on a lower temperature setting, between 11.2°C and 17.4°C. The standard deviation of the measured temperatures was relatively similar in ten living rooms (about 1.5°C) and eight bedrooms (about 1.3°C). Heating strategies elaborated later in this section explain this similarity. Some dwellings (H2 and H7) achieved more stable indoor temperatures while other dwellings (H6, H8 and H9) experienced more pronounced temperature changes.

As seen in Figure 82, agglomerated daily temperature profiles of dwellings suggested that most of the households preferred keeping living room temperatures between 20°C and 21°C degrees during times of occupancy. Four households (H1, H6, H7 and H10) preferred slightly warmer conditions, between 21°C and 24°C degrees during the occupancy hours.

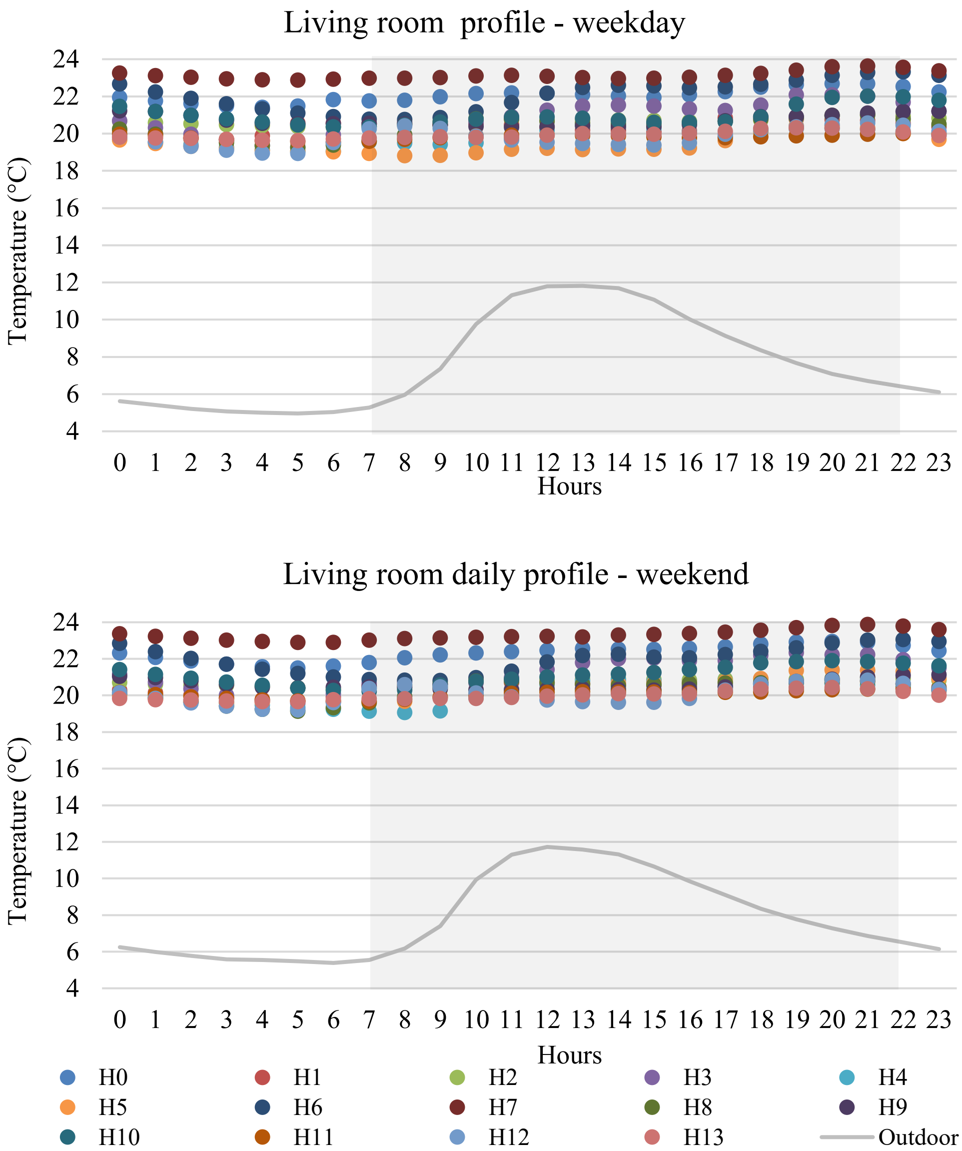


Figure 82 Weekday and weekend daily temperature profiles of living rooms, hourly data of 14 subset dwellings.

7.4.2. Heating Regime

Attempting to capture the heating regime, temperatures of a radiator in each living room of the dwellings were monitored throughout the year. Figure 83 shows the percentage of time the radiators achieved temperatures above 40°C. This temperature limit was used as a proxy for the radiator activity, showing the time heating was on per each month. The results of the analysis suggest that the heating season tends to start in October and ends between April and June, depending on the household. The maximal measured radiator temperature ranged between 55°C and 64°C.

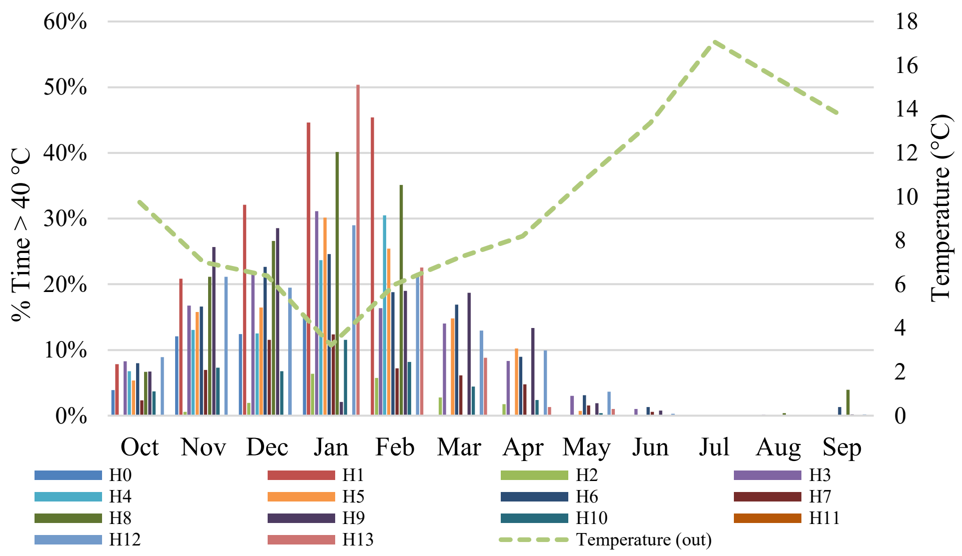


Figure 83 Percentage of time the living room radiators achieved temperature above 40°C, alongside outdoor air temperature averages throughout the year.

The data presented in the scatter plot (Figure 84) suggested that in most of the monitored dwellings the heating system was in operation on the days with mean daily outdoor temperatures up to about 14°C. This was lower than the degree day base temperature of 15.5°C (Monthly Degree Day Data, no date). In three homes (H6, H8, H12) the heating was activated on certain days with daily outdoor mean up to 16°C. This is probably related to occupant factors. The household H6 preferred slightly warmer indoor conditions (22.1°C in the living room), while households H8 and H12 reported keeping their heating system on throughout the summer period.

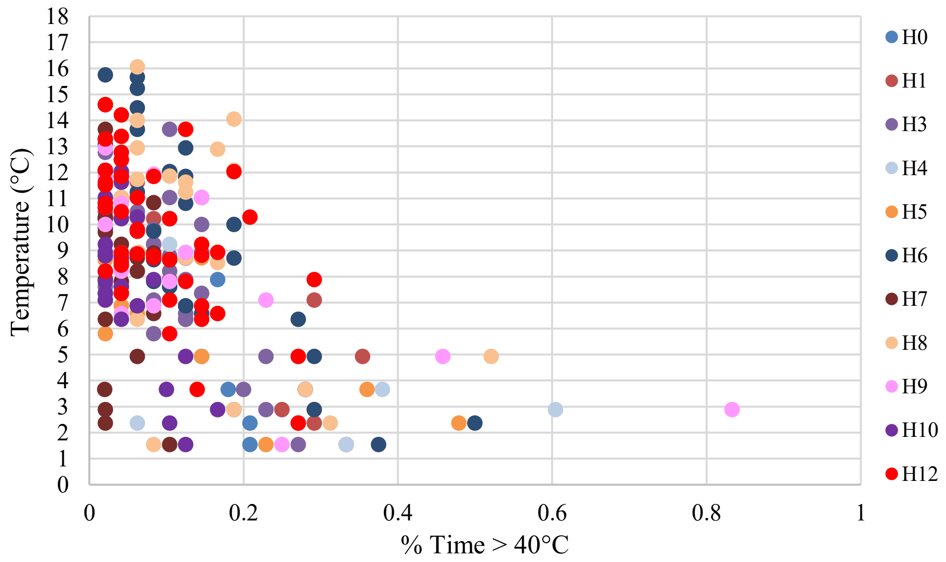
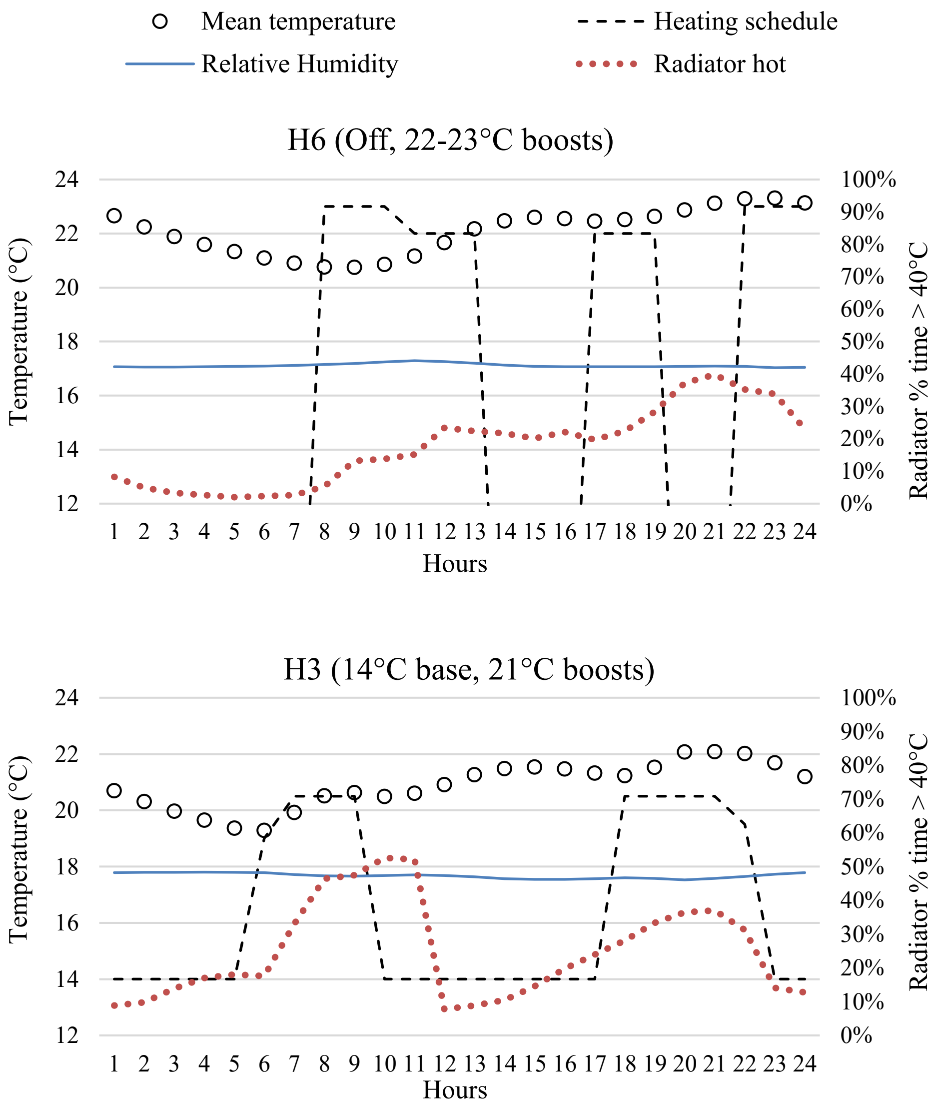


Figure 84 Scatter plot comparing length of heating (indicated by radiator temperatures > 40°C) and daily outdoor temperatures. Data from transitional heating months; May, June September and October.

In order to gain more understanding about their heating behaviours, the households were asked about the typical length of the heating season in their home. Findings from radiator temperatures were relatively in line with the given feedback. After sensing sufficiently high outdoor temperatures during months of March, April and May, most of the households would either turn the heating manually off, or use a low temperature setting during the summer period. Three households (H2, H8 and H12) had a tendency to leave their thermostat on during the winter setting, to allow some heating if needed. Most of the interviewed residents started to heat their home in mid to end October.

Households were asked about their typical heating schedule and thermostat temperature setpoints. The majority of households preferred to schedule a lower temperature when not at home or during night hours (14°C to 19°C), and then boost the heating to reach a more comfortable temperature (19.5°C to 23°C) when occupancy was expected. Figure 85 showcases different daily heating regimes during the working week (Monday to Friday) that were reported in the interviews. The stay-at-home households (H6 and H8) found it most convenient to manually switch the thermostat on and off throughout the day, according to the needs. H3 and H12 represent five households which tend to set a low indoor temperature (14°C to 17.5°C) during the unoccupied hours, again boosting this temperature during occupancy. Lastly, H1 and H7 represented the remaining five households which liked to schedule their temperatures above 19°C.



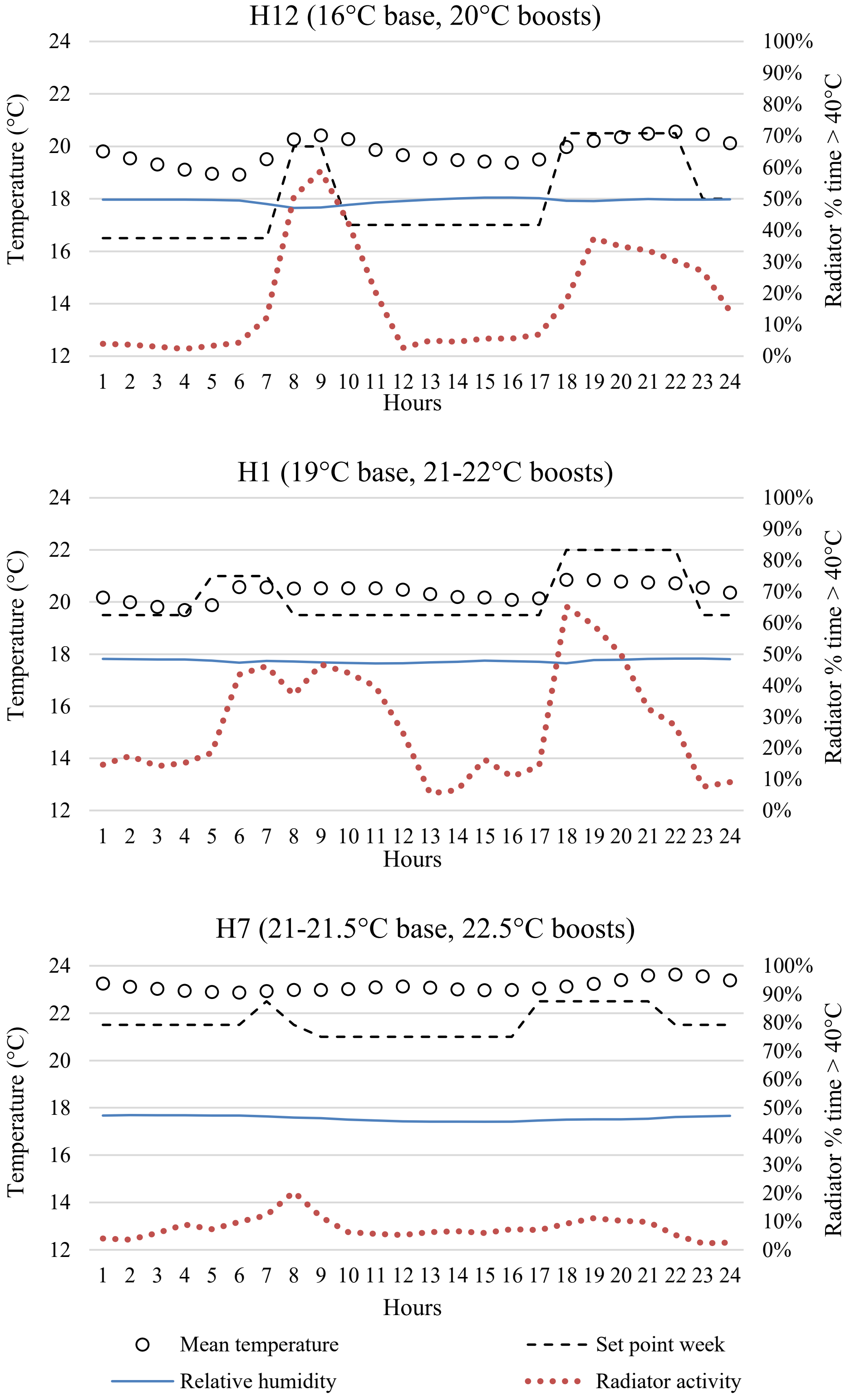


Figure 85 Examples of different daily heating practices in subset dwellings, using the reported heating schedule, mean hourly living room temperatures and the ration of time radiators were hot.

As it can be noticed in some cases in Figure 85, the measured living room temperatures were up to 3°C higher than the reported thermostat setting. In 11 dwellings the mean difference during evening hours (7 pm -10 pm) was 1.2°C. This could be possibly caused by different calibration of the thermostats and monitoring instruments. Figure 85 also demonstrated that despite the fact that some households have set the minimum temperature as low as 14°C, the mean living room temperatures did not seem to fall below 19°C throughout the day or night. The following quotes from the interviews confirm this notion:

It never gets down to 16°C. Last night, the temperature in the morning was 17.3°C. It was 20°C when it turned off. (H12)

Yes, so if we take the thermostat at 21°C in the evening, in the morning it never goes below 19°C. We have a loss of maximum 1-2°C. But even if the thermostat shows 17°C, it never goes below 18-19°C. (H10)

The data analysis showed that seven households which reported to set the temperatures lower during certain time periods, lose between 0.7°C and 2.7°C (mean of 1.7°C) of temperature in the living rooms during the night. This is related to good retention of heat by the highly insulated and airtight dwelling fabric. Results indicate that some households aimed to save energy and reduce heating costs by tolerating slightly lower temperatures, but not below 19°C. From there, their slightly inert heating system could still reach comfortable temperatures in few hours. Such approach to heating was confirmed some of the responses;

If you put it on 17°C, you wake up in the morning it is still 19°C, 19.5°C. There is no point in switching it on. (H10)

What we tend to do here is try and keep the minimum temperature. So, downstairs we would keep the minimum temperature of 18°C to 19°C. When we come in, it doesn't take so long to heat the room up. (H0)

It takes ages to heat this house up. If we ever go away it is down to 15-16°C, it will take three or four hours to heat up to like, 19°C. So, we never do that. We never let it get cold. We just leave it at a warm temperature. (H4)

Three households reported experimenting with heat saving practices in the past. This would entail turning the heating off or reducing the setpoint temperatures during unoccupied hours. However, such strategies were considered to not be beneficial, and were soon after abandoned:

Yes, well initially, we only used to turn the heating on when we wanted it. So, when we went out for the day, it was turned right down to about 15°C. But, we had so many issues with the heating. It could take four to five hours to heat the room to a comfortable temperature. I prefer to be at constant temperature, I do not like getting up in the morning into a freezing cold room. (H0)

Because in the past we have experienced that setting the temperature on and off, like on set times of the day, we would spend more because the house would be colder. The heat exchange unit has to work harder the temperatures. If you set the constant temperature, you spend little bit less. No, not in this house, in the past. (H2)

Five subset dwellings were provided with an additional thermostat located in the main bedroom on the first floor. Overall, the second thermostat was used to provide slightly cooler conditions in the first floor. It was mostly used to provide comfortable temperatures during short periods of the day when the first floor was more actively used. On the first floor, temperature would be typically boosted during early morning hours to make usage of the bathroom more comfortable. Temperature could be also briefly boosted later in the day if needed. During all other periods, the second thermostat was off, or set on a lower temperature setting. As one resident explained:

It is off a lot upstairs. The heat rises so much in this house. We use it every day, but it is not as long as... downstairs we might have the heating on for 6-7 hours, but upstairs rarely more than couple of hours daily. In the morning to get up... I like to have the bathroom warm. Sometimes again in the evening if it's really cold, it might go on for a little bit. (H6)

7.4.3. Understanding and Regulating Heating

Understanding of the Home Heating System

When asked whether they understand how the heating system works in their home, interviewees generally felt like they understand it enough to achieve the preferred indoor temperature. In addition, many have admitted that beside controlling the temperatures, they do not have a greater understanding about how the heating system in their home actually works:

> *I think I can operate it in the sense that I have set the thermostat there. (H1)*

> *I think I know how it works but I do not know where to touch. I would need to call SSE. I have to say, if I am confident with it, I am not. (H2)*

> *Anything to do with the cupboard, I don't understand how it works. I only understand that that is where the heating comes from. I have no idea how the programming works, I have tried it, it's beyond me. (H6)*

It seems that many households were not motivated to acquire a deeper technical knowledge about the system, as the billed standing charge was covering the system's maintenance. Also, the households were requested by the developer not to fiddle with the heat exchange unit (HEU), piping, radiators and other heating elements. One interviewee who experienced prolonged issues with the heating system and poor maintenance support, was not satisfied with such request. The interviewee felt like the residents should be trained to perform some basic maintenance operations, such as topping up the water in the system and bleeding the radiators:

> *After this training, from the system maintenance company, now I understand. I did not know how to top up. That is the basic. That should be by the developer. To organise it to explain where to set it up. It's not like, you guys, you are not allowed to touch anything in the cupboard. It's nonsense. (H7)*

Interestingly, only a few interviewees noted that when heating was on, radiator temperatures were stratified. The radiators were designed to drop the district heating's water temperature to almost an ambient temperature. In a traditional central heating system with a gas boiler, all the surface of radiators would be equally hot. The temperature stratification in radiators caused confusion in some households:

> *We always reach the temperature, but how the radiators work… they are always half cold half warm. They say it is supposed to be like that. But I have never understood the reason for that. (H10)*

> *The developer said they are supposed to be cold in the bottom. The SSE man said, I do not know what kind of book he is reading but… some fittings in the back needed to be re-done. That why it was cold at the bottom. (H6)*

Provision of Information and Advice About Heating

Households received information about how to operate their home from various sources. A home user guide booklet included information about the house systems, green design features and infrastructure, and more technical documents. Informative videos about the home systems were also provided on the Shimmy home information display. A Facebook page was created by the operator where residents were able to make contact. One interviewee shared that the district heating operator also provided a couple of informative sessions to some residents about the heating system.

