TOWARDS ZERO ENERGY BUILDINGS: LESSONS LEARNED FROM THE BEDZED DEVELOPMENT

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Declaration

I, Janet YOUNG, 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.

Abstract

In order for the UK to meet carbon reduction targets and increased demand for housing from a growing population, houses need to be built that use less energy.

Designers have responded by designing low energy buildings but little research has been undertaken on the actual performance of such buildings in use. This study compares the performance in use of 24 dwellings at the Beddington Zero Energy Development (BedZED) designed as a zero energy development. A unique feature is that, for the first time in energy monitoring studies, measurement of dwelling performance in use was undertaken both in the newly built dwellings and dwellings occupied previously by the study's participants.

The results show that the dwellings achieved their design temperature during the heating season and that occupants were generally satisfied with winter comfort levels. Energy usage was lower in the new properties than previous dwellings and lower than comparable new dwellings at the time, broadly achieving the Passivhaus standard. The dwellings achieved a good standard of airtightness although there were some reports of condensation. Internal temperatures in the summer months showed a potential to overheat during hot spells and occupants were less satisfied with summer comfort. It is considered that this was partly because occupants were not familiar with how to cool their homes.

The study reviewed Energy Performance Certificates issued for BedZED properties sold/rented and found them to be inconsistent and inaccurate. This has implications for the marketability of future low energy homes if not addressed by industry. It also found inconsistency in the application of measurement systems in the various models used.

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Chapter 1 Introduction

1.1 Research Context

The UK Government is concerned about rising levels of carbon emissions which contribute to climate change. It has been known for some time that fossil fuel energy use is a significant contributor to carbon emissions and that domestic energy use makes up a significant proportion of overall energy use. The UK has committed to addressing this with its support for the UN commitment in Kyoto in 1998 and European Union legislation in the form of the Energy Performance of Buildings Directive in 2002 and the recast Directive in 2010 with its commitment to reducing targeted greenhouse gas emissions by 80% by 2050, enacted in the 2008 Climate Change Act. The 2011 Carbon Plan stated that by 2050 all buildings will need to have an emissions footprint close to zero. Earlier Governments have also been concerned with the rising cost of energy and the impact on low income households who have had to spend an increasing proportion of their income on energy. There is also a body of research that makes the link between poor levels of warmth and health and more recent research highlights the impact of overheating on health. So in addition to reducing carbon emissions, there have been initiatives to reduce energy usage in dwellings to keep energy affordable and minimise health impacts.

The vehicle for ensuring that new buildings meet the Government's commitments to reducing carbon emissions is Part L of the Approved Documents to the Building Regulations which govern the conservation of Fuel and Power in new dwellings, last revised in 2013.

The case study used in this research is the Beddington Zero Energy Development (BedZED) in the London Borough of Sutton. The development was designed to have 82 dwellings and 19 live-work units. It was designed holistically around sustainable land and resource use, passive design principles, renewable energy, a green transport plan and a plan for sustainable food sourcing. Peabody Trust (now Peabody) funded the

BedZED development in 1999 with construction starting in the same year and completing in 2002.

Data were collected in three phases specifically for this PhD: the principal phase (Phase 2) involved regular temperature, relative humidity and electricity usage monitoring in a sample of 24 properties on the BedZED development for a period of almost two years. A preceding phase (Phase 1) collected similar data in 14 properties occupied by BedZED residents before moving into the BedZED development. Occupant surveys were undertaken during Phase 1 and at the end of Phase 2. A heat loss survey was undertaken in a sample dwelling at the end of Phase 2. In the final phase, eight years after the development was completed (Phase 3), energy consumption data were collected for the whole development and Energy Performance Certificates (EPCs) issued on BedZED properties were downloaded and analysed.

1.2 Research Aim, Hypothesis and Research Questions

The aim of this research is to use a detailed case study of a new build housing development to investigate the application of zero/low energy design techniques and evaluate the results taking into account changes in the design during the construction and changes in occupant behaviour after moving into the development.

The hypothesis for the study is:

"There is a performance gap between predicted and actual energy performance in low energy dwellings and this is due to occupant behaviour".

The research questions that will test this hypothesis are as follows:

- How do the constructed units perform compared with the theoretical design performance?

- What is the difference, if any, between the constructed units and the units as designed?

- Why is there a difference?

- What conclusions can be drawn about this and can the energy model or design practices be changed to reflect this?

- Have participants changed how they use energy at home as a result of moving to the new development?

1.3 Research Significance

The significance of this thesis is that it provides an in-depth assessment of a case study housing scheme designed on holistic principles of minimising the impact of the development on the environment, not just in terms of building construction and operation but also other aspects of occupants' lifestyles including transport and food purchases. Even ten years after the development was completed, it remains the largest of its kind in the UK although the Little Kelham development in Sheffield will be larger when completed.

There can be many reasons why buildings do not perform as built: the design might not deliver the performance required; the construction process might be flawed or may change in response to unforeseen requirements once the project gets underway; building users might not use the building as expected; or a combination of these factors. Evaluating the actual performance of dwellings in use provides valuable feedback to designers about what does and doesn't work and feeds forward into future design and developments. This is particularly important in the light of the Government's commitment to zero carbon emissions from new buildings.

The thesis evaluates how the original construction and design aims have been achieved in use. The following qualities make this study unique:

1. An in-depth study of the performance of this newly built housing scheme which was the first large scale zero energy development in the UK;

2. A longitudinal comparison of the participants in the study sample, enabling a comparison of the same participants in their zero energy dwellings with their former homes;

3. An assessment of summer overheating in well-insulated dwellings during one of the hottest summers on record;

4. Analysis of EPCs issued on the UK's first large-scale zero energy development.

This study was completed over the period 2002 – 2014. The main data collection (Phases 1 and 2) took place during 2002-2004 with subsequent data collection in 2013 – 2014 (Phase 3). The original intention had been to complete the study in 2005 but this was delayed owing to career reasons. The study still offers new insights into what remains one of the most innovative housing developments built in the UK and the additional time provided an opportunity for additional data collection.

1.4 Thesis Structure

This section summarises the structure and content of each chapter.

1.4.1 Chapter 2 Literature Review

The chapter provides the rationale and justification for the thesis through a summary of scientific studies that chart the link between buildings and climate change and the political and legislative response of the UK. It analyses changes in domestic energy demand over time. It highlights human factors research relevant to this thesis. It analyses the taxonomy for low energy and zero energy housing developments and it describes energy measurement systems in use and their applicability to such developments.

1.4.2 Chapter 3 Comparative Low Energy Case Studies

This chapter discusses other low energy and energy efficient housing developments which provide the source of measurement and evaluation methods used in the BedZED study and discussed in Chapter 6 Methods. Additionally, the results from some of these other case studies are compared with the results from the BedZED case study in future chapters.

1.4.3 Chapter 4 BedZED Case Study

This chapter introduces the BedZED case study with reference to original project documents. The scale of ambition for BedZED is discussed from the original design theory for the development to the energy strategy and passive design principles applied to the construction design. The chapter also describes the dwellings lived in by a sample of occupants prior to moving to BedZED in preparation for the longitudinal comparison in Chapter 12.

1.4.4 Chapter 5 Summer Overheating

This chapter discusses the growing importance of summer temperatures and overheating for building designers and occupants. It summarises the trend towards higher summer temperatures and discusses definitions of hot spells. The chapter explains the significance of summer temperatures and hot spells with regards occupant comfort and the impact on health. The hot spell in 2003 that occurred during the Phase 2 monitoring period for this study is discussed.

1.4.5 Chapter 6 Methods

This chapter sets out the methods for testing the hypothesis, drawing upon the earlier case studies discussed in Chapter 3. The justification for using a case study is addressed. The three phases of data collection for this study are discussed and the data analysis methods that have been adopted.

1.4.6 Chapter 7 Energy Usage Results and Analysis

This chapter is the first of six chapters that presents the study results. This chapter summarises the actual performance of the dwellings at BedZED with regards energy usage, drawing upon results from Phase 2 and Phase 3. It analyses and discusses the EPCs issued for BedZED.

1.4.7 Chapter 8 Internal Temperatures Results and Analysis

This chapter compares the internal temperatures achieved at BedZED with the design target. It comprises analyses of both winter and summer temperatures including the hot spell in August 2003 and it compares the BedZED results to some of the other case studies discussed in Chapter 3.

1.4.8 Chapter 9 Air Tightness Results and Analysis

This chapter compares the air tightness results achieved at BedZED with the design. It includes the results from air tightness tests and a heat loss survey carried out at a sampled property and it also analyses relative humidity readings for the property.

1.4.9 Chapter 10 Occupant Surveys Results and Analysis

This chapter presents the results from the two occupancy surveys carried out on samples of BedZED residents. The findings are analysed to evaluate the perceptions and views of occupants about their properties and to provide useful qualitative evidence to compare to the monitoring data.

1.4.10 Chapter 11 Changes to BedZED during the Development Process

This chapter refers to source documents from the project and discusses changes made to the design during the development and occupation phases to establish whether any changes impacted on the actual performance of the BedZED properties in use.

1.4.11 Chapter 12 Longitudinal Study

A unique feature of this study was the inclusion of a measurement phase prior to participants taking up residence in BedZED. This longitudinal element provided a baseline of occupants' behaviour in their previous homes and enabled the study to assess whether it changed as a result of moving into the new dwelling.

1.4.12 Chapter 13 Discussion

This chapter discusses the findings of the study in the light of the research questions set out in section 1.2. It discusses the key differences identified between design and performance in chapters 7 – 12 and puts forward reasons for the differences.

1.4.13 Chapter 14 Conclusions

This chapter discusses the key findings from the research study.

1.4.14 Chapter 15 Limitations of the Study and Future Work

This chapter sets out the limitations of the study and makes recommendations for future follow up work.

Chapter 2 Literature Review

2.1 Introduction

The purpose of this chapter is to review the literature that provides the rationale and justification for the research topic. It provides policy context for the thesis with a brief summary of scientific research on climate change and the UK's policy response. This includes the Government's legally binding commitments to balance its carbon budget through emissions reduction and mitigate the impact of climate change.

The chapter provides a brief review of forecast demand for energy and the impact of demographic changes.

The chapter then reviews the Government's strategy to address climate change and energy reduction for construction with an analysis of the regulatory environment for construction and the commitment to zero carbon new buildings. To introduce energy performance assessments later in the study, the chapter briefly discusses energy measurement systems used for construction and housing. This information is contextualised with a summary of energy efficiency trends from national Housing Stock studies.

The chapter goes on to review the literature on human factors associated with the provision of energy efficient housing, specifically the definition of comfort and the issue variously known as rebound, comfort taking or take-back and which is thought to affect performance of dwellings in use.

The chapter concludes with a summary of the taxonomy used to describe and classify zero energy and low energy buildings in preparation for the BedZED case study that forms the basis of research for this thesis. BedZED is an early example of a housing development that was described as zero energy and designed without the normal whole heating system usually found in new housing construction. For all these reasons, BedZED is an interesting case study which helps inform the Government's energy and emissions reduction strategy for new housing development and new building regulations.

2.2 Scientific context

The impact of extracting and using energy on the environment was first observed in the nineteenth century by Svante Arrhenius who calculated the relationship between atmospheric levels of carbon dioxide and ground temperatures (Arrhenius 1896). In 2007, the Intergovernmental Panel on Climate Change published reports assessing the available scientific information on climate change. They confirmed that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations and that, for the next two decades, a warming of about 0.2°C per decade was projected for a range of emissions scenarios (IPCC 2007).

The latest IPCC assessment (2014) confirms that “Human influence on the climate system is clear”. IPCC scenarios show that even with low-emission mitigation strategies, mean temperatures are forecast to increase by a further 1 - 2°C above pre-industrial levels and high emission scenarios by as much as 4°C or more above pre-industrial levels. The consequences of increased temperatures could include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising human activities such as growing food or working outdoors in some areas for parts of the year (IPCC 2014).

Governments have responded variously with mitigation strategies to minimise or slow down the predicted temperature increases. Some are also developing adaptation strategies which seek to adapt the built environment to the expected changes in weather patterns resulting from climate change. This thesis focuses on mitigation approaches.

2.3 Policy context

The Kyoto Protocol to the United Nations Framework Convention on Climate Change set a long term commitment to maintain global temperature rises below 2°C and the signatory parties agreed to a reduction commitment in CO_2 emissions. The European Union's contribution to this global target was a target to reduce emissions by 8% between 2008 and 2012 (UN 1998). The Kyoto Protocol was signed by all European Union member states and the European Union subsequently published the EU Directive on the Energy Performance of Buildings (EPBD) in December 2002. This legislation recognised that buildings were responsible for about 40% of Europe's energy consumption and it bound EU member states to achieving a reduction in total end energy consumption and an 8% reduction of CO_2 emissions by 2010 when compared to the base year of 1990 in order to comply with the EU's commitment to the Kyoto Protocol (EC 2002). The 2010 recast of the EPBD in 2010 establishes the 'nearly zero energy building' as the building target from 2018 for all public owned or occupied by public authorities buildings and from 2020 for all new buildings (EC 2010).

In 2006, the UK Government introduced the Code for Sustainable Homes (DCLG 2006a) as part of a commitment that all new homes would be zero carbon from 2016. It stated its intention to use this as the basis for future developments of the Building Regulations in relation to carbon emissions from and energy use in homes and so provide greater regulatory certainty to housing developers. It estimated that, if the rate of housing development matched what was required, by 2050 one third of the total housing stock could have been built in accordance with the Code. The Code comprised six levels with Level 6 defined as a home with zero carbon emissions resulting from heating, lighting, hot water and all other energy uses in the home. A Zero Carbon home would go beyond insulation and heat loss calculations and require designers to have regard to a comprehensive set of requirements to reduce the environmental impact of the dwelling in construction and in use and for the dwelling to be completely zero carbon which is defined as zero net emissions of CO_2 from all energy use in the home.

In 2007, the Government set out its intention in a policy statement to achieve a zero carbon goal in three steps: by 2010 to a 25% improvement in the energy/carbon performance set in Building Regulations; by 2013, to a 44% improvement; then, finally in 2016, to zero carbon. It defined zero carbon as, over a year, the net carbon emissions from all energy use in the home would be zero (DCLG 2007).

The Climate Change Act enacted in 2008 commits the UK by law to ensuring that the net UK carbon account for 2050 will be at least 80% lower than the 1990 baseline excluding international aviation and shipping. The 1990 baseline was defined as “the aggregate amount of net UK emissions of carbon dioxide for that year, and the net UK emissions of each of the other targeted greenhouse gases for the year that is the base year for that gas” (Parliament UK 2008). The subsequent Carbon Plan published in 2011 set out how the UK Government intends to meet its Climate Change Act 2050 carbon budget obligations across all sectors. For buildings, the aim was that “by 2050 all buildings will need to have an emissions footprint close to zero” (HM Government 2011).

2.4 Demand for Energy

This section reviews the literature about changes in demand for energy and some aspects of energy supply.

2.4.1 Demand

Over the last 40 years, domestic energy consumption has increased, see Figure 2.1.

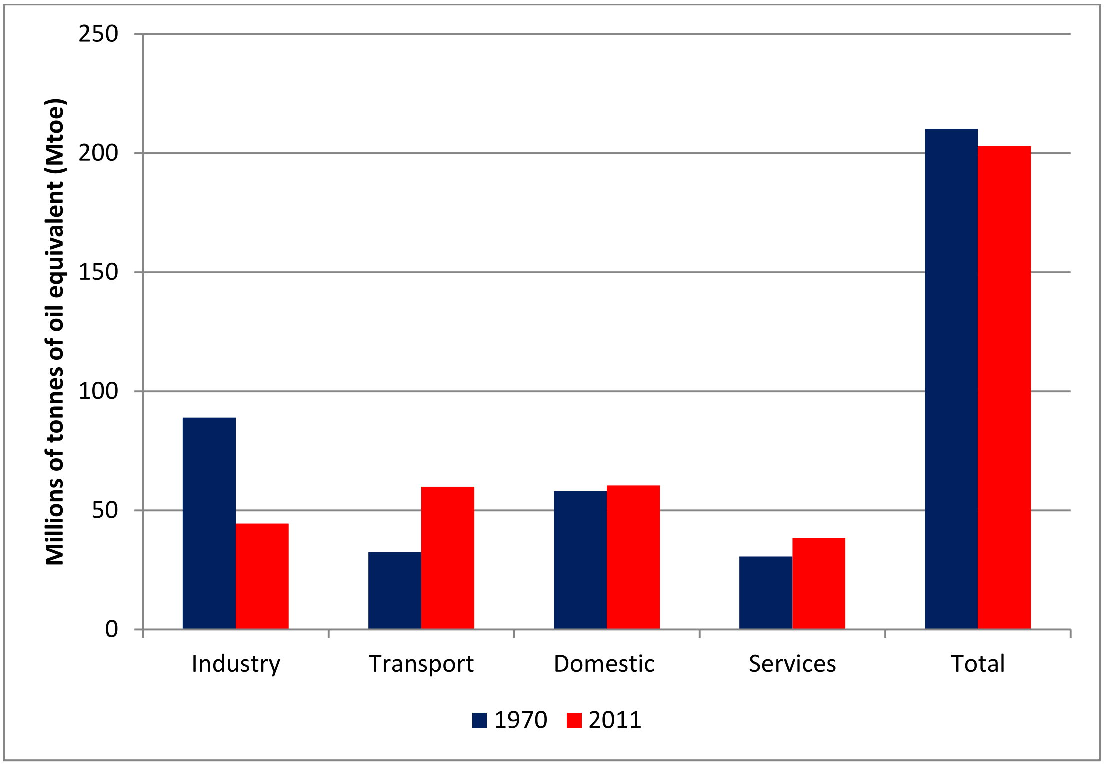


Figure 2.1: Energy Consumption by Sector 1970 – 2011

Source: Table 1.02 DECC 2014

Between 1970 and 2011, energy use by the domestic sector increased by 4.1% from 58 million tonnes of oil equivalent (mtoe) to 60.4 mtoe. Overall, energy consumption fell as a consequence of reduced industry consumption which goes some way to offset the increases from transport and other sectors.

There are a number of factors that affect how much energy is used in dwellings: the number and size of dwellings, population and household size and what energy is used for within dwellings. Table 2.1 shows that while the overall UK population and domestic energy consumption has increased over the last 40 years, energy use per household and per person has reduced.

Table 2.1: Changes in Population, Households and Energy Usage

	1971	**2011**	**% change (changes in number)**	**Sources**
Population (millions)	55.9[1]	63.2[2]	+13% (+7.3)	[1]ONS 2011 [2]ONS 2012a
Households (millions)	18.6[3]	26.3[4]	+41% (+7.7)	[3]ONS 2009 [4]ONS 2012b
Number people per household	3	2.4	-20% (-0.6)	
Overall domestic energy consumption (MWh)	674,540,000[5]	702,452,000[5]	+4.14% (+27,912,000)	[5]DECC 2014 data converted from mtoe to MWh using DECC 2013a conversion factor
Mean annual energy consumption per household (KWh)	36,266	26,709	-26% (-955)	
Mean annual energy consumption per person (KWh)	12,067	11,115	-8% (-952)	

Although energy use by dwellings increased overall between 1971 and 2011, Table 2.1 suggests that this is a function of increased population size (+13%) and number of households (+41%). When measured at an individual property level, energy use fell by 26% between 1971 and 2011. Reasons may include the impact of energy efficiency initiatives and also changes in energy pricing. If energy consumption per household had remained at 1971 levels, then overall domestic energy consumption would have increased by significantly more than the 4% shown in the 40 year period.

Further analysis of demographic change since 2011 shows that in 2013 there were 26.4m households in the UK (ONS 2013a), maintaining the upward trend illustrated in Table 2.1. The proportion of adults living alone almost doubled in the 40 years between 1973 and 2011 from 9% to 16% (ONS 2013b) contributing to the reduction in household size and increase in the number of households. Looking ahead, the UK population is forecast to increase by a further 15% over the next 25 years, shown in Table 2.2.

Table 2.2: Forecast Changes in UK Population Size

Year	**Millions**
2012	63.7
2017	65.8
2022	68
2027	70.0
2032	71.7
2037	73.3

Source: ONS 2013c

If energy consumption per person remained unchanged from 2011 levels, this would result in a 15% increase in energy used by dwellings. The relevance of these demographic changes on domestic energy use is two-fold. Firstly, a net increase in energy consumption to support the increasing population size. Secondly, a marginal increase in energy usage per person resulting from smaller household units distributed across the existing housing stock, that is, we now occupy more space per person which needs more energy to condition it. These demographic changes impact on the UK's ability to meet statutory carbon emissions reduction targets required by the Climate Change Act. Carbon reduction targets are absolute and not relative to the number of households. It means that even more energy efficiency and carbon reduction programmes are required to offset the overall increase in usage in addition to reducing baseline carbon emissions.

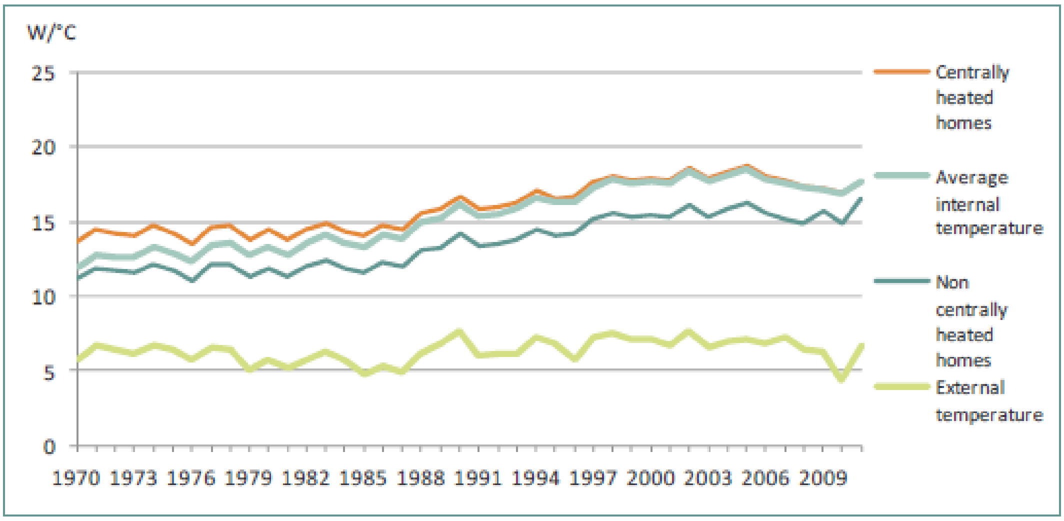
The breakdown of what domestic energy is used for has changed. Table 2.3 incorporates Palmer and Cooper's modelled results for the 40-year period 1971-2011 using the Building Research Establishment Housing Model for Energy Studies (1970-2008) and the Cambridge Housing Model (2008 onwards). The Palmer and Cooper data for total domestic energy usage are 63% and 55% less than the DECC usage figures for 1971 and 2011. Their modelled data suggest an overall increase in energy use by the domestic sector of 9.3%, more than twice that of the DECC actual data quoted in Table 2.1. The difference between the total energy used is thought to be because the DECC data in Table 2.1 is primary energy equivalent (which includes the energy used during the production process and its relative efficiency, e.g. of the power station) whereas the energy in Table 2.3 is delivered energy and is therefore a lower figure. The comparison also shows a reduced difference between primary and delivered energy by 2011, indicating the improved efficiency of energy production during that time period. Additionally, Table 2.3 is modelled whereas Table 2.1 is based on measured energy flows. Comparing measured with modelled data is one of the key research questions for this thesis. However, within those limitations, Palmer and Cooper's models provide an indication of changing trends in what domestic energy is used for.

Table 2.3: Modelled Changes in Domestic Energy Usage 1971 - 2011

	TWh		**% increase**
	1971	**2011**	
Space heating	230.1	279.6	21.5
Hot Water	125.6	82.6	-34.2
Lighting	10.7	14.0	30.8
Appliances	21.5	62.8	192.1
Cooking	25.6	12.8	-50.0
Total	413.5	451.8	9.3

Source: Palmer & Cooper 2013 Appendix 1, Tables 5b,c,d,e.f

Table 2.3 shows an overall increase in energy used for space heating, lighting and appliances, partially offset by reductions in energy used for hot water and cooking. The table is a simple comparison of energy used and does not take into account the change in the number of homes with whole house heating which increased from 28% of total number of dwellings in 1971 to 91% in 2011 (Table 6a, Palmer & Cooper 2013). There is also no reference to the output achieved by heating systems and improved technological efficiency. Palmer and Cooper's modelling suggests that in 1970, during the winter, the average internal temperature in homes with central heating was estimated to be 13.7°C. By 2011, this estimate had risen by 4°C to 17.7°C. Figure 2.2 suggests that the modelled Mean Internal Temperature (MIT) in all homes has increased including those without central heating.