Four interviewees who mentioned the handover process, regarded it as too brief. The provided information about the dwelling's heating system was considered quite basic. All interviewed households acknowledged receiving the home user guide, but only one household admitted that they have actually read it. Many interviewees felt like there was no need to check the guide, as they were able to go by without it. One household shared that the guide focused more on explaining the role of the energy centre, rather than the house heating system. Few households also mentioned that the provided thermostat manual printed on a A4 leaflet seemed too brief.

Since they moved in, less than half of the interviewed households were given advice how to heat their home. It seems that there was no organised and controlled provision of such information. Advice could sporadically be given by the developer (handover staff or sales team), or the heating operator (maintenance engineers or plumbers). Two households were advised to maintain a constant indoor temperature. One of the interviewees was told that this strategy was more efficient for the boilers, and cheaper for the households as well. Similarly, two other households were advised to not turn the thermostat off. One of them was told that this was to prevent the hot water pipes from freezing. Some households were also warned that the heating system should be always on because the house takes longer to heat up. Following quotes elaborate some of the suggestions provided to the households:

They were saying how it is best to keep the house on a constant temperature. But we thought it did not really work for us because, we are out of the house most of the time. It would be stupid to keep it on. (H5)

I have heard from the neighbours that they have been told either by the developer or the heating engineer that they should run it as a constant temperature. That's not the way I am doing it. And they have been told that this is something to do with the efficiency of modern homes. Few people I know are doing that, because they were told. (H12)

One person said; leave it at a constant temperature, it is more efficient for the boilers. But then we have been told by someone else that because you are only drawing in what you need and you are paying for the kW, it doesn't really matter. It is not more efficient to keep it at constant temperature. And, there should not be any cost difference between drawing it in when you want it or having it at constant temperature. So, I am still a bit confused about what do they think it's the best way. (H0)

However, no interviewee reported that they have altered their preferred heating strategy due to the heard advice. As mentioned earlier, the majority of households seem to favour keeping a low base temperature when away, and increase the temperature to more comfortable levels when the dwelling was actively used. The difference in the advised heating regime and the regime preferred by the households was noted by one interviewee:

That is why they have set it up like this, so that we as a house, give back a low return temperature. That's why, what they said is not strictly incorrect, that the efficiency is better. The point is that it's not the efficiency of the HEU, it's the efficiency of their system. Which is not directly my problem! They would much prefer that this is constant *small flow. Gives them a constant low return temperature. I think they know if they say that to us, people would be hey, I want instant heat! (H12)*

Experience with the Thermostat

Eleven interviewed households rated the thermostat in their home and shared their experience with its use. The majority of the households found the device to be good overall, one household rated it as average, while three households rated it poorly. With regards to specific rating criteria (Table 33), for *Ease of use* and *Usefulness of labelling and annotation* were given average score (3). For the remaining four criteria, the median score was good (4).

Criteria	Poor	Neutral		Excellent
Clarity of purpose			4 (3.6)	
Intuitive switching			4 (3.8)	
Usefulness of labelling & annotation		3.5 (3.3)		
Ease of use		3 (3.2)		
Degree of fine control			4 (3.4)	
Accessibility			4 (3.7)	

Table 33 Median and mean (in brackets) votes in regard to different thermostat criteria (n=11).

Five out of 12 the households found the thermostat difficult to operate. Due to the encountered issues, two interviewees preferred to control the heating system manually. One household replaced the provided thermostat with a new system that was easier to use and allowed remote control of heating. Another household preferred the manual control, as it provided higher level of flexibility. Experiences with using the thermostat were elaborated in the following responses:

This is one is a nightmare. Even the engineer said leave it on a manual. It does not work as it should. (H7)

If you press buttons too hard it crashes. You cannot press down as well, it crashes too. Not fun to use. It is an elaborate system that I do not know how to alter that well. I find it quite hard how to do that. (H4)

We have a flexible working schedule, so if I work from home, I want a bit of temperature. I like to be in control of the temperature. I do not want to have a fixed programme and then to change constantly because... maybe I am home one day per week. (H10)

7.4.4. Views About the Community Heating

From all the interview questions, households were most vocal about the community heating system. Only two households were generally satisfied with the system. Two other households were unsatisfied, while the big majority of households gave it an average rating, having mixed feelings. However, when asked whether they would prefer having an individual gas boiler instead, all but one interviewee preferred their current system.

Most commonly mentioned advantage of the community heating system was being relatively care-free about possible system malfunctions. A third of the households liked that they do not have to worry about the system maintenance, as it was covered by the heating bill. A few households were pleased with the fact that, so far, hot water outages would be promptly registered by a neighbour, and typically solved within the same day. Interestingly, only two interviewed households mentioned that this system was supposed to be more efficient and eco-friendlier than the conventional gas boilers. One household also preferred not having a gas installation due to safety concerns. The following quote included some positive aspects also mentioned by other households:

I think I like it. When you come to the village, and when you realise that there are no boilers in the houses, it feels great, right? They fix very quickly if there is a problem, we do not need to worry. Like, if it's our fault, we need to call the engineer. We have no expenses because we pay the monthly fee, which a lot of people complain about. But in the end, if you understand that it gives you a piece of mind for whole life. (H10)

Interviewees were more vocal about what they dislike about the system. The first of the two key issues highlighted by the majority of households was the standing charge. All interviewed households found the current standing charge quite expensive, apart from one interviewee who never used a heating system before, and another who was paying the discounted rate for social housing. Many surprisingly noted that the standing charge was higher than the actual cost of heat used. The interviewees who were attracted to buy the house due to the sales team's promises of lower bills, now felt disappointed. Also, the gradual increase of the standing charge over the years was in contrast to the claims of the heating operator that the charge will be reducing.

The second key issue raised the majority of households was being contractually bound to a single heat supplier. Many found the lack of supplier competition unfair, as it would undoubtedly result in lower prices. Some households were informed that the standing charge will be fixed to the rate of the inflation and be comparable to the rates of other large UK energy suppliers. Some also felt that there should be more transparency in the way how the rate was established. Three interviewees suggested that the community heating system market should be regulated. Other issues mentioned frequently by the households include no hot water back-up system in the development, frequent outages during the initial year of occupation, poor response from the operator to reports of system breakdowns, and lastly, the lack of assurance that the system is indeed more eco-friendly. The following responses show different experiences:

I have come to terms with it. I think the problems are not technical, the problems are with the business model and the lack of transparency in the cost. (H12)

We feel a bit annoyed. I was talking to SEE quite a bit before I moved in, I tried to work out how they will be going to peg it the rate to the inflation and things, they were rubbish at getting back to us. And then they said; if you do not sign this contract, we will give this house to someone else. (H4)

I think the problem here is that these solutions are not yet regulated. But I think it is a better way to control the district heating. When you want to heat its heating up good. I think there is not so much competition on this, so the provider does what they want. They are also raising the prices as they want. (H0)

What we don't like is the fact that you have to stay with the same supplier, that means that that supplier can put the prices as they like. As well as service charge. In fact, what we pay for, what we use is a third of what we pay for the service charge. That is ridiculously high. It is not really fair, because we would save so much more money. This we knew from the beginning, but we did not expect it to be that costly. (H5)

The operator also attempted to reassure some households that having the current system is more affordable for them compared to the individual gas boilers. Households shared the cost of heating in 2020; 1.375 £/day for the standing charge and 4.6 p/kWh for the heat used. These costs were higher than in Derwenthorpe (Quilgars *et al.*, 2015, 2019), but similar to the costs in One Brighton development (Lowe and Altamirano, 2014). The standing charge was within the price range of a sample of heat suppliers (Guijarro, 2017). Taking the mean measured dwelling heat consumption of 4,830 kWh, the mean annual cost of heating would be £758.3, including VAT. In order to test the operator's claim, this cost was compared to the estimated cost for an individual gas boiler system (Table 34). The first estimation was based using an the online heat cost calculator tool[20] (Heat Trust, 2016). The second estimation was using the market cost of gas (4.17 p/kWh) and the standing charge (25 p/day) [21]; 87% boiler efficiency; annual heating system servicing cover of £187[22] and; a nominal cost for boiler installation of £170 (£2600 over 15 years)[23]. Both estimations were subject to a number of uncertainties. With that in mind, both results indicate that in contrast to claims of the heat supplier, private owners in the case study development seem to pay a 10 - 16% cost premium for the heat provided by the community heating system.

	Individual gas boiler (estimated)	Individual gas boiler (estimated by Heat Trust)	District heating (actual)
Heat use (kWh)	4830	4830	4830
Gas use, 87% boiler efficiency (kWh)	5552	-	-
Cost of heat (p/kWh)	4.17	-	4.83
Standing charge (p/day)	25.58	-	143.85
Cost of heat (£/year)	324.9	282.0	758.3
System servicing (£/year)	187	199.9	0
Cost of new boiler (£/year)	170	149.7	0
Total cost of heating (£/year)	681.9	631.5	758.3

[20] https://heattrust.org/test-the-comparato

[21] https://energysavingtrust.org.uk/about-us/our-data/

[22] https://www.britishgas.co.uk/home-services/boilers-and-heating/boiler-and-heating-cover.html

[23]https://www.which.co.uk/reviews/boilers/article/buying-a-new-boiler/boiler-prices-how-much-does-a-new-boiler-cost-aK2dh2j3Cabo

Table 34 Comparing heating costs between actual cost and cost estimations for an alternative heating system.

7.4.5. Issues with the Heating System and Building Fabric

<u>Teething issues</u>

The interviewed households reported experiencing various issues in relation to the heating system and dwelling fabric. Issues were differentiated into teething issues and ones which still existed at the time of the interview.

Almost half of the interviewed households from both Phases (H0, H2, H6, H7 and H10) experienced initial difficulties with warming up the house. Some households noticed that heating was very slow, while other were unable to warm up the space to a comfortable temperature. These issues were eventually sorted out, mostly by increasing the pressure of the house heating system. In one household, this solution was discovered very late, three years after moving in. A couple of dwellings also required fixing of radiators, which were either wrongly plumbed, not bled or properly balanced. Two residents explained the initial issue with heating up their home:

> *And initially we could only put our heating to 19°C. You couldn't take it above 19°C, no matter how long you had it on. (H0)*

> *Once an engineer came and that the pressure was set at the minimum. That's why it is always not really hot, and it took longer and longer to warm the house. So, he advised to put in on the highest. (H10)*

The households have also reported experiencing frequent outages of the hot water supply to their homes. One interviewee in Phase 1 counted 26 outages in the first seven months after moving in. This luckily occurred in the summer period, disrupting only the hot water for showering. In the past two years since the interview, just a couple of outages were noted per year.

Cold rooms

Households which reported no heating issues were able to achieve warm indoor temperatures with thermostatic radiator valves (TRVs) mid-opened (setting 4 or 5) in the ground floor rooms, and slightly closed (setting 2 or 3) in the first floor rooms. Five households reported that they were still unable to warm certain rooms to comfortable temperatures, even with the TRVs opened to the maximum setting (6). In three households, the second bathroom still felt too cold at the time of the interview. Other rooms that were considered cold included the entrance hall, the main bedroom and the living room. Two interviewed households associated this to the poor insulation of the attic above the cold room. Seven households reported that some bedrooms can feel slightly cooler than the rest of the house. In some cases, this was probably due to the infrequent usage of these rooms, and slightly closed TRVs. The following complaints described the mentioned issues and the suspected causes:

> *Yes. The other bedroom. The reason why is because here above the bed, here is the water tank, in the loft. That has not been insulated. So, that is quite bad. (H7)*

> *We just think it does not work properly… But even if we the turn the heating higher, because we know we will be showering in an hour or so, the bathroom is always cold. (H5)*

> *Three bedrooms are colder. I will tell you why, the thermostat is in my room, next to the door. Once the main bedroom is warm, the other rooms stop heating. (H8)*

Apart from the occurrence of colder rooms, the households were generally able to keep their home warm. About half of the households kept their TRVs fully open, mainly to make the heating system more responsive. Three households (H0, H4 and H5) found it necessary to open the TRVs to the maximum position in order to make their home sufficiently warm. Interestingly, two households also expressed doubt that the provided radiators are sufficient to heat up the space:

> *It is a little slow. They have got very small radiators in here. They are definitely smaller than we are used to. They pumped up the size for the next development. I have seen houses at Phase 2, and they are bigger. Also, positioned differently. (H4)*

The reason this sofa is where it is because its sits right back against the wall there that is so cold. Its crying out for either for the radiator on the wall behind you, or a bigger radiator. The heater does not seem to get there. I am not sure if you are aware but there is inadequate heating for the houses. One of the other residents, he had NHBC in, and he had his actually renewed last week. Only after he got solicitors involved. They increased the size of his radiators. (H6)

<u>Fabric issues</u>

Some households have reported keeping window trickle vents mostly open during the heating season. Few residents would close the vents if they sensed uncomfortable drafts, typically while seated. In some dwellings, vents would be closed during particularly cold weather or due to whistling noise caused by the wind. This is explained in the following quotes:

Trickle vents in the living room are closed. We sit on this couch watching TV. Obviously then we are very sedentary. It can be very noticeable then. Because we put our couch directly underneath them. I had to close them. I was commented on by my wife. She also closed them in her office room. (H12)

The only time we had problems with noise with our window vents is if it's really windy, we had to close the ones in the main bedroom because, the wind whistles through them. (H0)

Less than half of the interviewed households have complained about the drafts coming from the front door, while one household complained feeling cold in the proximity to the big patio doors in the living room. The suspected causes of these drafts are air gaps caused by the improper fitting of the fenestration, the keyhole and the letterbox on the front doors.

7.4.6. Thermal Imaging

Indoor and outdoor thermal imaging survey of three subset dwellings (H0, H2 and H4) was conducted by the Researcher on 26 Jan 2019. Resulting images are presented in Figure 86 to Figure 89. Overall, the thermal imaging confirmed the suspicion of some households, and detected thermal bridges and cold ingress. This was expected to reduce the targeted energy efficiency of the building fabric.

The cold air ingress at the patio and entrance doors appeared to be the strongest (Figure 86 and Figure 87). This indicated poor insulative properties of the door threshold, not effectively sealing the air gap. At the patio doors in dwelling H4, cold ingress was also visible near the central door frame, indicating that the doors perhaps could not close well. In H2, the gap between the entrance door frame and the door leaf could be clearly seen during the sunny weather. A cold ingress in that same area was also evident, indicating poor fitting of the doors (Figure 87). Figure 88 shows inadequate positioning of the insulation around the loft hatch. The main bathroom in dwelling H0 and the second bedroom in H7 were both reported to be colder than other rooms. Figure 87 shows that the ceiling in both rooms was colder than the walls, probably due to inadequately installed insulation around the water tank in the attic. Figure 89 showed the thermal images of the exterior of three dwellings (H2, H3 and H8). In addition to the previously noted issues with fenestration, cold ingress can be seen along the roof eaves.

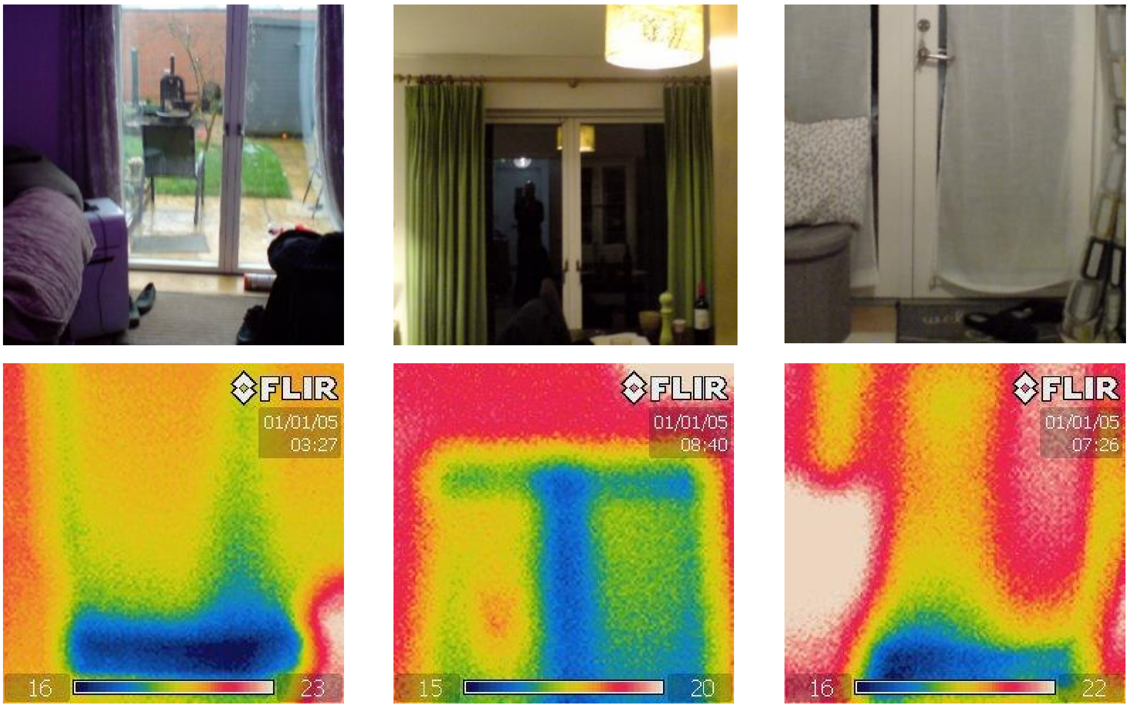


Figure 86 Thermal imaging of the bi-fold patio doors, taken from the living room. From left to right; dwellings H0, H4 and H2.

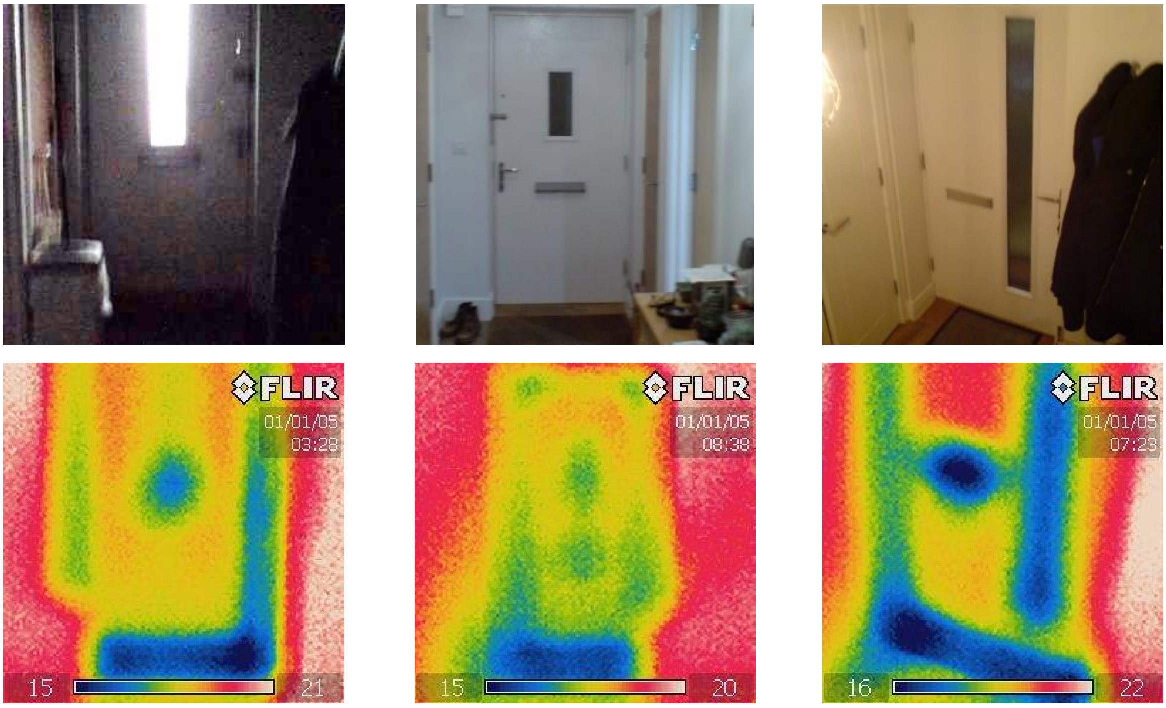


Figure 87 Thermal imaging of the entrance doors, taken from the hallway. Left to right; dwellings H0, H4 and H2.

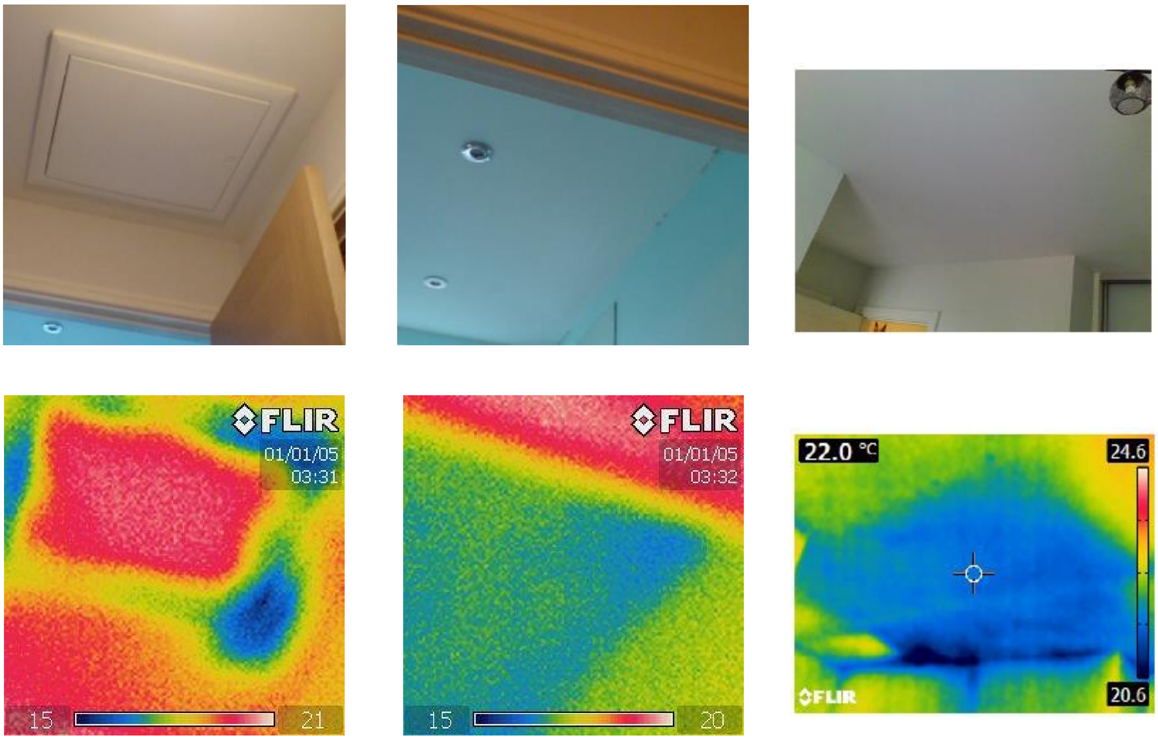


Figure 88 Thermal imaging of the loft hatch (left) and ceiling of the main bathroom (middle) in dwelling H0 taken from the hall on floor 1. Images on right show thermal imaging of the ceiling in the second bedroom in dwelling H7 (Source: House Scan report).