Source: Palmer & Cooper (2013) Graph 6o

Figure 2.2: Average winter internal and external temperatures 1970 - 2010

In their research, Elwell et al took into account external temperatures and showed that the mean balance temperature for UK dwellings (the temperature at which the heat demand to reach the desired internal temperature is just met by free heat gains) has not increased over the period 1998 to 2014 as a consequence of improved efficiency in boilers and fabric heat loss (Elwell, Biddulph, Lowe et al 2014).

The size of dwellings is relevant. The size of households fell from 3 to 2.4 persons between 1971 and 2011; if the size of new dwellings fell commensurately, this could go some way to mitigating overall domestic energy consumption. The 2011 English House Survey found the mean average total usable floor area of UK dwellings (which equates to NIA as defined by the RICS Code of Measuring Practice 2007) in 2011 was 91.2m^2 across all households, tenures and age of properties excluding integral garages, balconies, stores accessed from the outside only and the area under partition walls (DCLG 2013, Table 12). The register of Energy Performance Certificates shows that average floor area of new dwellings in 2012 was 89.7m^2 and in 2013 was 93.6m^2 (Table 2, DCLG 2014c). No clear trend is yet emerging that new dwellings are getting smaller contrary to RIBA research that found that the size of the average new UK home was 76m^2 (Roberts-Hughes 2011).

Over time, a reduction in the size of dwellings might reduce further the energy used for space heating and lighting since these are dependent on property size. However the number of new housing units completed in the UK for the last full recorded year (2012) was 143,690 (DCLG 2014a). At that rate, the existing housing stock is not being replaced fast enough to counter the effect of increased demand and smaller household size. Given the increase in overall population size and numbers of households, it is likely that the new dwellings are adding to the housing stock rather than replacing it.

In summary, the ONS forecast of a 15% increase in population between 2012 and 2037 and the proportionately larger number of homes resulting from smaller households mean that energy consumed in the domestic sector could rise further without new technological solutions. In 2007, Boardman estimated that by 2050 there could be 23% more households with a commensurate increase in energy consumption (Boardman 2007). In their 2010 paper Vale and Vale highlighted the paradox that houses in many developed countries have become more energy efficient but occupants demanded greater floor area and amenity, offsetting some or all of the energy savings from more efficient design.

The significance of increased demand is even greater when applied globally. United Nations global population projections estimate that the population will increase from 6.9bn in 2010 to 9.5bn by 2050 (UN 2012). The US Department of Energy estimated that global energy consumption will increase by 56% between 2010 and 2040, from 524 quadrillion Btus in 2010 to 820 quadrillion Btus in 2040 with the majority of the increase coming from developing economies (EIA 2013).

The projected increased demand for energy plus commitments to reduce absolute carbon emissions from energy use provides the rationale for the Government's commitments towards zero carbon building discussed earlier in this chapter and the justification for evaluating the actual performance in use of the BedZED case study.

2.4.2 Supply

The 2009 EU Renewable Energy Directive required the UK to obtain 15% of all energy from renewable sources by 2020 (EC 2009). This represents an increase in the share of renewables in just over a decade by almost a factor of seven from about 2.25% in 2008. By 2012, 4.1% of the UK's energy consumption was from renewable sources, much of this from traditional renewable sources such as hydro-power rather than new sources of renewables such as wind power (DECC 2013b). To achieve the target, strategies to meet the remaining 10.9% will need to be delivered within the eight years from 2012.

The requirement to source more energy from renewables is a further rationale for this thesis which includes an assessment of the effectiveness of the BedZED on-site renewable energy sources.

2.5 Building Regulations

Buildings make a significant contribution to climate change both directly in their use of energy for heating and lighting and running electrical appliances and also indirectly in their construction and sourcing of materials. Part L of the Building Regulations (HM Government 2014) sets standards for energy efficient performance of new buildings and enables the Government to comply with its obligations under the Energy Performance of Buildings Directive to improve the energy efficiency of new buildings and thereby reduce energy consumption and carbon emissions.

2.6 Modelling and Measurement systems

There are two types of systems relevant to this study. Energy modelling systems model typical performance for a construction and housing type, for example design principles such as building orientation, solar shading, heavyweight or lightweight construction, construction design such as cavity wall thickness or window design. The outputs from the Palmer and Cooper models have already been discussed (Palmer & Cooper 2013). The second is performance measurement systems that measure actual buildings in use. This study compares the energy model (SAP) produced prior to the construction of the case study development with the actual performance achieved in a sample of dwellings. This section of the chapter describes modelling systems used in industry in preparation for later chapters.

2.6.1 BREDEM

The energy modelling systems used in the UK are based on the Building Research Establishment Domestic Energy Model (BREDEM). Until the release of BREDEM in 1990 little, if any, attempt had been made to establish a comprehensive means of assessing a broad range of environmental considerations in buildings (Cole 1998). BREDEM was developed in the early 1980s by the Building Research Establishment for various applications including energy efficiency analysis, determination of investment cost effectiveness of investment and/or the assessment of improvement in average internal thermal conditions (Anderson 1985). It estimates energy requirements in different dwelling types, forecast running costs of a property, most appropriate measures for upgrading existing dwellings, savings from energy efficiency measures and internal temperature conditions for a given energy input (Energy Saving Trust 1996).

2.6.2 NHER

The National Home Energy Rating (NHER) was launched in 1990 and based on the BREDEM model. It models the energy efficiency of a dwelling in terms of energy system running costs per m^2. It takes into account house design and construction, location, heating system efficiency and controls, fuel type used, lighting system and appliances, the number of occupants and the way the dwelling is heated. NHER is a non-linear scale originally ranging from 0-10, with 10 being the most energy efficient. The scale was updated in 2006 to 1-20 with 20 being the most energy efficient (Jie 2010). Houses built to the 1995 Building Regulations (in force at the time that the BedZED case study sought building regulations approval) typically scored between 6 and 8, while the UK average rating was approximately 4 (Todd 1997). Todd discusses how the NHER index score depends on many factors, including occupancy patterns that can affect the energy used in identical houses by up to a ratio of 5:1. The NHER index is calculated primarily using fuel costs, normalises for building size and takes account of heating systems and insulation levels in the building. The index aims to give the same values to houses with the same heating appliances, level of insulation and fuel conversion efficiency.

NHER has different levels of analysis, each with different data requirements and producing ratings to different degrees of accuracy. The simplest is level 0 and is designed to provide a very crude NHER assessment of all the dwellings based on minimum information; the most complex analysis is a complete NHER (level 2/3) assessment and requires a full set of data on the property (Todd 1997). NHER Level 2 surveys were undertaken for the Phase 1 dwellings occupied by BedZED case study participants prior to moving into BedZED.

2.6.3 Standard Assessment Procedure (SAP)

The BREDEM method also underpins the SAP. SAP is based on annual energy costs for space and water heating and predicts energy use and CO_2 emissions. The SAP calculation assumes a standard occupancy pattern, derived from the measured floor area of the dwelling and a standard heating pattern. The rating is normalised for floor area so that the size of the dwelling does not strongly affect the result which is expressed on a scale of 1 – 100, where the higher the number the better the performance (BRECSU 1996). The SAP rating can be difficult to interpret as it uses a logarithmic scale to convert fuel cost per m^2 to a rating. The SAP model can, however, also calculate normative energy and fuel costs. SAP ratings depend on many variables including thermal insulation, efficiency and control of the heating system, ventilation characteristics, solar gain characteristics, and the price of fuel.

In 1995, SAP was incorporated into the revised Part L of the Buildings Regulations. Thereafter, new dwellings and conversions that required Building Regulations consent, had to have a SAP rating to demonstrate compliance with Part L of the Building Regulations. Since its adoption by the Building Regulations, SAP has become the national standard method. From 2005 lighting was included in the calculation and from 2009 thermal mass was explicitly modelled. The latest version of SAP, SAP 2012, takes account of geographical location (but not as it affects space heating energy use due to changes in external temperature). The number of occupants and occupancy lifestyles such as fuel used for cooking and appliances are not included as variables in the SAP model (Griffiths 2010).

SAP has undergone considerable evolution in the last decade including moving from annual degree day calculations to monthly calculations using external temperature.

2.6.4 Comparing NHER and SAP

NHER was a pre-cursor to SAP with high levels of training required. It was designed to be more flexible in its modelling, taking more account of the impact that geographical variation in climate had on space heating and allowing different occupancy patterns to be used. This flexibility was constrained in SAP, particularly in early versions, so as to make the calculations manageable by hand and to allow the same home located in different parts of the UK to have the same rating.

McNeil states on the National Energy Services Ltd website that an average dwelling in England would score between 4.5 and 5.5 on the NHER scale, whereas a gas-heated masonry semi-detached dwelling meeting Building Regulations Part L1a 2006 would score NHER 10. A dwelling with an NHER rating of 20 achieves zero CO_2 emissions along with zero net running costs (McNeil 2010). SAP ratings are used to underpin EPCs so a dwelling with a SAP rating of 92 or more would be in the EPC A band.

2.6.5 Housing Stock Studies

A number of studies record the energy efficiency of houses. The largest scale study of multiple housing types is the English Housing Survey (EHS). This is a continuous national survey commissioned by the Department for Communities and Local Government (DCLG) and merges the former English House Condition Survey and Survey of English Housing. It collects information about people's housing circumstances and the condition and energy efficiency of housing in England. It consists of two surveys: an interview of almost 14,000 households and a physical inspection of almost 15,000 properties. The data are used to monitor the condition and energy efficiency of the housing stock so that policies and resources can be targeted to where they are most needed.

The latest EHS headline report for 2011-12 shows that energy efficiency of the English housing stock has continued to improve. Table 2.4 shows that between 1996 and 2011 the average SAP rating of a dwelling increased by 12 SAP points from 45 to 57 and the proportion of dwellings achieving the highest Energy Efficiency Rating (EER) Bands has increased considerably since 1996 (DCLG 2013). The EHS therefore provides a high level assessment of the changing profile of housing and measures improvements to the overall housing stock as a consequence of policy and regulatory changes. The survey tracks overall trends and is not intended to provide detailed examination of which design solutions work. For that, detailed case studies such as this BedZED case study are required.

Table 2.4: Mean SAP rating by tenure, 1996 – 2011

	1996	2001	2003	2004	2005	2006	2007	2008	2009	2010	2011
Owner occupied	43.9	45.6	46.4	47.0	47.4	48.1	49.3	50.4	52.0	53.7	55.3
Private rented	40.5	43.8	45.4	46.7	47.1	47.6	48.9	50.1	51.9	53.8	55.4
Private sector	43.5	45.3	46.3	47.0	47.4	48.0	49.2	50.3	51.9	53.7	55.4
Local authority	47.6	50.2	52.0	53.7	54.7	55.3	55.7	56.8	58.3	59.9	61.9
Housing Assoc.	52.6	55.9	55.9	56.6	57.8	58.2	58.3	59.0	60.8	62.6	63.8
Social sector	48.6	52.1	53.6	54.9	56.1	56.7	57.0	57.9	59.6	61.4	62.9
All tenures	**44.6**	**46.7**	**47.6**	**48.5**	**49.0**	**49.6**	**50.6**	**51.7**	**53.2**	**55.0**	**56.7**

Source: Table 13, English Housing Survey Headline Report 2011-12 (DCLG 2013)

2.6.6 Energy Performance Certificates (EPCs)

In 2007, EPCs were mandated through Statutory Instrument 2007/991 (HM Government 2007) under the Energy Performance of Buildings Directive 2002/91/EC (EC 2002). This requires an EPC to be issued for all dwellings sold or rented. The EPC includes two ratings: an energy efficiency rating and an environmental impact rating that measures CO_2 emissions. Ratings are derived from a SAP calculation and are combined into a sliding scale of A – G with A being the most energy efficient and least environmental impact. The 2007 English House Condition Survey found that the majority of existing UK dwellings would receive a band D or E energy efficiency rating with the overall average being a band E (Watts, Jentsch & James 2011).

The limitations of using SAP for EPCs were recognised by Murphy, Khalid and Counsell, particularly with regards to low energy dwellings. They proposed a refinement to the current SAP methodology to address concerns in using SAP for the production of EPCs, notably in how SAP calculates the energy requirement for low energy dwellings (Murphy et al 2011). A number of BedZED properties have been sold since the introduction of EPCs and the ratings in these EPCs are discussed in Chapter 7.

2.6.7 Homes Energy Efficiency Database

The performance in use of houses is monitored by the Homes Energy Efficiency Database (HEED) operated by the Energy Saving Trust. It contains data on the UK housing stock and energy efficiency measures dating back to 1995. Since 2008, the Carbon Emissions Reduction Target (CERT) requires all domestic energy suppliers with a customer base greater than 250,000 customers to make savings in the amount of CO_2 emitted by householders. Suppliers meet this target by promoting the uptake of low carbon energy solutions to domestic energy users. CERT data are collected by individual energy suppliers and then collated, anonymised, and processed by a data processing bureau before being provided to the Energy Saving Trust for loading into HEED (Energy Saving Trust 2013a).

The HEED database collects information about housing characteristics including property age, construction features, heating systems and whether any micro generation technologies are installed. It contains at least one piece of information for around 48% of all UK dwellings, with an average of over 10 items per dwelling, principally information about property age and type. HEED also collects details of domestic energy meter readings (Energy Saving Trust 2013b). DECC has also built a framework called National Energy Efficiency Data-framework (NEED) to enable statistical analysis of the data collected in HEED. The results from this BedZED study could support future development of the national database and comparative studies of energy efficiency performance.

2.6.8 Why measure actual performance?

From April 2006 and after the completion of the BedZED development, SAP 2005 and its subsequent updates was adopted as the basis for checking new dwellings for compliance with UK Building Regulations relating to the conservation of fuel and power (HM Government 2010a). However, as Banfill identified, buildings are assessed on their design rather than on the performance of the completed construction (Banfill and Peacock 2007). The exception to this is pressure testing to ensure compliance with air tightness standards and the Robust Details approach used for acoustic performance. The use of Robust Details, which are high performance construction details, is permitted by Part E of the Building Regulations as an alternative to pre-completion testing (HM Government 2010b). The Government has recently consulted on future zero carbon homes regulations and how an Allowable Solutions method might work for zero carbon design. It cites the work of the Zero Carbon Hub which has looked into how the gap could be closed between design and as-built performance of new homes (DCLG 2014b).

Sanders and Phillipson illustrated the significance of the gap between design and performance. They found that measured energy savings are about half of the savings predicted theoretically from the design and that about half of the discrepancy is due to higher internal temperatures in the houses concerned (Sanders & Phillipson 2006). Until SAP 2009, earlier versions of SAP did not take account of thermal mass, leading to the BedZED architect to state “it is important that a tool capable of a full thermal analysis is used in order to show the effect of the thermal mass and other aspects of building physics accurately. For this reason standard assessment tools such as UK SAP/NHER or SBEM are avoided” (Dunster et al 2008). SAP 2009 now includes thermal mass in its calculation. One aspect of this study is to compare the original assumptions used in the design and energy strategies and the SAP calculation with actual performance measurements of the development in use including assessments of performance in EPCs issued using RdSAP.

2.6.9 Ecological Footprint

Although not covered by legislation, another perspective in the literature relating to modelling and measurement and relevant to the BedZED case study is the concept of ecological footprint.

In their Living Planet Report published in 2000, the World Wildlife Fund (WWF) stated that the Earth’s natural ecosystems had declined by about 33% over the previous 30 years and the ecological impact of humanity on the Earth had increased by about 50% over the same period and was exceeding the biosphere’s regeneration rate (WWF International 2000). This was the first report to include a calculation of the ecological footprint which measures a population’s consumption of food, materials, and energy in terms of the area of biologically productive land or sea required to produce the resources and to absorb the corresponding waste. The footprint varied significantly across countries but WWF concluded that, overall, the world was consuming at a rate at least 30% more than the area available and therefore depleting the natural resources (WWF International 2000).

Bioregional were part of the BedZED development team and their sustainable development philosophy was influenced by the WWF's Living Planet Report. Underpinning the BedZED concept was the rationale that if "everyone on the planet consumed as much as the average person in the UK, we'd need three planets to support us" (Desai & Riddlestone 2002). Their philosophy was to reduce ecological footprint by two thirds, by which they meant the consumption of raw materials and fossil fuels so that resources are consumed sustainably and equitably on a global level. This sustainable vision permeated the BedZED development and was pivotal to the vision of a zero energy housing estate that would be capable of producing as much energy as it used.

2.7 Human Factors

This section discusses how people use their homes and how they impact on energy used. As discussed earlier, energy modelling is based on assumptions including some or all of: the location and orientation of buildings, heat loss, type and efficiency of heating and hot water systems, type of fuel used and the number of occupants. Human behaviour is also a factor in energy consumption and of interest to policy makers. Over time, as regulations have changed to reduce the amount of energy consumed in dwellings, it might be reasonable to assume that energy used at an individual dwelling level would reduce. However, this assumes that user behaviour remains unchanged when the dwelling or technology in the dwelling is changed. There is some evidence that users respond to improved energy efficient homes by consuming some of the energy saved by way of higher comfort levels. This is known variously as "taking back", "comfort-taking" or the "rebound" effect.

Bell, Lowe and Roberts (1996) noted that there are many behavioural and social barriers to energy efficiency as well as the more obvious practical ones. They found that on the whole, people are unsure what to do, given their individual circumstances and find it easier to adjust to price rises rather than spend money on improving the performance of their property or heating system. People are concerned with their levels of comfort and often do not get the best out of heating systems because the systems themselves can be difficult to understand. They queried whether if people then move into a better performing property which can be heated to the same levels for less money, will they maintain the same comfort levels and make a financial saving or will they increase their comfort level and pay more? This relationship between improved energy efficiency and human behaviour is a question for this thesis.

2.7.1 Thermal Comfort

Many of the early standards for comfort are underpinned by the work of Fanger who examined the physiological response to the environment and undertook a series of experiments on a range of different subjects in steady state thermally controlled chambers (Fanger 1986). These resulted in what Fanger termed the "predicted mean vote" (PMV) which predicts the mean thermal sensation of a group of people on a scale from cold (-3) to hot (+3) together with the predicted percentage of people dissatisfied (PPD) with the environment. The PMV/PPD model which applies to steady-state conditions now forms the basis of the International Standard (BSI 2006).

Subsequently the applicability of these laboratory-derived relationships was questioned by Humphreys et al (Humphreys, Nicol & Raja 2007) in the context of people occupying buildings where they are living or working. They asked building occupants to rate the environment at their place of work and developed a theory of adaptive comfort where people would adapt their comfort depending on external environmental conditions, for example, feeling more comfortable indoors at higher temperatures when it is warmer outside. Adaptive models have gradually been introduced into thermal standards as the empirical evidence to support their use has strengthened.

Energy models need assumptions about what temperature occupants would find comfortable. Fanger's equation is based on the assumption that thermal comfort is a function of environmental factors such as air temperature, mean radiant temperature, air movement and air humidity and that these are influenced by individual levels of activity and clothing (Fanger 1986). Fanger found that comfort requirements for the winter ranged from 20-24°C, assuming sedentary activity and that this would be acceptable to about 80% of occupants.

Dear and Brager discussed thermal comfort in naturally ventilated buildings (Dean and Brager 2002). They noted the limitations of heat balance models with regards people's adaptation to their environments through personal control or perceptions of comfort. They concluded that it is not reasonable to assume that there can be a "one size fits all" with regards thermal comfort. They suggested that environments kept at a single temperature were outdated and a more appropriate goal is to enable people to control their own environment better.

More recently, Orosa and Oliveira (2011) discussed the fit of Fanger's Predicted Mean Vote approach to modelling thermal comfort for naturally ventilated buildings. They found that people living in naturally ventilated spaces appeared to adapt to a wider range of temperatures than people living in air conditioned spaces.

Turning to industry standards for comfort modelling, the Chartered Institution of Building Services Engineers' (CIBSE) recommended comfort criteria for dwellings are set out in Table 2.5.

Table 2.5: Recommended comfort criteria for dwellings

	Winter operative temperature °C	**Summer operative temperature °C Air conditioned**	**Summer operative temperature °C Non air conditioned**	**Benchmark summer peak and overheating criteria °C**
Bathrooms	20-22	23-25		
Bedrooms	17-19	23-25	23	26
Hall/stairs/landings	19-24	21-25		
Kitchen	17-19	21-23		
Living Rooms	22-23	23-25	25	28
WCs	19-21	21-23		

Source: CIBSE 2006a

CIBSE noted that sleep may be impaired at temperatures above 24°C and that while temperature is usually related to the likelihood of comfort or discomfort, it may be related to other factors such as productivity or health. If the benchmark temperature is exceeded the building has overheated and if this occurs for more than a set amount of time, the building is said to suffer from overheating. For dwellings, the overheating criterion is 1% of the annual occupied hours over the benchmark.

Shove, Chappells, Lutzenhiser et al (2008) took a pragmatic view of comfort. They cited the priority for policy makers to ensure that all households are adequately and affordably heated to an acceptable level, generally taken to be circa 21°C in the living room and circa 18°C for the rest of the dwelling. However, they noted that in the 1996 English House Condition Survey, people reported that they are satisfied with home temperatures within a much wider range. This illustrates the difference between design aspirations and people's actual response to buildings. The CIBSE design criteria enable buildings to be designed to allow most people to be comfortable; but in a given situation people will tend to make the best of it. This BedZED case study includes an analysis of the extent of control that participants had over their environment and how it affected their satisfaction levels.

The emerging importance of summer comfort is highlighted by Chappells and Shove in their 2005 paper where they considered the impact of higher temperatures and potential demand for cooling within dwellings. They noted that Government policy (DTI 2003) had been focused on ensuring that all UK homes were adequately, affordably and efficiently heated with a particular priority being to bring all fuel-poor households up to a decent standard and to ensure that peak demand can be met in exceptionally cold weather. But apart from recognising that air conditioning may become more widespread in the future, there was little about how comfort expectations may change and how the existing building stock will need to be adapted to respond to global warming. Chappells and Shove stated that if the Government's approach to cooling paralleled the approach towards heating, then steps would have to be taken to provide households with adequate and affordable cooling (Chappells & Shove 2005).

In contrast, Strengers (2008) wrote about the Australian experience where air conditioning in dwellings is already standard. She noted that although people have reported being comfortable across a wide range of temperatures from 6°C to 30°C that comfort expectations are converging towards artificially heated and cooled environments and occupants are less likely than previously to use other strategies such as opening windows to cool their environment. One interpretation of this could be that the more control that is provided centrally in buildings for overall comfort conditions, the more standardised occupants' expectations of comfort become and the less tolerant they are of conditions outside that comfort range.

The space heating required for a property to achieve a comfortable internal temperature is dependent on external temperatures which vary seasonally and from year to year. Heating degree days are used to standardise internal temperature data to different external temperatures to enable comparison of the performance of heating systems from year to year. Heating degree days are a measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain level. They are commonly used in calculations relating to the energy consumption required to heat buildings. The same method applies to cooling degree days. Mourshed (2012) defined degree-days as the summation of temperature differences between ambient outdoor temperature and the base/balance point temperature. He further defined the base temperature as the outdoor air temperature at which heating or cooling systems do not need to run to maintain comfort conditions. At the set point temperature (the specified indoor air temperature), the heat loss from the space is equal to the heat gain from the sun, occupants, lights and equipment.

In summary, comfort needs to be defined in terms that can be input into energy models when designing buildings. Air temperature is generally used and, taking Fanger's equation and assuming medium weight clothing and sedentary activity, this will generally produce an internal temperature requirement of circa 21°C.

2.7.2 Changes in behaviour following energy efficiency interventions

This section discusses changes in behaviour following energy efficiency interventions. It discusses whether occupants maintain the same indoor temperatures and consume less energy or whether they increase indoor temperatures and consume the same energy. The assumption that better efficiency will lead to reduced consumption was identified in the nineteenth century by William Jevons who argued that in fact the efficient use of fuel tended to result in an increase in consumption, subsequently called the Jevons paradox:

> "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth".
>
> (Jevons 1865)

The Jevons paradox was picked up in Saunders' 1992 work on the Khazzoom-Brookes postulate which asserts that energy efficiency improvements might increase rather than decrease energy consumption with the potential for energy conservation policies worsening rather than improving climate change (Saunders 1992).

The work by Schnieders on German low energy ‘passive’ houses (2003) suggests that people living in these houses regard a mean internal temperature of 22°C as comfortable. Schnieders found that for the circa 100 buildings in his study, the mean indoor temperature across the whole measurement period was above 20˚C. Occupants typically set temperatures between 21˚C and 22˚C and achieved a range from 17-25˚C in occupied houses. He concluded that when the insulation standard of a building is improved, a trend towards higher indoor temperatures can generally be observed.

Sanders and Phillipson (2006) compared actual energy savings resulting from cavity wall and loft insulation retro-fit projects across 13 different studies. They noted that actual savings were commonly found to be less than expected from the predictions of models such as BREDEM, on average about 50% less. Of that 50% about 15% could be attributed to “comfort taking” whereby occupants increased internal temperatures rather than using less energy. The greater part of the shortfall was however owing to poor engineering estimates of potential savings, inadequate performance of equipment, deficiencies in installation and so on. They found that standard engineering models may overestimate energy savings from energy efficiency improvements in household heating systems by up to a half. They concluded that behavioural change is just one explanation of temperature take-back but not the only explanation of shortfall. They estimated that for household heating and cooling in OECD countries, the direct rebound effect is likely to be less than 30%.

Sorrell (2007) also found that many energy efficiency improvements do not reduce energy consumption by the amount predicted by simple engineering models. Improvements result in lower energy usage and bills with the result that consumption increases. Instead of taking the financial saving from more efficiently designed dwellings and heating systems, occupants increased the internal temperature of their home and/or heat their home more comprehensively for longer periods. Sorrell terms this the “rebound” effect (variously termed “comfort taking” and “take-back” in other studies) and where the effects are sufficiently large to lead to an overall increase in energy consumption (the Khazzoom-Brookes postulate), Sorrell terms this “backfire”. It has the potential to negate some policy benefits of improved energy efficiency, such as carbon emissions targets. He notes that as the consumption of a particular energy service increases, there will be a saturation effect. For example, direct rebound effects from improvements in the energy efficiency of household heating systems should decline rapidly once whole-house indoor temperatures approach the maximum level for thermal comfort which Sorrell found was around 21°C. However, this finding should be treated with caution because it is not clear exactly how the internal temperature is derived, for example whether 21°C is the demand temperature set by the occupant using thermostats or actual measured temperatures during, say, the heating season and standardised to external temperatures.

In a study to quantify ‘take back’, Hamilton, Davies, Ridley et al (2011) analysed data from a national evaluation of the Warm Front domestic energy efficiency scheme which was a major domestic energy efficiency refurbishment programme for existing housing to reduce fuel poverty. It comprised retrofit of cavity wall insulation, loft insulation, draught stripping and installation of energy efficient heating systems. Monitoring data were collected for two–four week periods during the winters of 2001-02 and 2002-03 (Oreszczyn, Hong, Ridley et al 2006, Hong, Oreszczyn & Ridley 2006). The programme gathered detailed indoor environmental and energy efficiency data from around 1,600 dwellings. They calculated that the take back factor was circa 6%, that is, the energy saving from a retro-fit to an existing property will be lower by circa 6% than planned as a result of the occupants choosing to increase the temperature. A follow up to Warm Front, the 2011 Energy Follow up Survey (EFUS), monitored 823 dwellings over 13 months and found that mean internal temperatures standardised to an external temperature of 5°C saturated at 18.4°C in living rooms and 18.7°C in bedrooms (Hamilton 2014). EFUS confirmed that dwellings that receive energy efficiency improvements will increase temperatures and reduce potential energy savings that might be predicted on the assumption that there would be no change in internal temperature.

Love (2014) found that after retro-fitting insulation into 13 dwellings, mean internal temperatures also increased. However, rather than take-back, Love found that the reason for increased temperatures is not changing occupant behaviour but the improved thermal efficiency of the building fabric. She also found that the number of hours that properties were heated decreased. She concluded that the better-insulated buildings cool down more slowly and therefore need heating for less time. The ability of high mass construction to heat up and cool down slowly was one of the key design principles of the BedZED scheme.

Gauthier and Shipworth's research finds another perspective on thermal comfort (Gauthier & Shipworth 2014). They probed the difference between occupant behaviour and perception in relation to internal temperatures and found that occupants' perceptions about temperatures can be markedly different from actual body temperatures experienced. Their findings could impact on post-intervention occupant surveys of the kind undertaken at BedZED which sought to correlate participants' views about comfort with actual monitored data.

Another perspective was found in a study of 3,400 German homes. Sunnika-Blank and Galvin (2012) found that occupants used on average 30% less heating energy than the calculated rating before any interventions such as retro-fit are delivered. They found that, the worse a home is thermally, the more economically the occupants tended to behave when using their space heating. They described this concept as the pre-bound effect and note that it is important for policy-makers since retro-fits cannot save energy that is not being consumed in the first place.

Another factor that may affect energy efficiency policies is picked up by Kelly. In his paper investigating whether energy efficient homes in England consume more energy, Kelly (2011) found that dwellings with a propensity to consume more energy due to higher occupancy rates, higher household incomes, larger floor areas, increased energy patterns and warmer internal temperatures are more likely to have higher SAP ratings. He concluded that occupiers of such homes would consume even larger amounts of energy if it were not for the fact that these homes were already relatively more efficient when compared to the rest of the building stock. He recommended that policy makers should target occupant behaviour in such homes with economic penalties and incentives and homes with low SAP rates should be targeted for whole home efficiency upgrades.

However, such policies could only be substantiated by good measurement data. The literature discussed above illustrates that energy efficiency policies and energy modelling can be over-optimistic about the level of energy savings that can be achieved. Punitive economic policies targeted at such cases would need to be supported by evidence and carefully designed to avoid unintended consequences. For example, in their paper about the effect of energy efficiency improvements in low-income homes, Milne and Boardman estimated that if energy retrofit works were carried out in an average income UK household with a mean internal temperature of 16.5°C, only 70% of the energy efficiency benefit would result in reduced fuel demand with the remaining 30% used to increase internal temperatures and that figure increases to 50% where the mean internal temperature is 14°C (Milne & Boardman 2000). In this instance, taking some of the benefit of the measure through increased temperatures seems reasonable in the light of the low baseline but this approach is less reasonable in the higher SAP rated homes described by Kelly above.

In conclusion, an intervention, whether moving into a more energy efficient home or retrofitting an existing one, could produce a different outcome from that modelled. This might be because occupants heat their homes to a higher temperature (rebound) or they weren't heating their homes as well as expected prior to the intervention (pre-bound). Alternatively the new technical system may mean that the house is maintained at a higher temperature without any intervention from the occupant, a technical rebound owing to whole house heating or an insulated home cooling down less quickly. These findings have implications for the development of new low-energy houses.

The above studies have mostly examined the impact of small changes in efficiency as a result of retrofitting existing buildings or have not been longitudinal in nature. There is now a body of data on monitored internal temperatures in UK dwellings and evidence that occupants can feel comfortable in the range of 18 - 21˚C. There is less evidence that people will live in super-insulated homes without an occupant-controlled heating system and what, if any, changes in behaviour occur when people move into them. This forms the basis of this study.

2.7.3 Changing occupant expectations

Comfort expectations change over time. In their study to track variations in indoor winter temperatures, Mavrogianni, Johnson, Ucci et al (2013) found that an increase of up to 1.3°C per decade may have occurred in UK mean dwelling indoor temperatures from 1978 to 1996. In an earlier paper, Healy (2008) discussed the reasons for this increase which he describes as an increase in occupant preference for “thermal monotony”. Causes include the increased take-up of central heating and air conditioning resulting in a standardised homogenous “comfort zone”, increased wealth in modern societies, relatively lower fuel prices and better building and services technology for energy efficient buildings.

In order to record changes in indoor domestic winter temperatures, Mavrogianni et al (2013) undertook a comparison of indoor temperatures in 1978 and 2006 using the Building Research Establishment’s Housing Model for Energy Studies (BREHOMES). They found that the mean internal temperature increased by 5.7°C between 1970 and 2006 despite the fact that these two years were characterised by similar external temperature conditions with the difference in mean external temperature for the two years being only 1°C. By 2006, 91% of UK homes had central heating compared to 31% in 1970. They compared the results of their modelling with a number of other studies that had been carried out using measurements on site, both spot measurements and occupant recorded measurements. While there are limitations with all these methods they found a clear upward trend for indoor temperatures.

Meyer (2002) argued that once people are accustomed to a high level of comfort, they are not willing to compromise. He argued that as a result, human adaptability to future thermal conditions is bound to become narrower in the future. Others predict that there is still potential for behavioural change: Leaman and Bordass (1999) described the “forgiveness factor” which is used to describe the higher levels of tolerance that occupants have with low energy and passive heating, cooling and ventilation systems.

What does this mean for the BedZED case study? There is disagreement in the literature about whether occupants will tolerate a wide comfort range around the industry benchmarks but the literature is clear that over time, dwellings are being heated to higher temperatures than previously and closer to industry benchmarks.

2.8 Passive Design, Low Energy and Zero Energy houses

This section provides the context behind passive design and the history of low energy and zero energy houses and their definitions. It sets the scene for the discussion of low energy case studies in Chapter 3 and the BedZED case study in Chapter 4.

Hachem and Athienitis (2013) set out the key principles of passive design. These are good thermal mass, adequate shading and favourable building shape and orientation. They define good thermal mass as good wall insulation and window design, recommending for example in northern cold climates, south facing windows covering 35-40% of the elevation to maximise solar gain. They also recommend use of controlled reflective blinds on all windows to reduce summer overheating. The overall orientation and form of buildings is also important to passive design with southern orientated buildings better able to benefit from solar energy generation and solar gains.

Rectangular buildings are also considered to be the optimal shape for reducing energy since this shape offers the least surface area to volume and therefore reduces heat loss.

Free heat gains are also an important element of passive design. Roby (2013) defined free heat gains as the energy contributions to space heating of a building from the normal activities that take place in it, including occupants' body heat and heat from cooking, washing, lighting, and electrical appliances.

Although the terms "low energy" and "zero energy" buildings have been in use for some time, there is not yet agreement over terminology. Marszal, Heiselberg, Bourrell et al (2011) noted the lack of a commonly agreed definition of a Zero Energy Building which results in a wide range of terminology and a number of different methodologies being adopted. Sartori, Napolitano and Voss (2012) asserted that there is a conceptual understanding of a zero energy building (ZEB) as an energy efficient building that will be able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand. They stated that it is therefore implicit that this focuses on buildings that are connected to an energy infrastructure (for example, a national grid) and not autonomous buildings by which they mean buildings that generate energy for their own consumption only. The Autonomous House was coined in the 1970s and comprised a dwelling that collected its own energy and water, grew its own food and treated its own waste on site. (Vale and Vale 2010). Many of the Autonomous House concepts were adopted in the original BedZED development. Sartori et al (2012) argued that the term Net ZEB can be used to refer to buildings that are connected to the energy infrastructure, while the term ZEB is more general and may include autonomous buildings. Their definition of a Net ZEB underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year. The concepts adopted by BedZED are discussed in Chapter 4.

The Government's aspiration that all new houses had to be zero carbon by 2016 was originally set out in the Building a Greener Future policy document (DCLG 2007). The policy required emissions from both regulated and unregulated energy to be accounted for. Regulated energy comprises building-related energy uses such as heating, cooling, hot water, ventilation, auxiliary services and lighting. Unregulated energy comprises user-related energy uses such as cooking and plug-in appliances. In the published policy document, there was no requirement to include embodied energy in the assessment of a zero carbon home, for example, energy used for the extraction, manufacture, transport and construction of buildings and materials.

In the recast of the Energy Performance of Buildings Directive in 2010 (EC 2010), the European Union stated that by the end of 2020 all new buildings should be "nearly zero-energy" with the very low amount of energy required covered to a very significant extent by energy from renewable sources including energy produced on site. In the same year, a revised edition of the Building Regulations Part L Approved Document, Conservation of Fuel and Power was issued (HMG 2010a), now superseded by the 2013 edition (HMG 2014). The Building Regulations sets a Target Emissions Rate for carbon emissions, expressed in terms of CO_2 emissions, in kg/m^2/year emitted as the "result of the provision of the specified fixed building services for a standardised household when assessed using approved calculation tools". The tools require designers to adjust the calculation to take account of heating fuel type (fuel factor). However, the factor for "any fuel with a CO_2 emission factor less than that of mains gas" is given the same factor as mains gas which does not capture the environmental benefits of using renewable energy over mains gas. The footnote to the fuel factor table says that the fuel factors will be kept under review as progress is made towards the zero carbon target.

Heffernan, Xi Liang and De Wilde (2013), also supporters of the use of "Net" to indicate a connection to the grid, took Zero Carbon Hub's UK Zero Carbon House (ZCH) standard as a model. This standard requires dwellings to have a fabric energy efficiency of no greater than 39 kWh/m^2/annum for apartments and mid terrace houses or 46 kWh/m^2/annum for end-of-terrace, semi-detached and detached houses (Zero Carbon Hub 2011). However, compared to the ‘Passivhaus’ standard where the maximum specific heat demand is 15 kWh/m^2/annum, a ZCH will potentially be permitted to use 200% more energy for heating than a Passivhaus.

2.9 Passivhaus

The Passivhaus standard was developed by Dr Wolfgang Feist in the 1990s and there are now estimated to be over 30,000 buildings built to the Passivhaus standard (Mead & Brylewski 2015). Based on passive design principles the standard aims to reduce heat energy use and provide comfortable indoor conditions. The standard requires high levels of insulation, very high levels of airtightness and the use of whole house mechanical ventilation. The standard is summarised in Table 2.6.

Table 2.6: Passivhaus standard

Specific Heating Demand (or) specific heating load	≤15kWh/m^2/annum ≤ 10W/m^2
Specific Cooling Demand	≤15kWh/m^2/annum
Specific Primary Energy Demand (all domestic energy use including appliances)	≤ 120kWh/m^2/annum
Airtightness	≤0.6ach @50pascals (n50)
Thermal Comfort	≥16°C

Source: Mead & Brylewski 2015

The most important element of Passivhaus design is continuous envelope insulation with no thermal bridges. In addition to reducing heat loss, this maintains good internal comfort conditions both in winter and summer, providing there is good shading and ventilation in summer. While the Passivhaus standard is an energy performance standard that provides very good energy efficiency standards, it does not cover broader environmental themes such as sustainably sourced materials, biodiversity and so on.

Passivhaus design aims to minimise the requirement for space heating and cooling and to provide good air quality and thermal comfort. The specification consists of very airtight building envelopes with no more than 0.6 air changes per hour at a pressure differential of 50 pascals, a mechanical ventilation system with heat recovery to provide fresh air and compensate for the low levels of air leakage and the space heating demand (and cooling, if required) is reduced to 15kWh/m^2 or less. The Passivhaus design featured in the BRE's 1996 review of ultra-low energy houses was calculated to use energy at a rate of 31 kWh/m^2/annum, excluding solar contribution and the actual performance of the case study reviewed was 32 kWh/m^2/annum of which 10 kWh/m^2/annum was for the space heating (Oliver & Willoughby 1996) which puts these properties under the maximum 15 kWh/m^2/annum for heat.

Ridley, Clarke, Bere et al 2013) reported on monitored performance of the first new London dwelling certified to the Passivhaus standard, the Camden Passive House. The annual space heating demand achieved the 15 kWh/m^2 Passivhaus target and the overall annual primary energy demand of 125 kWh/m^2 was marginally above the 120 kWh/m^2 target. A recent case study of two Passivhaus dwellings in Wales reported that the properties achieved 9.3 and 25.6 kWh/m^2/annum for space heating compared to the design target of 10 kWh/m^2/annum and the Passivhaus standard of 15 kWh/m^2/annum for heat. The biggest contributor of CO_2 emissions was electrical appliance use (Ridley, Bere, Clarke et al 2014).

Taking all energy into account in his German Passivhaus study, Cutland stated that the total primary energy demand of a Passivhaus including space heating, cooling, domestic hot water, lighting, fans, pumps, white goods and all appliances should be no more than 120 kWh/m^2/annum (Cutland 2012) which is a higher load than the case study reviewed by the BRE in the early 1990s. The 120 kWh/m^2/annum was also the target adopted by the German-led CEPHEUS project which measured the performance of over 100 Passivhaus homes (Schnieders 2003). Schnieders' conclusions were that these houses succeeded in very low space heat consumption during the heating season and comfortable summer conditions with indoor temperatures rarely rising above 25°C. There was also a high degree of user satisfaction with the dwellings.

In their 2012 study, Mlecnik, Schütze, Jansen et al analysed a number of post-occupancy evaluations of nearly zero-energy houses in Austria, Germany, Switzerland and the Netherlands. They concluded that comfort and health conditions (particularly criteria such as indoor temperature, humidity and noise level) and their operability (for example of mechanical ventilation systems) are important factors influencing occupants' perceptions of energy-efficient houses. They reported that a number of studies have found that occupants perceive that their living conditions improved after moving into Passivhauses, particularly with regard to winter thermal comfort and indoor air quality. However, occupants often feel more comfortable during the winter than during the summer. Mlecnik et al quoted one study where 40% of occupants installed additional solar shading suggesting issues with the original design for that development. Another study highlighted the importance of reducing internal heat gains from appliances and lighting in order to avoid overheating in summer. But three other studies reported high levels of satisfaction with summer comfort conditions. In conclusion, there would not appear to be inherent issues achieving winter and summer comfort conditions with low energy housing designs but the literature does highlight some adverse results. The authors concluded that this could be related to design or technical defects and they also emphasised the importance of providing good information to occupants about how to use the dwellings effectively.

Prior to 1985, very few dwellings in the UK had been built to a super-insulated standard. In 1985, the Commission of European Communities funded a scheme of 12 timber-framed dwellings to be built in Milton Keynes, four of which would be super-insulated which comprised heavily-insulated fabric, airtightness and controlled ventilation. These were among the first super-insulated properties in the UK (Ruyssevelt 1987). By the time the BRE published their 1996 report on ultra-low energy homes (almost 20 years ago), there were 40 different examples in the UK and 12 overseas at that time. However in terms of the impact of low energy housing design on the overall housing stock, Vale & Vale estimated in their 2010 paper that there were around 12,000 Passivhaus standard houses in Europe comprising an estimated 0.006% of all European housing stock. So although low in total numbers built, the industry does have experience of building a variety of low and zero housing designs.

Although the move towards low carbon/zero energy development as a way to reduce emissions is still in its infancy, the introduction of Feed In Tariffs in 2010 made the installation of domestic renewable installations more attractive to householders but the circa 400,000 installations installed by June 2012 have an installed capacity of only 1,333 MW (Palmer & Cooper 2013).

Another relevant factor in the light of the Government's commitment to reducing emissions and moving towards zero-energy housing (and the separate issue of increasing housing demand) is housing density. Hamilton, Summerfield, Steadman et al (2010) proposed a method for working out relationships between new building and increasing densification of existing low energy developments with additional building. In so doing, they highlight the factor of site density. If on-site renewable energy is provided then there is an economic and environmental argument to use the infrastructure optimally. Conversely, the higher the density of development, the less potential there is for on-site energy generation. The challenge of balancing site density with on-site energy generation is relevant to the BedZED case study which was designed for suburban densities and was constructed with an on-site biomass Combined Heat and Power (CHP) plant.

As policy makers clarify their requirements and put in place regulations to achieve the policy aims of the recast European Directive, designers have continued to interpret the emerging requirements for practical application within the industry. Wang, Gwilliam and Jones (2009) put forward this definition of a zero energy building:

> "A zero energy building refers to a building with a net energy consumption of zero over a typical year. It implies that the energy demand for heat and electrical power is reduced, and this reduced demand is met on an annual basis from renewable energy supply. The renewable energy supply can either be integrated into the building design or it can be specifically provided for the building, for example as part of a community renewable energy supply system. It also normally implies that the grid is used to supply electrical power when there is no renewable power available, and the building will export power back to the grid when it has excess power generation. This 'two way' flow should result in a net positive or zero export of power from the building to the grid."

Wang and Gwilliam's definition of a zero energy building assumes that the national grid takes surplus energy generated from buildings and delivers it to buildings at times when their on-site renewables cannot meet local demand. This approach depends on the diversity of demand and supply and the inherent energy storage in the system. Wang and Gwilliam's definition resembles very closely the approach adopted in the design philosophy for BedZED.

2.10 Performance Gap

The Zero Carbon Hub (2014) analysed 94 studies of new housing and found "clear evidence of a gap between the designed and as-built energy performance of new homes." There is potential for the performance gap to emerge at all stages of the asset life span from concept design through to construction, testing and modelling.

Burman, Momovic and Kimpian (2014) found overwhelming evidence for the theory of a Performance Gap. Although their principal field of study is schools and office buildings, they quoted a number of housing case studies with performance gaps ranging from 20% to 68%. They attributed the discrepancy between actual and theoretical performance to four sources: inaccurate inputs into models; inadequate modelling methods; construction and commissioning processes; and inefficient building management. These reasons for the discrepancy have shaped the research questions for this thesis. Ridley, Clarke, Bere et al (2013) also noted that occupant behaviour is an important factor in the performance of low energy buildings.

2.11 BedZED in the literature

The BedZED case study is discussed in Chapter 4 using original source documents from the project. The impact of BedZED, the UK's first large scale zero housing development, is clear from the literature: the Energy Saving Trust published an Energy Efficiency Best Practice report in 2002 towards the end of the construction phase (Energy Saving Trust 2002). Around the same period, Nicole Lazarus of BioRegional published two toolkits that described the green materials sourcing strategy for the development (Lazarus 2002) and how to produce affordable carbon neutral developments (Lazarus 2003). Simon Corbey's MSc thesis published in 2005 provided a holistic analysis of the BedZED development (Corbey 2005) and the architect, Bill Dunster, produced "The ZEDbook" in 2008 which was a mixture of analysis of the BedZED scheme and a toolkit for designers (Dunster, Simmons & Gilbert 2008). The continuing interest in BedZED is seen from, for example, the publication of "BedZED Seven Years on" by Hodge and Haltrecht (Hodge & Haltrect 2009), a review of BedZED by Tom Chance (Chance 2009) and a paper on ecovillages "A review of progress in BedZED and Masdar City (Zhu, Kung & Zhou 2015).

2.12 Conclusions

This chapter provides background for the research topic through a literature review. It analyses the scientific basis for the field of investigation and the growing body of domestic and international political commitments to addressing how energy is used in buildings. It describes demand considerations including increased demand for energy from a larger population of smaller households. The chapter discusses Government policy and regulations applicable to the construction industry to use energy more efficiently, modelling systems prescribed and measurement systems available. The chapter examines human factors in particular thermal comfort and the extent to which this is predictable in the delivery of solutions for using energy more efficiently in buildings. There is much research about the impact of human factors and design factors on the actual performance of improved energy efficiency but not, as yet, consistent agreement. Finally the chapter discusses the concept of zero energy buildings and finds differences in exact details and definitions. And while the number of low and zero energy houses is relatively low as a proportion of the total housing stock, there are now a number of built examples for industry to draw upon. This helps support the implementation of Government policies

There is little doubt that major improvements in the energy efficiency of dwellings in developed countries will be required if there is any chance of achieving carbon targets as well as increased use of renewables. Governments around the world are therefore introducing regulations to motivate the design and refurbishment of buildings to zero or near zero carbon. However there is also increased evidence of a performance gap between modelled and measured performance, some of which is attributed to change in internal temperature in dwellings in efficient buildings. There is little evidence in the UK as to how such highly efficient zero carbon buildings will perform or be rated by their occupants. This study aims to provide that evidence.

Chapter 3 Comparative Low Energy Case Studies

3.1 Introduction

This chapter discusses low energy and energy efficient housing case studies that provide the source of measurement and evaluation methods used in the BedZED study. The results from some of these case studies are also compared with the results from the BedZED case study in future chapters. Previous Case Studies

There are precedents for undertaking case studies which focus on a single housing development. Typically such Post-Occupancy Evaluations are completed after the construction of a new housing design or after an intervention to existing housing, such as refurbishment, insulation and heating systems improvements. Such case studies tend to include monitoring after construction is completed to determine its effectiveness, for example, the Linford, Pennyland and Milton Keynes studies (Everett, Horton & Doggart 1985, Lowe, Chapman & Everett 1985 and Edwards 1990). These are relevant to this BedZED case study for three reasons. Firstly, they trialled some of the methods that have been applied to this BedZED case study. Secondly, the findings from these studies contributed to the broader knowledge base about how to design housing that is energy efficient and easy to build. Thirdly, they evaluated the success of the technologies at a property level. With so little housing stock renewed annually – only 13.4% of the housing stock in England was built since 1990 (DCLG 2013), it would be difficult to measure the effectiveness of new energy efficiency construction techniques solely from data collected by, say, the English House Survey given the slow rate of replacement and the time-lag between construction, occupation and surveys.