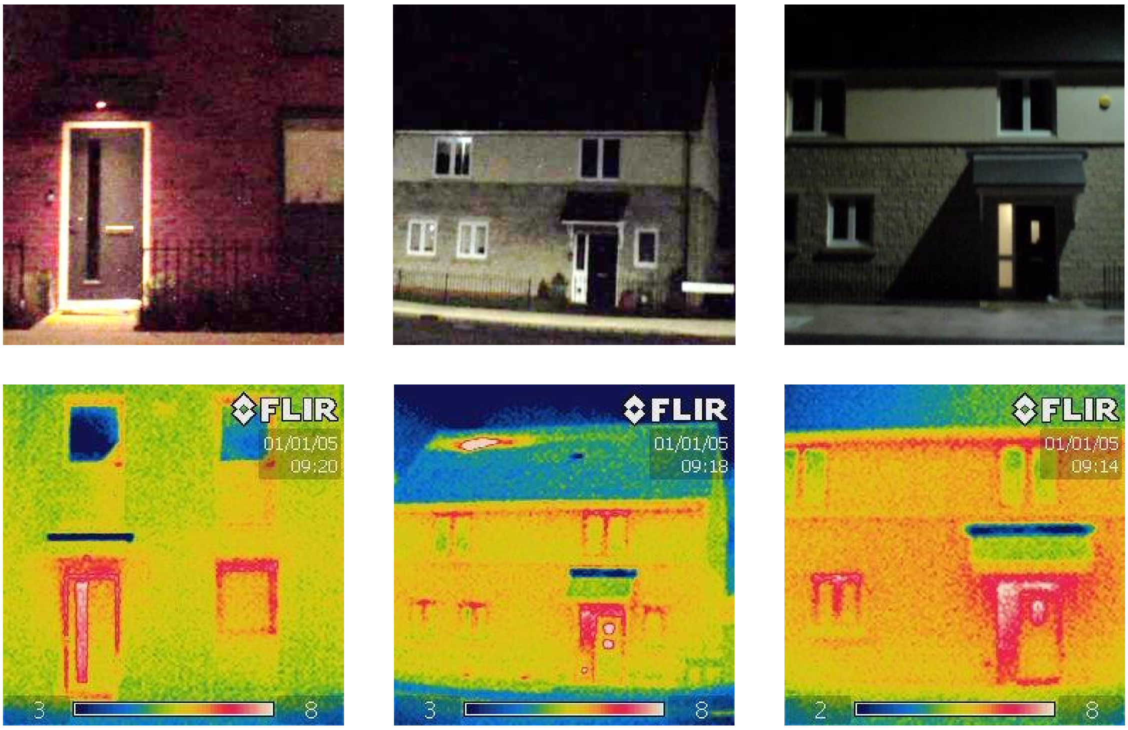
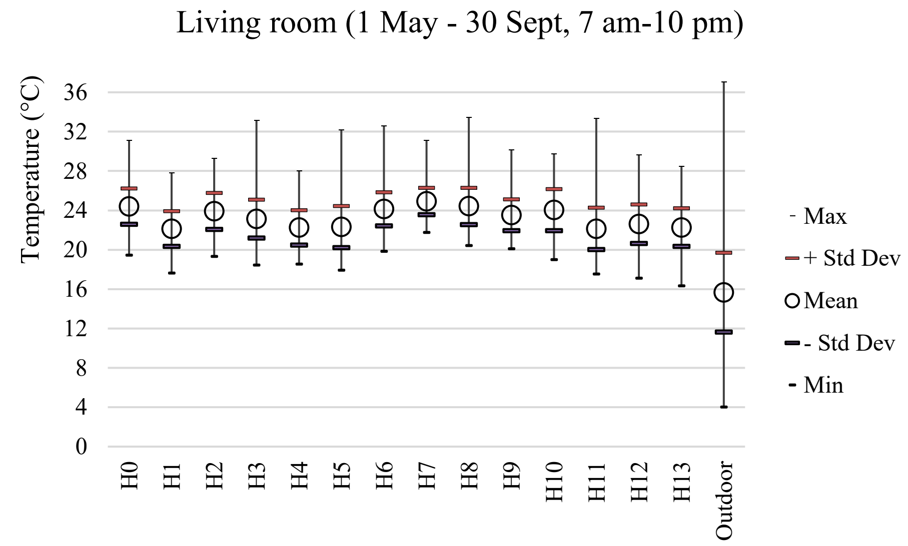


Figure 89 Thermal imaging of the exterior of dwellings H2, H3 and H8.

7.5. Non-heating Season; Temperatures, Overheating and Cooling Behaviours

7.5.1. Temperatures

As seen in Figure 90, the mean temperature of the monitored living rooms during the typical occupancy hours ranged from 22.1°C to 24.9°C, with the sample's time-weighted average of 23.3°C. The highest temperature of 33.5°C was measured during one of the heat waves. The mean bedroom temperatures recorded during the typical occupancy hours ranged between 22°C and 24°C, with the time-weighted average of 22.9°C. It was noticed that lower living room temperatures (almost 2°C cooler than the time-weighted average) were recorded in six dwellings (H1, H3, H4, H11-13). This difference was less prominent in bedrooms, with about 1°C lower temperatures on average.



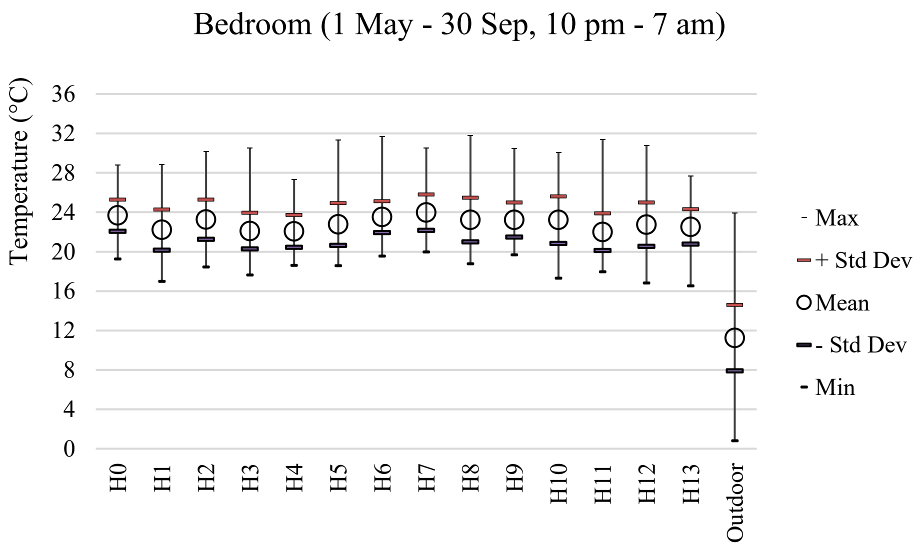


Figure 90 Maximum, minimum, mean and standard deviation of living room and bedroom temperatures during the non-heating season.

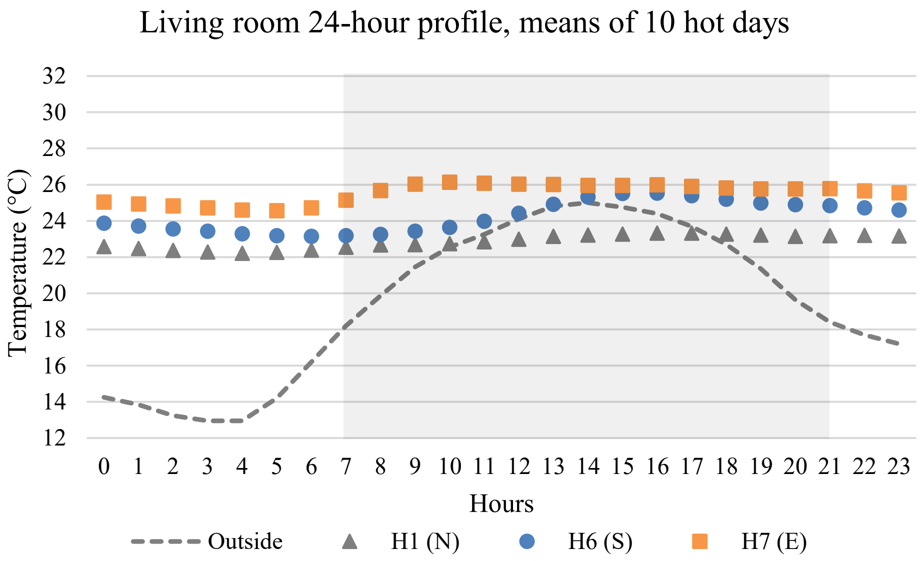
7.5.2. Performance During Warmer Days

One of the design aspirations of the case study development was to provide cool indoor conditions during warmer months of the year. In contrast to this, questionnaire responses suggested that the majority of residents felt hot in their homes, which caused discomfort and dissatisfaction with the indoor conditions (see section 5.2.5). In response to these findings, an additional data analysis was conducted, focusing on the indoor temperatures and occurrence of overheating during days with above-average temperatures and during heat waves.

Overall, the analysis showed that during warmer summer days, the monitored rooms ensured relatively comfortable temperatures. In contrast, during the hottest days of the year, only the north oriented rooms were able to maintain temperatures within comfortable levels. The reported discomfort and dissatisfaction with the thermal conditions is expected to increase over time, due to the warming climate and increased frequency and severity of heat waves (Chapman, Watkins and Stainforth, 2019).

The year 2019 was slightly (0.8°C) warmer than the national average, but within the expected temperature deviation (Met Office, 2019b). The 17 warmest days of the one year monitoring period were identified. For the purpose of the analysis, these days were clustered into two groups. During ten warmer days, the maximum outdoor temperatures reached ~25°C. The remaining seven days were classified as heat waves (McCarthy, Armstrong and Armstrong, 2019), with the maximum temperatures between 31°C and 37°C, and ~31.7°C as the mean of the seven days maximums. The 24-hour temperature profiles were sourced from the local weather station (The Weather Company, 2020).

During the ten warmer days, the mean indoor hourly temperature during the typical occupancy hours was relatively comfortable, ranging from 21.8°C to 26.7°C in living rooms and 22.8°C to 26.6°C in bedrooms. The difference in time-weighted average temperature of occupancy hours between living rooms was up to 3°C and 2.1°C in bedrooms. The analysis showed that the room temperatures varied in relation to room orientation (Figure 91). Interestingly, the east oriented living rooms (H0, H2, H7, H8, H10) were about 2°C hotter during occupancy hours than the rest of the sample, probably due to the retained solar radiation. Expectedly, the effect of orientation seems less significant in bedrooms, as they are used during the night.



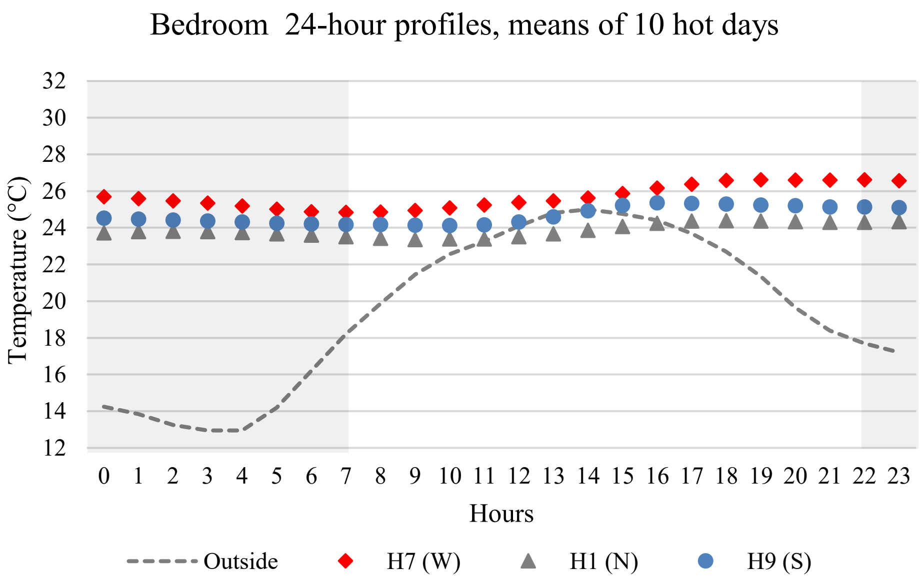
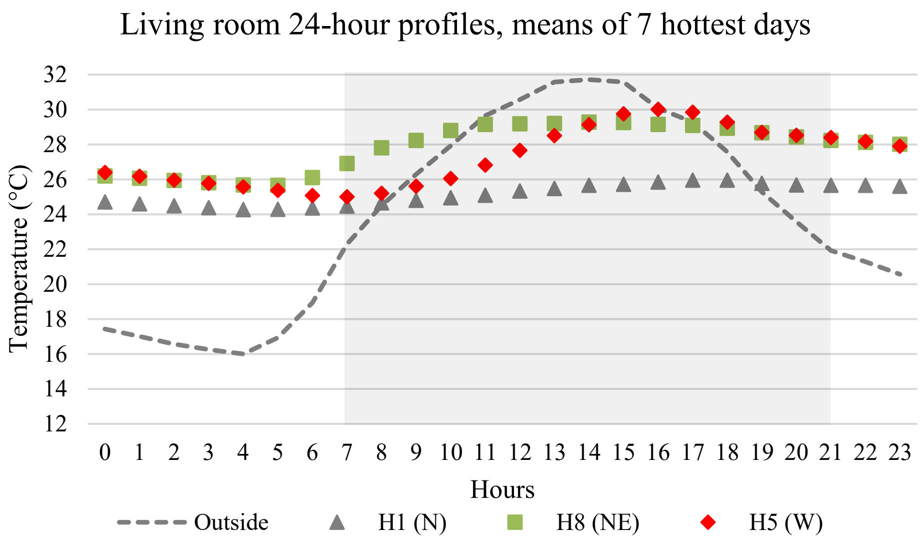


Figure 91 Daily temperature profile during warmer summer days, in three cases of bedrooms and living rooms with different orientations.

On the seven hottest days in the year, the mean temperatures during the typical occupancy hours ranged between 24°C and 30°C in living rooms, and similarly between 24.1°C and 29.3°C in bedrooms during the night-time. Half of the living rooms reached temperatures over 28°C. Bedrooms were generally unable to dissipate the accumulated solar gains before the typical start of occupancy. At 10 pm, temperature in bedrooms ranged from 26.4°C to 29.3°C. Compared to a sample of London dwellings (Wright, Young and Natarajan, 2005), the difference between the indoor and outdoor temperatures during the night hours of a heat wave period was more prominent in case study dwellings (9K on average). As demonstrated in Figure 92, four out of five coolest living rooms were north oriented (H1, H9, H12 and H13), achieving 1.6°C lower mean temperature (26.1°C) during hours of typical occupancy, compared to the living rooms with other orientations (27.7°C). North oriented bedrooms managed to keep temperatures below 26°C during the night-time.



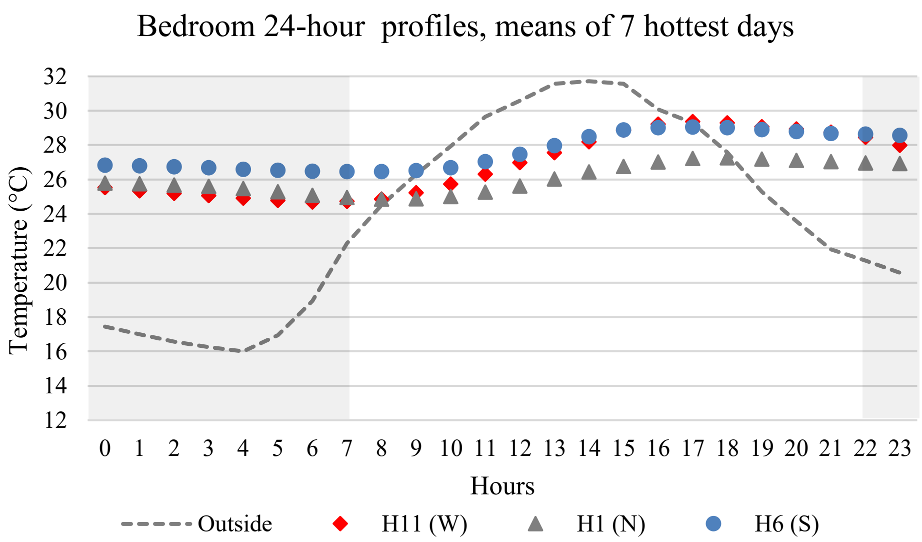


Figure 92 Daily temperature profile during hottest summer days, in three cases of bedrooms and living rooms with different orientations.

Interestingly, although both are south-oriented, the living room in dwelling H4 remained about 3°C cooler compared to the same room in dwelling H6. This difference demonstrates the impact of occupant factors on indoor temperatures. The household in dwelling H4 reported to be mostly away during the day, keeping their curtains and windows closed. In contrast, the household in H6 tends to stay at home throughout the week, preferring to keep the curtains and windows open to enable the views to the outside.

7.5.3. Overheating Analysis

As presented in the section 2.2.5 of the thesis, CIBSE TM 59 standard recommends using the dynamic criterion for living rooms and static criterion for bedrooms when assessing overheating in naturally ventilated dwellings. To make the results more robust, the occurrence of overheating in this study was assessed against the static and dynamic criteria for both rooms, focusing on the period between 1 May and 30 September 2019. Temperature distribution of indoor temperature (15-minute readings) during typical occupancy hours was compared against the standard defined by the static criterion. Hourly outdoor temperature readings sourced from a nearby weather station (The Weather Company, 2020) were used to generate the *maximum acceptable temperature* needed to measure the ratio of temperature exceedance defined by the dynamic overheating standard.

As seen in Figure 93, temperature distributions differed among the monitored dwellings. Using the static criterion, the analysis suggested that overheating occurred in the majority (nine out of 14) of living rooms, and in all bedrooms. Using the dynamic criteria, almost the opposite was suggested; overheating did not occur in living rooms, and occurred only in two bedrooms.

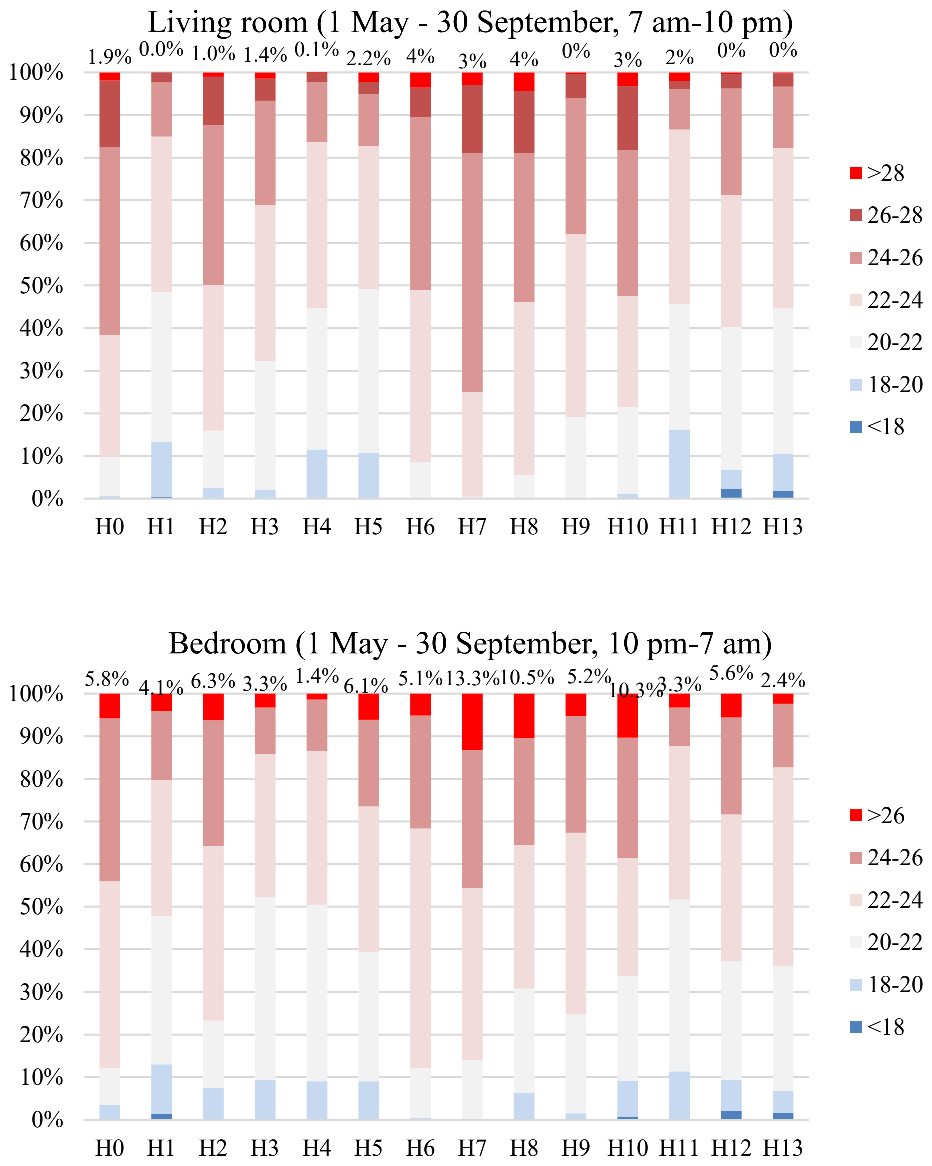


Figure 93 Temperature distribution during occupancy hours in living rooms and bedrooms, May to September period.