The Home Energy Efficiency Database (HEED) is compiling a record of energy efficiency improvements to the UK housing stock and this provides an anonymised source of information about property characteristics such as heating systems, insulation and micro-generation technologies (Energy

Saving Trust 2013a, 2013b). This is supported by the National Energy Efficiency Data-Framework (NEED) which enables detailed statistical analysis of energy efficiency (DECC 2013a). Over time this will provide a national dataset of energy performance for housing.

The methods used in this BedZED case study research draw heavily upon the Pennyland and Linford studies both published in 1985 and the Milton Keynes Energy Park which was reported in 1990 and follow-up studies published in 2007 and 2010.

3.2 Pennyland

The Pennyland study (Lowe et al 1985) involved the design, layout, construction and monitoring of an estate of 177 low energy houses in Milton Keynes with the aim of producing a cost effective mass-market low energy housing design for the UK. Half the estate was built to the 1982 UK Building Regulations standard with 50mm cavity wall insulation, 80mm roof void insulation, single glazed windows and no floor insulation. The other half was built to Danish standards and comprised 100mm cavity wall insulation, 140mm roof insulation, double glazed windows and ground floor edge insulation. The majority of houses were equipped with a conventional gas fired boiler and partial radiator heating system, with radiators installed in the downstairs rooms and the bathroom only. At this time, comprehensive whole-house heating systems were not universal in the UK. Following the oil crisis in 1973, the Building Regulations had been changed in 1976 to increase inter alia the energy efficiency performance of new dwellings with U-values of 1.0 W/m^2K for exposed walls, floors and non-solid ground and exposed floors, 1.7 W/m^2K for semi-exposed walls, average 1.8 W/m^2K for walls and windows combined and 0.6 W/m^2K for roofs (DoE 1976). However, as now, while the regulations set maximum heat loss standards, houses did not have a minimum comfort requirement which is determined by occupant expectations and the market response to them.

Pennyland used a number of methods for thermal performance monitoring. Construction was inspected for build-ability by a team of researchers from the BRE. The purpose of this was to ensure that any good practice noted in the study could be easily replicated by the wider building industry. External thermographic surveys were carried out and air tightness tests undertaken on a sample of houses. A social survey was carried out by Milton Keynes Development Corporation.

The principal performance monitoring involved the measurement of energy consumption and internal temperatures over two heating seasons. Energy performance was monitored by reading gas and electricity meters on a monthly basis. A special house temperature meter was developed for the project which recorded the temperature in three rooms of the house and which measured the cumulative difference between each of these and an external temperature sensor, which was considered to be an attempt to record real degree-days for each house. Weather data were recorded at the nearby Linford site, including air temperature, solar radiation, wind speed and wind direction on an hourly basis. The study found a wide variation in gas consumption and reported large effects of different occupant behaviour.

Pennyland used a computer model to assess the energy effects of various passive solar measures incorporated into the design. These were avoidance of over-shading of one house by another, correct orientation, concentrating the glazing on the south side of the house and varying the total area of glazing. It found clear energy benefits from these measures, but little benefit from increasing the glazing beyond 40% of the south-facing wall area. They also showed that a southerly orientation for a house both maximised the passive solar gains and minimised the peak summer temperatures. Surveys of midsummer internal temperatures carried out on hot July days were satisfactory. The authors concluded that additional thermal mass in the Pennyland design was not necessary to minimise overheating with the normal medium-weight construction used in the control group being adequate. They concluded that the additional thermal mass of the passive solar design was not cost effective. However, the study also noted the trend towards whole house heating and since that time the demand for higher internal temperatures has increased, as discussed in Chapter 2 of this thesis.

A conclusion of Pennyland was that specifying low U-values for building elements does not fix the total amount of energy consumed but other factors such as air-tightness and heating efficiency are also very important. Relationships between different design elements are now better understood and the combination of a number of different design principles and technologies is a feature of the BedZED development.

3.3 Linford

Linford was a field trial involving the design, construction and monitoring of eight low energy houses in Milton Keynes at a time when there was little knowledge in the UK about the detailed performance of well insulated passive solar houses (Everett et al 1985). The study aimed to assess the interactive effects of high levels of insulation, passive solar and incidental heat gains and the performance of the heating system. Houses were monitored over two years including the 1981-82 and 1982-83 heating seasons, during which time seven houses were occupied and one was unoccupied. Monitoring comprised recording temperatures, gas and electricity consumption, heat flows and solar radiation in order to establish the thermal performance of the houses. Additionally a thermographic survey and a build-ability study were carried out. The thermographic survey gave an insight into the quality of the installed insulation and highlighted the position of cold bridges. The build-ability study was carried out by the Building Research Establishment (BRE) who concluded that generally the insulation was easy to incorporate into the construction. Some problems were identified with the design. For example, there was potential for cold bridges over window lintels if glass fibre wall batts were not installed with care. The study noted that placing large areas of glazing on the south side of the houses could potentially produce overheating during the summer. However, measurements during a heatwave in July 1983 found this not to be a great problem with the houses' thermal mass and ventilation keeping peak internal temperatures below external temperatures. These findings support the later design philosophy for BedZED which relied on extensive south-facing glazing for solar gain. However, BedZED also incorporated heavy mass construction which was not the case for Linford.

To put Pennyland and Linford in context, Table 3.1 shows the insulation standards adopted by these two studies (based on Danish Building Regulations standards) and compared to the UK Building Regulations in operation at the time.

Table 3.1: Insulation standards required by UK Building Regulations compared to Pennyland & Linford

	UK 1982 Building Regulations	Pennyland	Linford
Walls	50mm fibreglass	100mm fibreglass	100m fibreglass
Roof	80mm fibreglass	140mm fibreglass	140mm fibreglass
Windows	Single glazed	Double glazed	Double glazed
Floor	None	25mm polystyrene edge insulation	25mm polystyrene edge insulation

Both Pennyland and Linford found a variance in the amount of energy used by the different low energy houses. Pennyland concluded that this was a result of changed occupant behaviour. Linford did not interrogate the reasons for the different consumption levels but noted that occupants were delighted by the significant reduction in their fuel bills compared with their previous houses. It would have been useful to set a baseline before carrying out the study so that the variance could be better understood. Accordingly, this thesis included a longitudinal study.

3.4 Milton Keynes Energy Park

Another relevant case study is the Milton Keynes Energy Park. This consisted of 160 new houses that incorporated higher standards of energy performance than required by the Building Regulations in operation at the time. Floor insulation, increased wall insulation, double glazing and condensing boilers that corresponded to the building standards that would apply a decade later in the 1995 edition of the Building Regulations were installed (Edwards 1990, DoE 1995). Edwards' review of the development referred to the higher incidence of conservatories which she stated was "crucial ...to the design, construction and use… if a positive energy benefit is to be achieved from the passive solar gain". Later, BedZED included sunspaces for the same reason.

In the Milton Keynes Energy Park study, gas and electricity consumption was monitored hourly over a period of 18 months, from January 1989 to April 1991. In a sub-sample of 29 dwellings, hourly internal temperatures and relative humidity were also measured. A detailed social survey was undertaken which asked households how they used their homes and also recorded physical changes to dwellings during the monitoring period. The results after one year's monitoring showed that average energy use was 33% less than the UK national average. However, it is not clear from Edwards' paper whether the Milton Keynes results were compared to all UK houses or to new UK houses built to the standards of the day.

A follow-up study of the Milton Keynes Energy Park was undertaken in 2005-07 (Summerfield, Lowe, Bruhns et al 2007). This study aimed to measure whether internal temperatures and energy use had remained the same or changed over time. This longitudinal study found no significant change overall over the 15 year period in average internal temperatures. However, there was evidence that daily gas consumption had increased by 10% and that electricity usage had increased by more than 30%. Although the authors were careful to caveat their findings owing to the small sample of 15 dwellings selected, there is no evidence of occupants increasing the overall comfort level of their homes over time but some evidence of increased energy consumption for hot water, appliances and lighting.

And while there is no evidence of "take-back" over the 15 year period, the authors made the point that "take back" is more likely to occur when improvements are made.

In 2010, Summerfield, Pathan, Lowe et al (2010b) reviewed both the original 1990 Milton Keynes Energy Park project and the 2005 follow-up study. They found that the energy efficiency improvements from fabric insulation delivered over the medium-term. They also found that occupants do not appear to upgrade their properties further when new energy efficient technologies become available but rather they wait until a component fails. The authors concluded that energy-efficiency measures should be carried out to maximum effect, rather than in half measures, since once they have been implemented and provide comfort with lower energy costs, little evidence is found of the occupants undertaking further improvements such as increased loft insulation or renewed draught stripping, unless forced to by component failure. Their conclusion supports the comprehensive super-insulation philosophy adopted for the BedZED development. The three phases of monitoring at the Milton Keynes Energy Park also highlight the value of longitudinal monitoring to track longer term effects of energy efficiency initiatives and occupant behaviour over time.

3.5 Brixton Super-Insulated Houses

The Brixton super-insulated dwellings case study consisted of nine super-insulated properties constructed in 1991 and monitored for an 18-month period (Ridley 1995, Summerfield, Lowe, Firth et al 2006). The case study was part of a larger development of circa 100 dwellings for a social housing landlord. The basic housing design was modified for nine properties to achieve a super-insulated standard, see Table 3.2.

Table 3.2: Brixton Super-insulated Design Standard

U-value				
Walls $W/m^2/K$	**Roof** $W/m^2/K$	**Floor** $W/m^2/K$	**Windows** $W/m^2/K$	**Air changes/ hour**
0.19	0.12	0.28	1.2	0.2^{-1}

Source: Ridley 1995, Table 4.1.2

A further five properties were also included in the study as a control. The predicted SAP ratings for the control properties and the super-insulated properties were 76 and 95 respectively. Energy usage and internal temperature monitoring in living rooms, kitchens and hallways, but not bedrooms, was undertaken in the completed dwellings for an 18-month period (Ridley 1995, Summerfield, Lowe, Firth et al 2006).

The study found that energy used for space heating the super-insulated houses was significantly less, circa 52%, than for the control houses and the super-insulated houses also achieved a 0.7°C higher mean temperature than the control houses. The main issue found with the super-insulated houses was air-tightness; the properties did not achieve the design air-tightness and the mechanical ventilation and heat recovery system proved expensive to operate.

3.6 Retrofit Studies : York Energy Demonstration Project and the Warm Front Programme

The York Energy Demonstration Project was a series of retrofit projects to York Council's social housing stock that comprised various energy efficient improvements for circa 230 dwellings. The study found that energy consumption was reduced by between 20-47% depending on the package of measures applied. The paper provided a high level analysis of the economics of the project, taking into account long term benefits and shorter term capital affordability constraints (Bell & Lowe, 2000). Although this project did not include formal occupant satisfaction analysis, the authors conducted a single open ended interview with one occupant which highlighted some perverse behaviour and which illustrates the value of including more comprehensive occupant surveys in such projects.

The Warm Front programme comprised 1,372 existing dwellings variously retro-fitted with cavity wall and loft insulation, draught stripping and new heating systems. Properties were monitored for a 2-4 week period during the two winters of 2001-02 and 2002-03. The programme was evaluated by recording the energy efficiency performance of the houses in the programme before and after the interventions (Oreszczyn, Hong, Ridley et al 2006, Hong, Oreszczyn & Ridley 2006). The study found that insulation reduced space heating energy consumption by 10% in centrally heated properties and 17% in non-centrally heated properties but the installation of new central heating systems did not have a significant impact in reducing fuel consumption even after adjusting for the increased internal temperature (Hong, Oreszczyn & Ridley 2006). The Energy Follow Up Survey (EFUS) in 2011-12 of 823 dwellings found, inter alia, that there are real differences in internal temperatures between households, in that older households tend to have higher temperatures than younger or non-retired households (Hamilton 2014). This is another interesting finding in the context of the demographic changes discussed in Chapter 2.

As a retrofit programme for existing housing, the use of pre- and post-intervention monitoring for the Warm Front enabled the authors to assess the success of the programme. The Warm Front's pre- and post-intervention approach was adapted for this BedZED case study with the aim of assessing the significance of participants' behaviour on the performance of the BedZED houses.

3.7 Carbon Reduction in Buildings (CaRB)

Summerfield, Lowe, Firth et al (2006) and Summerfield, Pathan, Lowe et al (2010b) discussed the case studies included in the Carbon Reduction in Buildings (CaRB) Building Data Repository project. The CaRB project compiled field study data for the existing building stock in the UK and assessed how energy use changed over time (Lomas 2010). The project compiled results from different energy monitoring studies in a consistent way so that studies could more easily be compared and energy demand data tracked over time. The project collected both building energy usage and also social data and carried out longitudinal studies using existing data from earlier studies where available, such as the Milton Keynes study discussed above (Summerfield, Pathan, Lowe et al 2010b). The methods developed for CaRB for data formatting have been applied to this BedZED case study, enabling direct comparison with other studies.

The BedZED data from this study were uploaded into the CaRB repository by Dr Alex Summerfield of UCL Energy Institute. The CaRB repository provides a consistent format for comparing the results from this BedZED case study to other case studies. The data available from the CaRB database include the Milton Keynes Energy Park study, the Brixton super-insulated study and the Warm Front study.

3.8 Comparative Case Studies Conclusions

This chapter shows that case studies are a source of detailed information about how energy-efficient housing performs in use. Actual performance information is collected through field studies and compared to pre-construction design and modelling. There is now a body of case studies in this field and tried and tested methods to call upon. The development of standard protocols by the CaRB study for compiling data from such studies enables easier comparison between studies to be made.

Chapter 4 BedZED Case Study

4.1 Introduction

The case study used in this thesis is the Beddington Zero Energy Development (BedZED), located in Hackbridge in the London Borough of Sutton. This chapter discusses the key parties involved in the development with reference to original source documents produced prior to construction by the design and development team. The original aims and objectives of the BedZED development are summarised and the design theory relating to the building physics and passive design principles, including the designed SAP and air tightness, the building fabric and services design are discussed, together with how these would contribute to the stated aim of the development to be zero energy.

The dwellings occupied by BedZED residents prior to moving into the BedZED development are described in preparation for the longitudinal study in Chapter 12. This section includes a summary of National Home Energy Rating (NHER) surveys undertaken on pre-BedZED properties.

4.2 BedZED Development Team

The BedZED concept design was developed in 1999 in a partnership between Bioregional Development Group and Bill Dunster Architects (BDA), with building physics and associated mechanical and electrical design input from Arup. BDA specialised in sustainable development in particular low energy and renewable energy technologies. The practice worked from Hope House, a prototype live/work property that tested many design aspects later incorporated into BedZED. Bioregional Development Group was an environmental organisation with the aim of bringing local sustainability into mainstream business and industry. Their role in BedZED was to integrate the building design with transport, materials selection, recycling and renewable energy (Peabody Trust 2000).

Peabody Trust (now Peabody) agreed to fund, procure, build and market the development in 2000. Peabody is registered charity and housing association with a mission to "help the poor of London". It had an active development programme to build new housing in London, the majority for rent to housing association tenants at affordable rents, with the remainder sold or rented at market rents to help cross-subsidise the cost of properties built for rent to housing association tenants. Peabody also had an active research programme and, at the time that BedZED was initiated, was trialling a range of innovative construction and development techniques (Peabody Trust 2000). BedZED offered Peabody Trust the opportunity to build the first large zero energy development in the UK, using a variety of concepts and technologies that had individually been applied elsewhere but which had not been combined in a single development. At the time of construction and initial operation, the thesis author worked for Peabody. Her role comprised, inter alia, setting technical standards for properties and evaluating their quality and performance.

4.3 BedZED Timelines

The concept design was completed in 1999. Peabody decided to fund the development in 2000 and construction started on site in the same year. Construction completed in phases in 2002 and the first occupants moved in in 2002. For this study, Phase 1 took place between February and October 2002 and comprised a study of the participants in their former homes. Phase 2 took place between August 2002 and December 2004 and comprised a study of participants in their BedZED homes. Phase 3 took place between January 2008 and July 2014 and comprised a study of all BedZED properties.

4.4 BedZED Location

Figure 4.1 shows the location of BedZED.

Figure 4.1: **Location of BedZED**

4.5 BedZED Scheme

When construction was completed, BedZED comprised 82 dwellings with a mix of one and two-bedroomed flats and three and four-bedroomed maisonettes and townhouses. There were also 19 live-work units some of which were later converted to dwellings. There was a mix of tenures comprising privately owned, shared ownership and social rented properties. Some 2,500m^2 of space was allocated for 19 work-live units plus studios, shops and community facilities. The breakdown of property types, size and number of occupants prepared by Corbey (2005) is in Appendix 1.

4.6 BedZED Design Aims

At the time of construction, the aim of the development was unique in the UK in that the design aimed to be carbon neutral from cradle to grave. BedZED would make significant use of passive design principles, there would not be a typical central heating system and the scheme also planned to provide all its energy requirements from renewable resources.

BedZED aimed to be a carbon neutral development with no net addition of CO_2 to the atmosphere. BedZED buildings were designed to achieve a 60% reduction in energy demand including a 90% reduction in heat demand compared to typical new dwellings built to the 1995 Building Regulations in operation at the time of design and electricity consumption would be reduced by 10% compared to typical domestic houses. The predicted total energy consumption for BedZED was 75 kWh/m^2/annum compared to the standard required by the 1995 Building Regulations of circa 163 kWh/m^2/annum (Arup 1999a).

4.7 Land Use

The site was a former sewage works and as a brownfield site enabled the recycling of redundant suburban land for housing, an important theme of the recently published Urban Task Force report (Rogers 1999) which promoted recycling of brownfield land to meet housing development targets together with good integration with public transport. The development achieved an overall density of 50 dwellings per hectare compared to an average of 25 dwellings per hectare for new housing at that time (TCPA 2003), 120 workspaces per hectare and over 4,000m^2 of green open space per hectare. This was an important part of the design philosophy because at these densities, around three million new homes could be provided on the existing stock of 28,800 hectares of derelict brownfield land while staying within a three-storey limit required by many planning authorities (Energy Saving Trust 2002).

4.8 Passive Design Principles

The site was laid out to maximise the benefits of passive design. Housing units were designed into blocks orientated west to east, so that one elevation would be facing due south to make use of solar gain and to minimise heating requirements, shown in Figure 4.2.

Figure 4.2: Typical block at BedZED from south east corner

The project architect, Bill Dunster, described the BedZED prototype:

> "The idea was to show how it was possible to combine workspace with housing while matching the residential densities of the surrounding dormitory suburb, and actually increasing overall standards of amenity – particularly gardens and public open space. This was achieved by matching south facing rows of single aspect residential terraces with north-facing live/work units or workspace. By placing gardens on the workspace roof, it was possible to give almost every home a garden or terrace, while achieving high levels of cool northlight within the office space."
>
> Dunster, Simmons & Gilbert (2008)

Figures 4.3 and 4.4 show the typical design and layout of a BedZED property and the location of sunspaces and gardens provided for all properties.

Figure 4.3: Section through typical block, ground and first floor maisonette

The section in Figure 4.3 runs north to south (left to right) with the south-facing sunspace for each property on the right hand side. The roof garden is allocated to the top storey flat and ground floor properties have a ground floor garden. Blocks have a three-storey glazed southern aspect with a fully glazed enclosed sunspace. The north facing aspect is two storeys with workspaces located on this side, retaining the southern aspect for dwelling space. Each dwelling above the ground floor has its own roof top garden on the north face. Houses have minimum glazing on the north face to prevent heat loss.

Ground floor plan **First floor plan**

Figure 4.4: Typical Ground Floor and First Floor plans

The floor plans in Figure 4.4 show that the outer wall of the building forms the inner wall of the sunspace with the sunspace located at the bottom of the plan and coloured orange. The sunspace design was predicated on windows being closed in winter and the inner doors between the dwelling and the sunspace opened to allow sunlight to penetrate into the house. The design assumed that in summer windows would be opened to ventilate excess heat out and inner doors kept closed to keep the dwelling cool. At least 50% of the external window area of the outer glazed screen was openable and internal balcony floors shade the internal glass wall. Dunster stated (2008) that the sunspace acts as a buffer, reducing heat losses from the building on the south elevation. Photovoltaics were installed within the sunspace glazing (roof and elevation windows) on the upper storeys, shown in Figure 4.5.

© Peabody

Figure 4.5: Sunspace at BedZED also showing photovoltaic cells in external glazing

Table 4.1 lists the principal components of the BedZED dwellings relevant to this study, recorded in the Health & Safety File (Peabody Trust 2002b).

Table 4.1: BedZED dwelling components

Element	Construction
Structure	Grade 43 steel beams and columns, re-used from former railway station
Roof	200mm pre-cast concrete hollow core units, insulated with 300mm Styrofoam and sedum roof
External Walls	Brick and block, some cedar cladding, insulated with 300mm Rockwool
Floors	200mm pre-cast concrete hollow core units 300mm expanded polystyrene
External Windows, doors and roof lights	Rationel timber windows, argon filled triple glazing on all elevations except south facing, double glazing on south facing
Photovoltaics	BP Solar PV laminated units
CHP	B9 wood gas CHP designed to produce 130 kW of electricity and 200kW heat

Source: Peabody Trust 2002b

Table 4.2 compares the minimum standards required by the 1995 Building Regulations (using the elemental method) with the standards adopted for the BedZED design.

Table 4.2: Comparison of BedZED Fabric U-values with 1995 Building Regulations elemental method

Element	1995 Regs W/m^2K	BedZED W/m^2K	BedZED material
Roof	0.25	0.10	300mm styrofoam
Exposed Walls	0.45	0.11	300mm Rockwool
Floors	0.45	0.10	300mm expanded polystyrene
External Windows, doors and roof lights	3.3	1.2	Argon filled triple glazing on all elevations except south facing, double glazing on south facing

Source: Energy Saving Trust (2002) Table 1

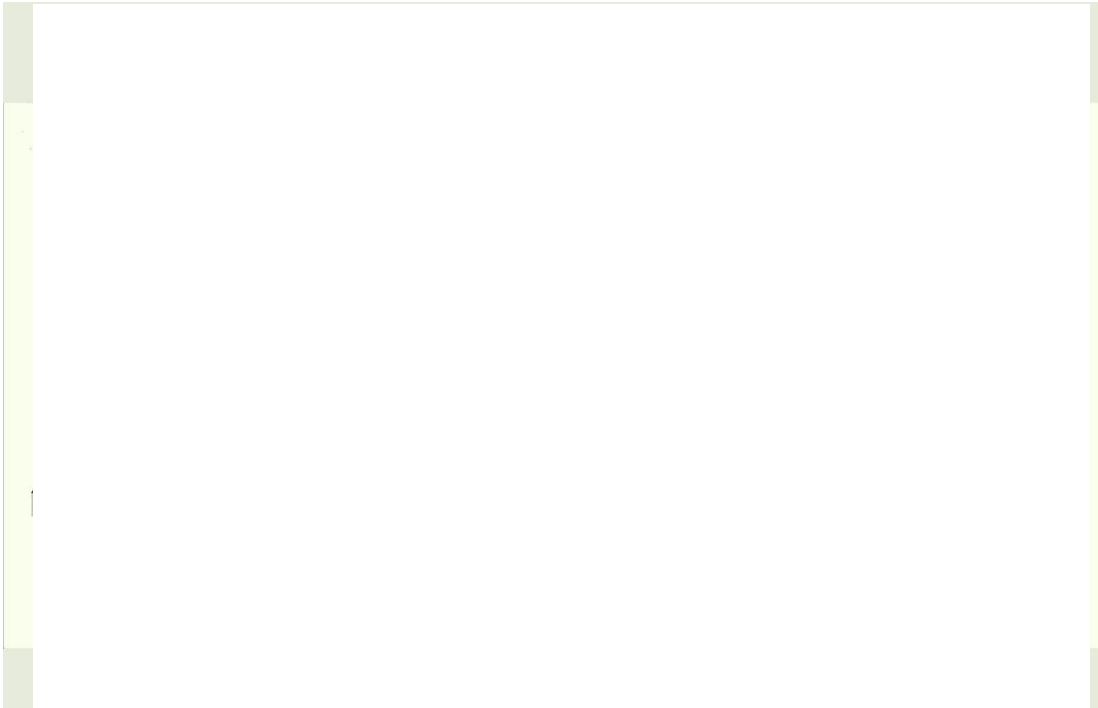
Buildings at BedZED were designed as heavy mass, highly insulated structures. Walls were constructed of 100mm blockwork with a fully insulated 300mm cavity and a 100mm brick external skin and some parts of the façade were clad in cedar. Floors and ceilings were constructed of 205mm concrete hollow core beams with a 30mm concrete screed on top. Soffits were un-plastered to expose the high thermal capacity of the concrete which enabled the walls and ceilings to trap heat in the winter and cool in the summer. Daytime warmth would be stored by the structure for slow release at night in the winter in the same way that bricks in electric storage heaters store heat for later release. The reverse applied in summer with night time cool stored for slow release through the daytime in the summer, levelling out peaks and troughs in the ambient temperature (Dunster et al 2008).