Other studies similarly noticed a higher tendency of overheating in bedrooms and the contrasting findings provided by the static and dynamic criteria (Gupta and Kapsali, 2015; Gupta, Gregg and Bruce-Konuah, 2017; Gupta, Gregg and Irving, 2019). The light structure of the case study dwellings built with the structural insulated panels (SIP) probably contributed to the occurrence of overheating (Lomas and Kane, 2013; McGill *et al.*, 2017). This study did not capture temperatures in flats, which are expected to be even warmer (Lomas and Kane, 2013).

The results of the overheating analysis were related to the resident responses from the questionnaire and interviews. As seen in Table 35, the lack of a clear association between responses and the overheating results indicates the variation in households' preferences, tolerance and adaptation to the higher temperatures. When exposed to relatively similar rates of overheating, some households were tolerant (H3, H6), while others had divided opinions (H13) or felt uncomfortable (H0, H2).

Case	Living rooms (7am-10pm)		Bedrooms (10pm-7am)		Questionnaire Vote(s)		Interview responses about the particularly hot rooms
	Time above > 28 °C (%)	Hours with +1 K above limit (%)	Time above > 26 °C (%)	Hours with +1 K above limit (%)	Uncomfort -able	Hot	
H0	1.9%	0.4%	5.8%	1.2%	✓ / ✓	✓ / ✓	*Whole house*
H1	0.0%	0.0%	4.1%	0.5%			
H2	1.0%	0.0%	6.3%	1.4%	✓ / ✓	✓ / ✓	*Living, bedroom*
H3	1.4%	0.3%	3.3%	0.6%			
H4	0.1%	0.0%	1.4%	0.0%		✓	
H5	2.2%	0.1%	6.1%	2.0%		X / ✓	*Living, bedroom*
H6	3.6%	0.5%	5.1%	2.1%			*Living, bedroom*
H7	2.9%	0.9%	13.3%	3.3%	✓ / ✓	✓ / ✓	
H8	4.3%	2.6%	10.5%	3.0%	✓ / ✓	✓ / ✓	*Whole house*
H9	0.4%	0.0%	5.2%	0.6%			-
H10	3.2%	0.5%	10.3%	2.5%	X / ✓	X / ✓	*Bedroom*
H11	2.0%	0.3%	3.3%	1.0%		X / ✓	-
H12	0.3%	0.0%	5.6%	0.7%		X / ✓	*Both bedrooms*
H13	0.2%	0.0%	2.4%	0.0%	X / ✓	X / ✓	*Bedrooms*

Table 35 Side-by-side comparison of occurrence of overheating using two criteria and occupant feedback.

Some household responses about the possible occurrence of overheating in their home are presented below:

Uh… not that we have so many hot days. Hm... Maybe the living room, but we open the door and we do not notice. (H1)

It is good. For me I never felt like it was overheated, for me overheated is when its 45°C. In the UK there are a couple of hot weeks, its fine. (H10)

How this house was sold to us by the sales team is that the windows were designed to keep the heat in during the winter and keep the heat out in the summer. Now this room in the summer, the windows and doors were kept closed throughout the day, the curtains were drawn all day, it is too hot. (H0)

This summer was OK, last summer was worse. I have problems sleeping when it is too hot. Because of the orientation of our building we only get sunlight in this face in the afternoon. It can be uncomfortable to work in these two spare bedrooms in summer, during the day. I do close the roller blind, in the afternoon on a sunny day. I wouldn't want to sleep in these in the summer. (H12)

It seems that the developer was aware that some dwellings become hot in the summer months. Interestingly, this finding was used for advertising. As one interviewee shared:

When we were buying, they were saying that; you know that it is so hot in summer that people actually complain how hot this house is. It sounded more like it’s a selling point. They said that the houses are so well built, that it gets really hot. (H10)

7.5.4. Cooling Behaviours

In order to reduce solar gains during warm weather, majority of households would keep windows, curtains and blinds closed until the evening. This strategy was also advised to some households by the developer. In contrast, few households opposed this strategy, preferring to have curtains and patio doors open when at home, in order to look at the garden outside:

If it was a summer’s day, and I would be home, everything would be open. I would keep the blinds open because I like the light and the air to come through. I didn’t want a dark house. (H13)

We do exactly the opposite the developer has told us. They have told us to keep the windows closed and to draw the curtains. Well I am home all day long and there is no way I will sit in my lounge like that. People who work all day long said that its good, that it works. But I am home all day long and I do not want to sit here with my curtains closed. Our neighbours are doing exactly the same. (H6)

In addition to using passive strategies, a third of the households also reported that using fans during hot days seemed necessary. Two households used a portable AC system. In one dwelling, the AC was briefly used to pre-cool the bedroom before occupants went to bed. In another, AC was used to cool the office space during the sunny weather, in order to exploit the available solar PV electricity.

7.6. Ventilation

7.6.1. CO_2 Measurements

In order to ensure good ventilation levels, the monitored private and shared ownership dwellings were provided with window trickle vents and a MEV system. Continuously operating extract fans were located in wet rooms (kitchen and bathrooms). CO_2 concentrations were recorded every 15 minutes in main bedrooms for eight consecutive months, from 1 February to 30 September 2019. CO_2 concentrations under 1,000 ppm were considered indicating adequate ventilation levels (Azuma *et al.*, 2018).

The data analysis indicated inadequate ventilation levels in the monitored bedrooms during the typical night-time occupancy hours (10 pm – 7 am). On average, 14 bedrooms achieved CO_2 concentrations below 1000 ppm during the 66% of the night hours in the non-heating season, and only 38% in the heating season. Figure 94 shows the distribution of measured CO_2 levels in different bedrooms. During the three captured heating months (1 February to 30 April), ventilation levels in five bedrooms were significantly better compared to the rest of the sample, achieving the recommended CO_2 concentrations for about 70% of the night-time. In contrast, in other nine bedrooms this was achieved only between 3% and 36% of the night-time, with the mean concentrations ranging from 1,155 ppm to 1,620 ppm. In the non-heating season (1 May – 30 September), most of the monitored bedrooms achieved the recommend CO_2 levels during 70% to 90% of the night-time. Inferior conditions were still measured in five bedrooms (H0, H1, H6, H7, H10), with the mean concentrations above 1,000 ppm.

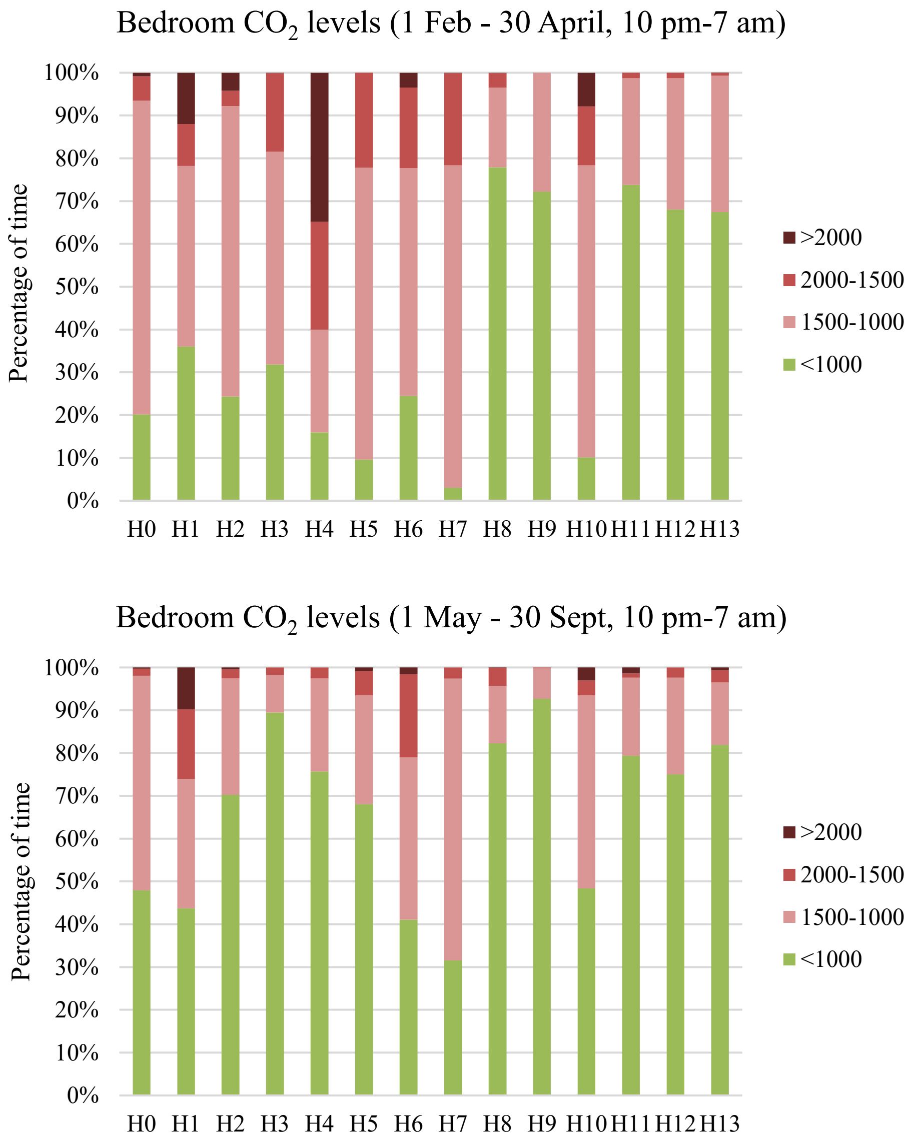


Figure 94 The distribution of CO_2 concentrations during the heating and non-heating season.

The findings of this study are in line with the existing evidence. Both passive and active ventilation strategies seem to frequently fail to deliver adequate ventilation in dwellings, including the MEV system (Balvers *et al.*, 2012; Staepels *et al.*, 2013; McGill *et al.*, 2015).

7.6.2. Ventilation Behaviours

In order to complement CO_2 measurements with contextual data (typical room conditions), the interviewees were asked about their preferred position of window trickle vents, window, curtain and room doors, during the night- and day-times and both seasons. In addition, the opening/closing of the main bedroom window was monitored during the same eight-month period. The available contextual data was presented in Table 36. In addition, Figure 95 related the CO_2 and window data.

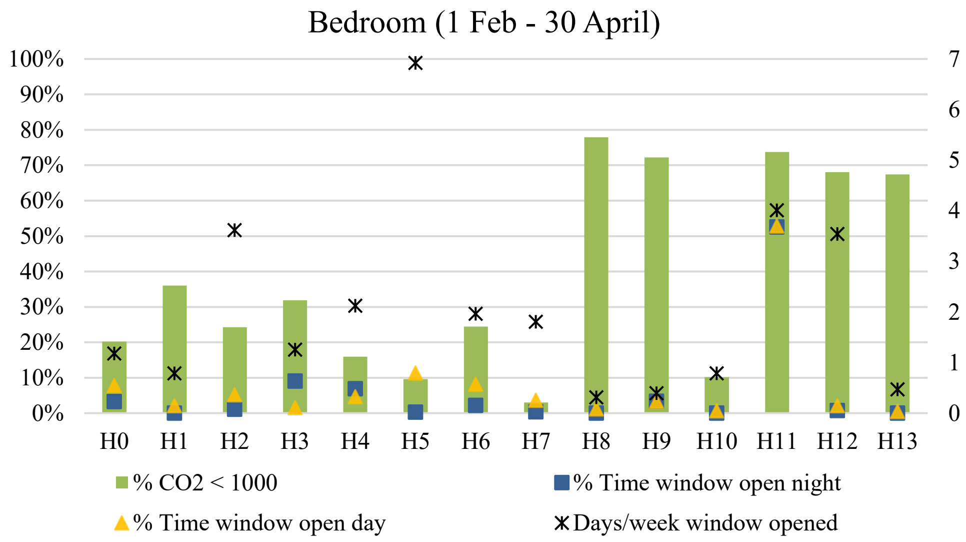
		H0	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13
	Bedroom occupancy	2	2	2	2	2	2	2	1	1	2	2	2	2	1
	Ensuite bathroom	✓	✓	✓	✓	✓	✓			✓	✓		✓	✓	✓
Feb-Apr	% CO2 < 1000	20%	36%	24%	32%	16%	10%	24%	3%	78%	72%	10%	74%	68%	67%
	Window open day/week	1.2	0.8	3.6	1.3	2.1	6.9	2.0	1.8	0.3	0.4	0.8	4.0	3.5	0.5
	% Window open night	3%	0%	1%	9%	7%	0%	2%	0%	0%	3%	0%	53%	1%	0%
	% Window open day	8%	2%	5%	2%	5%	11%	8%	4%	1%	3%	1%	53%	2%	0%
	Trickle open	✓		✓	✓/X	✓	✓/X	✓		✓	✓		✓✓	✓	✓
	Door to hall open	✓	✓	✓	✓		✓	✓			✓	✓		✓	✓
	Door to bath open	✓	✓	✓	✓			N/A	N/A		✓	N/A		✓	
	Curtain open			✓	✓/X						-			✓	
May-Sep	% CO2 < 1000	48%	44%	70%	89%	76%	68%	41%	32%	82%	93%	48%	79%	75%	82%
	Window open day/week	4.0	2.7	5.5	6.2	6.1	7.0	5.2	5.0	1.8	4.5	3.2	4.6	4.9	3.9
	% Window open night	39%	9%	32%	71%	81%	49%	26%	10%	17%	47%	8%	65%	19%	32%
	% Window open day	41%	18%	21%	30%	74%	78%	46%	16%	17%	42%	19%	65%	29%	7%
	Trickle open	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	-	✓	✓
	Door to hall open	✓	✓	✓	✓		✓	✓			-	✓	-	✓	✓
	Door to bath open	✓	✓	✓	✓			N/A	N/A		-	N/A	-	✓	
	Curtain open										-	✓	-		

Table 36 Side by side comparison of measured CO_2 levels and occupants' ventilation practices. Shaded cases achieved better ventilation levels.

Table 36 shows that three bedrooms were occupied only by one person, and the rest by two people. All but three rooms were designed with an ensuite bathroom. Constant operation of the ceiling fan located in ensuite bathrooms was expected to enhance the ventilation in the adjacent bedrooms, by drawing the air through the room. Window data suggested that households generally preferred to close the windows at night during the heating season. In a study of naturally ventilated dwellings, about third of households kept their windows open (Sharpe *et al.*, 2015).

During the non-heating season, it was evident that many households increased bedroom ventilation, which resulted in lower CO_2 concentrations. The majority of the households would ventilate the bedrooms four to six times per week. However, only five from 14 households would keep the windows mostly open during the night. Higher concentrations in three bedrooms (H6, H7, H10) were probably related to the lack of an ensuite bathroom.

In the heating season, CO_2 concentrations were elevated, despite the open trickle vents and doors to the hallway in two-thirds of the bedrooms, and partially open trickle vents in in two additional bedrooms. Degree to which the room doors were opened was not captured. Ten out of 14 households were childless at the time of the interview. Therefore closing the doors to the hallway was probably not necessary privacy-wise. In about half of the bedrooms, doors to the ensuite bathroom would be open too. Two households reported that closing the door to the ensuite bathroom was necessary. This was due to noise from the ceiling fan (H4), and due to the perpetually cold bathroom (H5). Window curtains would be drawn in most bedrooms, occluding the air flow from any open trickle vents.



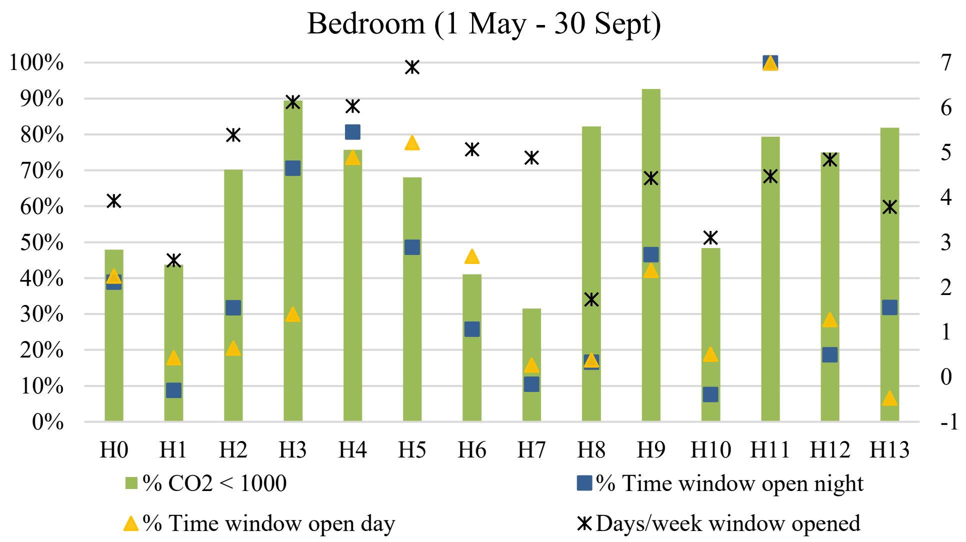
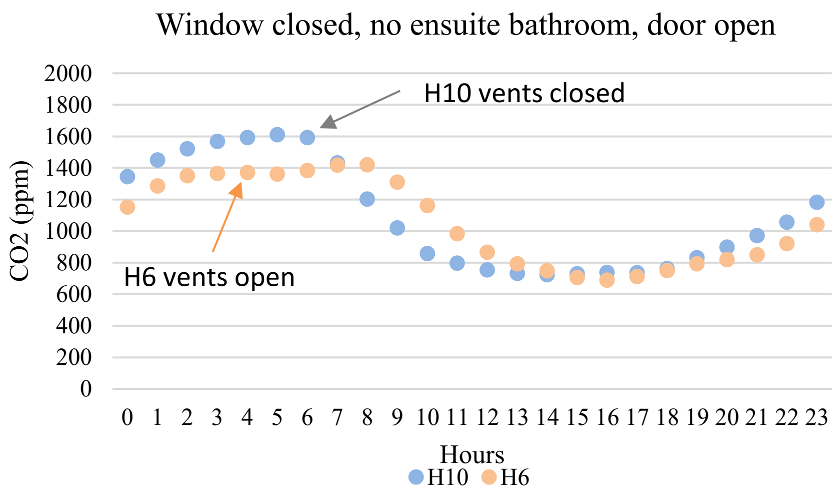
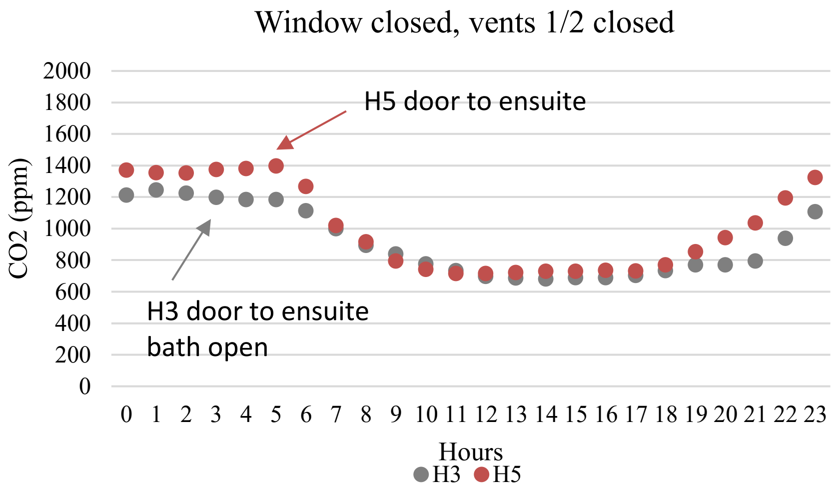


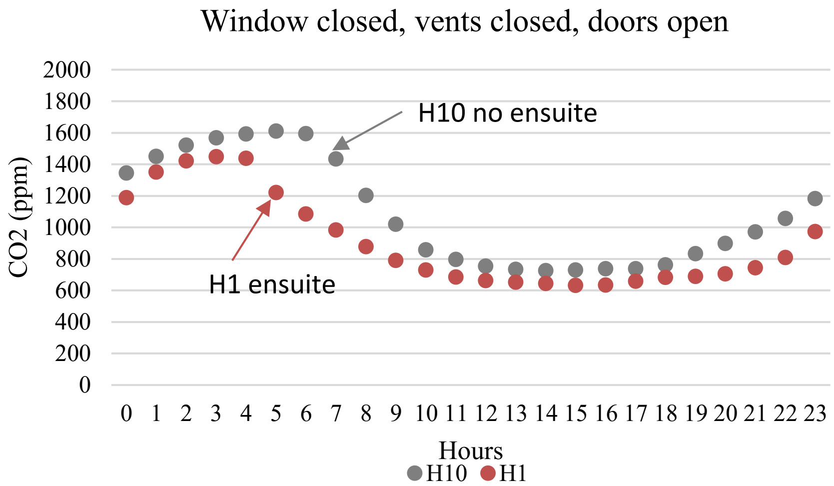
Figure 95 Superimposing achieved time of recommended CO_2 levels, window opening times and frequency, heating and non-heating season.

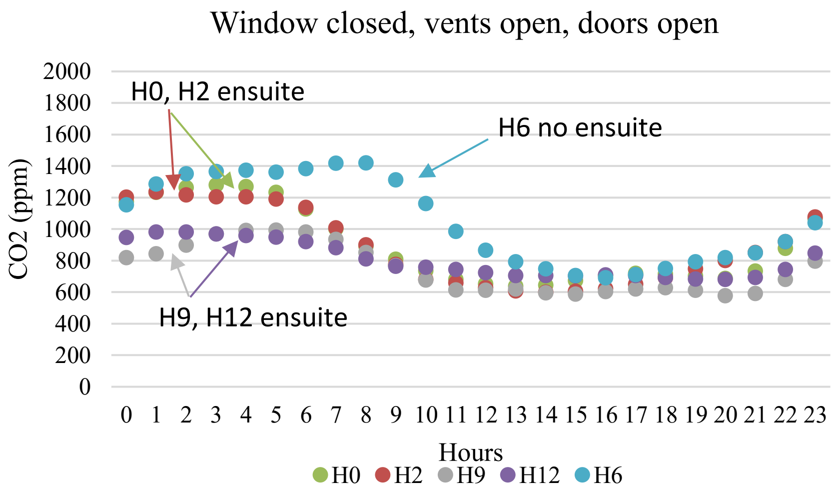
Statistical analysis using linear regression did not identify contextual factors which significantly predicted the measured concentrations. Due to the small number of monitored bedrooms (n=14), varying room characteristics and occupant behaviours, it was difficult to grasp the effect of a particular factor on the resulting concentrations. Nonetheless, daily profiles showing the mean concentrations and the room conditions suggested some tendencies (Figure 96). The suggestions should be treated with caution due to the small sample size. As expected, slightly increased (~ 1.2 times) mean CO_2 concentrations during the night-time occurred when either trickle vents (comparing H6 and H10) or the doors to the ensuite bathroom (comparing H3 and H5) were kept closed. Similar increase in concentrations was noted in bedrooms without an ensuite bathroom (H1 compared to H10, also H6 compared to H0, H2, H9, H12). In line with these tendencies, combinations of two unfavourable factors, such as keeping both room doors closed (H4 compared to H0, H2 and H12) or doors and trickle vents closed (H7 compared to H8 and H13), resulted in a more prominent increase in the concentrations (~1.5 times).