Figure 4.6 shows the designed and installed wall construction.

Figure 4.6: Section through typical BedZED external wall and installed wall section

4.9 Building Physics

The building physics principles applied to BedZED aimed to maximise the passive design principles of high mass construction and solar heat gains with minimal shading from adjoining buildings. The building envelope would be very air tight to minimise heat losses and buildings would be orientated so that dwellings were south facing with workspaces facing north, as illustrated in Figure 4.7.



© Arup

Figure 4.7: BedZED Building Physics

The principal benefit of this south-orientated, high mass, super-insulated construction was that dwellings could be designed without conventional heating systems or air conditioning. The designed heat loss was so low, Heat Loss Parameter of 0.86 W/m^2K in the original SAP calculation (Arup 1999b), that heat losses would be offset by incidental gains from occupants, cooking and hot water use, waste heat from appliances and solar gains from the south facing windows. For this to work effectively, the high mass, super-insulated construction needed to be air tight. Air tightness was designed at two air changes per hour at a differential pressure of 50 pascals (2 ach at 50

Pa) or 3m3/hr/m^2. By comparison, the current standard for Passivhaus is lower at 0.6 ach at 50 Pa (BRE 2015) and the current Building Regulations is higher at 10 m^3 (h.m^2) at 50 Pa, (DCLG 2014).

4.10 Zero Energy

The term "ZED" derived from Zero Energy Development and was driven by the desire for a net 'zero energy development'. The original scheme design documents defined this as a development that will produce at least as much energy as it consumes and the original intention was that only energy from renewable sources would be used to meet the energy needs of the development (Bioregional 1999). The BedZED zero energy concept aimed to have a holistic energy profile over the lifetime of the buildings, by minimising energy used in both the construction and buildings operations and offsetting the energy used by the production of energy from the buildings by renewable energy, the surplus of which would be transferred back to the national grid.

The BedZED zero energy ambition was not limited to buildings but also encompassed transport, the whole building life from the selection of the site and provision of workspaces to minimise commuting, construction, energy used by residents to run the buildings and travel and also provision of recycling facilities to minimise consumption of raw materials. The original definition of ZED fits closely with current definitions of Net Zero Energy Buildings discussed in Chapter 2 in terms of energy in use and connectivity to the national grid, but ZED goes further since it also includes all embodied energy and all energy used by occupants for working, leisure and travel. There are therefore some aspects of the Autonomous House in the BedZED concept. Only energy used within dwellings is examined in this thesis.

Arup (1999a) stated that an objective of BedZED building physics and resulting mechanical and electrical design was to match the building's energy demand to available renewable energy sources so that there would be no net fossil fuel carbon dioxide emissions. It is not clear from the original concept design whether this relates to renewable energy sources from the site only.

Arup noted that renewable energy sources were generally more expensive and more difficult to match to normal demand than fossil fuels because they are dependent on external events, such as the amount of and intensity of sunshine. A key requirement of the building physics design was therefore to substantially reduce the demand for energy. In turn, low levels of energy demand enabled more capital to be made available for each renewable unit of energy supplied. In this way, technology that was relatively expensive at the time, such as photovoltaics, would be more affordable because fewer units were needed. The low energy demand design also meant that capital saved by omitting plant such as heating and cooling systems could instead be used to pay for the enhanced building fabric.

4.11 BedZED Energy Strategy

The BedZED energy strategy comprised the use of passive design principles described above to minimise energy demand and energy supplied by a biomass-fuelled CHP unit and photovoltaic cells (PV). At the time that BedZED was designed, energy consumption in typical domestic houses was between 150 and 288 kWh per m^2 floor area per annum (kWh/m^2/annum) and typical dwellings built to the 1995 Building Regulations in force at the time would have a total energy consumption of circa 162.5 kWh/m^2/annum. The predicted total energy demand from BedZED dwellings was expected to be less than half of typical new housing, shown in Table 4.3.

Table 4.3: Dwelling Energy Use

	Total energy KWh/m^2/annum
Typical housing built to 1985 Building Regulations	230
Typical housing built to 1995 Building Regulations	163
BedZED housing	75

Source: Arup 1999a

Included within this model was a predicted 10% reduction in electrical demand from installing energy efficient, A-rated, electrical appliances and some reduction in water heating demand due to well insulated cylinders, low-flow shower heads and short hot water pipework lengths.

Table 4.4 gives the breakdown of a typical UK household fuel bill at the time of the BedZED scheme.

Table 4.4: Typical breakdown of fuel bill costs

	% of total cost
Space heating	46.4
Water heating	17.6
Lights & appliances	25.5
Cooking	2.8
Standing Charge	7.7

Source: Bakewell 1999

At BedZED the plan to eliminate the need for space heating was expected to save almost half of a typical fuel bill.

Table 4.5 shows a breakdown of forecast energy demand for BedZED dwellings. The 500 kWh for space heating was added as a contingency to account for times when the properties are not fully occupied and to allow for dwellings being occupied by babies or the elderly.

Table 4.5: Comparison of energy consumption at BedZED and typical dwellings

	Typical 1985 kWh pa	**Typical 1995 kWh pa**	**ZED 1999 kWh pa**
Space heating	14,483	7,926	500
Hot water	5,350	4,548	3,650
Pump & fan		175	20
Cooking	1,067	656	590
Lighting & appliances	2,445	3,000	2,700
Total	**23,345**	**16,305**	**7,460**

Source: Bioregional (1999)

Arup estimated that ZED houses would use less energy for water heating than a typical 1995 house owing to well insulated cylinders, low flow shower heads and short hot water pipework lengths. Energy demand for pumps and fans was also reduced owing to passive wind driven ventilation with their passive heat recovery units and the absence of heating pumps. Cooking demands were estimated to be lower than for a typical 1995 house due to installation of induction hobs and occupant awareness of energy saving techniques.

The Energy Saving Trust summarised the four strands of the BedZED zero-carbon energy strategy as follows. Firstly the energy efficient design of buildings comprised reducing heat losses and making use of solar gain to the point where it is feasible to eliminate conventional central heating systems altogether. Secondly, energy demand was reduced by energy efficient and hot-water-saving appliances which set the design capacity for the CHP system. Thirdly, the use of renewable energy sources in the form of a biomass-fuelled CHP and photovoltaic power cells integrated into the sunspace roofs meant that BedZED could become a net exporter of renewable energy. Finally the green transport plan minimised residents' use of fossil-fuel cars and the need to commute to work (Energy Saving Trust 2002).

4.12 BedZED SAP Calculation

Prior to detailed design, Arup completed thermal modelling for BedZED and also produced a generic SAP calculation for a hypothetical dwelling. The SAP calculation, but not the thermal modelling, was made available for this study and provides useful insights into early design assumptions. Arup's SAP calculation was completed in 1999 using SAP version 9.53. It assumed a two-storey, south facing 100m^2 well-insulated property with 23m^2 of glazing. The SAP calculation resulted in a SAP rating of 150, reported as 100 since this was the maximum possible score with the SAP tool, illustrating one of the limitations of the early versions of the SAP procedure for low energy developments.

The underpinning assumptions for the BedZED SAP calculation appear to be that the high level of insulation coupled with large expanse of south facing glazing would result in a relatively low base temperature of 9.7°C compared to a traditional base temperature of 15.5°C (CIBSE 2006b) thus minimising the requirement for space heating. The calculation assumes significant solar gains (864W) from the large expanse of glazing. As part of this study, a typical two storey maisonette elevation drawing was measured and the area of glazing found to be broadly in line with the SAP assumption: 26m^2 actual compared to the SAP assumption of 23m^2.

Glazing on the top floors of dwellings also had PV installed integral to the glazed units. This will have reduced some of the solar gain (see Figure 4.5) although the solar will have been converted to renewable energy.

The SAP calculation assumed that the heating system efficiency would be 100%. It is assumed that this is because the designers had "designed out" the need for traditional space heating in the dwellings in the form of individual central heating systems. However the provision of back up space heating via the hot water storage cylinder and finned tube heating element, only expected to be required in unoccupied properties with no incidental gains, meant that the domestic hot water supply was effectively part of the space heating strategy. Despite minimising pipe runs and locating them within buildings where possible, it is assumed that in practice there would have been some heat loss on pipe runs between the CHP/central boilers and dwellings. It was not possible to measure this specifically, but Chapter 7 reviews the designed and actual energy usage at BedZED and also the EPCs issued for BedZED properties are discussed together with the challenges of using the RdSAP calculation for properties like BedZED.

4.13 Designed Energy Usage

BedZED domestic electrical requirements were based on typical demand from house-types and assumed that occupants used energy efficient appliances. The design team recognised that that this was a best case scenario. They noted that one "worst case" family would cancel out about four “best case” families, with the result that the site- wide mean was likely to be more than their “typical” consumption figures used in the table below. The design team assumed that all options for residents in the households were equally likely, i.e. there would be roughly equal numbers of flats with single young people, single old people, young couples and elderly couples. The estimates of electrical energy requirements are shown in Table 4.6.

Table 4.6: Predicted annual electrical energy requirements for each house type at BedZED

House type	Worst case scenario kWh/year	Typical scenario kWh/year	Best case scenario kWh/year	Suggested figure for CHP sizing* kWh/year
1 bed flat	4,343	1,723	989	2,247
2 bed flat	4,867	2,028	1,189	2,596
3 bed maisonette	5,863	2,657	1,663	3,298
3/4 bed house	6,137	2,882	2,449	3,533

*ratio of 1 property from worst case to four properties from typical category/5

Source: Bioregional (1999) from Total Energy Strategy p56, Arup calculations

The scenarios in Table 4.6 are in line with the design estimates of 3,290 kWh/annum for electricity for a typical property.

Domestic heat requirements were based on estimated number of occupants because heat would primarily be taken in the form of hot water. Assumptions were made about the predicted number of people in each dwelling size, together with the maximum number. The 300 litre hot water cylinders with a 3kW immersion heater installed in all properties would store hot water produced by the CHP for the heavy morning and evening hot water demands (Bioregional 1999). Estimated heat requirements are shown in Table 4.7.

Table 4.7: Predicted annual heat requirements by number of occupants at BedZED

Number occupants in dwelling	Hot water use per day (litres)	Equivalent heat demand over 24 hours (W)	Annual equivalent heat demand (kWh)
1 person	130	348	3,045
2 people	141	377	3,302
3 people	165	441	3,864
4 people	187	500	4,380

Source: Bioregional (1999) Total Energy Strategy p57, Arup calculations

The heat requirement is circa 4,170 kWh/annum for a typical property (total energy estimate per dwelling 7,460 less 3,290 for electricity above).

A summary of the design electricity and heat requirements for the different property types at BedZED are shown in Table 4.8.

Table 4.8: Design Energy Requirement for BedZED property types

	Hot water and heating		Electricity	Total energy
	litres hot water/day	kWh/annum	kWh/annum	kWh/annum
1 person flat	130	3,045	2,247	5,292
2 person flat	141	3,302	2,596	5,898
3 person maisonette	165	3,864	3,298	7,162
4 person house	187	4,380	3,533	7,913
Typical dwelling				7,460

Source: Bioregional (1999) Total Energy Strategy p58, Arup calculations

The typical energy requirement per dwelling of 7,460 kWh/annum was also described in the concept design as 75 kWh/m^2/annum.

Domestic energy requirements were then added to the wider site energy requirements for street lights, pumps and heat and power for the communal services including the club house and the healthy living centre (water recycling plant). The full calculation is in Appendix 2.

4.14 Whole Life Energy Use

The BedZED energy strategy was based on fully exploiting the use of low-technology building fabric form and materials and avoiding heavy dependence on sophisticated electrical and mechanical systems in individual buildings which would require maintenance and cyclical renewals. As far as practical, capital would be invested into long life passive building fabric components which are generally difficult and costly to upgrade during future refurbishment. This aligns with the later findings from Summerfield, Pathan, Lowe et al (2010b) that the installation of energy efficiency measures should be maximised in the construction phase as they are unlikely to be retro-fitted later. Over the long design life of the building this strategy was intended to result in the lowest 'cradle to grave' embodied and consumed energy needs. Figure 4.8 shows the sourcing strategy for construction materials for BedZED. The aim was to source from a 25 mile radius from the site where possible to minimise transportation energy and recycled materials were actively sourced by the design team.

Figure 4.8: Sourcing materials for BedZED

Embodied energy of building components used is not analysed in this study but given the relevance to the energy strategy, would be worthy of a future study to assess the impact of reduced transportation of materials on the overall energy footprint of BedZED and the actual component performance in use.

4.15 Mechanical and Electrical Systems

The high level mechanical and electrical design for BedZED is summarised in Figure 4.9.

Figure 4.9: Schematic of Mechanical and Electrical Systems at BedZED

Figure 4.9 shows that the primary source of heat and electricity was from the CHP unit. This was designed to be fuelled from urban tree waste, chipped, dried and fed into the CHP via a gasifier. The long term plan for the biomass fuel was to grow short rotation willow coppice and space was earmarked for this purpose at the BedZED site, item 19 in Figure 4.10.

Figure 4.10: Future eco-park at BedZED providing biomass for fuel

4.16 CHP Design

The original design concept was that the CHP would be biomass fuelled by sustainable sources of timber grown on site with zero CO_2 emissions that would provide hot water and power to all properties in the development as well as power for the site infrastructure such as street lighting and the living machine which recycled waste water for re-use. Until the short-rotation willow crop was established at the BedZED site, tree waste was initially sourced as the biomass fuel for the CHP from the London Borough of Croydon. The CHP was designed to supply hot water for which daily total demand is relatively constant throughout the year. But because demand for hot water fluctuates during the day, heat storage was provided by the hot water cylinders in each property so that the CHP could continuously trickle-charge them. The site's mixed use of dwellings and offices would also serve to smooth out demand fluctuations across the day with an export/import connection to the National Grid allowing the constant CHP electrical output to be matched to demand changes.

BedZED's CHP unit would generate electricity for lighting and appliance use within dwellings and also distribute hot water around the site via a district heating system of insulated pipes. A schematic diagram of the system is shown in Figure 4.11.

© Arup

Figure 4.11: Schematic of Combined Heat and Power plant at BedZED

The CHP system was designed with an import/export meter to the grid, to enable excess electricity to be sold back to the National Grid and imported as required.

By storing hot water in each dwelling the additional capital cost of installing boiler plant to match peak loads was avoided. The CHP heat distribution pipework to each property was sized to minimise the amount of energy required for pumping, with cylinder demand controlled by simple direct-acting thermostatic two-port valves. Cylinder immersion heaters provided a hot water standby facility and emergency back-up in case of failure of the CHP plant. (Arup 1999a)

The design intention was that energy use would also be minimised by encouraging occupants to monitor their reduced energy usage once the dwellings were occupied. At the time, this was often not practical for new developments because energy supply authorities wanted external access to the meters. In BedZED, energy meters were prominently located in kitchens in order to make occupants aware of their own consumption.

4.17 Sizing the CHP plant

Arup used the electrical and heat energy estimates, summarised in Table 4.8, to size the Combined Heat and Power (CHP) system, using a safety margin of circa 20% higher than peak capacity required (Twinn 2014).

For site electricity requirements, the CHP plant was sized so that over the year it produced enough electricity to match the energy consumed. The aim was not to cover for peaks in demand. During peak periods, electricity would be imported from the grid (with the design team intending to source "green electricity" for these periods) and an equivalent amount exported to the grid at off peak times (Bioregional 1999).

The heat from the CHP would be used primarily to heat domestic hot water and for some supplementary heating via the towel rails and by heating air via an integral finned tube heater in the airing cupboards. The 300 litre hot water cylinders with 3kW immersion heater installed in all properties would store hot water produced by the CHP for the heavy morning and evening hot water demands. The heat required for hot water supply was not expected to vary greatly over the year, but any supplementary heating requirement would be greatest in winter. Accordingly the design team based their estimates of heat requirements on a winter day.

The additional heating requirement was more difficult to quantify. In summer amounts were expected to be small with some heat required from time to time such as on cooler evenings or to dry clothes. The design team's thermal modelling showed that if the high insulation and low infiltration targets were achieved together with a 40% heat recovery on the ventilation system, no additional space heating would be required for a typical winter, providing dwellings were occupied. A key design consideration was avoiding the room temperature falling during un-occupied periods since there was no conventional heating system to bring temperatures back up to normal when occupants returned. The design team's analysis showed that there was little energy benefit to be gained in such a super-insulated high thermal mass home in allowing room temperatures to drift downwards during intermittent occupancy. Another consideration was maintaining room temperatures in adjacent homes, given the additional heat lost through party walls, should unoccupied adjacent dwellings be allowed to become colder. If the dwellings were unoccupied, around 500W (12W/m^2) incidental heat gains normally provided by the occupants and their activities (e.g. TV, cooking, lights, etc.) would be missing and hence a backup would be required to meet heat losses. The heat gains required in unoccupied houses would be partially offset by the fact that when the house is unoccupied there is no hot water demand, saving around 400W (~8.2W/m^2). They estimated the output from the finned tube heater to be around 50 to 100W. To cover the additional heating in sparsely occupied or unoccupied dwellings, they allowed extra gains of 3.5 W/m^2 in all dwellings.

The design team's figures gave a daily site wide demand for additional heating on a winter day as around 3.2 GJ (890 kWh), and including the hot water a total daily site heat demand of 7.1 GJ (1960 kWh). The calculations underpinning these requirements can be found at Appendix 2 and a summary is provided at Table 4.9.

Table 4.9: Sizing the BedZED CHP system

	Hot Water kWh/day	Extra Heating kWh/day	Electricity kWh/day
Dwellings	825.2	443.3	722.5
Offices (live work units)	54.7	244.7	188.6
Other (clubhouse, healthy living etc.)	191.9	203.8	455.8
Site infrastructure (streetlights, pumps etc.)			250.8
Total Heat		**1,963.6**	
Total Electricity			**1,617.7**
Over CHP hours (17/day)		115.5	95.1
Losses (heat 20%, elec 5%)		138.6	99.8
Design margin (10%)		*152.4	*109.8
CHP heat required kW/day		**153**	
CHP elec required kW/day			**110**

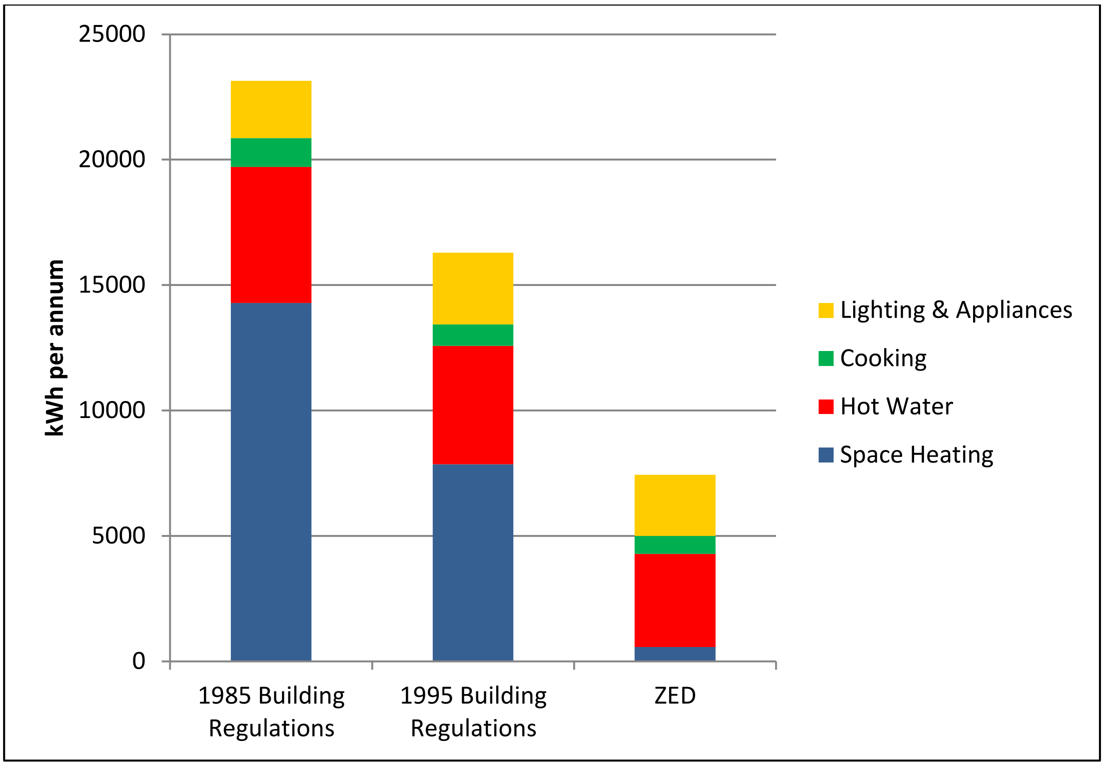
*rounding

source: Appendix 2 CHP Sizing Calculation *from* Bioregional (1999) Total Energy Strategy p59, Arup calculations

The CHP performance specification required a flow temperature of 80ºC and return temperature of 60ºC. Modern district heating schemes with pre-insulated pipework would assume 5% heat loss from pipework of their delivered peak demand whereas at BedZED the losses were assumed to be circa 20% because of the very small amounts of heat being delivered to the dwellings compared to a conventional district heating scheme. Consequently where possible the pipelines were routed inside the buildings. Any pipeline heat losses inside buildings would be treated as incidental gains since they would help to keep internal spaces warm.

The CHP performance requirements were tendered and detailed design undertaken by the CHP supplier.

Figure 4.12 shows how the design team's estimated energy use in a typical BedZED household compared to typical UK new houses at the time (Bioregional 1999).



Source: Bioregional 1999, pp24-25, after Shorrock 1999, DETR 1998 and Knight 1999 (NB, excludes minimal energy for pumps and fans)

Figure 4.12: Comparative total household energy consumption in new houses

Figure 4.12 shows that the greatest reduction in energy use at BedZED was to be in the space heating requirement.

4.18 Daylighting Design

Daylighting design was important for two reasons. Firstly, good daylighting provides a more pleasant living and working environment and secondly it reduces the amount of energy used for artificial lighting. A daylight factor (ratio of internal light level to external light level) of more than 2% means that artificial lighting is unlikely to be needed for most office type tasks during the day. Orientation, room uses and comfort thresholds were important factors for the window design and daylighting.

Window design and daylighting are key factors that affect occupants' enjoyment of their home. The trend of Building Regulations over preceding years had been increased energy efficiency of building envelopes, higher levels of insulation and reduced heat loss. One consequence of this was that new houses were being built with smaller windows and reduced overall window area. Bill Dunster, the BedZED architect, was keen to demonstrate that there were alternative design approaches to small windows which would perform well in energy efficiency terms and provide good daylighting levels. The completed dwelling is illustrated in Figure 4.13.

Figure 4.13: Interior view of BedZED

4.19 Ventilation Design

The BedZED building physics model depended upon good control of ventilation to minimise heat loss and eliminate the need for a conventional heating system. The building envelope was intended to achieve a very high level of air-tightness of 2 ach at 50 Pa test pressure.

The BedZED ventilation design was based on natural ventilation to minimise capital costs and use and maintenance of electrically operated fans.

Occupant-controlled opening windows of an area equal to 5% of the floor area were provided for purge ventilation and cooling in all habitable rooms. For night-time cooling secure locking windows allowed them to be held open with a minimum clear 50mm opening. At the time of design, the typical approach for the supply of fresh air to dwellings was to fit trickle ventilators to windows. However in a low energy building without radiators, trickle ventilators could have been a significant energy drain, particularly on a wintery cold and windy day. BedZED sought to provide pre-heated fresh air by using passive stack ventilation with heat recovery. This took advantage of the sealed building envelope to create a balanced air supply and exhaust using a combination of internal heat buoyancy and wind pressure through a vertical pipe inside a duct flat plate heat exchanger fitted with a roof wind cowl. The passive stack ventilators were provided for exhausting local moisture/pollutants. The ventilation cowls, shown in Figure 4.14, were sited on the top of each block and designed to provide fresh air to each dwelling and heat recovery on the stale air being discharged. Supply air would enter living rooms and bedrooms and the exhaust air extracted from the kitchens, bathrooms and toilets. One side draws out air from the higher outlet in the rooms and the other pushes air in to the lower inlet, by taking advantage of naturally occurring pressure changes. By-pass flaps stop high winds from over ventilating rooms.

Figure 4.14: Roof wind cowls at BedZED

Key to the control of energy losses through ventilation in ZED houses is airtight construction which means all incoming and outgoing air can be controlled and passed through the flat plate heat exchanger allowing up to 70% heat transfer from the stale exhaust air to the incoming fresh air. The wind cowl is a natural ventilation system that offers passive ventilation with heat recovery without using electrically powered fan motors and was designed on passive stack ventilation principles for conditions with little or no wind (Dunster 2008).

4.20 Heating Design

The heating strategy design set out in the engineers' *Beddington ZED Concept Stage Report* aimed to achieve "almost constant room temperatures above 20ºC". The heating strategy was based on the principle of avoiding the need for a mechanical system by designing the building fabric so that the natural heat gains would be adequate to cope with the heat losses using heat gains from people, lighting and appliances, cooking and domestic hot water, solar heat gain, super-insulation, very high envelope air-tightness, ventilation heat recovery and high thermal inertia room surfaces to store excess heat until it is needed (Arup 1999a).

While it can be assumed from the source documents that “constant room temperatures above 20ºC” means that the indoor temperatures will not fall below 20ºC during the heating season, a specific upper limit for summer temperatures was not set. Control of excess temperature would be provided by manually opening windows.

The CHP was designed to deliver constant hot water to the 300 litre domestic hot water cylinders, keeping them ‘charged up’. Cylinders were installed with electric immersion heaters for emergency back-up and sited in centrally-located cupboards within each dwelling with an integral finned tube heater so that they could double up as a radiator in cold spells and when properties were unoccupied, shown in Figure 4.15. The primary heat main circuit passed through the towel radiator after circulating through the hot water cylinder primary coil and was fitted with a manual valve and bypass to enable the occupant to switch off during high summer.

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Figure 4.15: Finned return to heated towel rail from hot water cylinder in airing cupboard and fan panel

BedZED is different to other dwellings with traditional central heating systems and which have thermostatic controls that are visible in the living space and directly adjusted by the occupants. In such developments, occupants might choose to set thermostatic controls at a higher internal temperature rather than reducing the amount of energy used for heating (take-back, discussed in Chapter 2).

To increase the internal temperature at BedZED, occupants would need to adjust the thermostat on the hot water storage cylinder and/or the heated towel rail since the waste heat from the cylinder contributes to background warmth of the property. The Residents' Handbook states that the immersion heater will come on automatically if the internal temperature of the property falls below a set level, generally 18°C (for instance if the dwelling is empty) to avoid the property draining heat from its neighbours (Peabody Trust 2002). Occupants could therefore increase the internal temperature of their home by switching on the immersion heater and/or setting the temperature of the hot water cylinder higher (initial setting 50ºC) in order to increase the waste heat from the hot water cylinder. The BedZED Residents' Manual also describes how occupants can increase internal temperature by increasing the thermostat on the finned tube heater above the standard setting of 18°C. However it also states that this is not recommended since it will result in a reduction in hot water temperatures.

In summary, it is clear that the operation and control of the background space heating and hot water systems at BedZED are quite different to the typical whole heating systems and thermostatic controls that most people in the UK are now used to (see section 2.4.1: 91% of households had whole house heating by 2011).

Traditional gas-fired central heating systems require statutory inspection and maintenance by landlords so for Peabody, the landlord, eliminating these was an additional benefit. It would save time and money for both the landlord but also the tenants and owner-occupiers. Providing homes that were cheaper to heat would also help tackle fuel poverty since social housing tenants would have lower fuel bills.

In conclusion, if BedZED were successful in reducing energy consumption, the potential for the Government's carbon reduction policy objectives would be considerable.

4.21 Other BedZED studies

4.21.1 Resident Satisfaction Survey

Peabody Trust and Samantha Elvy carried out a general resident satisfaction survey for the BedZED development and released their findings in May 2004 (Ellis & Elvy, 2004). The survey sought residents' views on the whole development including their overall view of the design of the estate and their homes, the location and neighbourhood, refuse and parking facilities, estate lighting, security, internal design and layout, fixtures and fittings, sunspace and gardens, internal services, the cost and value, defects and repairs, the information provided to residents, communal facilities and activities, the sense of community, transport and travel patterns.

Like the post-occupancy survey for this study, the Peabody Trust survey was undertaken when there were operating problems with the CHP plant. Regarding internal services (electricity, water, heating and hot water and using renewable energy), the Peabody Trust survey reported some gaps in residents' awareness about how to operate their internal services. Half the sample said they had noticed a reduction in their fuel bills since moving to BedZED.

In the section on sunspace design, the feedback from residents was that it was a particularly popular design feature with many residents saying that it was one of the most enjoyable aspects of their home. Two residents (from a sample of 38) said that it got too hot in the summer. Two participants cited the lack of control over the bathroom radiator as a problem and three participants quoted the overheating in the summer as a problem.

4.21.2 Renewable Energy

The monitoring for this thesis did not include renewable energy generated and therefore other sources are discussed here. The design specification proposed to install a total of 777m^2 of photovoltaic (PV) panels comprising 1,138 laminates with a peak power of 109 kW on rooftops and in south-facing second floor windows (Arup 2000). The original intention had been that they would provide the power for 40 electric vehicles which would be operated as a car club. However, the uptake of electric vehicles was much lower than planned and therefore the electricity produced by the photovoltaics was used by the site as a whole with surplus supplied back to the grid.

Hodge and Haltrecht (2009) quoted an estimate from BP Solar that the array would provide 88,000 kWh of electricity per annum. In his 2005 thesis, Corbey estimated that the energy produced by the PV in 2004 was 31,200 kWh. Corbey made his estimate by reading the PV display board at BedZED where the total energy produced at the time of his writing was 78MWh over a three year period. He omitted the first six months because the panels were not operational to arrive at his annual estimate of 31,200 kWh (Corbey 2005). The results from the Corbey study and the Hodge and Haltrecht study are compared with the original design intent and presented at Table 4.10.

Table 4.10: Annual Energy from PV at BedZED

kWh	Source
98,000	Design, Arup 2000
88,000	Hodge & Haltrect 2009
31,200	Corbey 2005

Using Corbey's estimates, actual PV produced was approximately one third of that designed. The renewable energy produced by the PVs was not used for an electrical car pool but was used by the dwellings.

Corbey estimated how much non-renewable energy was used by the site in 2004 and this is summarised in Table 4.11.

Table 4.11: Annual renewable and non-renewable energy use at BedZED

		MWh
Electricity	Total estimated site demand	297
	- PV	31.2
	- CHP generated electricity	46.2
	- Electricity imported from grid	219.6
Gas	For hot water, based on 8 month monitoring period	535.5

Source : Corbey 2005

This shows a total annual usage of 832.5 MWh with 31.2 MWh (3.7%) of total energy being derived from renewables.

4.22 Before BedZED

This section of the chapter describes dwellings occupied by BedZED residents prior to moving into the BedZED development, including a summary of NHER surveys undertaken on these properties. This prepares for the longitudinal comparison of the BedZED occupants before and after moving into BedZED in Chapter 12.

A unique feature of this study is that it tracks a group of occupants (referred to as participants) from their former homes before they moved to the BedZED case study. While the BedZED dwellings are different sizes and types, they are a consistent design. This is not the case for participants' former homes. The reason for starting the study while participants were living in their former homes was to set a baseline that would enable analysis of whether there were any behavioural factors that changed once they moved into their BedZED homes. For example, the number of electrical appliances they used; the type of clothing they wore indoors in the winter; or whether they experienced health problems that could be related to the dwelling.

A total of 24 BedZED residents took part in the main monitoring study which is termed Phase 2. Of that sample, 14 took part in the pre-BedZED occupation study, termed Phase 1. As far as practical, the pre-BedZED phase comprised NHER surveys of the dwellings together with environmental monitoring for a period of approximately four to six weeks in the period February to October 2002. Participants were also surveyed about how they used the dwellings and how satisfied they were with the environmental performance of the dwelling.

The NHER surveys illustrated the variety of dwellings that the participants lived in prior to moving to BedZED. Three participants lived in properties built around or before 1900, six lived in properties built since 1980 and the other three lived in properties built between 1930 and 1976. There was also a variety of construction styles, some solid walled properties, mixture of pitched and flat roofs, three properties were wholly single glazed and three properties a mixture of single and double glazed. Heating systems were also different. Three properties had gas-fired wet central heating systems, one had a gas warm air system, five properties had off-peak electrical storage heaters and three properties used individual room heaters for heating. Table 4.12 summarises the energy rating results for properties occupied prior to BedZED. SAP results ranged from 29 up to 68 compared to the design SAP of 100 for BedZED.

Table 4.12: Summary of energy rating results for pre-BedZED properties

Property	**SAP**	**NHER**
B	50	6.5
D	29	3.5
F	55	6.7
J	40	5.6
N	35	3.8
P	61	7
Q	58	7.2
R	51	5.8
S	66	8
V	29	4
X	61	8.4
AB	68	8.4

Marketing literature promoted BedZED as “the UK’s first truly green village” (Peabody Trust 2000). However, although there were a number of surveys to assess occupants’ satisfaction with various aspects of the BedZED scheme, none of the surveys reviewed to date, including the two surveys undertaken for this study asked occupants why they moved to BedZED. Therefore it is not possible to assess whether the energy performance of the BedZED homes was a significant factor in their decision.

4.23 Case Study Conclusions

A unique feature of the BedZED development was that it brought together so many technologies and techniques in one development. While the individual design principles and technologies used in BedZED had previously been tried out separately, they had not been built altogether in a single development. BedZED aimed to harness the comprehensive benefits of all these technologies.

Research has shown that human behaviour can change if the energy efficiency of people’s homes is improved, for example, by higher internal temperatures rather than reduced energy bills. Tracking the study’s participants from their pre-BedZED homes to BedZED could provide new insights into this body of research. However, there were some specific factors which might affect these results. For example, the scheme attracted a very high profile at the time of its construction and occupation (and during the monitoring phase of this study). This might potentially distort occupants’ behaviour by, for example, making occupants far more conscious about their energy use than a more typical development.

The BedZED building and systems design was quite different from standard dwellings. This could present a challenge if, for example, occupants wanted to easily increase internal temperatures. Since there were no traditional wall mounted thermostatic controls, occupants would need to increase the thermostat on the hot water storage tank and/or plug in stand-alone electrical heaters to provide additional space heating.

Assumptions were made about how BedZED buildings would perform in use. This case study measures actual energy used and internal temperatures achieved in the surveyed dwellings. Additionally, it analyses what participants thought about the energy performance of their homes.

The next chapter discusses the literature on summer overheating.

Chapter 5 Summer Overheating

5.1 Introduction

Since the energy supply crisis of the 1970s, the focus of building design and regulations with regards internal temperatures has been to minimise heat loss to reduce fuel poverty and carbon emissions from domestic energy used. Most of the literature relating to domestic systems, environmental impact and user comfort has focused on heating, insulation and the cost of providing heating and hot water. This chapter discusses the emergence of overheating within dwellings. It discusses the literature relating to the growing importance of summer temperatures and overheating for building designers and occupants. It summarises the trend towards higher summer temperatures and discusses definitions of hot spells. The chapter explains the importance of summer temperatures and hot spells with regards occupant comfort and the impact on health.

Overheating is important for two reasons. Firstly internal temperatures impact on human comfort in dwellings and building design needs to reflect changing external conditions in order to maintain comfort levels. Secondly, if internal temperatures increase beyond acceptable comfort levels during hot spells, occupants are likely to install electrical cooling systems, such as air conditioning. This will increase electricity use and contribute to increased carbon emissions. Summerfield, Lowe and Oreszczyn (2010a) predicted that domestic fuel consumption will increase owing to a demand for cooling when average external summer temperatures rise above 18°C.

5.2 Weather Trends

In the last decade, a growing body of research has focused on summer temperatures. In the UK, the Central England temperature has increased by about 1°C since the 1970s with 2006 being the warmest on record. Under the Intergovernmental Panel on Climate Change's medium emissions scenario, the UK is projected to warm even further with mean daily maximum temperatures in summer increasing by up to 5.4°C in Southern Britain and

2.5°C in Northern Britain by the 2080s. The warmest day of the summer is projected to increase in the range of 2.4°C - 4.8°C by the 2080s depending on location (Eames, Kershaw and Coley 2011).

The theory of Urban Heat Islands is relevant to BedZED. This theory states that urban settings absorb larger amounts of solar radiation during the day than rural settings and cool less at night. The additional heat emissions from the urban population are also a source of heat (Mavrogianni, Davies, Batty et al 2011).

5.3 Definition of Hot Spells

Although there is no generally agreed definition of a heatwave, Hajat et al defined a heatwave as a three day rolling average above the 97th percentile value of 21.5°C (Hajat, Kovats, Atkinson et al 2002) based on their analysis of 21 years of data between 1976 and 1996. Using this definition, Wright, Young & Natarajan (2005) concluded that the heatwave experienced in the summer of 2003 ran from the 3rd to the 13th August. For the purposes of their study, Wright et al interpreted the heatwave period as the continuous set of days when the daily average temperature was above 20°C. Monitoring data were collected throughout this entire period for the BedZED Phase 2 sample.

5.4 Summer Comfort

Internal temperatures are an important indicator of occupant comfort. CIBSE Environmental Design Guidance recommends thresholds for general summer indoor comfort temperatures for non-air conditioned dwellings in warm summer conditions. Summer operative temperatures for non-air-conditioned dwellings are deemed to be 25°C and 23°C for living rooms and bedrooms with summer peak and overheating deemed to occur at 26°C and 28°C respectively. CIBSE define operative temperature as a combined single value for air temperature and mean radiant temperature. The guidance states that overheating occurs when more than 1% of the annual occupied hours have internal temperatures of more than 28°C. When bedrooms achieve temperatures over 24°C, quality of sleep may be compromised and 26°C should not be exceeded unless ceiling fans are installed (CIBSE 2006).

In the BedZED project documentation reviewed, there is no specific reference to a summer design temperature. On the subject of summer temperatures, the concept design stated that passive cooling using thermal inertia would be used to avoid mechanical cooling. It also referred to building massing that minimises over-shading, south facing glazed sunspaces and no external shading to block the beneficial solar heating effect (Arup 1999a).

In this BedZED study, temperatures were recorded as mean average daily temperatures rather than occupied hours (which would take account of occupant interventions such as opening windows). Because no specific design temperature for the summer months was set for the project, the CIBSE benchmark of 26°C for bedrooms and 28°C for living rooms has been adopted in the analysis. Occupancy data were not collected. Another recent study did collect occupancy data by installing occupancy sensors within dwellings. While there were issues with this method, learning from that experience and adopting the approach in future studies would provide a much richer source of data for the assessment of overheating (Love 2014).

5.5 Impact of Hot Spells on Health

The impact of dwellings that are too cold on occupants' health is well documented. The comprehensive document review by Thomson, Thomas, Sellstrom et al (2009) found that housing improvements, particularly warmth improvements, led to health improvements for occupants with little evidence of detrimental impacts. The significance of overheating was discussed in Hajat et al's 2002 study. They took mortality and climate data over the 20-year period from January 1976 to December 1996 for Greater London and found that heat-related deaths begin to increase when average daily temperature rises above the relatively low average external temperature of 19°C with a linear relationship between deaths and temperature above 19°C.

The study found a 3.34% increase in deaths for every 1°C increase in average temperature above this value. The duration of exposure to high temperatures was also found to be an important factor in increased mortality.

5.6 Building Design for Summer Temperatures

Orme, Palmer & Irving (2003) highlighted that increased summer overheating could lead to an increase in the use of domestic air conditioning. They stated that the key physical house characteristics shown to influence overheating are thermal mass, solar gain, ventilation and incidental gains and that natural night-time cooling of the thermal mass, for example, window opening, is the most effective way to prevent overheating. Wright et al found that during hot spells rooms in general stayed considerably warmer than outdoors at night and suggested that better use could be made of night ventilation. They also called into question the wisdom of heavyweight construction for bedrooms (Wright et al 2005).

An interesting perspective on heavyweight construction and overheating is offered by Mavrogianni, Wilkinson, Davies et al’s 2012 study. This paper comprised dynamic thermal simulations of 3,456 combinations of dwelling types to establish the likelihood of high indoor summer temperatures. They found that retrofitting roof/loft insulation and windows would reduce average daytime living room temperatures but retrofitting wall and, to a lesser extent, floor insulation would increase internal temperatures. They concluded that internal solid wall insulation may potentially increase overheating during a warm spell if no night time ventilation is provided.

Conversely, Gaze, Swainson, Hodgson et al (2008) found the potential for overheating could be minimised in low-energy buildings by a combination of good ventilation, shading/solar design and appropriately located thermal mass. They downplayed the significance of thermal mass compared to air-tightness and thermal insulation. They explained that the inclusion of thermal mass, and controlled night ventilation to remove heat build-up within the building fabric offers the potential to minimise the variation of internal temperatures throughout the day and night. If night time ventilation is not undertaken the thermal mass of the building fabric would become increasingly hot over an extended period of hot weather and take a significant period of time to cool after a change to cooler conditions. This could exacerbate the perception of overheating and lack of ability to control temperatures, potentially encouraging mechanical cooling options.

Beizaee, Lomas & Firth (2013) published one of the first national scale studies of summertime temperatures in English dwellings. They recorded temperatures in living rooms and bedrooms in 207 homes during the relatively cool summer of 2007 and found that older homes built before 1919 and detached homes tended to be cooler than other property types. They found that living rooms in flats were significantly warmer than other dwelling types and top floor flats particularly susceptible to overheating. They attributed this to modern housing being better insulated and to flats having a reduced external wall area to volume compared to detached houses and therefore cooling down more slowly. They surmised that their results could be a result of external solid walls having a higher U-value than cavity walls. They stated that higher U-values of older properties enable excess internal heat to be lost more readily while the thermal mass causes internal air to respond slowly to external temperature variations and internal heat gains.

In summary, the literature is not wholly clear about the potential for high mass, low U-value construction to overheat compared to other designs. However, in the literature reviewed there is a consistent theme of the importance of ventilation and particularly night-time ventilation to control overheating.

5.7 Air Conditioning

Peacock et al assessed whether predictions of higher summer temperatures would require UK dwellings to plan for a cooling season with associated mechanical cooling (Peacock, Jenkins & Kane 2010). They quoted evidence from the United States which suggests that the market for domestic air conditioning is likely to be determined by overall cooling degree days and not extreme events such as the 2003 hot spell. They used a simulation to calculate when external summer temperatures in the UK would produce demand for domestic air conditioning. This is a function of both building design and also how used people are to air conditioned environments outside the home (work, leisure, transport) and therefore how normal air conditioning is. They proposed that the two principal criteria for overheating are the proportion of internal temperature readings that exceed 28°C (which accords with the assumption made in this study for summer design temperatures for living rooms) and also the number of ‘‘cooling nights’’ in a year. They quote empirical data from He, Young, Pathan et al (2005) which states that, once bedroom temperatures reach 23.9°C, occupants will act to reduce the temperature. If there is air conditioning, the results of their simulation are that, were occupants of UK dwellings to respond in the same way as occupants of US dwellings, then 18% of homes in the UK would have installed domestic air conditioning by 2030.

Chappells and Shove (2005) took a different view. They noted that people's expectations about comfortable indoor temperatures are becoming narrower with the expectation that temperatures will be maintained between 21–23°C, requiring ever more efficient ways of maintaining indoor temperatures. They suggested that people's expectations of comfort should be challenged and that instead of further standardisation of indoor climate, people should expect a greater diversity and variety in the built environment.

In summary, installing air conditioning in dwellings would have a significant impact on domestic energy consumption and overall carbon emissions. It is preferable to design out the need for air conditioning in the first place. However, as previously discussed in relation to thermal comfort, there is also a behavioural aspect to overheating and air conditioning. For this study, BedZED participants were therefore asked for their perceptions about comfort in the summer months.

5.8 Summer Temperatures in 2003

The summer of 2003 was particularly hot. Johnson, Kovats, McGregor et al (2005) estimated 2,091 (17%) more deaths occurred in England during the heatwave than the average for the same period over the previous five years. Lomas and Kane cite statistics reported by the World Health Organisation that there were potentially 70,000 excess deaths between June and September across Europe as a whole in the summer 2003 heatwave (Lomas and Kane 2013) whereas Wright et al estimated a lower total of 35,000 additional deaths across Europe with the elderly most affected by the heat wave (Wright et al 2005). The monitoring Phase 2 of this study included the summer of 2003 and these data are analysed for this thesis.

5.9 Summer Overheating Conclusions

Designing for summer temperatures is of growing importance given the trend for increased summer temperatures and the impact on occupant comfort and health of higher temperatures. It is also important for designers to design for higher summer temperatures given that overheating could result in occupants using more air conditioning and therefore increasing energy use and carbon emissions from dwellings.

Chapter 6 Methods

6.1 Introduction

This chapter sets out the methods for testing the hypothesis, drawing upon the earlier case studies discussed in Chapter 3. The chapter begins with the justification for using a case study and an analysis of case study methods. It describes the three phases of data collection used in this study. While other studies have conducted follow-ups of occupants after they have moved into energy efficient properties, the unique feature of this case study is the pre-occupation data collected before the participants moved to a new development and post-occupation data collected over a decade and spanning design, construction, occupation and certification, together providing a longitudinal study of one of the first generation of zero carbon developments. Finally, the chapter sets out the methods used to classify and analyse the data collected for this thesis.

6.2 Outline Methodology

The thesis uses a hybrid of research methods to test the hypothesis and the primary method used is the case study. The case study selected is the BedZED mixed-use, mixed tenure development described in Chapter 4 and this research focuses on the housing element. The research comprises an uncontrolled experiment with intervention: it involves monitoring the energy use and internal temperatures of a sample of households in their original homes and then in their new homes with social aspects evaluated through occupant surveys.

6.3 Case Study

Yin (1994) defined a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.

This is relevant to this study because the boundary between the phenomenon (the buildings monitored in the case study) and the context (the high profile nature of the scheme, the participants attracted to the scheme) may be blurred. It was important to measure actual building performance because, for instance, some participants, mindful of the high profile sustainable nature of the scheme, might have changed how they used their dwelling to fit in with the design: they might have kept their home cooler in winter than previously or might have worn thicker clothing instead of increasing the internal temperature. It was important to distinguish these contextual factors because they may challenge the assumptions made at design stage and affect the replicability of the concept. Living in a high profile experiment might have changed occupant behaviour because occupants were aware of the impact of their behaviour on the environment.

Mitchell (1983) stated that the benefit of a case study is not that the features of the subject studied are a representative sample of the population studied, but that the rich detail that emerges in a case study provides “illuminating insights”. One aim of this study is that by studying this case in detail, insights into the limitations of energy modelling and other assumptions governing design and construction of low energy housing will be uncovered which will enable models to be improved and refined or technology and practices changed to better achieve the theoretical potential. While the case selected was not typical of most housing developments in the UK, the innovative nature of the scheme made it highly suitable for testing the limits of assumptions made in conventional energy modelling and provided useful information for zero carbon policy and practice.

6.4 Experiment versus Observation

Under definitions put forward by Eberhardt & Thomas (1991), this study consists of an intervention analysis. The study comprises a series of events which are uncontrolled by the researcher but where there is an intervention, that is, the removal of the sample from their former homes to BedZED. One aim of the study is to determine whether the change in dwellings effects a behaviour modification.

Manly (1992) stated that a potential problem with observational studies is that a prima facie conclusion may be invalid because of the confounding effects of uncontrolled variables. That is, there may be no way of knowing whether an effect observed in the data is due to a change in the variable of interest, or is instead due to changes that happen to also occur in other variables at the same time. This is particularly relevant to this study because of the nature of the intervention – the participants moved to a unique development which was different in design to their previous homes. One uncontrollable element of the study, for example, could be that energy prices may have changed during the study period, creating changes in energy use by the occupants. Confounding effects are addressed, as far as practical, by focusing on actual monitored data: energy used and internal temperatures achieved (controlling for external temperature), rather than measuring the amount spent by participants on energy.

There was no control group in the study. It was hoped that the social housing dwellings might form a control group since occupants within this tenure tend to have less choice about where to live. However, the overall number of social housing units at BedZED was small (ten) and participation from this group in the research was modest with only two social housing households taking part in the study. While it is possible to use national domestic energy consumption data, such as the Digest of UK Energy Statistics (DUKES), for comparison purposes, those data are too high level to form a control data set. It was concluded that a control group was just not practical for a case study of this type.

6.5 Modelling versus Monitoring

Energy modelling comprises a forecast of how buildings will perform using computer-based simulations compared with monitoring which measures actual performance. In their 2010 paper, Summerfield, Lowe and Oreszczyn set out two new approaches to energy modelling called ADEPT and STEP

(2010a). Both models enable policy makers and consumers to assess at a macro level whether energy reduction programmes are on track. The models are complementary to but do not replace detailed models such as BREHOMES which model energy consumption at a single property level. While models are useful to assess whether policies are broadly on track and to map trends, they are not a substitute for property level monitoring which provides a more granular level of analysis of a group of properties.