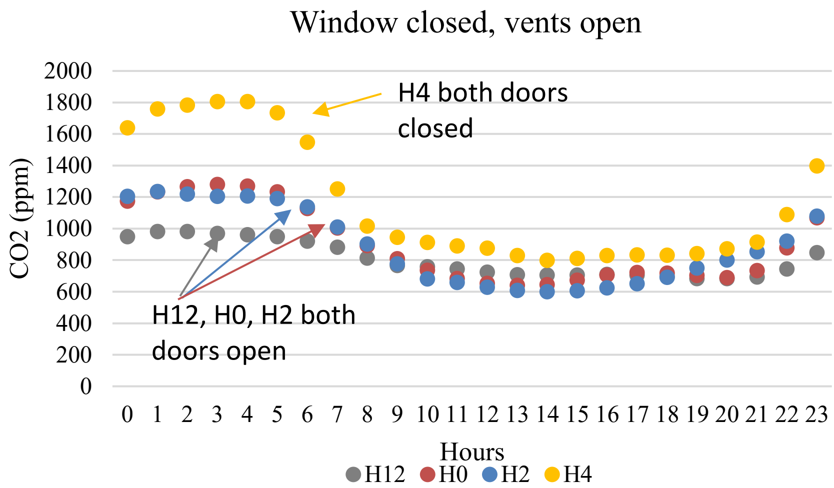
An assessment of 28 case study bedrooms with natural ventilation reported a similar increase of mean CO_2 concentrations when the window vents were closed (1.2 times) (Sharpe *et al.*, 2015). However, the same study found even more prominent increase in concentrations when the doors to the hallway (factor 1.3-1.7), or both the vents and the room doors were closed (factor of 2). Interestingly, among the four monitored bedrooms (H0, H2, H9 and H12) with same room conditions (both doors and trickle vents open), two bedrooms performed distinctively better due to unknown factors.




Window closed, vents 1/2 closed
CO2 (ppm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
H5 door to ensuite
H3 door to ensuite
bath open
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hours
H3
H5


Window closed, vents closed, doors open
CO2 (ppm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
H10 no ensuite
H1 ensuite
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hours
H10
H1


Window closed, vents open, doors open
CO2 (ppm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
H0, H2 ensuite
H6 no ensuite
H9, H12 ensuite
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hours
H0
H2
H9
H12
H6



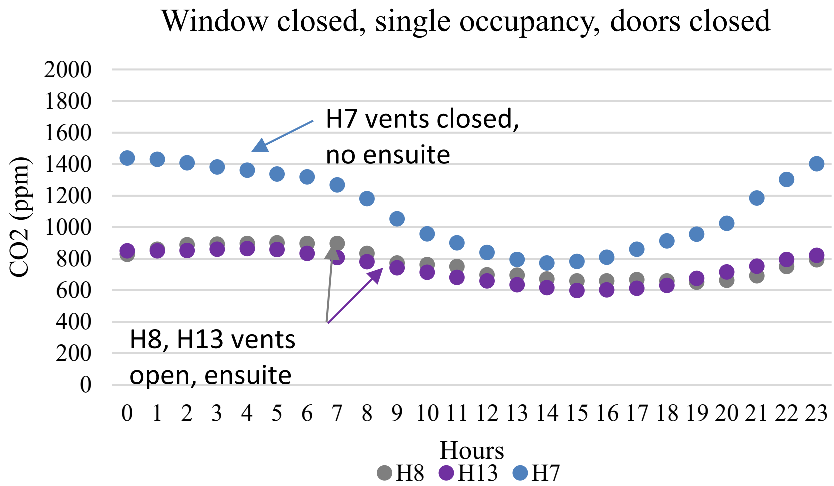


Figure 96 Comparing daily (24-hour) profiles of CO_2 concentrations between dwellings which slightly differ in contextual factors (room conditions). February - April data.

The lowest CO_2 concentrations occurred during low bedroom occupancy or day-time absence. In the heating season, the lowest concentrations ranged from 578 ppm to 798 ppm (sample mean of 672 ppm). This was significantly higher compared to the outdoor CO_2 concentrations of ~400 ppm. The increased ventilation during the non-heating season resulted in lowest daily concentrations from 503 ppm to 701 (mean of 596 ppm). As expected, the mean night-time concentrations of the bedroom sample were negatively corelated to the open window ($r = -.76$, $p < .001$) and outdoor temperature ($r = -.7$, $p < .001$) variables. The scatter plots (Figure 97 and Figure 98) indicated that, on average, the bedroom sample achieved the recommended CO_2 concentrations when the windows were kept open more than a quarter of the night-time, and the mean night-time temperatures were above ~12 °C . These conditions were common the non-heating season, between the months of May and September (Figure 99).

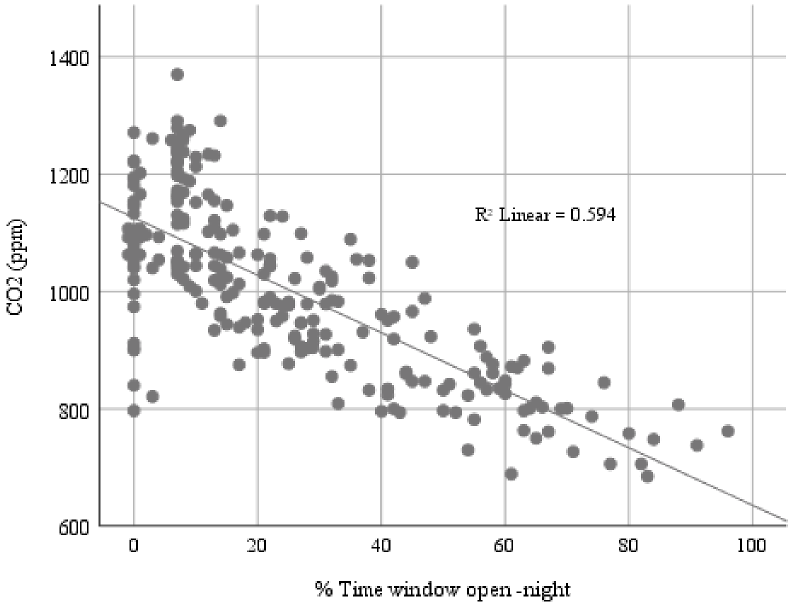


Figure 97 Scatter plot, relating the mean night-time CO_2 concentrations and the time window was open (n=14).

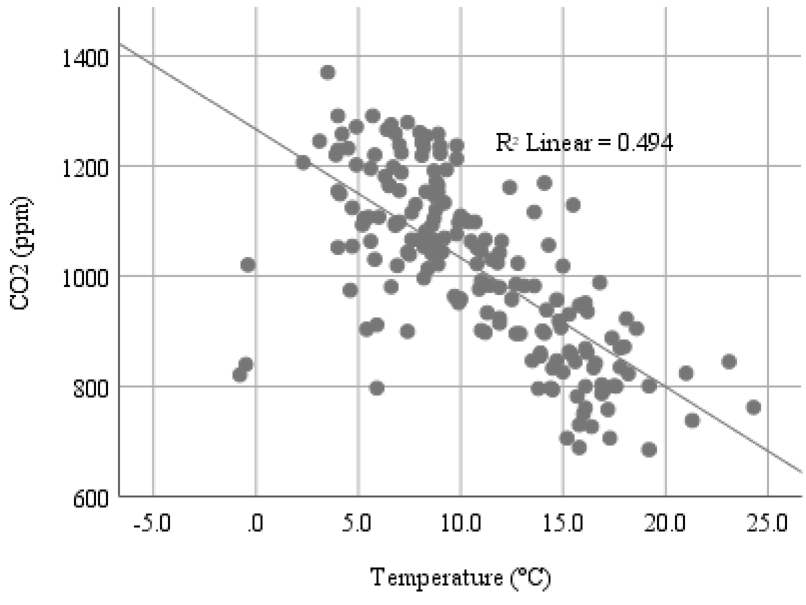


Figure 98 Scatter plot, relating the mean night-time CO_2 concentrations (n=14) and the mean night-time outdoor temperature.

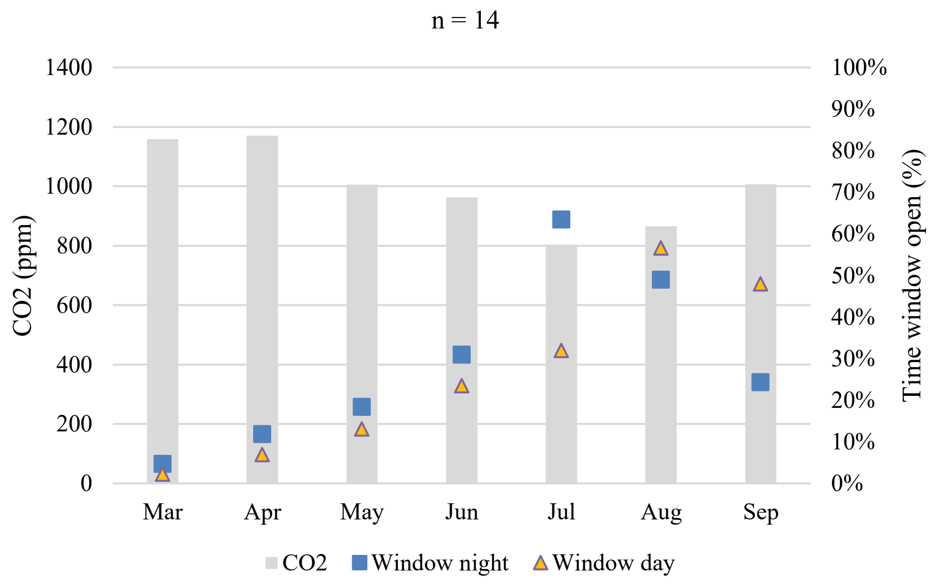


Figure 99 Monthly average CO_2 levels and window opening times (n=14).

7.7. Home Energy Use Behaviours; the Shimmy and Solar PV's

About a third of the survey participants reported that the Shimmy home information display made them more cautious in using energy. However, none of the interviewed households regarded the Shimmy as a useful device. For many interviewees, the energy data presented in the Shimmy did not make sense. It did not resemble the actual usage, or seemed totally out of scale. The provision of invalid energy data was eventually confirmed by the Shimmy's data manager. In addition to this issue, many households reported that the device was frequently malfunctioning. It was also disliked that the information about the bus departures was not live. The use of the provided how-to videos and notifications were only mentioned by two households.

Not long before the time of the interview, the device was replaced with a mobile application. However, about two-thirds of the interviewees already lost trust in the provided energy information, and were not motivated to use the offered application. Two interviewees decided to install their own energy monitoring system, while one resident was content with manually reading the smart meters. Even if the Shimmy was fully functional, home energy monitors are thought to have a modest effect on energy saving behaviours (Hargreaves, Nye and Burgess, 2013; Nachreiner *et al.*, 2015).

The following quotes present the experiences with the Shimmy:

> *We had like a meeting where the Shimmy expert came along. Probably, 9-10 months after we moved in. And told us that everybody's information was incorrect. And that they will fix it. And they never fixed ours. (H13)*

> *For the start, it only gives you day by day data. And then I did some comparisons. I looked at the values on the meters every day and I looked at the values on this device and if they match up. The Shimmy was just making stuff up totally. It was data from three days added into one day, or it was just totally wrong day. Just totally useless. There was nothing you could do with it. (H4)*

> *I couldn't see historical data which would allow me to actually take action on the information. And I did not trust the information. It wouldn't help me to know. I had to work out myself by looking at my smart meter and whatever. When is my solar at the maximum? When would it be the best time to turn on my washing machine? I couldn't get that information without looking at it all the time, because it is laggy. Not very intuitive. I couldn't be bothered. I gave up really quickly. (H12)*

Over two-thirds of the survey participants have reported to frequently use energy intensive house appliances when the solar energy was available. Almost all the interviewees reported developing a cautiousness to use the washing machine, dishwasher and tumble dryer during the daylight only. Many would try to use the appliances during the sunny weather, but only if this was convenient. Households would not go as far as to wait for a sunny day to wash their clothes. Only half of the interviewees reported to use the in-built timer, mainly for delaying the start of the dishwasher before going to work. Two households charged their electric cars using a slow-charge mode during the day.

Another two households tried to further exploit the available solar PV electricity to achieve more comfortable conditions in their home office rooms. One interviewee reported to use portable AC unit during the sunny weather. The other used an electric heater in the office room. Quotes below elaborate how some residents were maximising solar PV electricity:

I tend to put only my dishwasher and my electricity during the day. And I try to turn them on when I know the sun is going to be pointing towards them. If I leave 7 am, I will put 3-4 hour delay. (H0)

That was part of the reason we got the car because we get very little money back from the grid. We do get feed-in tariff, but it is such a small amount that you get. Yeah, about 100 pounds or something a year. So, we try to use it as much of it as we can. (H4)

The only time when I ever tried to maximise the use of it is as I got the electric car. I would put my car on the super slow charge. That was the only time when I was really concentrating what the solar panels were doing. For our convenience, we just used our appliances as when we needed to, instead as when it would be slightly better, and we just save a little bit more money. (H13)

Yes, so the washing machine and the dishwasher both have timers, so we make sure they always go during the day. Even during the winter. There is much less sun in the winter obviously, but it is something. And in the winter, for the room that is used as an office, the heating is down to 14°C for the entire house. But I have a low power electric heater in there. And that just comes on during the day, again just trying to draw the heat from the solar panels. It gets on at 10am and gets off at 4pm. (H3)

7.8. Summary

The last data analysis chapter presented the results of an in-depth assessment of 12 to 14 dwellings, as a subset of the 157 dwellings of the case study development. The aim of the assessment was to complement the questionnaire responses about the indoor conditions with in-site measurements and explain the quantitative data with household interviews. Using data loggers, indoor environmental monitoring was conducted during the one year period in living rooms and main bedrooms in 14 dwellings. The monitoring captured air temperature and relative humidity (in living rooms and bedrooms), radiator temperature (living rooms only), CO_2 concentrations and window opening frequency (bedrooms only). Within the subset of 14 monitored dwellings, 12 households were interviewed about their behaviour and experience with heating, ventilating and cooling their home, and use of the Shimmy device and solar PV electricity.

In the heating season, the mean temperature during the hours of typical occupancy was 20.8°C in living rooms and 20°C in bedrooms. In order to increase the efficiency of the community heating system, some households were recommended to constantly heat their home. However, most of the households were keen to save energy by heating only when it was needed. The households would allow indoor temperatures to drop to about 19°C whilst away or during the night, from where more comfortable temperatures could be achieved in just few hours by boosting the heating. Despite having moved-in already two to three years before the time of the interview, about half of the interviewed households were still unable to sufficiently warm certain rooms in their home. Thermal imaging conducted on a sample of the monitored dwellings found reoccurring inefficiencies of the building fabric which confirmed some of the households' suspicions. Cold air ingress was noted at the patio and entrance doors, while thermal bridges were detected at window frames and the attic. Residents had mixed feelings about their community heating system. On one side, many appreciated not needing to worry about the system maintenance. On the other side, the households complained about the high standing charge for private ownership (over £500 annually), and for being contractually bound to one heat supplier.

During the seven hottest days of the monitoring period and maximum temperatures of ~32°C, the north oriented rooms provided slightly cooler indoor temperatures. Bedrooms with other orientations struggled to dissipate the heat accumulated throughout the day. During the night-time, bedrooms were 9K warmer on average than the outdoor air. In line with the developer's suggestion, many households kept the windows and curtains closed during the day and hot weather. However, this strategy seemed to be less suitable when staying at home, as it would block the daylight and views to the outside. Similar to the findings in other studies, using the static and dynamic overheating criteria yielded contradicting results. Using the static criterion, overeating occurred in all monitored bedrooms and in the majority of living rooms. Using the more stringent, dynamic criteria, only two bedrooms overheated. The interview responses showed variation in the household perception and tolerance to elevated indoor temperatures.

The monitored dwellings were designed with window trickle vents and a constantly operating MEV system, with fans located in wet rooms. The results of CO_2 monitoring in bedrooms indicated inadequate ventilation levels. On average, the bedroom sample achieved the recommended CO_2 concentrations below 1000 ppm only during 38% of the night-time (10 pm-7 am) in the heating season, and 66% in the non-heating season. The interviewed households preferred to keep the windows closed at night during the heating season. Most of the households relied on using the trickle vents (mostly occluded by the curtains) and open room doors for ventilation. Relating measured CO_2 concentrations and contextual factors (room characteristics and reported ventilation behaviours) did not offer a robust understanding about the impact of different factors. The analysis indicated that closing the window vents and doors, and the lack of ensuite bathroom slightly increased the CO_2 concentrations. However, cases of different CO_2 levels measured in bedrooms with similar conditions were also noted. The analysis also suggested that, on average, the bedroom sample provided adequate ventilation levels if the windows were opened more than a quarter of the night-time. Expectedly, this would occur mostly during the non-heating season.

Although about a third of the surveyed residents reported that the Shimmy made them more cautious in using energy, none of the interviewed households regarded the device as particularly useful. The device's two main drawbacks were the provision of unreliable dwelling energy data and frequent malfunctions. Owning a solar PV system made the households cautious to use the washing machine, dishwasher and tumble dryer during the day-time (daylight) only.

Chapter 8: Discussion

8.1. Introduction

The aim of this study was to systematically and empirically evaluate the actual dwelling performance (energy, water and indoor environmental conditions) and residents' environmental behaviours (energy, transportation, waste and food) in the case study eco-housing development, against the design targets. To achieve this aim, the following six objectives were designed to:

1. Critically examine the environmental design of the case study development in terms of dwelling energy and water use, carbon emissions and the household energy, transportation, waste and food behaviours.
2. Assess the development-wide, time-series data on the dwelling energy use, energy generation, carbon emissions and water use for one year.
3. Conduct a development-wide survey to gather household responses about the experience and satisfaction with their home and indoor environmental conditions, and about the energy, waste, food and transportation behaviours.
4. Evaluate the indoor environmental conditions of a subset of dwellings through in-situ monitoring during one year period of indoor temperature, relative humidity and CO_2 levels, with household interviews about heating, ventilation and cooling behaviours.
5. Compare the achieved environmental performance of the case study development with the design intent and the performance of similar eco-developments.
6. Produce performance-based guidelines for policy-makers and practitioners for designing the forthcoming eco-housing developments.

In order to address these objectives, the study used mixed methods approach, and collected empirical data via field work activities on two spatial levels. Development-wide data was sourced from the existing dwelling monitoring system and by conducting a questionnaire survey. An in-depth analysis of 12-14 subset dwellings included monitoring of indoor environmental conditions and conducting household interviews.

Chapters 5 to 7 presented the results of the data analysis. This chapter will discuss the key findings that emerged from the data analysis. New contributions to the field of low/zero carbon housing and eco-housing developments will be presented. The discussion will be grouped around the following key themes:

- Dwelling performance in regard to energy, indoor temperatures and ventilation.
- Community heating performance in regard to energy and carbon emissions.
- Reported environmental behaviours (transportation, waste and food).
- Overall performance of the development, in regard to its urban context, the aspiration to deliver an exemplar development, and to enable sustainable lifestyles.
- Holistic development performance evaluations.

Table 37 presents an overview of the case study development's design targets, achieved results and performance benchmarks, per environmental criteria.

Criteria	Case study performance	Benchmark
Energy	○ Design target: 75.4 kWh/m^2/year ○ Achieved: 76 kWh/m^2/year ○ Sample size: 74 dwellings ○ Meeting the design target: ✓	○ National average: 206 kWh/m^2/year (Gupta and Gregg, 2020) ○ True zero carbon housing: 43-92 kWh/m^2/year (Oreskovic, Gupta and Strong, 2021)
Water	○ Design target: 80 litres/person/day ○ Achieved: 96.2 litres/person/day ○ Sample size: 43 dwellings, Phase 2 ○ Meeting the design target: X	○ SE England average: 146 litres/person/day (AC, 2018)
Temperatures	○ Design target: Dwellings are warm in winter and cool in summer. ○ Achieved: Dwellings are comfortable in winter. In summer 40% participants felt uncomfortable and 64% felt hot. Overheating detected in all bedrooms and most of the living rooms. ○ Sample size: 90 residents in 64 households (responses), 14 dwellings (overheating). ○ Meeting the design target: ✓/X	○ Based on the questionnaire responses, the case study dwellings were hotter and more uncomfortable in summer than the mean of the sample of 58 new-built housing case studies of (Leaman, no date). ○ Based on the overheating analysis, higher rate of living rooms overheated in the case study dwellings compared to similar studies (Gupta and Kapsali, 2015; Gupta, Gregg and Bruce-Konuah, 2017; Gupta, Gregg and Irving, 2019).

Criteria	Case study performance	Benchmark
Ventilation	○ Design target: Dwellings provide adequate ventilation levels. ○ Achieved: The bedroom sample achieved the recommended CO_2 levels for 38% and 66% of night-time in the heating and non-heating season, respectively. ○ Sample size: 14 dwellings. ○ Meeting the design target: X	○ Inadequate ventilation levels were repeatedly found in other case study dwellings using the MEV system (Balvers *et al.*, 2012; Staepels *et al.*, 2013; McGill *et al.*, 2015).
Carbon	○ Design target: Net zero carbon emissions from dwelling use. ○ Achieved: 20.2 CO_2/m^2/year per dwelling. ○ Sample size: 74 dwellings. ○ Meeting the design target: X	○ National average: 38.1 CO_2/m^2/year (ESC, 2019).
Waste	○ Design target: 80% rate of household waste is diverted from the landfill. ○ Achieved: 50% rate of waste diversion as a three year average. ○ Sample size: all dwellings. ○ Meeting the design target: X	○ Local average: 55% rate of waste is diverted from the landfill (DEFRA, 2021a).
Transportation	○ Design: 55% of all trips are car-based. ○ Achieved: 70% of all trips are car-based. ○ Sample size: 90 participants in 64 households. ○ Meeting the design target: X	○ National average: 62% of all trips are car-based (DT, 2017a). ○ Urban City and Town ward average: 65% of all trips are car-based (DEFRA, 2014).
Food	○ Design: Enable access to low-impact foods on site. ○ Achieved (residents): 37% buys organic food, 31% grows a vegetable patch, 36% meat-free meals. ○ Sample size: 90 participants in 64 households ○ Meeting the design target: X	○ National averages; 34% buys organic food (DAFM, 2014), 33% grows a vegetable patch (DEFRA, 2009), 35% meat-free meals (Quilgars *et al.*, 2019).