Beizaee, Lomas and Firth described the benefits of monitoring over modelling (Beizaee et al 2103). They stated that dynamic thermal modelling has been used to predict the possibility of overheating for different UK house types, constructions, occupant behaviours and climate change scenarios. They posited that such studies cannot capture true occupant behaviour and occupant interaction with heating and ventilation systems. The design team for BedZED used dynamic thermal modelling but this research shows that they did not fully predict how occupants would interact with the building design in hot temperatures. Other modelling completed prior to development included a generic SAP calculation for the whole scheme. And a key element of the Phase study is the analysis of EPCs produced for the BedZED development and which are based on SAP models.

Monitoring studies do not take place in scientific laboratories but in real homes. As such, they are subject to unpredictable or uncontrollable human behaviour. As Beizaee et al highlighted, occupants may move data loggers, potentially putting them near a heat source such as in direct sunlight or near an electronic device. And there is inherent data uncertainty if only one logger is placed in a room without a second logger to provide a control reading. Beizaee et al stated that future monitoring studies may be able to make more use of digital technology such as smart meters and gateways to provide a channel from which to collect data from wireless temperature, occupancy and other sensors. Such technology was not available at the time of this study. Centralised logging systems were originally proposed but were discounted on the grounds of cost and the impact on the construction programme.

Kane, Firth & Lomas's paper suggested that models such as BREDEM do not fully reflect how people use their homes and in particular the diversity of use across different occupancy groups such as older, retired people and people who work (Kane et al 2015). They posited that reliance upon these models could misrepresent the benefits of energy efficiency measures to some groups of society. This thesis discusses monitoring carried out on BedZED and the limitations of SAP when applied to low energy houses.

6.6 Methods Selected to address the Research Questions

Yin (1994) stated that a case study is an appropriate choice of method where the research study is researching a "how or why" question about a contemporary set of events over which the investigator has little or no control. The hypothesis for this thesis is "There is a performance gap between predicted and actual energy performance in low energy dwellings and this is due to occupant behaviour". The hypothesis requires the following research questions to be answered and these comprise the "how or why" questions appropriate to a case study. The principal questions for this study were set out in section 1.2 and are re-stated here:

- How do the constructed units perform compared with the theoretical design performance?

- What is the difference, if any, between the constructed units and the units as designed?

- Why is there a difference?

- What conclusions can be drawn about this and can the energy model or design practices be changed to reflect this?

- Have participants changed how they use energy at home as a result of moving to the new development?

It is proposed to answer these questions using the following methods:

- Monitoring and analysis of the performance of a sample of dwellings with regards energy used and internal temperatures achieved over varying time periods spanning a decade;

- A longitudinal study to monitor the performance of a sample of dwellings occupied prior to moving into the case study development;

- Comparison of the results of the case study with the original design intent in order to assess whether the performance varied from the design and if so, why;

- Comparison of the results of the case study with the results of the dwellings occupied prior to moving into the case study to identify whether there are any occupant behavioural changes resulting from moving into low energy dwellings.

The strength of the case study is its ability to deal with a full variety of evidence – documents, surveys and observations, all of which are used in this research study.

6.7 Statistical Testing

It is essential that limitations in the data are highlighted prior to conclusions being drawn. Fielding and Fielding (1986) stated that if diverse kinds of data support the same conclusion, confidence is increased. In this study, a range of data has been collected, both quantitative and qualitative. The confidence level of the data has been tested for validity and reliability using a range of methods.

6.7.1 Validity

A fundamental precept of a case study is that for it to be externally valid, it must be possible to generalise the results to a wider population of interest.

The importance of a case study is not that it is necessarily a representative sample of the population, but that the findings embody some general principles or learning that is relevant beyond the case study. Thus, while this case selected is a unique housing development, the research questions selected (how the dwellings perform compared to design and why there is a difference) could be applied to any housing development.

The unique nature of the example selected may enable deeper insights to be made. For example, there is no conventional space heating system in the case selected. This may have affected occupants' perceptions of comfort more than if they had moved to a more conventionally designed scheme. It could be difficult to determine whether comfort perceptions are based on the perception that their new home may be cooler because there is no conventional heating system, or whether it is indeed cooler. Therefore the pre-occupancy phase, which surveyed participants in their previous home and also collected energy monitoring data, tested these perceptions and provided objective and consistent data from data loggers about how the participants used their homes and their preferences with regards to comfort.

Although construction completed in 2002 and the principal monitoring phase (Phase 2) completed in 2004, the continuing importance of this case study is emphasised by Chance (2009) who states that BedZED remains one of the most coherent visions of sustainable living in the world. Learning from low energy developments like BedZED is essential if the UK's carbon emission targets are to be met. Other developments at the same scale as BedZED are now being completed, such as the Little Kelham development in Sheffield comprising 153 Passivhaus dwellings.

6.7.2 Reliability

To ensure that the data collected and analysed were reliable, externally accredited and auditable data collection systems that met ISO 9002 quality assurance standard were used where available. The National Home Energy Rating (NHER) system surveys of the pre-BedZED properties were undertaken by Rickaby Thompson Associates (RTA) who were fully accredited NHER surveyors. And the NHER survey itself has ISO 9002 quality assurance.

Environmental monitoring within dwellings was undertaken using HOBO H8 series Temperature and RH data loggers supplied by Tempcon Instrumentation. The H8 data loggers were accurate to ±0.7ºC and ±3% RH.

Tempcon employed a quality system registered to ISO 9002 and loggers were supplied with calibration equipment and BoxCar Pro 4.0 software to enable data analysis and export.

Temperature data files for each logger at each site were merged with external temperature data by site, data and time, to form a single dataset by Dr A J Summerfield at the UCL Energy Institute, using an automatic import/export macro developed in SAS 9.1 for the CaRB project. Through CaRB, this process had been tested on other datasets and enabled a direct comparison with the results from other studies.

6.8 Longitudinal Study

A unique feature of this study was the inclusion of a measurement phase prior to the participants taking up residence in BedZED. The purpose of this was to track over time participants' behaviour and assess whether it changed as a result of moving into the new dwelling. The longitudinal element of the study enabled a baseline of participants' behaviour and preferences to be set before moving to BedZED.

6.9 Sample

Statistical sampling was not used. There were 82 dwellings in the BedZED development and all prospective occupants were invited to participate in this study. It was wholly voluntary and no incentives or rewards were offered. From these 82 dwellings, 24 households agreed to participate in the main part of the study (Phase 2). They are referred to as “the participants” and represent 29% of the total households. Compared to the size of other field trials, the BedZED sample size falls part way between the 1980 Linford study of 8 dwellings and the 1985 Pennyland study of 177 dwellings described in Chapter 3.

Of the 24 participants in Phase 2, 14 agreed to take part in Phase 1 which focused on participants' previous homes. These 14 households represented 17% of the total BedZED households. All Phase 2 participants were invited to take part in Phase 1 but reasons for not taking part in the earlier phase were various: some lived in shared accommodation or hostels and it would not be possible to make a direct comparison with their sole occupancy in Phase 2; other participants were close to completing their purchase of a BedZED property and there was not enough time to take part in the Phase 1 survey as they were about to move.

The Phase 1 sample was further classified into three cohorts: Cohort 1 which had an NHER building survey of their pre-BedZED home; Cohort 2 had temperature monitoring and energy usage readings; and Cohort 3 which took part in the occupancy survey. A full schedule of participants for each of these Phases and Cohorts is at Table 6.1.

Table 6.1: Survey samples for each element of BedZED study

Participant	**Phase 1**			**Phase 2**		**All elements**
	Cohort 1 Building	Cohort 2 Monitoring	Cohort 3 Survey	Monitoring	Survey	
A				✓	✓	
B	✓	✓	✓	✓	✓	✓
C				✓	✓	
D	✓	✓*		✓	✓	
E				✓	✓	
F	✓	✓	✓	✓	✓	✓
G				✓	✓	
H				✓		
J	✓		✓	✓	✓	
K				✓	✓	
L		✓		✓	✓	
M		✓	✓	✓	✓	

Participant	**Phase 1**			**Phase 2**		**All elements**
	Cohort 1 Building	Cohort 2 Monitoring	Cohort 3 Survey	Monitoring	Survey	
N	✓	✓	✓	✓	✓	✓
P	✓	✓	✓	✓	✓	✓
Q	✓	✓	✓	✓	✓	✓
R	✓	✓	✓	✓	✓	✓
S	✓	✓	✓	✓	✓	✓
T				✓	✓	
V	✓	✓	✓	✓	✓	✓
W				✓		
X	✓			✓		
Z				✓		
AB	✓	✓	✓	✓		
AE				✓	✓	
Total	**12**	**11**	**11**	**24**	**19**	**8**

*Property D: energy usage data available for Phase 1 but not internal temps

For the longitudinal comparison, care was taken to ensure that results from the same sample of participants were compared. For example, there were 11 participants in the pre-occupancy monitoring. In the longitudinal comparison, the results from these 11 participants were compared to the post-occupancy results from the same 11 participants.

Phase 3 comprised all BedZED properties. Energy usage data was anonymised and was not therefore comparable to the sample used in Phase 1 and 2. The EPCs analysed for this thesis were not anonymised, enabling a comparison with the Phase 2 sample.

Tables 6.2, 6.3 and 6.4 provide a breakdown of the BedZED sample by size of dwelling, number of occupants in the household and tenure type.

Table 6.2: BedZED case study sample – size of dwellings

1 bed	9
2 bed	5
3 bed	9
4 bed	1
Total	**24**

Table 6.3: BedZED case study sample – number of occupants in the dwelling

1 occupant	9
2 occupants	7
3 occupants	3
4 occupants	4
5 occupants	1
Total	**24**

Table 6.4: BedZED case study sample – tenure type

Outright Sale	14
Shared Ownership	8
Social Housing	2
Total	**24**

Some details of participants' age and gender were volunteered during the two occupant surveys but these data were incomplete, see Table 10.2.

6.10 Data Used in this Thesis

Figure 6.1 summarises the three phases of data collection in the study.

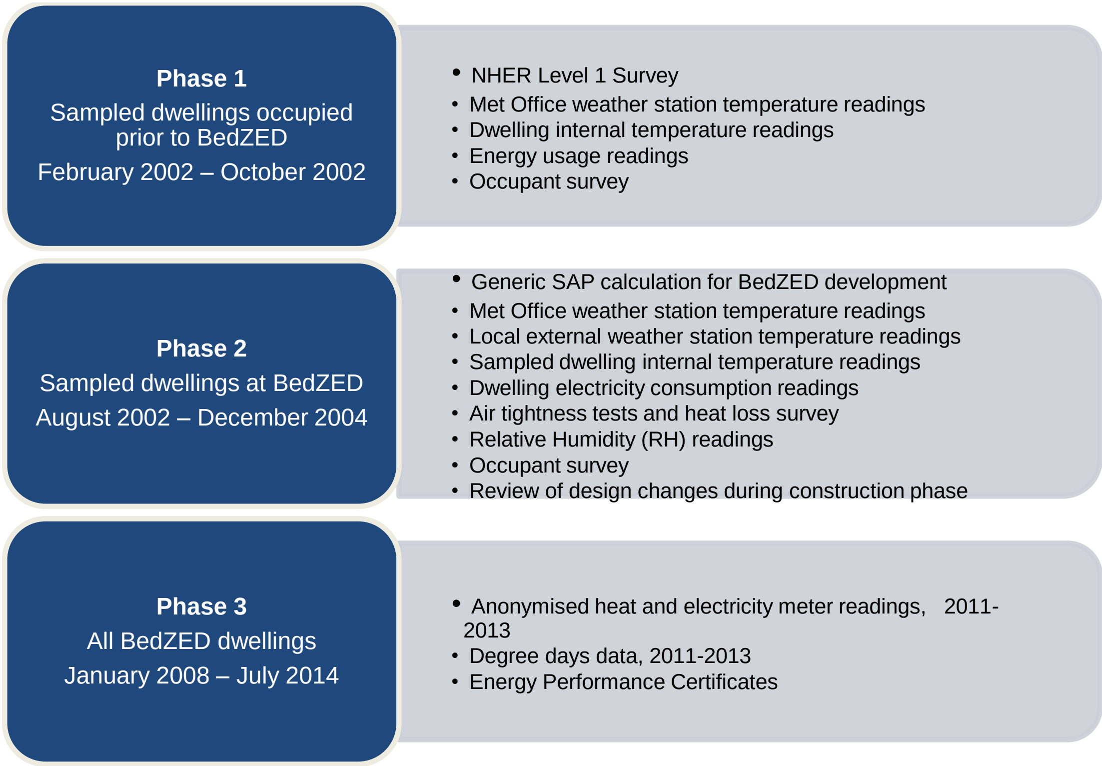


Figure 6.1: Data collected for BedZED Case Study

Other data were collected but not used such as water consumption readings. The data used in this case study are described in more detail below.

6.10.1 Phase 1

Phase 1 comprised 14 dwellings occupied by households prior to moving to BedZED.

Level 1 NHER survey

The author commissioned Rickaby Thompson Associates (RTA) to carry out NHER surveys on 12 properties using version 3.5/build:51 and she analysed the results. Two further participants had volunteered for this phase but they were living in shared accommodation and the NHER survey was not appropriate. The NHER survey compiled details of the physical fabric of the dwelling, its size and age, the heating system type and age, ventilation and lighting systems. The survey includes a prediction of space heating costs and CO_2 emissions. A SAP rating was also calculated.

Dwelling Internal Temperature Readings

For Phase 1, the author commissioned RTA to install data loggers in living rooms and principal bedrooms for an average period of nine weeks prior to the participant moving to BedZED. The actual position of the logger depended on furniture layouts but would typically be on a fixed shelf or piece of furniture that wouldn't be regularly moved. Loggers collected internal temperature readings at 30 minute intervals. Data were downloaded by RTA and analysed by the author.

External Weather Station Temperature Readings

Participants lived in different locations in their pre-BedZED dwellings. The monitoring periods for the pre-occupancy phase, Phase 1, were not long enough to warrant setting up external weather stations at each dwelling. Accordingly, the author procured data from the Meteorological (Met) Office for the Kenley Airfield Weather station in Surrey for the Phase 1 period. The Kenley data were provided in the form of a daily maximum and daily minimum reading for both temperature and relative humidity.

Energy Usage

RTA took electricity and gas meter readings when data loggers were installed and removed in Phase 1. The data were analysed by the author.

Occupant survey

The author designed a questionnaire survey for Phase 1 participants in their previous homes before they moved to BedZED. The survey design is included in Appendix 3. The survey collected a mixture of quantitative data such as the number of electrical appliances used by the household and qualitative data about lifestyle and preferences such as whether the participants found the dwelling warm enough. Where questions were about occupant perceptions, a grading system was used to provide a consistent, common framework for all respondents. For example, one question asked how easy the heating system controls were to operate. The respondent is required to grade the ease of use from 1-5 where 1 is easy and 5 is very difficult.

RTA administered the surveys face-to-face when they carried out the NHER surveys. Owing to the advanced construction and move-in programme there was not enough time to pilot the questionnaire prior to using it for the Phase 1 surveys. The pre-occupancy survey included the following main headings listed in Table 6.5. The thesis author carried out data analysis of the survey results.

Table 6.5: Phase 1 Occupant Survey

	Category	**Question Summaries**
1	Household Details	Number and age of people in household When home is occupied Electrical appliances and low-energy light bulbs used Fuel used for cooking.
2	Heating System	Ease of operating controls and whether they are adjusted Effectiveness of controls at maintaining comfort Comfort levels in winter, hot and cold spots in the home, whether additional forms of heating used.
3	Hot Water System	Does system supply enough hot water Is temperature comfortable Does occupant know how to adjust temperature.
4	Fuel Costs	Does occupant know how much their fuel cost and if so, how much spent per annum on gas and electricity.
5	Ventilation	Does occupant have mechanical ventilation Does occupant open windows to improve air quality Does occupant consider home to be draughty.
6	Other	Has household experienced health problems linked to the home Is there mould or condensation Overall satisfaction with heating, hot water and ventilation systems How much clothing is worn in the home during winter

6.10.2 Phase 2

Phase 2 comprised 24 BedZED dwellings and covers the design and construction phase and the first two years of occupation.

SAP Rating

Arup, M&E engineers for BedZED, completed the SAP calculation. Their generic SAP rating for the development was analysed to identify design assumptions in comparison to the actual performance in use. The author carried out a further SAP calculation as part of this study, using construction drawings for a one-bedroomed flat to enable a direct comparison with the generic rating.

Dwelling Internal Temperature Readings

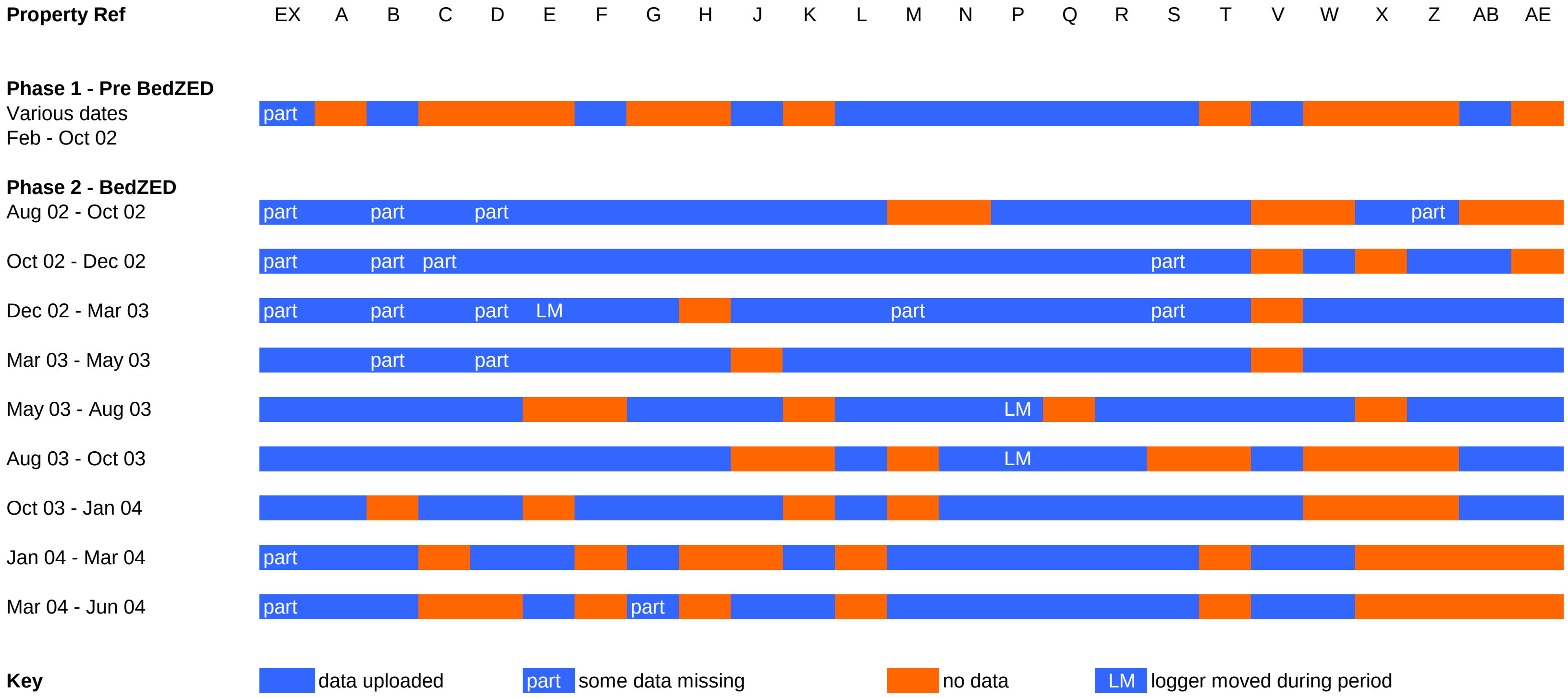
As for Phase 1, internal temperatures were recorded by Tempcon HOBO data loggers. In Phase 2, the author commissioned RTA to install two loggers in each of the 24 sampled BedZED properties, one in the living room and one in the bedroom. In some properties, additional loggers were sited in the bathroom, second bedroom or sunspace. As for Phase 1, loggers were set to record temperature and relative humidity at 30 minute intervals. Phase 2 data were collected for almost two years and results downloaded by RTA at approximately three monthly intervals by gaining access to the dwellings, downloading data into the BoxCar Pro software programme held on a laptop and resetting the loggers for the next period. The first interval was set for six weeks to check for operating problems or defects with individual loggers. The monitoring period of August 2002 to June 2004 enabled data collection throughout the two heating seasons of 2002-03 and 2003-04 and the hot summer of 2003. The period also allowed the high mass construction to dry out during the first year.

There were some cases of loggers that failed and these were generally re-set at the next data download. There were also cases where participants moved loggers or they became lost. Again, where practical, this was rectified at the next data download. However, the most common issue encountered during the monitoring process was lack of access to properties to download the data from the loggers. The data loggers stored approximately four months of data and so if the download appointment was missed, approximately a further month of data would be stored in the logger but not the full three months of the next logging period. The impact of this was that some data were missing from the dataset.

Table 6.6 shows the number of data downloads collected during Phase 1, prior to participants moving to BedZED and Phase 2, after moving into BedZED. The author supervised and managed RTA and completed data validation and analysis.

Table 6.6: Record of Logger Data Collection for Phase 1 and Phase 2

RECORD OF LOGGER DATA COLLECTION



				%
Maximum potential monitoring periods	216	Total full data downloads	150	69
		Total part	13	6
		Total missing	53	25

Table 6.6 shows that 69% of data was collected successfully during the Phase 2 monitoring period and a further 6% of partial data collected. 25% of data were not downloaded from loggers, generally as a result of not being able to access the property on that date. This is probably an over-estimate of the data lost because in practice, the loggers were able to record up to four months data.

At an early stage of designing the study, the author considered the feasibility of installing a monitoring system with remote access to data. This would have enabled data to be downloaded remotely and removed the need for access to each dwelling every three months to download data, unless a fault developed. It would have required loggers to be permanently fixed in location which would have had the additional benefit that the loggers could not be inadvertently moved and would have improved further the consistency of results. This option was not pursued because at the time of designing the study, the construction programme was so far advanced that it was not feasible to specify, procure and install a permanent monitoring system in the dwellings. For future studies, it is recommended that monitoring requirements are identified at an early stage of design so that the option of an integrated monitoring system with remote access can be fully considered. This would minimise the access issue encountered in this study although it would be wise to allow for some additional access to properties early in the programme to resolve teething problems.

RTA downloaded data from loggers into the BoxCar Pro software and exported to individual Excel spreadsheets produced for each dwelling for each monitoring period. The spreadsheets comprised temperature and relative humidity readings for each logger for the period. Any issues or interventions that affected the data were recorded on the spreadsheet, for example, that the logger had failed to launch properly or that the occupant had moved the logger. Data was supplied to the author for validation and analysis.

Data reliability was checked at the time of downloading and any perceived issues that affected the reliability of the data were recorded on the data spreadsheet. Further checks were made against all the data to ensure that the data loggers had not failed or been moved but that they continued to collect data in the same property and location. The internal temperature readings were plotted for each property against external readings from the Met Office weather stations (Phase 1 and first part of Phase 2) and the local weather station set up at BedZED (second part of Phase 2). Any significant or abrupt changes to both temperature and relative humidity readings were investigated to ensure that the loggers were not disturbed.

External Weather Station Temperature Readings

For the first part of Phase 2, external temperature data in the form of a daily maximum and daily minimum reading was obtained from the Met Office for the Kenley Airfield Weather station in Surrey. In March 2003, seven months into Phase 2, the thesis author commissioned RTA to establish a local weather station at BedZED and, in line with the internal loggers, temperature and relative humidity were recorded at 30 minute intervals.

Energy Usage Readings

RTA collected electricity meter readings from each sampled dwelling at each visit to download internal temperature data. Data consisted of kWh usage from the main meter in all dwellings and also the sub-meters that had been installed in 16 of the dwellings. Although properties also had heat meters installed, there were operational problems with the provision of heat from the site CHP system. This resulted in some disruption to the CHP provision of hot water to properties with the result that participants may have derived more of their hot water from immersion heaters than expected and may have used temporary space heaters. Such usage would have affected electricity usage readings in the sample properties. Exact dates of when the CHP system was non-operational are not known and heat data from the CHP system during the monitoring period are not available. For properties that had sub-meters installed, the author has carried out analysis of the energy used by the immersion heaters compared to other electricity use. This enabled her to make some assumptions about the proportion of electricity used for heat for the Phase 2 sample.