Table 37 Comparing the key design targets per criteria to the achieved performance in the case study development.

8.2. Dwelling Performance

8.2.1. Energy

Based on 74 monitored dwellings (47% of the dwelling sample), the mean energy usage of 76 kWh/m^2/year per dwelling achieved the design target. This can be considered a success, in the context of the widespread performance gap (Zero Carbon Hub, 2014; Innovate UK, 2016; Gupta and Gregg, 2020). This result ranked the case study among the housing developments with the lowest energy usage. It also suggested that low energy use in the level of Passivhaus dwellings could be achieved in less airtight and insulated homes if the use of electricity is significantly reduced. A closer inspection revealed, however, that lower than projected hot water usage and electricity usage masked an increase in the projected space heating use.

When compared to other true zero carbon housing (Ecoarc, 2013; NEF, 2014; Ridley *et al.*, 2014), it is apparent that case study dwellings were designed with a less energy efficient fabric. As a result, the estimated space heating energy use was twice as high when compared to the Passivhaus standard. The rationale behind such a design decision is probably related to the selection of a community heating system, which promised to deliver a very low carbon coefficient of heat. In this context, higher heat demand increases the cost-effectiveness of the community heating system with no significant repercussions on the resulting carbon emissions. The case study therefore demonstrates a possible negative consequence of a design approach focused on a single carbon metric.

Among similar dwellings, the difference in electricity use was in line with the findings of other studies. However, the difference between the minimum and the maximum heat use among similar 3-bed (8.1 times, n=23) and 5-bed dwellings (4.6 times, n=12), was more prominent. As this difference occurred among the dwellings with the same building characteristics, it was attributed to the occupant factors (Gill *et al.*, 2010). The results indicate that the impact of occupant factors in low energy dwellings might be even higher than previously thought.

The early integration of the remote energy monitoring system is commendable. The actual performance data can be used to potentially reduce energy use in current dwellings and forthcoming development phases by informing the occupants and the design team, respectively. Unfortunately, in the case study development, this potential was diminished due to the poor delivery of the monitoring system. Three years after the first households moved in, about a third of the meters in Phase 1 dwellings were still not functional. The home energy feedback device was regarded as useless by almost all the interviewed households, due to the provision of unreliable data.

Once all four phases are completed, the aggregated PV system size of 1.4 MWp will make the development one of the largest residential solar PV sites. The provision of roof PV's is a welcomed measure, offering multiple benefits and supporting the transition toward a smarter energy network (HMG and Ofgem, 2017; Moroni, Antoniucci and Bisello, 2019). Substantial PV systems are essential in zero carbon housing for offsetting the remaining carbon emissions. However, combined with the low electricity demand, this resulted in a significantly higher solar energy surplus in comparison to the typical residential systems (McKenna, Pless and Darby, 2018). Connecting increasing numbers of PV-equipped, low-energy housing to the energy network is susceptible to causing technical issues in the energy network (Infield and Thomson, 2006). Increasing the self-consumption rate of PV electricity is therefore more and more recognised as an important design aspect in forthcoming dwellings. The case study dwellings self-consumed only 23% of generated solar electricity, which is about half of the rate deemed by the Government. The results indicate the need for battery storage in the future. Home batteries are expected to become more cost-effective due to continuous reductions in cost and the introduction of time-of-use (TOU) tariffs, using dynamic energy pricing for the energy import and export.

8.2.2. Indoor Temperatures: Heating and Non-heating Season

The case study development was designed to offer comfortable indoor conditions throughout the year, and to be future-proofed. Based on the monitored data and the responses from the questionnaire and interviews, the dwellings provided relatively good indoor conditions during the heating season. However, two to three years after moving in, less than half of the interviewed households were still experiencing uncomfortable drafts from badly fitted fenestration, and were unable to sufficiently warm up certain rooms. Considerable effort has been invested during the construction phase to deliver the targeted dwelling fabric efficiency levels. The project developer should be similarly motivated to promptly eliminate the issues raised during the building occupancy stage, which can result in an increase in dwelling energy use and occupant dissatisfaction.

Considering the use of light structure, high fabric efficiency, the omission of the suggested future-proofing strategies and the site's location in SE England, it is not surprising that the monitored dwellings did not stay cool during the summer months as intended. According to the questionnaire responses, the dwellings provided among the warmest and uncomfortable summer temperatures of the sample of 58 other housing projects. During the heatwave periods, temperatures in the monitored living rooms were reaching 29°C on average, which was only two degrees lower than the mean outdoor temperature peaks. The bedrooms struggled to dissipate the accumulated heat during the day. Night-time temperatures of the sample were 9K higher on average compared to the outdoor air. Using the static criterion, widespread occurrence of overheating in bedrooms was in line with the findings of other housing studies. However, overheating in living rooms was more frequent. With only a quarter of dissatisfied residents, the experienced indoor temperatures seem to have been mostly tolerated. Nonetheless, this tolerance is expected to weaken in the future. The trend of working from home will expose more occupants to increased temperatures and higher frequency of heatwaves, as the negative consequence of climate change. Feeling unable to cool their home with passive means, and the perception of having access to *free* solar energy, might entice many households to purchase an AC system in the future.

8.2.3. Ventilation

In order to provide minimum ventilation levels, the 14 monitored dwellings were designed with window trickle vents and a constantly operating MEV system, with extract fans located in wet rooms. On average, the monitored bedroom sample achieved the recommended CO_2 concentrations below 1000 ppm during 66% of the night hours in the non-heating season, and only 38% of the night hours in the heating season. These findings indicate that the provided ventilation system was not robust enough to provide adequate ventilation levels in bedrooms, exposing occupants to health risks. It is concerning that elevated CO_2 concentrations in the heating season were measured also in ensuite bedrooms, even though the bathroom fans were continuously drawing the air through the bedroom.

In increasingly airtight homes, the responsibility of providing good indoor air quality switches from occupants to the mechanical ventilation systems. Therefore, designing a ventilation system which delivers adequate ventilation levels is essential. However, this study demonstrated once more that the provided ventilation system was inadequate in achieving this objective in reality. Achieving high CO_2 concentrations also in rooms where doors and trickle vents were kept continuously open, indicates a faulty system operation due to poor design and/or installation of the ventilation system. A more detailed BPE study could reveal whether the actual air extraction rates of the MEV system were too low (Balvers *et al.*, 2012; UCL Energy Institute and Crest Nicholson, 2014). Ventilation design calculations might not have taken into account the actual room conditions (Sharpe *et al.*, 2015). For example, many residents preferred to close the room doors and cover the windows (and consequently the trickle vents) with heavy curtains, to ensure their privacy. More assessments of indoor environmental conditions would be beneficial in understanding the effect and the interrelation of various mechanisms on the indoor air quality. Novel smart ventilation systems (Guyot, Sherman and Walker, 2018) could help in addressing the problem of inadequate ventilation in the forthcoming dwellings.

8.3. Community Heating Performance

Although the energy use target was met, the case study development, however, did not achieve the carbon target during operation. As in many other zero carbon housing developments, this was caused by poor operation of the community heating system.

The heating system's underperformance was firstly attributed to the choice of fuel. In the present case study development, favouring gas as the cogeneration engine's fuel perhaps avoided possible issues attributed to biomass. However, the selection of gas fuel also greatly hindered reaching the expected system performance. The design calculations based on 2009 SAP carbon factors projected achieving an attractively low carbon factor of heat. This was, however, a short-sighted approach. Rapid decarbonisation of the UK electricity grid has continuously driven the carbon intensity of heat above the projected value, diminishing the carbon reduction potential in gas fuelled CHP systems (CIBSE, 2018). Considering such technological limitations of the vital LZC strategies and other hindrances in delivering net zero housing during the past two decades, the decarbonisation of the national energy grid appears to be essential for an effective decarbonisation of new dwellings. In hindsight, community heating using heat pumps would offer much higher carbon reductions for the case study development (DECC, 2016).

The underperformance of the community heating system was also attributed to insufficient heat load. At the time of this study, only two project phases were occupied, while the plant was designed to cater for all four phases. For larger housing delivered in phases and supported by the community heating, reduced plant efficiency that can be expected during the initial years, could be compensated by designing to surpass the targeted performance in the following years.

The complaints about the high standing charge, and the inability to switch the heat supplier raised in this and other studies (Which?, 2015; Guijarro, 2017; Smith, 2017) call for stronger market regulation of district heating (Wissner, 2014). The majority of the interviewed households preferred to save energy by boosting the indoor temperatures when needed. Excluding the temperature shut-off during the night and the morning peak is thought to increase overall energy use, but also decrease peak demand and lead to better efficiencies of the plant (Noussan, Jarre and Poggio, 2017). Consequently, keeping a constant indoor temperature, as advised by the district heating operator, might be more expensive for the residents. However, increased efficiency of the plant operation would reduce its operational cost, which could be translated into lower standing charge.

The study findings strengthen the argument that a widespread delivery of well-performing net zero dwellings demands a prompt change in the culture of building delivery. Building Regulations play an essential role in driving this change; from designing for compliance towards designing for ongoing performance, using multiple performance metrics and monitoring and reporting of actual performance. Without the changes in the current policy, narrowing the performance gap and achieving advanced performances would require the design teams to look beyond the regulatory requirements, consider the trends in the energy networks and use system efficiencies proved by empirical studies. The reoccurring underperformance is concerning, considering that district heating is regarded as one of the key low carbon heating strategies (BEIS, 2017). In order to deliver zero carbon performance in larger housing developments, it is vital that the delivery of district and community heating systems in the UK speedily matures.

8.4. Environmental Behaviours

8.4.1. Transportation Behaviours

Based on the questionnaire responses, 70% of the reported trips were car-based. This was higher than the design target of 55% for 2016, and the mean rates reported for the local town and the ward. The households seem to also own more cars and drive more miles compared to households living in other eco-housing developments. The mechanisms which drive transportation behaviours are complex. In the case study, increased car-dependency in the case study development was attributed to the selection of on-site infrastructure, the small development scale lacking basic amenities, the development's edge-of town location and household lifestyles.

In regard to the infrastructure, on one hand, providing a bus line to town and private electric car chargers is commendable. The former supported many residents in moving away from frequent driving. The latter is thought to increase willingness to buy an electric car (Patt *et al.*, 2019). On the other hand, the modal shift potential with car club and bike rental services is thought to be limited (Bonsall, 2002; Fishman, Washington and Haworth, 2013). In addition, the limited parking space resulted in parking in undesignated areas in the case study, as well as in other eco-developments (Bioregional, 2009; Quilgars *et al.*, 2019).

At the time of the study, and with the last Phase 4 underway, the delivery of the planned on-site amenities was still not feasible, due to the small development size. In this context, the development's geolocation was vital, determining the access to amenities and employment in the surrounding area. The reported transportation behaviours in the case study and Derwenthorpe developments indicated that the edge-of-town location hindered the frequent use of eco-modes of transportation. The town's central services were not within walking distance; the bus did not operate in the evening hours and on Sundays; while the existing road infrastructure offered detached bicycle lanes for only about half of the distance to the town centre. Taking eco-mode of transportation seems to have been particularly inconvenient for about half of all the reported trips, which were heading to destinations in the area surrounding the town.

Higher socio-economic backgrounds for households in the eco-developments can lead to higher transportation footprints (Hanson and Hanson, 1981). This makes achieving the reductions in car use in eco-housing even more challenging. The reported transportation behaviours suggested that the local town was deemed suitable for grocery shopping. However, about half of escorting trips and the significant majority of leisure and commuting trips ended outside of the town. This indicated that the town lacked leisure and employment options for the young and highly educated residents living in the case study development.

Eco-housing developments which were more successful in reducing the car-dependency were based on deep-green values (Findhorn eco-village) and resource sharing (Lancaster Cohousing), or were more appropriately located; in the city centre (One Brighton) or in proximity to fast public transportation options (BedZED and Adamstown).

8.4.2. Waste and Food Behaviours

Although waste recycling appeared to be more widespread based on questionnaire responses, the measured waste recycling and composting rates were relatively similar to local and national averages. Reaching the targeted rate of 80% will probably require introducing additional measures proven effective in the past waste reduction initiatives (Barton, 2000; Phillips *et al.*, 2011; WRAP, 2018). The findings of this study demonstrate the importance of supplementing household feedback with actual waste measurements, which offers a more robust view of the achieved waste performance (Read, Gregory and Phillips, 2009). Due to the challenges associated with monitoring waste at the development scale (WRAP, 2018), waste behaviours in eco-developments will probably remain not well understood.

The reported food behaviours were rather conventional. This was expected, considering that the planned on-site measures were not really delivered. Small community allotments were launched in spring 2019, about 6 months after this survey was conducted. The infrequent gardening club meetings held in the community house’s garden have attracted only a few residents. However, just providing opportunities to purchase and grow low-impact foods in on-site shops and gardens seems to have a limited effect on household food behaviours

(Wang *et al.*, 2007; Bioregional, 2009; Freytag, Gössling and Mössner, 2014; Quilgars *et al.*, 2019). An increase in low-impact food behaviours probably requires introducing additional measures that might influence personal factors shaping food purchasing (Guido, 2009) and urban gardening (Evers and Hodgson, 2011), which is beyond the current scope of housing developers. In this context, it is not surprising that reducing household food footprints is often not prioritised in eco-developments. Nonetheless, defining aspirational targets for low-impact food behaviours would probably motivate housing developers to test different measures, evaluate the outcomes and generate new learning.

8.5. Overall performance

8.5.1. An Eco-housing Exemplar?

In line with the intention of the eco-town planning policy, the overall aspiration for the development was to deliver an exemplar of sustainable housing, which can be widely emulated. A similar goal was aspired to in other eco-housing such as Derwenthorpe, BedZED and One Brighton. Based on the results of the data analysis, the case study development could be classified as low energy housing, rather than an exemplar in sustainability.

Compared to the performance of other new-build housing, the case study development achieved a mixed success. The households' overall satisfaction with the indoor conditions was similar to the mean score of a sample of 58 low carbon housing case studies. On the one hand, the monitored dwellings were more energy and water efficient and generated higher levels of renewable energy compared to conventional housing. On the other hand, the dwellings were more prone to overheating, were not future-proofed for the warming climate, and, in most cases, did not ensure adequate ventilation levels. With only a few years in operation, the community heating system was already producing more carbon-intensive heat than the heat that would be produced by, for instance, individual gas boilers. Finally, the development was not successful in enabling more pro-environmental behaviours in terms of transportation, waste and food. Also, there was no clear evidence which would suggest that significant improvements in performance can be expected, once all four building phases are delivered.

The findings of this study suggest that, before it is emulated in the forthcoming phases, the design of this 4-phase development needs to be significantly improved toward the compliance with the eco-town standard. This would increase the potential in reducing environmental impacts on a large scale; in about 6,000 dwellings planned for the future eco-town.

8.5.2. Enabling Pro-environmental Behaviours

Reduction in demand in carbon-intensive household behaviours plays a vital role in the planned decarbonisation of the economy (IPCC, 2018; CCC, 2020). Hence, the case study development should be commended for integrating a wide range of sustainability measures and for the attempt to enable more sustainable lifestyles. However, the findings of this study suggested that household pro-environmental behaviours in terms of energy, transportation, waste and food were not increased.

The results of the data analysis suggest that the captured energy and water saving, waste recycling, and low-impact food behaviours were similar, while the transportation behaviours were less environmental compared to the national averages. In contrast, more than two-thirds of the residents perceived their new lifestyles as more eco-friendly, and felt more cautious in recycling waste and using energy in their homes. Similarly to the study of Derwenthorpe (Quilgars *et al.*, 2015), this perception was attributed to the intrinsic effect of dwelling energy efficiency and low-carbon technologies, rather than to significant changes in behaviour. Evaluations of low-carbon and eco-developments demonstrated significant reductions in dwelling energy use and resulting carbon emissions. Achieving additional reductions from changes in transportation, waste and food behaviours appears to be far more challenging.

It can be argued that the limited impact on environmental behaviours in the developer-led eco-housing could be attributed to several factors. Firstly, the developers are primarily profit-driven home builders, not proficient in delivering sustainable communities. The industry has yet to advance and deliver well-performing low carbon dwellings, which are far less complex than the eco-housing. Secondly, space constraints can limit the development in providing the needed on-site infrastructure and amenities. This is apparent in high-density housing on small sites. Thirdly, empirical evidence about the effectiveness of different design measures on household lifestyles is scarce and difficult to access by the design teams. This greatly hinders the ability to select the measures needed for achieving the designed performance in a given urban context. The significantly lower household footprints reported in intentional housing communities (Daly, 2017) support the argument that the transition to more sustainable lifestyles might demand a shift from the recurrent, top-down to a more community-based model of housing delivery (Willett, 2011), and a change in personal values (Smith, 2007).

8.5.3. Delivering an Eco-housing Development in a Semi-Rural Setting

The case study development showcases an attempt to deliver an eco-housing development in a semi-rural setting. The design aimed to balance the potential negative environmental impacts of the development's greenfield edge-of-town site, by exploiting the advantages of low-density housing and large development scale. The findings of this study did not indicate clear environmental advantages of choosing the semi-rural, over more urban settings for the development's location.

In regard to the benefits of low-density housing, the vast roof areas of the case study development did not result with larger PV systems (3.7 kWp) or lower daily potable water use (220 litres) per dwelling, compared to other, higher-density developments, such as Sinclair Meadows (4 kWp) (NEF, 2014), and BedZED (162 litres) (Bioregional, 2009). The loss of the farmland due to the construction of the case study development was partly compensated with a more biodiverse landscape, and a substantial green plot (40% of site area). However, the majority of this vegetated area was either patchy (small pockets along the footpaths) or not accessible to the public (green roofs, private gardens, river basin area and the school playground). Also, the potential for using the vegetated area for development-wide food growing was also not exploited, giving preference to decorative plants.

Findings of this study also demonstrated how the delivery of larger developments (favoured for achieving self-sufficiency) can result in certain trade-offs in regard to environmental performance. On the one hand, the economy of scale makes the needed LZC technologies and amenities more viable. On the other hand, reaching the planned number of buildings takes time, during which the initial phases of the growing development can be even more carbon intensive compared to smaller completed developments. This can be particularly visible in regard to energy and transportation categories. It takes about six to eight years to fully deliver a development like the case study or Derwenthorpe, and finally benefit from the advanced energy efficiency of the optimally operating community heating system. It also takes a long time for developments to become large enough to make the planned on-site infrastructure and amenities viable, reducing car use.

It is suggested that urban sustainability is driven not just via new settlements and large urban extensions, but across all housing development scales; from clusters of dwellings like the Sinclair Meadows development, to small neighbourhoods like Derwenthorpe. Consequently, this would instigate taking a more thoughtful approach to housing delivery, considering the impacts of the site location on the household behaviour. The forthcoming sustainable planning policies could offer a distinct set of performance requirements, adapted to different development scales. This differentiation would avoid the cases like the one presented in this study, where it was required that the performance of a growing development with 157 dwellings is (unjustly) evaluated against the eco-town standard developed for large settlements.

8.6. Toward Holistic Performance Evaluations

The growing interest in delivering more sustainable urban areas will drive the need to evaluate the emissions associated with household lifestyles, not only with dwelling use (Vale and Vale, 2010). More holistic evaluations which capture the actual carbon-intensive household behaviours can provide the much-needed empirical evidence about the effectiveness of different planning models and design measures in shaping carbon-intensive behaviours, and build the knowledge base. Narrowing the reoccurring gap between the aspired and actual lifestyles in new developments would result in stronger carbon reductions associated with multiple sectors of the economy, not just the building sector. This would be in line with the whole-system thinking that the UK Government has been adopting for meeting the net-zero economy target (CST, 2020).

Differences in the research approach, assessment criteria and methods make it difficult to effectively compare the impacts of design measures on behaviours in the available eco-housing case studies, and generate new knowledge. Developing a methodological framework for more holistic environmental performance evaluations of new urban areas would standardise the whole evaluation process, as it was already done for the POE and BPE methods (Preiser and Vischer, 2005). In the future, the collected empirical knowledge could be used for the development of new design tools for predicting emissions of new urban areas during the planning and design stages.

8.7. Summary

Chapters 5 to 7 presented the results of the data analysis. In this Chapter 8, the key results were placed in the context of the existing evidence, discussing the implication, significance and contribution of the findings to the field of sustainable housing and urban areas.

It was discussed how the case study development achieved the energy use target, albeit as a balance between higher heat use and lower electricity use. The result ranked the case study among the housing developments with the lowest energy usage. The choice of using less energy efficient dwelling fabric was regarded as a negative consequence of a design approach focused on the single carbon metric. Prominent differences in heat use among similar dwellings indicated that the impact of occupant factors in low energy dwellings might be even higher than previously thought. The energy saving potential of the remote energy monitoring system was diminished due to the poor delivery of the monitoring system. The provision of home batteries in the future could improve low self-consumption of PV electricity and minimise possible technical issues in the energy network.

In regard to the indoor environment, the majority of the monitored rooms did not continuously provide cool conditions during the summer, as aspired. With the trend of working from home, the current tolerance to higher indoor temperatures is expected to weaken in the future. The majority of the monitored rooms also did not provide adequate ventilation levels during the night hours of the heating season. The Building Regulations need to introduce more effective design requirements, which can ensure adequate ventilation levels and prevent overheating in increasingly airtight and insulated dwellings.

The community heating system delivered significantly more carbon intensive heat, causing the development to miss the zero carbon performance target. The underperformance was attributed to the selection of gas fuel and the insufficient heat load from the initial two building phases. Resident complaints voiced in this and similar studies call for stronger market regulation of district heating. The study findings strengthen the argument that a widespread delivery of well-performing net zero dwellings demands a prompt change in the culture of building delivery. In order to deliver zero carbon performance in larger housing developments, it is vital that the delivery of district and community heating systems in the UK speedily matures.

The case study development did not achieve the aspiration to enable more pro-environmental transportation, waste and food behaviours. High car use was attributed to the selection of on-site infrastructure, small development scale lacking basic amenities, the development's edge-of-town location and household lifestyles. Reaching the targeted waste recycling rate of 80% is estimated to require introducing additional measures proven effective in the past waste reduction initiatives. It was discussed how just providing the opportunity to purchase and grow low-impact foods in new developments might not be sufficient to motivate residents to adopt a more low-impact diet.

The development did not demonstrate in reality its proclaimed exemplar credentials. Based on the study results, the development could be classified as low energy housing, rather than an exemplar in sustainable housing. It was also argued that the limited impact on environmental behaviours in mainstream eco-housing could be attributed to; the developers as profit-oriented housebuilders; space constraints of small sites and; the poor access to evidence about the actual effect of measures. The transition to more sustainable lifestyles might demand a shift from the recurrent, top-down to a more community-based model of housing delivery. The findings of this study also did not indicate clear environmental advantages of choosing the semi-rural, over more urban settings for the development's location. It was discussed how the delivery of larger developments can result in certain trade-offs in regard to environmental performance. It was suggested that urban sustainability is driven not just via new settlements and large urban extensions, but across all housing development scales. The chapter concluded by discussing why more holistic evaluations of urban areas which capture the actual carbon-intensive household behaviours are needed.

Chapter 9: Conclusion

9.1. Introduction

This study presented an environmental evaluation of a case study eco-housing development located in England against the design intent. Chapter 1 introduced the reader to the aims, objectives and the structure of the thesis, but also the study limitations and the glossary of frequently used terms. The literature review in Chapter 2 described the key drivers and policies which have shaped eco-housing developments. The following Chapter 3 of the literature review presented more prominent methodologies which can be used for evaluating the performance of eco-housing, and the key results from the available assessments of different case study developments. Chapter 4 presented the environmental design of the case study development, and the research methodology. After conducting the field work, data collection and analysis, the main findings of the study were presented in Chapters 5 to 7. The significance of the key findings was discussed in Chapter 8. Chapter 9 presents the conclusion of the thesis, identifies the key contributions to the field, guidelines for policymakers and eco-housing practitioners, and recommendations for future research.

9.2. Summary of Conclusions

9.2.1. Environmental Design

The first objective of the thesis was to critically examine the environmental design of the case study development. Following the eco-towns standard, the design and the targeted environmental performance of the development was quite ambitious. Similarly to the design approach in other eco-housing developments, the preference was given to physical measures, such as energy efficiency, LZC technologies and on-site infrastructure. A range of informational measures supporting pro-environmental behaviours proposed in the design brief were mostly omitted in the actual delivery.

To date, achieving the stringent, true zero carbon performance was attempted by only a handful of dwellings and smaller housing developments. The design approach in regard to carbon performance was distinct; opting for a gas fuelled CHP community heating technology, and a significantly weaker dwelling fabric efficiency compared to the Passivhaus level. This approach is understandable. Gas is generally considered a more reliable fuel compared to biomass. Weaker fabric efficiency increased the total heat demand, and consequently the cost-effectiveness of the community heating system. In addition, as the projected carbon intensity of heat was very low, slightly increased heat demand did not significantly increase the associated carbon emissions.

The majority of the on-site measures are repeatedly used in eco-housing developments. However, studies have suggested that some of these measures seem not to be very effective in actually enabling behavioural change. The bike rental service is not effectively reducing car use, while car clubs tend to struggle financially in such low-density areas. The planned on-site shop with low impact foods would probably have a limited effect on the residents' dietary preferences. At the time of the study, almost all of the planned basic amenities were still not viable. The involvement of the local council in developing the waste management strategy and conducting waste monitoring was possible partly due to the development's exemplary status, and its significance for the district. The lack of measures which could increase residents' access to low-impact foods, indicated that the aspiration to reduce household food footprints was side-lined in the actual delivery. This was related to the omittance of quantifiable performance requirements in the eco-town policy.

9.2.2. Energy, Water and Carbon Performance

The second objective of the thesis was to assess the development-wide data on dwelling energy use, energy generation, carbon emissions and water use. The study findings were based on the provided annual energy performance data of the community heating system, and the time-series energy and water data collected over the one year period in 74 dwellings (40%) and 43 dwellings (27%), respectively. The 74 dwelling sample was considered to be relatively representative in regard to the dwelling characteristics of the case study development (157 dwellings).

The mean energy use of 76 $kWh/m^2/year$ (ranging from 25.8 to 139 $kWh/m^2/year$) per dwelling met the design target. This result placed the development among the most energy efficient housing in the UK. The energy use was achieved as a balance of 11% lower electricity use (27.4 kWh/m^2/year) and higher heat use (48.5 kWh/m^2/year) compared to the design projections. Notably, the achieved mean electricity use was lower compared to the reported usage in other low energy housing developments. The mean space heating use of 38.3 kWh/m^2/year per dwelling was estimated by using the July heat use, as the equivalent of the monthly hot water use throughout the year. This estimation was slightly lower compared to the FEES standard (39 - 46 kWh/m^2/year) proposed for the weakened zero carbon standard, and significantly above the Passivhaus standard (15 kWh/m^2/year). The mean heat use of similar 2-bed, 3-bed and 5-bed house groups was up to 1.4 times higher compared to the SAP estimations, indicating the performance gap. This was partly attributed to the reduced as-built fabric efficiency detected in third-party in-situ testing on a sample of dwellings. The annual electricity use differed up to ~4 times among the groups of similar dwelling types and up to ~5 times among the dwellings with the same occupancy. The difference in heat usage of 4.6 and 8.1 times found in the groups of similar 5-bed and 3-bed dwellings, respectively, seems to be more prominent compared to the findings in other low energy housing studies.

The mean solar energy generation of 992 kWh/kWp (2.9 kWp) per dwelling, met the design target. The large PV systems and the low mean electricity use contributed to a mean self-consumption rate of only 23%. Hence, the usage of home batteries seems necessary in such PV-equipped, low energy housing developments. The mean water use of 96.2 l/day/person missed the design target. Nonetheless, the achieved use was still about a third lower compared to the national averages.

Lastly, it is estimated that 20.2 kgCO_2e/m^2/year was emitted on average per dwelling, clearly missing the zero carbon target. To the best of the Researcher's knowledge, the true zero and zero carbon performance has not yet been achieved in a housing development. In line with the findings of similar studies, the resulting carbon intensity of heat (0.432 kgCO_2e/kWh) was significantly higher compared to the design projections (0.014 kgCO_2e/kWh). This was attributed to the two key factors; the rapid decarbonisation of the electricity grid, and the reduced system efficiency of the community heating system, caused by insufficient heat load from the initial two building phases.

9.2.3. Environmental Behaviours

The third objective of the thesis was to conduct a development-wide survey to gather household responses about the experience and satisfaction with their home and indoor environmental conditions, and about the energy, waste, food and transportation behaviours. Resident feedback was collected from 90 participants living in 64 households (40%), using the door-knocking method and self-administered questionnaires. The collected sample was considered representative of the households living in houses, but only one response from 28 households living in flats was collected.

Compared to the averages for England, the participating households were younger, more educated, and more knowledgeable but not more concerned about the environment. In line with the findings from similar studies, households were significantly more open to further try to save energy and water in their home, than to recycle more or adopt an eco-friendlier diet. About a third of the households that frequently used their car(s) felt that a suitable greener alternative is yet to be offered, while the rest of these households felt either constrained, or not open to shift away from car use.

High car use was partly attributed to the limited effect of the provided infrastructure, household profile, edge-of-town location of the site and the lack of basic on-site facilities. Households reported using the car for 70% of all trips, which was higher compared to the aspired rate of 55% for 2016 and national averages. The results suggested that driving was far more convenient compared to the greener alternatives for reaching destinations located beyond the borders of the town and within 50 miles. Being younger and more educated on average, the households seem to gravitate significantly less to the local town for leisure and employment, compared to the households living in the local town. Only one household was car-free, which indicated that owning a car was considered necessary in the given context.

Resident responses about waste behaviours were in contrast to the annual results of the weight-based monitoring conducted by the local council. Almost all households reported regularly recycling, and 57% used the garden compost bin, which was in both cases higher compared to the national averages. In addition, 70% of the households felt that the provided facilities made them more cautious in recycling. However, rates of waste diverted from the landfill measured over the three consecutive years (45%, 45% and 60%) was significantly lower compared to the aspired target of 80% for 2020, and not far from the average rate for the district (55%).

The reported pro-environmental food behaviours were similar to the national averages. About a third of the questionnaire participants reported regularly buying organic food (37%) and growing a vegetable patch in their gardens (31%), while 15% regularly visited the farmers markets. The households included meat in 7.6 meals per week on average (in 36% of all meals), which was similar to the responses in conventional households.

The reported home energy and water saving behaviours were also similar to the national averages. In contrast, more than the two-thirds (72%) of surveyed households reported feeling more cautious in using energy in their home. In about half of these households, this was associated with having a home information display (the Shimmy). The interviews conducted with 12 households (as a subset of 64 surveyed households) provided more understanding about the use of the Shimmy and the solar PV energy. All the interviewees regarded the Shimmy as not beneficial, mainly due to the faulty operation and the provision of unreliable feedback data. The later introduction of a substitute mobile app motivated only about a third of the households to re-engage with the offered information. The households seem to be accustomed to using the solar PV electricity; over two-thirds (70%) of households reported using it very often, or always. During the interviews, households reported being cautious in using major appliances only during the daytime. However, they would not postpone their routine of washing clothes if the sky appeared to be overcast and energy generation was probably marginal.

9.2.4. Indoor Environmental Conditions; Temperatures and Ventilation

The following objective of the thesis was to evaluate indoor environmental conditions of a subset of dwellings. The findings were based on the empirical data collected from three different sources. First, the development-wide survey captured the residents' feedback about the satisfaction with indoor conditions. Second, in-situ monitoring of indoor conditions was conducted in 14 subset dwellings, with data loggers taking 15-minute readings during a one year period. Air temperature, relative humidity, CO_2 concentrations and window opening frequency was monitored in master bedrooms, while air temperature, relative humidity and radiator temperature was monitored in living rooms. As the third source, within the 14-dwelling sample, 12 households were interviewed about their heating, ventilation and cooling behaviours.

The results of the data analysis suggested that the dwellings have provided relatively comfortable conditions during the heating season (October-April). However, a quarter of the residents, predominately living in Phase 1, placed their vote within the cold spectrum of the thermal sensation scale. The interviews suggested that this could be partly attributed to the initial heat outages and cases of imbalanced home heating systems, but also to issues that were still persisting at the time. Less than half of the interviewed households still struggled to warm up certain rooms to comfortable temperatures, and have experienced cold drafts. Thermal imaging conducted in four subset dwellings revealed cold air ingress and thermal bridging at the fenestration and in the attic area.

Data analysis suggested that most of households preferred not to continuously heat their homes. During the night hours and/or daily absence, the households would reduce (or put off) the heating and tolerate the drop of indoor temperatures to about 19°C. From there, more comfortable temperatures could be reached in just a few hours by turning the heating back on. During the typical occupancy hours, the mean temperature of the dwelling sample was 20.8°C in living rooms and 20°C in bedrooms, in line with assumptions in the SAP method. In most of the subset dwellings, the heating system was in operation on days with the mean daily outdoor temperatures up to about 14°C. This was slightly lower than the degree day temperature of 15.5°C in the UK.

The interviewed households had mixed feelings about their community heating system. They mostly liked feeling care-free about the system maintenance. The complaints about the high standing charge and inability to switch heat suppliers were also reported in other studies. It was estimated that the households in privately owned dwellings were paying a small cost premium (10 - 16% more) for the total cost of heat from their community heating system, compared to the cost of heat from individual gas boilers, as a common alternative.

Resident responses placed the case study development among the warmest and uncomfortable developments during the summer months, in a sample of 58 other new-build housing developments. Although 40% of the residents felt uncomfortable and 64% felt hot, only a quarter of them were unsatisfied with these conditions, which indicated a fair level or tolerance. However, global warming and working from home trends are expected to increase dwelling energy use. Already 8% of households purchased an air-conditioning (AC) system, while a third were considering purchasing one in the future.

In contrast to the design intent, monitored indoor temperatures suggest that the dwelling design was ineffective in keeping the house cool during the heat waves (daily peak >27°C). During seven heat wave days of the monitoring period with temperature peaks ~31°C, the time-weighted average temperature during typical occupancy hours ranged from 27.2°C to 28.7°C in the subset living rooms, and 25.1°C to 27.4°C in bedrooms. Half of the monitored living rooms reached afternoon temperatures close to or above 29°C. Bedrooms struggled to dissipate the accumulated heat. Two-thirds of bedrooms were warmer than 28°C at 10pm, while the mean difference between the indoor and outdoor temperatures of the bedroom sample was 9K during the night hours. Expectedly, north-oriented living rooms were 1.6°C cooler, and bedrooms were 0.6°C cooler on average, compared to the same rooms with other orientations. Using the static criterion, all bedrooms and two-thirds of the living rooms overheated. In contrast, the more stringent dynamic criterion suggested that only two bedrooms overheated. Compared to other studies, overheating in living rooms was more frequent in the monitored case study dwellings. This was partly attributed to high fabric efficiency and the use of a light-weight structural system. The study findings suggest that the forthcoming Building Regulations need to introduce more effective design requirements against overheating in dwellings. The building industry could support this objective by further developing improved design strategies (Baborska-Narozny and Grudzinska, 2017; Li, Taylor and Symonds, 2019), which are affordable, reliable and visually appealing.

The monitored dwellings were provided with window trickle vents and a continuously operating extract ventilation (MEV) system, with fans in wet rooms. Using CO_2 measurements as a proxy, ventilation levels in many bedrooms were inadequate. The recommended CO_2 concentrations below 1000 ppm were achieved more than 70% of the night-time (10 pm - 7 am) in only a third of bedrooms during the heating season, and in two-thirds of bedrooms during the non-heating season. Inadequate ventilation levels seem to be widely reported across the housing stock. During the heating season, windows were generally kept closed, while two-thirds of households reported to keep the trickle vents open. During the non-heating season, only a third of households would keep the windows open during more than half of the night hours. The results also suggested that, on average, the captured bedroom sample achieved the recommended CO_2 concentrations during periods when windows were kept open for more than a quarter of the night hours. This condition tended to occur in the non-heating season only (May-Sept).

9.2.5. Overall Performance

The penultimate objective of the thesis was to compare the achieved environmental performance of the case study development with the design intent, and the performance of similar eco-developments.

The mean dwelling energy use and generation achieved the design target. However, the design intent in regard to carbon emissions, water usage, indoor temperatures, ventilation and environmental behaviours was not achieved. Compared to other advanced housing, the development could be considered a housing exemplar regard to low energy and water use, and large PV systems. However, the community heating system produced more carbon intensive heat compared to the heat from individual gas boilers.

In regard to indoor conditions, residents have had better control over heating and felt generally healthier and more satisfied with the noise and light levels, compared to the means of resident responses from a sample of other 58 new-builds. However, residents were less satisfied with the summer conditions, and seem to have had higher heating costs than in their previous accommodation.

In regard to environmental behaviours, waste recycling was more widespread, but the recycling and composting rates were lower compared to the rates in conventional housing. Compared to other eco-housing developments, households seem to own more cars, drive more miles, and include meat more often in their diet.

9.2.6. Reliability of findings

The limitations of the study presented in sections 1.4 and 4.3 are expected to reduce the reliability of the findings and consequently, the developed guidelines.

Due to the self-selection bias and widespread calls for more sustainable household behaviours, household responses provided in questionnaires and interviews may be more pro-environmental than in reality.

The study also captured data form only a portion of dwellings and households in the development. The sample captured in the questionnaire (40% of all households) underrepresented households in flats. As a possible consequence, issues with overheating (more prominent in flats) may be underreported. More affluent dwelling owners may have slightly inflated the reported use of cars and electric car ownership. The sample with energy data (47% of all dwellings) slightly underrepresented flats, 3-bed and affordable dwellings. Hence, the reported energy use may be slightly lower in reality, as flats and affordable dwellings tend to use less energy compared to privately owned houses (DBEIS, 2018b). The sample with water data captured only a quarter (28%) of all dwellings, therefore the resulting water use should be taken with caution.

9.2.7. Guidelines

The last objective of the thesis was to produce performance-based guidelines for policy-makers and practitioners for designing the forthcoming eco-housing developments. The key recommendations that can be considered in the delivery of sustainable planning policies and Building Regulations are summarised below:

- Considering the speedy decarbonisation of the energy network, it would be beneficial to update the SAP carbon factors more frequently. Using outdated factors can be especially disadvantageous for larger developments, hindering their carbon reduction potential. Phased delivery and the use of district heating are associated with significant time spans between the design stage, completion and the end of the heating plant's technical lifetime. In this case, carbon factors from 2009 SAP were used to design a development completed in 2022.

- In order to support the zero carbon economy goal, new sustainable planning policies could include advanced carbon reduction requirements which capture household lifestyles, not only dwelling use. This could increase carbon emission reductions associated with new developments. Distinct requirements need to be developed for different development scales.
- Supporting monitoring and reporting of the in-use performance in new developments is necessary to generate the needed learning about the effectiveness of different delivery models and design measures, and to narrow the performance gap in dwelling use and household lifestyles.
- The Building Regulations need to include more effective design guidelines for mitigating overheating in new dwellings. This would increase the comfort of occupants, safeguard their health and prevent the increase in energy use due to mechanical cooling.
- The Building Regulations need to ensure that the minimum ventilation levels are also delivered - in unfavourable, but very common room conditions - with closed doors and windows occluded with heavy curtains.
- The reoccurring operational underperformance and users' complaints are concerning, considering that district heating is regarded as one of the key low carbon heating strategies. In order to deliver zero carbon performance in larger housing developments, it is vital that the delivery of district and community heating systems in the UK speedily matures. Stronger market regulation of district heating is also needed.
- The findings of this study did not indicate clear environmental advantages of choosing the semi-rural (edge-of-town, greenfield site, low-density), over more urban settings (infill, brownfield site, high-density) for the location of new developments.

The key recommendations that can be considered by developers interested in delivering eco-housing developments are:

- Continuous in-use performance monitoring can provide many benefits for the developers and residents. However, the developers should first ensure that they are using credible performance data. Good management of the monitoring system includes user-friendly data access, and ensuring that the installed meters are fully operational and are providing sensible values.

- The decarbonising electricity grid is on its own slowly reducing carbon emissions of buildings. In this context, introducing performance metrics such as space heating use standard and energy use intensity (EUI) in the Building Regulations is vital for minimising building energy demand.
- For large developments using community heating, it is suggested that a slightly more stringent carbon performance target is defined, in order to compensate for the reduced plant efficiency that can be expected until all building phases are completed.

The key recommendations that can be considered by the designers and practitioners interested in delivering eco-housing developments are:

- Design strategies which can help mitigate overheating in buildings need to be further developed to become visually appealing, affordable and reliable.
- When developing design targets in regard to environmental behaviours, design teams should be mindful that households attracted to eco-housing developments seem to belong to higher socio-economic status, which is associated with increased consumption and associated carbon emissions.
- The design teams should aim to design for future performance. A more fair-sighted design approach takes into account the latest technological advances, system efficiencies proven by empirical measurements and foreseeable trends in the energy network.

9.3. Final Conclusions

Single case study research is limited in the wider application of its findings. Nonetheless, given the need for more sustainable housing and the scarcity of performance evaluations, the presented empirical evidence about the actual performance of an eco-housing development in England is valuable and timely.

The achieved performance in regard to carbon emissions, ventilation levels, and indoor temperatures during the non-heating season is not surprising. Studies have repeatedly shown that the compliance-focused design approach tends to result in underperforming dwellings. The findings of this study support the argument that the delivery of well-performing buildings demands a change in the culture of housing delivery. The Building Regulations play an essential role in driving this change; from designing for compliance toward designing for ongoing performance, using multiple performance metrics and monitoring and reporting of actual performance.

Given the urgency of climate change mitigation, the objective of new planning policies needs to expand from delivering efficient dwellings, to delivering more sustainable developments. Expanding urban zones offer an opportunity to integrate high levels of energy efficiency and the latest technologies, but also to shape environmental behaviours and achieve further reductions in carbon emissions. Due to the small number of rigorous evaluations, the potential of eco-developments in encouraging pro-environmental behaviours is still not well understood. The findings of this and other studies of developer-led eco-housing developments suggest that the recurring top-down design model associated with physical determinism seems to be limited in achieving the needed change in households' lifestyle. Hence, more empirical evidence about the effectiveness of different design strategies and housing delivery models is urgently needed to understand the sustainability potentials of the forthcoming developments. A more widespread delivery and evaluation of eco-urban and eco-housing developments can be driven by new sustainable planning policies.

9.4. Contributions to the Field

Due to the following qualities, the case study has made the following contributions to the field of sustainable housing:

- A more holistic in-use performance evaluation of a housing development, capturing household behaviours (energy, transportation, waste and food) and dwelling use (energy, carbon, water, indoor conditions).

- Richness of the dataset allowed identifying multiple associations between measurements and household responses, casting more light on the "why", not just the "what", in regard to the actual environmental performance.
- The conducted development-wide assessment (157 dwellings) and the more detailed assessment of a subset of 14 dwellings, were both larger in scale compared to common evaluation studies which tend to capture a small number of case study dwellings.
- The study evaluated the sole housing development designed in compliance with the Planning Policy Statement 1 (PPS1) for eco-towns.

9.5. Future Research

The following research topics could be considered in future studies:

- Performance evaluation of the case study development in regard to other sustainability criteria, such as the embodied energy use and carbon emissions, biodiversity, health, governance, employment and others.
- Development of a methodological framework for a more holistic housing evaluations, which capture development level performance in a wide range of sustainably aspects.
- Development of a design tool for predicting performance of new urban areas in regard to household environmental behaviours.
- Assessing the effect of different heating regimes on the energy efficiency of community heating systems and the resulting cost of heat.

Appendix

Questionnaire sample: Housing Evaluation (Part 1)

Housing Evaluation

This survey is being conducted to help with future planning and design of residences. The information collected will be treated as completely confidential by the survey team. Survey reports will use summaries of information and not reveal the identities of individuals.

Please fill in as many questions as you can. Write any further comments in the spaces provided or on a separate sheet. Thank you for your help

Queries:
If you have any queries please contact: Luka Oreskovic (PhD Researcher)
Email: 16113647@brookes.ac.uk Tel: 07 387 85 3105

Who should fill this in?:
Anyone over the age of 18 who has lived in the residence for at least six months. This will normally be one person from the household.

Background

Please note: We ask about age and sex because these are both relevant to people's needs in buildings. We ask for names so that we can follow up any matters that may arise.

What is your age…? *Please tick* 18 - 24 [1] [2] 25 - 34; 35 -49 [3] [4] 50 - 64; [5] 65 +

… and your sex? *Please tick* Male [1] [2] Female

How long have you lived here …? *Please tick* Less than one year [1] [2] One year or more

How many other people live with you who are **over 18** years old …? *Number over 18*

How many other people live with you who are **18 years old or under** …? *Number 18 or under*

Please add your address … and postcode *Address and postcode*

Are you normally at home …? *Please tick* Most of the time [1] [2] Evenings and week-ends only; [3] Other; [4] I work from home — *Please state if other*

Are you in a …? *Please tick* Detached house [1] [2] Semi-detached house; Flat [3] [4] Mid terrace; [5] End of terrace — *Please state if other*

Is this a …? *Please tick* Tenancy [1] [2] Owner-occupied; Shared ownership [3] [4] Other

The residence overall

Location How do you rate the overall location …?
Please tick Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory — *Comments about location*

Space Is there enough space …?
Please tick Not enough space overall [1] [2] [3] [4] [5] [6] [7] Enough space overall — *Comments about space*

Layout Does the layout suit you …?
Please tick Poor layout [1] [2] [3] [4] [5] [6] [7] Good layout — *Comments about layout*

Storage Is there enough storage …?
Please tick Not enough [1] [2] [3] [4] [5] [6] [7] More than enough — *Comments about storage*

Appearance How do you rate the appearance from the outside …?
Please tick Poor [1] [2] [3] [4] [5] [6] [7] Good — *Comments about appearance*

Your needs

We are thinking about e.g. the kitchen, bathroom and toilet, living room, garage (if there is one), but please add other things if you wish.

How well do the facilties provided meet your needs …?
Please tick Very poorly [1] [2] [3] [4] [5] [6] [7] Very well

Please give examples of things which work well for you …?

Work well

… and examples of things which do not work well …?

Work poorly

Special circumstances

Do you have any special circumstances which make your needs different from the norm …?

Please describe any particular requirements that have not been properly catered for

Utilities costs

How do your utilities costs compare with your previous accommodation…?

Heating *Please tick* Much lower [1] [2] [3] [4] [5] [6] [7] Much higher

Electricity Much lower [1] [2] [3] [4] [5] [6] [7] Much higher

Water Much lower [1] [2] [3] [4] [5] [6] [7] Much higher

Comfort

This section asks how comfortable you find the building in both winter and summer.

How would you describe typical conditions in WINTER? If you have not lived here in winter then please leave these questions blank and just complete the questions on Temperature in Summer.

Temperature in winter *Please tick your rating on each scale*

Uncomfortable	1	2	3	4	5	6	7	Comfortable
Too hot	1	2	3	4	5	6	7	Too cold
Stable	1	2	3	4	5	6	7	Varies during the day

Air in winter

Still	1	2	3	4	5	6	7	Draughty
Dry	1	2	3	4	5	6	7	Humid
Fresh	1	2	3	4	5	6	7	Stuffy
Odourless	1	2	3	4	5	6	7	Smelly

Conditions in winter

Unsatisfactory overall	1	2	3	4	5	6	7	Satisfactory overall

Comments about heating

How would you describe typical conditions in SUMMER? If you have not lived here in summer then please leave these questions blank and just complete the questions on Temperature in Winter.

Temperature in summer *Please tick your rating on each scale*

Uncomfortable	1	2	3	4	5	6	7	Comfortable
Too hot	1	2	3	4	5	6	7	Too cold
Stable	1	2	3	4	5	6	7	Varies during the day

Air in summer

Still	1	2	3	4	5	6	7	Draughty
Dry	1	2	3	4	5	6	7	Humid
Fresh	1	2	3	4	5	6	7	Stuffy
Odourless	1	2	3	4	5	6	7	Smelly

Conditions in summer

Unsatisfactory overall	1	2	3	4	5	6	7	Satisfactory overall

Comments about cooling and/or ventilation

Noise

How would you describe the effects of noise …?
This question refers to conditions all year round

Please tick your rating on each scale

Noise overall	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
Noise from people between rooms	Too little	1	2	3	4	5	6	7	Too much
Noise from neighbours	Too little	1	2	3	4	5	6	7	Too much
Other noise from outside	Too little	1	2	3	4	5	6	7	Too much

Comments about noise and its sources

Lighting

How would you describe the quality of the lighting …?
This question refers to conditions all year round

Please tick your rating on each scale

Lighting overall	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
Natural light	Too little	1	2	3	4	5	6	7	Too much
Artificial light	Too little	1	2	3	4	5	6	7	Too much

Comments about lighting conditions

Overall comfort

All things considered, how do you rate the comfort of the residence's environment overall ?

Please tick

Unsatisfactory	1	2	3	4	5	6	7	Satisfactory

Comments about comfort

Health

Do you feel that the building affects your health by making you feel less healthy or more healthy?

Please try to evaluate this building with respect to your experience of using buildings in general.

Please tick

Less healthy	1	2	3	4	5	6	7	More healthy

Comments about health

Personal control

How much control do you personally have over the following …?

Please tick each scale

Importance of control *Please tick if important to you*

Heating	No control	1	2	3	4	5	6	7	Full control	1
Cooling	No control	1	2	3	4	5	6	7	Full control	1
Ventilation	No control	1	2	3	4	5	6	7	Full control	1
Lighting	No control	1	2	3	4	5	6	7	Full control	1
Noise	No control	1	2	3	4	5	6	7	Full control	1

Comments about personal control

Design overall

All things considered, how do you rate the design overall…?

Please tick

Unsatisfactory	1	2	3	4	5	6	7	Satisfactory

Comments about design overall

Environmental design features

If you have anything to add about the energy and water-saving features of your home please put them here.

Comments about energy or water-saving design features

Anything else …?

If you have anything else to add which is relevant to the topics raised please put it here.

Other comments

Thank you for your help

If you have any more comments on the topics raised, please add them on a separate sheet.

Please return the filled-in questionnaire to the researcher or as otherwise requested.

Questionnaire sample: Lifestyle Evaluation (Part 2)

Lifestyle Evaluation

Background

What is your highest formal qualification level? *Please tick*

- ❑ None
- ❑ 1-4 GCSE or eq.
- ❑ 5+ GCSE or eq.
- ❑ Apprenticeship
- ❑ 2+ A-Levels or eq.
- ❑ Degree or above
- ❑ Other ________
- ❑ Don't know

Which of these would you say best describes your current lifestyle? *Please tick one answer*

- ❑ I don't really do anything that is eco-friendly
- ❑ I do one or two things that are eco-friendly
- ❑ I do quite a few things that are eco-friendly
- ❑ I'm eco-friendly in most things I do
- ❑ I'm eco-friendly in everything I do
- ❑ Don't know

How much do you agree or disagree with the statements below?
Please mark one answer for each statement

"I need more information on what I could do to be more environmentally (eco) friendly"

Strongly disagree	Tend to disagree	Neither agree or disagree	Tend to agree	Strongly agree	Don't know

"I don't believe my everyday behaviour and lifestyle contribute to climate change"

Strongly disagree	Tend to disagree	Neither agree or disagree	Tend to agree	Strongly agree	Don't know

"Living in   has changed my lifestyle"

Strongly disagree	Tend to disagree	Neither agree or disagree	Tend to agree	Strongly agree	Don't know

"Since living in   my lifestyle has been more eco-friendly"

Strongly disagree	Tend to disagree	Neither agree or disagree	Tend to agree	Strongly agree	Don't know

Which were the most important reasons for choosing your home *Please tick one or multiple answers*

- ❑ Size and type of home
- ❑ Parking space for cars
- ❑ Convenient access to work
- ❑ Convenient access to friends / family
- ❑ Living in an eco-neighbourhood
- ❑ Potential energy and water savings
- ❑ Other ________________

Energy and water use

Please mark one answer for each statement
Please tell me how frequently you personally...

...leave the lights on when you are not in the room?

Never	Occasionally	Sometimes	Quite often	Very often	Always	Don't know

...wash clothes at 40 degrees or less?

Never	Occasionally	Sometimes	Quite often	Very often	Always	Don't know

...make an effort to cut down on water usage at home?

Never	Occasionally	Sometimes	Quite often	Very often	Always	Don't know

...use some appliances like the washing machine and dishwasher during sunny weather when solar energy is available?

Never	Occasionally	Sometimes	Quite often	Very often	Always	Don't know

Please tick one answer for each question below

Has living in your energy efficient home encouraged you to be ...?

- ❑ More cautious in using energy
- ❑ Less cautious in using energy
- ❑ No change in using energy

Does having information about home energy usage on Shimmy encourage you to be ...?

- ❑ More cautious in using energy
- ❑ Less cautious in using energy
- ❑ No change in using energy

Usual temperature setup of your thermostat?

- ❑ 14°C or less
- ❑ 15 - 19°C
- ❑ 20 - 21 °C
- ❑ 22 - 24°C
- ❑ 25 °C and more
- ❑ Don't know

Did you install air conditioning in your home due to hot weather?

- ❑ Yes
- ❑ No, but considering it
- ❑ No, I don't need one

Would you consider making additional energy and water savings?

- ❑ I'm happy with what I do at the moment
- ❑ I feel that I am doing everything that I can do
- ❑ I would like to do more
- ❑ I would do more but I don't know how
- ❑ My life circumstances limit me to do more
- ❑ Other ________________

Are there any other changes in the way you use energy and water in your new home you would like to mention?

Waste recycling

Which of these recycling facilities do you use regularly? *Please tick one or multiple answers*

- ❑ Blue bin (general recycling)
- ❑ Communal glass recycling bins
- ❑ Brown bin (food waste)
- ❑ Garden compost bin
- ❑ Segregated recycling bins (in kitchen)
- ❑ Other ________________

Please tick one answer for both questions below

Do available recycling facilities encourage you to be ...?

- ❑ More cautious in the way you recycle
- ❑ Less cautious in the way you recycle
- ❑ No change in the way you recycle

Would you consider recycling more?

- ❑ I'm happy with what I do at the moment
- ❑ I feel that I am doing everything that I can do
- ❑ I would like to do more
- ❑ I would do more but I don't know how
- ❑ My life circumstances limit me to do more
- ❑ Other ________________

Food choices

Which of these actions do you do preform regularly? *Please tick one or multiple answers*

- ❑ Shopping at local Farmers Market
- ❑ Shopping organic food
- ❑ Grow small vegetable patch in my garden
- ❑ Grow large vegetable patch in my garden
- ❑ Other ________________

In a typical week, how many of your household meals contain meat?

- Breakfast : __ meals contain meat per week
- Lunch : __ meals contain meat per week
- Dinner : __ meals contain meat per week

Would you consider adopting a more eco-friendly diet? *Please tick one answer*

- ❑ I'm happy with what I do at the moment
- ❑ I feel that I am doing everything that I can do
- ❑ I would like to do more
- ❑ I would do more but I don't know how
- ❑ My life circumstances limit me to do more
- ❑ Other ________________

Are there any other changes in the way you recycle or make food choices you would like to mention?

Transport	Per each purpose of transport please mark your transport mode choice with the destination and trip frequency in a typical week.										
	YOUR MODE OF TRANSPORT *mark one mode per each purpose*							YOUR DESTINATION *mark one destination per each purpose*			4.FREQ-UENCY *(number)*
PURPOSE OF TRANSPORT	Walk	Bicycle	Car/ van driver	Car/ van passenger	Motor-cycle	Other private transport (school bus etc...)	Public transport	< 3 miles	4-50 miles	> 50 miles	Number of trips per typical week
Commuting	○	○	○	○	○	○	○	○	○	○	___
Business	○	○	○	○	○	○	○	○	○	○	___
Personal business	○	○	○	○	○	○	○	○	○	○	___
Education / escort for education	○	○	○	○	○	○	○	○	○	○	___
Other escort (to activities etc.)	○	○	○	○	○	○	○	○	○	○	___
Groceries shopping	○	○	○	○	○	○	○	○	○	○	___
Shopping (other)	○	○	○	○	○	○	○	○	○	○	___
Leisure (visiting friends/ relatives)	○	○	○	○	○	○	○	○	○	○	___
Leisure (other)*	○	○	○	○	○	○	○	○	○	○	___
Other purpose including just walk	○	○	○	○	○	○	○	○	○	○	___

**Leisure (other) category includes entertainment, sport, holiday and day trip*

Transport	
Would you consider choosing a more eco-friendly travel (walk, cycle, public transport)?	*Please tick one answer* ☐ Already using eco-friendly travel ☐ Alternative exists, I am using car out of choice ☐ No adequate alternative to car is offered ☐ My life constraints make car the only option ☐ Other ____________
If you <u>do not</u> own or regularly use a standard car/van, were any of these facilities important to you in taking this decision?	*Please tick one or multiple answers* ☐ Brompton bike hire ☐ E1 bus ☐ Train and buses ☐ E-car club ☐ Electric car chargers ☐ Convenient cycle routes ☐ Convenient walking routes ☐ Other ____________ ☐ Not applicable

Please mark car type and annual mileage for each vehicle kept at your residence

Type of vehicle	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Petrol	○	○	○	○
Diesel	○	○	○	○
Hybrid	○	○	○	○
Full electric	○	○	○	○
Motorcycle	○	○	○	○
Miles/year	___	___	___	___

Thank you for your help Please return the filled-in questionnaire to the researcher.

Interview Questions

Date/Time of Interview:

Participant

BACKGROUND

1. Month and year of moving into the development:
2. What are the typical hours of occupation of your:

a) Living room weekday weekend

b) Main bedroom: weekday weekend

HEATING SEASON

1. Did you notice any rooms being often colder than the rest of your home? Noted draughts, cold surfaces, condensation and mould?
2. To what extent do you think you understand your home heating system and can operate it well?
3. Location of your thermostat(s). Can you rate the home thermostat using the scale below?

	Poor 1	Below average 2	Average 3	Good 4	Excellent 5
Clarity of purpose	1	2	3	4	5
Intuitive switching	1	2	3	4	5
Usefulness of labelling and annotation	1	2	3	4	5
Ease of use	1	2	3	4	5
Degree of fine control	1	2	3	4	5
Accessibility	1	2	3	4	5

4. State the preferred thermostat schedule and temperature set point during the heating season. Did you change this approach since you moved in?
   weekday weekend
5. Are you using thermostatic valves of the radiators to adjust temperatures in rooms? If not, why?
6. Are there any bedrooms heated differently? Why?
7. What kind of information or training about heating your home you were provided? (House Guide, verbal info) Did you apply this? If not then why not?
8. How and when do you decide to start or end the heating season in your home?
9. Did you experience any issues with the heating (or hot water) system? Briefly describe the issues and their frequency.
   ☐ Heat outages ☐ Radiator not working ☐ Radiator not very warm ☐ Slow warm-up speed ☐ Insufficient house temperature achieved
   ☐ Temperature instability ☐ Systemic issues

10. Based on your experience of living in your home, what is your opinion about the neighbourhood's district heating system?
Standing charge changes? Please rank your overall satisfaction with the system:

Unsatisfactory 1	 2	 3	 4	Satisfactory 5

VENTILAITON

Main bedroom – preferred ventilation			
Summer day time	**Summer night time**	**Winter day time**	**Winter night time**
Trickle-vents room 1,2,ensuite ☐Open ☐Closed ☐Open ☐Closed ☐Open ☐Closed	Trickle-vents room 1,2,ensuite ☐Open ☐Closed ☐Open ☐Closed ☐Open ☐Closed	Trickle-vents room 1,2,ensuite ☐Open ☐Closed ☐Open ☐Closed ☐Open ☐Closed	Trickle-vents room 1,2,ensuite ☐Open ☐Closed ☐Open ☐Closed ☐Open ☐Closed
Windows room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Windows room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Windows room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Windows room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed
Doors hall, ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Doors hall, ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Doors hall, ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed	Doors hall, ensuite ☐Open ☐ Slightly open ☐Closed ☐Open ☐ Slightly open ☐Closed
Curtains room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed	Curtains room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed	Curtains room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed	Curtains room 1,2,ensuite ☐Open ☐ Slightly open ☐Closed

☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed
☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed	☐Open ☐ Slightly open ☐Closed

1. What is your experience with the mechanical ventilation in your house? What do you think is the purpose of mechanical ventilation? How frequently do you use the boost option?

NON-HEATING SEASON

1. Do you experience any issues of overheating in your home during the summer? Which rooms?
2. During hot weather (such as heat waves), what actions do you take to keep the indoor space cool? (Operating windows, curtains, door opening, installed fans or AC …)
   a. Actions taken when at home (weekend) ____windows ___curtains ____doors
   b. Setup when at work and then actions after working hours (weekday)
      Morning setup ____windows ___curtains
      ____doors
      After work hours ____windows ___curtains
      ____doors
   c. Setup during the night ____windows ___curtains ____doors
3. What kind of information or training you were provided with to keep your home cool during summer? (House Guide, verbal info) Did you apply this? If not then why not?

MISCELANIOUS

1. How do you use the Shimmy (energy use display) device? What do you think is its purpose? Is it useful?
2. Briefly explain how you maximise the utilisation of solar energy?

Statistical test examples

Relating importance of living in an eco-neighbourhood with environmental attitude.

Test Statistics[a]

	ATTMoreInformation	ATTPerceivedEcoFriendly	ATTResponsibleBehaviourOP
Mann-Whitney U	612.500	503.000	628.000
Wilcoxon W	1837.500	1679.000	1853.000
Z	-2.373	-3.172	-2.185
Asymp. Sig. (2-tailed)	.018	.002	.029

a. Grouping Variable: Living in an eco-neighbourhood was one of important reasons for choosing your home.

Relating importance of potential energy and water savings with environmental attitude.

Test Statistics[a]

	ATTMoreInformation	ATTPerceivedEcoFriendly	ATTResponsibleBehaviourOP
Mann-Whitney U	724.000	742.500	738.500
Wilcoxon W	1465.000	1777.500	1819.500
Z	-1.439	-.903	-1.278
Asymp. Sig. (2-tailed)	.150	.367	.201

a. Grouping Variable: Potential energy and water savings was one of important reasons for choosing your home.

Relating number of bins used and environmental attitude.

Correlations

			WasteBinNumber	ATTMoreInformation	ATTPerceivedEcoFriendly	ATTResponsibleBehaviourOP
Spearman's rho	WasteBinNumber	Correlation Coefficient	1.000	-.306**	.296**	.330**
		Sig. (2-tailed)	.	.005	.007	.002
		N	84	84	82	84

Test for mean difference between dwelling type and bills.

Test Statistics[a,b]

	BillsElectricity	BillsHeat	BillsWater
Kruskal-Wallis H	10.199	16.960	2.952
df	3	3	3
Asymp. Sig.	.017	.001	.399

a. Kruskal Wallis Test

b. Grouping Variable: TypeNFlat

Test for difference between tenure and bills

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of BillsElectricity is the same across categories of B_Tenure.	Independent-Samples Kruskal-Wallis Test	.026	Reject the null hypothesis.
2	The distribution of BillsHeat is the same across categories of B_Tenure.	Independent-Samples Kruskal-Wallis Test	.033	Reject the null hypothesis.
3	The distribution of BillsWater is the same across categories of B_Tenure.	Independent-Samples Kruskal-Wallis Test	.002	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Weather conditions during the monitoring period

Regarding average monthly UK outdoor temperatures, Table 38 shows that during the monitoring period there were 9.6 less degree days recorded or 13% less compared to the long term means, which should result with reduced heating needs during the monitoring period.

Month	Long term degree days 1980 -2010	Degree days Jan 2018 - May 2019	Difference (degree days)
January	10.9	11.3	0.3
February	10.9	8.6	-2.2
March	9.0	7.6	-1.5
April	7.1	6.4	-0.7
May	4.2	4.3	0.1
June	2.0	0.5	-1.5
July	0.7	0.0	-0.7
August	0.8	0.5	-0.2
September	2.1	2.1	0.0
October	5.0	4.9	-0.1
November	8.3	7.3	-1.0
December	10.8	8.7	-2.1
Total	71.8	62.2	-9.6

Table 38 Comparing monthly long term mean degree days with the days during the monitoring period

Compared to the UK long term temperature means seen in the Table 39, SAP 2009 temperature standard is similar being overall only 3% higher, but SAP temperatures are 14% lower than temperatures recorded in the local weather station during the monitoring period, therefore again resulting in reduced real heating usage in town's homes compared to the design calculations using SAP 2009 temperatures.

Month	SAP 2009 temperature standard (°C)	Long term temperature 1980 - 2010 (°C)	Temperature Jan 2018 - May 2019 (°C)	SAP to long term difference (°C)	SAP to local difference (°C)	SAP to local difference factor
January	4.5	4.6	4.2	0.98	0.93	1.07
February	5.0	4.6	7.1	1.08	1.41	0.71
March	6.8	6.5	8.8	1.05	1.29	0.78
April	8.7	8.4	9.7	1.04	1.11	0.90
May	11.7	11.4	12.2	1.03	1.04	0.96
June	14.6	14.1	17.2	1.04	1.18	0.85
July	16.9	16.4	20.8	1.03	1.23	0.81
August	16.9	16.2	18.3	1.04	1.08	0.92
September	14.3	14.0	15.2	1.02	1.06	0.94
October	10.8	10.6	11.5	1.02	1.06	0.94
November	7.0	7.3	8.6	0.96	1.23	0.81
December	4.9	4.7	7.5	1.03	1.52	0.66
Overall average	10.2	9.9	11.7	1.03	1.18	0.86

Table 39 Comparing long term monthly temperatures, monthly temperatures during the monitoring period and temperatures used in the SAP calculation

The monitoring period had more sun hours compared to the 10 year (2002 to 2011) average (DBEIS, 2019c), with slightly (5%) more sun hours during the heating period (September to May) which should result in slightly increased solar gain and reduced need for heating (Table 40).

Month	Average sun hours long term mean (2002 to 2011)	Average sun hours (June 2018 - May 2019)	Difference heating season	Difference non-heating season
January	1.8	1.7	-0.1	
February	2.7	4.4	1.7	
March	4.1	4.2	0.1	
April	6.1	5.9	-0.2	
May	6.5	6.6	0.1	
June	6.8	8.1		1.3
July	6.2	8.7		2.5
August	5.6	5.6		0.0
September	5.1	5.3	0.2	
October	3.5	4.4	1.0	
November	2.3	2.5	0.2	
December	1.7	1.4	-0.3	
Total	52.4	58.7	2.5	3.7

Table 40 Comparing sun hours between long term mean

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