Air-tightness and heat loss survey

During the BedZED construction process, six empty, newly-constructed properties were pressure tested by the building contractor using a specialist consultant to assess air tightness. The tests were undertaken prior to completion of snagging items and handover and were made available for this study.

At the end of Phase 2, and specifically for this study, on-site infrared thermography and whole-house air infiltration rate tests were carried out in one of the sampled dwellings. The purpose was to measure actual airtightness and heat loss performance of the building fabric compared to the design. The tests were undertaken by Sung H Hong and Dejan Mumovic of UCL Bartlett School of Graduate Studies (Hong & Mumovic 2005). Two separate air infiltration rate tests were carried out with the four wall openings to the passive stack vent in both open and closed conditions. The sunspace was excluded from the test. An infra-red camera was also used to detect any cold air ingress along window seals while the dwelling was depressurized forcing cold exterior air into the dwelling. The airtightness test and infra-red thermograph were undertaken at the end of the Phase 2 monitoring period to give the high mass structure as long as possible to dry out.

Dwelling Relative Humidity (RH) Readings

RH readings were recorded at 30 minute intervals at the same time as the internal temperature readings by the HOBO data loggers and were downloaded onto spreadsheets by RTA. The author analysed RH results for the property surveyed in the heat loss and airtightness survey and the six properties that reported condensation in the occupant survey.

Occupant surveys

A follow up occupant survey was undertaken at the end of Phase 2 and the survey design is included at Appendix 4. The survey was left by RTA with participants when the loggers were collected at the end of the study. Participants returned completed surveys to the author by post and the author completed analysis of the surveys. The purpose of administering two surveys was to identify whether participants had made any adjustments to the way in which they used their home.

The survey administered at the end of Phase 2 was broadly similar to the Phase 1 survey but with some amendments and additions. These changes reflected feedback during the occupancy phase and some of the emerging findings from the data analysis, in particular, the apparent overheating of the dwellings during hot spells which had not been foreseen before the start of the study. In the Phase 1 survey, participants were asked only about heating. For Phase 2, additional questions were added to ask participants about summer comfort conditions. The survey was also adjusted to reflect the nature of the development. For example, the open question about which fuel was used for cooking was omitted since all dwellings at BedZED had electric cookers installed.

The following changes were made:

1. Question 1.5 in the post-occupancy survey on the type of fuel used for cooking was amended because all cookers and hobs were pre-installed at BedZED and ran on electricity.

2. Additional question 2.7 added to the post-occupancy survey to ask about comfort level of home during the summer. Additional question 2.10 added to ask whether additional forms of cooling were used.

3. Question 4.2 about the cost of fuel used was amended in the post-occupancy survey to reflect the single fuel supply at BedZED, ie electricity only.

4. Question 4.3 from the pre-occupancy survey requesting copies of fuel bills was omitted from post-occupancy survey since meter readings were taken during the occupancy period.

5. New question 4.3 added to post-occupancy survey to ask whether having fuel dials on display made a difference to participants' use of fuel and appliances, since this was a design feature of the BedZED properties.

6. Questions 5.1 to 5.3 about ventilation amended from the pre-occupancy survey which asked whether there was a mechanical ventilation system, how effective it was and whether the occupant opened windows to improve air quality. In the post-occupancy survey these questions asked whether the occupant found the BedZED ventilation system effective and whether they opened windows to improve the air quality and whether they opened windows to control the temperature of their home.

7. Question 6.1 in the pre-occupancy survey which asked whether the participants had any asthma or similar health problems that could be associated with the living environment was amended in the post-occupancy survey to ask whether any participants had experienced asthma or similar for the first time since moving to BedZED.

8. Finally at the end of the post-occupancy survey, a section was added to enable participants to add additional comments.

A further issue considered during the survey re-design was the need to be aware of the "goldfish bowl" syndrome of living on a high profile development. There was a risk that some participants would reach survey fatigue owing to the high levels of interest from researchers and the media in the development. This meant that the length of the survey was a factor and care was taken to try and minimise the size of the survey and not repeat questions asked by other surveys. Peabody Trust managed all research projects at the site to reduce occupant annoyance. Other surveys identified participants' views about the move to BedZED and the key study referred to is the BedZED Resident Satisfaction Survey Report by Peabody Trust (Ellis & Elvy 2004).

Review of design changes during the construction and operational phases

A review of minutes of project team meetings was undertaken to identify any design or construction changes that may have been material to the performance of the BedZED properties. Although not a complete record of design changes or construction issues, minutes were available for the period 1999-2000. Additional commentary was also received from Chris Twinn, lead energy engineer on the project design team (Twinn 2014). The literature was also consulted (Hodge & Haltrecht 2009).

6.10.3 Phase 3

Phase 3 covered the period 2010-14 and comprised two main elements, anonymised energy usage for the whole development and Energy Performance Certificates (EPCs) issued on all BedZED properties sold or leased following the 2007 legislation requiring EPCs.

Energy Usage

Anonymised heat and electricity meter readings for all BedZED properties for the three year period 2010-2013 were compiled. The purpose of this was to enable a truer assessment of energy use than Phase 2 which did not have heat data. By Phase 3, the biomass CHP had been replaced with centralised gas-fired boilers and was operating normally. Meters in individual properties recorded actual usage of heat and electricity. These data also contributed to the longitudinal element of the case study.

Peabody provided energy usage data for the whole development, anonymised in line with Data Protection requirements. It was not therefore possible to extract the data for the sampled properties or participants in Phase 2. However, since the data covered the whole development they provided evidence of the performance of the development as a whole against design intentions.

The energy usage data were recorded at each property according to individual household consumption, centrally collected and then billed back to occupants. The anonymised data were supplied by Peabody's energy supplier and checked by Peabody staff. Some of the data comprised estimated readings and it is not possible to distinguish actual readings from estimated. Additionally, some data were incomplete and missing, for example, house-type or number of bedrooms. Such readings were omitted from the analysis. The energy data provided covered years 2010-11, 2011-12 and 2012-13. The data supplied for 2010-11 were less comprehensive than the data for 2011-12 and 2012-13: only 36% of the 10-11 data comprised monitoring periods of more than 300 days compared to 69% for 11-12 and 77% for 12-13. The 10-11 data were therefore omitted from the analysis. There is a risk that the residual data used in this study is not wholly reliable but since the same data are also used for billing purposes by the utility suppliers, this is considered to be a reasonable control on the level of accuracy since occupants would challenge incorrect bills, particularly if they were being over-charged.

The data supplied were broken down into heat and electricity for each individual property which was described according to the house-type, e.g. flat or maisonette and number of bedrooms and tenure, e.g. social housing. To standardise the data to size of property, the house-type was compared with the property sizes in the Core Building Worksheet used for this study in order to extract the area of each property. Measurement of properties is discussed later in the chapter.

Energy Performance Certificates (EPCs)

EPCs were mandated in 2007 for all dwellings sold or rented and comprise an energy efficiency rating and an environmental impact rating measuring CO_2 emissions. Ratings are combined into a sliding scale of A – G with A being the most energy efficient and least environmental impact. The ratings are derived from the Reduced Data SAP (RdSAP) method for existing dwellings (DECC 2013c). A search of the Landmark Information Group site was undertaken to identify EPCs issued for BedZED properties, including the Phase 2 sample. At the time of the search, 43 EPCs had been issued for BedZED dwellings and these were all downloaded and analysed for this study.

EPCs are issued when properties are sold or rented out and they mark the final stage in this study which has traced occupants from before they move to BedZED, to living at BedZED and then moving on.

6.11 Classification of Data

6.11.1 Classification of Monitoring Data for Phases 1 & 2

The author organised the data for this research according to a method designed by Dr Alex Summerfield of UCL Energy Institute for the Warm Front study. The data were organised into three major sets according to protocols developed for the Carbon Reduction in Buildings (CaRB) project (Summerfield, Lowe, Firth et al 2006). This enabled the study to benefit from a tried and tested classification system and also capture the data in a format that could be retained for easier comparison with other studies, see comparisons in Chapter 8.

The three datasets were core building worksheet; core occupant worksheet; and core logger worksheet. The information compiled on each worksheet is shown in Table 6.7. The author organised all the data for these datasets from the raw data collected during the study.

Table 6.7: Organisation of Core Data for Phases 1 and 2

Worksheet	Data
Core building worksheet	Phase 1 and 2 (pre-BedZED and BedZED) Property reference number Postcode Local authority area Dwelling type, e.g. ground, mid or top floor flat Dwelling age Floor area m^2 GIA Number of bedrooms Number of rooms Logger position, e.g. bedroom, living room
Core occupant worksheet	Phase 1 or 2 (pre-BedZED and BedZED) Property reference number Name Postal address Number in household Tenure
Core logger worksheet	Phase 1 or 2 (pre-BedZED and BedZED) Property reference number Location within property, e.g. bedroom, living room Logger reference Start date of logger period Finish date of logger period Logger period file reference

This method enabled the collection of energy monitoring data in a consistent way and comparisons to be made between different research studies. Inter alia, the coding structure includes categories such as detached, terrace, purpose-built and converted flat and descriptions of which storey flats are located on. The extent of exposed external surfaces and the size of the property are relevant to the energy used. The coding structure is based on house-types and requires property size data and number of bedrooms and the occupant data sheet requires the number of occupants per household.

The measurement dataset for each logger was compiled according to the following format: Property reference; internal location reference; logger reference; start date of logger data; stop date for logger data; Excel file reference. Each individual download of data was recorded as a separate logger period. Generally these were three monthly with the first period being six weeks.

Individual data files for each logger at each site were merged with external temperature data by site, data and time, to form a single dataset. Owing to the scale of this task, this process was carried out by Dr Alex Summerfield, using an automatic import/export macro developed in SAS 9.1.

The BedZED CHP design calculations were predicated on property sizes and an assumed number of occupants per property, making a direct comparison between the design and the actual results possible. However, some of the descriptors used in the design calculations could be clearer. For example, a 2 person flat could be a one bedroomed flat or 2 bedroomed flat. There are merits in both the space driven method (since space heating demand is more likely to be affected by the size of a property) and the occupant driven method (since hot water demand is more likely to be affected by the number of occupants). By organising available data into the Building, Occupant and Logger worksheets, the protocol used for data classification in this study aimed to provide the most comprehensive dataset possible.

6.11.2 Calculation of Standardised Internal Temperature

Measurements were recorded at 30 minute intervals for mean average periods of 65 days for Phase 1 and 657 days for Phase 2. For Phase 1, this resulted in approximately 80,000 data points per dwelling for internal temperatures taken from the loggers in the living rooms and bedrooms. For Phase 2 this resulted in up to circa 1,500,000 data points per dwelling for living room and bedroom internal temperatures plus some additional data points for second bedrooms, bathrooms and sunspaces. The exact number of data points has not been calculated but will be lower than the figure quoted because some the measurements were not downloaded as described earlier.

The difference between the external and internal temperatures is the single most important factor affecting energy use in dwellings (Palmer, Cooper, Armitage et al 2012). External temperatures were therefore also recorded in at a weather station set up at BedZED from 5th March 2003, six months after the start of Phase 2 monitoring. Prior to this site being set up, data from the Kenley weather station were used as the nearest Met Office site to BedZED.

Two temperature variables were measured by the loggers: external and internal temperatures. To enable analysis of the data and comparability of the data with other time periods during the study and also other studies, it was necessary to standardise the internal temperature readings to fixed external temperatures. Indoor temperatures were analysed in relation to these external temperature readings and standardised to fixed external temperatures of 5°C, 20°C and 25°C. The average external temperature during the heating season in Great Britain during the two heating seasons in the Phase 2 monitoring study for this case study were 7.5°C and 7.2°C (Palmer et al 2012) and so, the standardized temperature for the heating season in this study at 5°C corresponds to colder external temperatures than the UK average.

A series of standardised internal temperature curves were produced from the external and internal temperature data. Indoor temperatures were analysed in relation to external temperature readings and regression curves produced for each property in the sample following methods developed by Oreszczyn et al (Oreszczyn, Hong, Ridley & Wilkinson 2006). Indoor temperatures were standardised to ensure comparability between properties included in the study and to enable comparison with other studies.

For each dwelling, average results for indoor temperatures against outdoor temperatures were produced and plotted as regression curves using dwelling-specific regression equations for each logger location in each property using a 95% confidence interval. In this merged form, it was possible to generate daily or other averages and compare estimates for the indoor temperatures across sites under standard external conditions. The estimates were obtained on daily internal versus external temperature data using a smoothed regression technique on the available data at each site and were generated by Dr A J Summerfield of UCL Energy Institute using the 'PROC LOESS' routine in SAS 9.1.

From these curves, 24-hour mean internal temperatures were calculated to show the internal temperatures standardised to fixed points of external temperatures of 5°C, 20°C and 25°C. The 5°C external temperatures represent the heating season and the 20°C and 25°C temperatures represent summer temperatures. A daily average temperature of 25°C is very high and enables analysis of potential overheating particularly since the BedZED Phase 2 monitoring period for this study included the hot summer of 2003. The internal temperature results were compared to the design temperature of 20°C for the winter period and proxy design temperatures of 26°C for bedrooms and 28°C for living room for the summer period.

The full set of curves for Phase 1, Phase 2 and results from other studies can be found in Appendix 5, 6 and 7 respectively. Estimates were obtained from the smoothed curve graphs using lines drawn from the x axis at the key points as follows:

Phase 2

- Average bedroom temperatures when external temperatures were 5ºC

- Average living room temperatures when external temperatures were 5ºC

- Average sunspace temperatures when external temperatures were 5ºC

- Average bathroom temperatures when external temperatures were 5ºC

- Average bedroom temperatures when external temperatures were 20ºC

- Average living room temperatures when external temperatures were 20ºC

- Average bedroom temperatures when external temperatures were 25ºC

- Average living room temperatures when external temperatures were 25ºC

Longitudinal comparison between Phases 1 & 2

- Average living room temperatures when external temperatures were 5ºC

- Average bedroom temperatures when external temperatures were 5ºC

The majority of the measurement for Phase 1, the pre-occupancy phase, took place in February to April when external temperatures did not go above 20ºC.

6.11.3 Degree Days Data

It was not possible to standardise Phase 3 data to exact weather conditions during the two year period to ensure that the periods monitored were identical and to adjust for seasonal variations such as hot spells or heating seasons. The data were provided on an annual basis and most of the properties included in the data set did not include full year readings, i.e. 365 days. Approximately one third of the data for 2010-11 comprised more than 300 days of data compared to approximately two thirds for 2011-12 and three quarters for 2012-13 comprising more than 300 days of data. 2010-11 data were not used and to account for differing external weather conditions for the 11-12 and 12-13 data, the data were standardised to the annual number of degree days. The monthly number of degree days in these three years for the Carshalton weather station (reference IEngland183) near the BedZED development was obtained from www.degreedays.net. Since the energy usage data were provided as annual totals, monthly degree days data were also consolidated into annual totals for comparison purposes. For each category of electricity and heat, data were corrected as follows:

$$\frac{\text{kWh/m}^2\text{/annum}}{\text{degree days.}}$$

6.11.4 Measuring Property Sizes

The Phase 1 NHER surveys calculated property floor areas using Net Internal Area (NIA). While the RICS Code of Measuring Practice (RICS 2007) prescribes standard methods of measuring floor area for industry, there is not a formula for converting one method to another since these will vary from building to building. An industry rule-of-thumb is that an efficient design would produce a ratio of NIA to Gross Internal Area (GIA) of circa 85% (Davis Langdon Everest 2004) and this has been applied here. If the actual ratio of NIA to GIA were lower this would result in lower kWh/m^2 measurements for the pre-BedZED properties.

The additional data supplied were broken down into heat and electricity for each individual property which was described according to the house-type, e.g. flat or maisonette and number of bedrooms. This was compared with the property sizes in the Core Building Worksheet used for this study in order to extract the area of each property. Property sizes in the Core Building Worksheet were taken from the architects' measurements on drawing schedules. These measurements are Gross Internal Area (GIA), defined by the RICS Code of Measurement Practice as the area of a building measured to the internal face of the perimeter walls at each floor level including internal walls and partitions (RICS 2007). This method of measurement is in line with the method of measurement required for dwelling dimensions in the Standard Assessment Procedure where floor dimensions are obtained by measuring between the inner surfaces of external or party walls, disregarding the presence of any internal walls.

6.11.5 Classification of Phase 3 Monitoring Data

Phase 3 data were anonymised and property addresses were not available. Data were standardised to property sizes. Accompanying information included property type, which was classified into Flat, Flat Loft style, House and Maisonette, and the number of bedrooms. Taking account of the classification used in Phase 2 (in turn based on CaRB) property sizes taken off architectural drawings and also the measurements in Corbey's thesis (see Appendix 1), assumptions were made about floor areas and these are shown in Table 6.8.

Table 6.8: Classification of BedZED Phase 3 Data

	GIA m^2
1 – bed property	46.28
2 – bed property	64.68
3 – bed property	108.3
4 – bed property	154.5

6.12 Statistical Analysis Tools

A range of standard statistical tests were used in the study to analyse the data using Statistical Analysis System (SAS) 9.1. Regression curves were produced for each logger in each dwelling in Phases 1 and 2 of the study, using dwelling-specific regression equations for each logger location, using a 95% confidence interval. Curves show the relationship between the external temperatures and the internal temperatures recorded within the properties.

Microsoft Excel 2010 was used to calculate means, standard deviations and confidence intervals on the data points drawn from the regression curves.

IBM SPSS Statistics 22 was used to produce correlations between, for example, number of occupants and electricity used and to carry out ANOVA tests to calculate, for example, whether differences between internal temperatures in living rooms and bedrooms were significant.

6.13 Methods Conclusions

The study is unique in that it includes a pre-occupancy phase where participants are measured and surveyed in their previous dwellings prior to moving to the new, low-energy BedZED properties. This enabled a benchmark to be established for each participant prior to the main study phase when participants took up residence at BedZED and was a unique opportunity to identify and track over time the human factors that impact on how dwellings are used. In addition, the study was undertaken over a ten year period allowing the buildings to be followed through the construction, occupation and then subsequent certification at point of sale.

It had been intended to track the implementation of the design through the construction phase to the occupancy phase but very little data were available about the construction phase. However, a sample of air tightness tests was available for six properties and these were compared to the air tightness test undertaken on a completed and occupied dwelling. Project meeting minutes from the construction phase were also reviewed and these provided insights into design discussions.

The next chapters present the results obtained from the three phases of data collection.

Chapter 7 Energy Usage Results and Analysis

7.1 Introduction

This chapter presents the results and analysis of energy usage at BedZED from Phases 2 and 3 of the study, enabling a comparison of BedZED performance to the design and with reference to the Phase 1 pre-BedZED dwellings. The results contribute evidence towards answering the first three research questions for this study: how do the constructed units perform compared with theoretical design performance; what is the difference if any; and why is there a difference.

Section 4.13 discussed the original design for energy usage at BedZED, which was 7,460 kWh/annum for a typical property or 75 kWh/m^2/annum.

7.2 Phase 1 Energy Usage

The Phase 1 (pre-BedZED) electricity results shown in Table 7.1 are from three pre-BedZED properties (B, D, R) that had separate gas heating systems and where heat and electricity were measured separately. Other properties had electrical heating and these readings could not be split between heat and electricity. Other properties' readings were missing. Phase 1 heat data comprised gas usage in three properties (D, J, R), including gas used for cooking as well as heat. Monitoring data were available for these properties for just over 8 weeks except for property D where data was collected for just over two weeks. Phase 1 data are not adjusted for degree days.

Table 7.1: Phase 1 pre-BedZED weekly energy usage

	sample size	Mean kWh/week
Electricity	3	130.0
Heat	3	175.7

7.3 Phase 2 Energy Usage

7.3.1 Phase 2 Data Issues

The energy usage data collected during Phase 2 covered two heating seasons. Electricity usage readings were taken at the 24 properties included in the Phase 2 sample, including sub-meters where these were available, for example, immersion heater, lighting circuits. Heat data were not available either at the property level or centrally from the CHP plant owing to the problems with the CHP plant during the Phase 2 period, discussed more fully in Chapter 11. These operational problems meant that the supply of heat to BedZED properties was inconsistent during the Phase 2 monitoring period leading to the possibility that additional electrical demand could have been recorded at the individual property level, either from the immersion heater being a back-up for hot water or additional heating being used in the property.

7.3.2 Phase 2 Electricity Usage Results

Table 7.2 shows mean overall electricity usage by the BedZED sample during Phase 2.

Table 7.2: BedZED Weekly electricity usage

	kWh/week	m^2 NIA	kWh/m^2/week NIA	Number occupants in household	Number bedrooms	Number appliances
A	84.2	90.9	0.9	2	3	9
B	49.9	39.4	1.3	1	1	3
C	56.4	39.4	1.4	3	1	3
D	85.5	92.4	0.9	4	3	
E	58.6	58.7	1.0	2	2	5
F	34.3	39.4	0.9	1	1	2
G	70.6	92.4	0.8	2	3	6
H	88.3	90.9	1.0	4	3	
J	39.3	39.4	1.0	1	1	6
K	44.9	39.4	1.1	1	1	4
L	46.8	39.4	1.2	1	1	6
M	31.5	39.4	0.8	1	1	5
N	48.7	52.6	0.9	1	2	6
P	58.5	92.4	0.6	3	3	7
Q	52.9	59.1	0.9	2	2	5
R	166.4	131.3	1.3	4	4	8
S	71.1	59.1	1.2	3	2	7
T	48.6	39.4	1.2	1	1	4
V	45.4	92.4	0.5	4	3	3
W	60.5	92.4	0.7	2	3	
X	45.9	92.4	0.5	5	3	
Z	132.7	92.4	1.4	2	3	
AB	36.5	39.2	0.9	1	1	
AE	70.5	45.5	1.5	2	2	4
Mean	**63.7**	**66.2**	**1.0**	**2.2**	**2.1**	**5.2**

The number of appliances is recorded only for those participants who completed the post-occupancy survey. Even with some heat usage captured in the electricity readings, the mean average usage of 63.7kWh per week is broadly in line with the design estimate of 3,290kWh/annum for a typical property (63.3kWh/week).

Table 7.3 shows the proportion of energy used for electricity only (main power supply and lighting) and for heat (immersion heaters) for the 15 out of 24 properties that had sub-meters.

Table 7.3: BedZED electricity usage by sub-meter

Property	Main % kWh	Lighting % kWh	Total elec % kWh	Immersion (heat) %kWh
A	90.08	2.24	92.32	7.68
B	60.73	0.62	61.35	38.65
E	75.88	4.11	79.98	20.02
G	85.02	3.63	88.65	11.35
H	66.69	1.24	67.92	32.08
J	89.04	4.43	93.46	6.54
K	91.10	1.19	92.29	7.71
L	80.44	1.10	81.54	18.46
M	75.16	2.14	77.30	22.70
N	76.54	1.82	78.36	21.64
Q	83.66	0.59	84.25	15.75
R	84.89	3.29	88.18	11.82
S	84.55	2.76	87.32	12.68
T	69.19	4.79	73.98	26.02
Z	84.50	5.69	90.19	9.81
Min	60.73	0.59	61.35	6.54
Max	91.10	5.69	93.46	38.65
Mean	**79.83**	**2.64**	**82.47**	**17.53**
Std Dev	8.97	1.61	9.45	9.45

If the above analysis is typical for the sample, then 18% of the electricity readings for Phase 2 were heat and not electricity. Adjusting the mean average electricity use in Table 1 gives the results shown in Table 7.4.

Table 7.4: BedZED Phase 2 electricity usage adjusted for heat

	kWh/week	
Phase 2 readings from Table 7.1	63.7	
Adjustment factor from Table 7.2		82.47%
Adjusted Phase 2 result	52.53	
Design	63.3	
Actual usage compared to design		-17%

Table 7.4 shows that the electricity usage at BedZED was 17% lower than the design if the electricity readings are adjusted for heat. Since heat readings from the CHP were not available during Phase 2, it is not possible to calculate the total energy usage.

Analysis of the number of occupants in each dwelling compared to the weekly kWh consumption (adjusted as set out in Table 7.4) was undertaken for the Phase 2 data and the results presented in Figure 7.1. Two outlier properties (R and Z) with a much higher kW/week were excluded from this comparison. Properties R and Z used a mean average of 166.4 and 132.7 kWh electricity per week respectively. Property R was the largest property by floor area in the sample at 154.5m^2 (GIA) and property Z the second highest at 108.7m^2 (GIA). Nine properties in total were the same size as property Z.

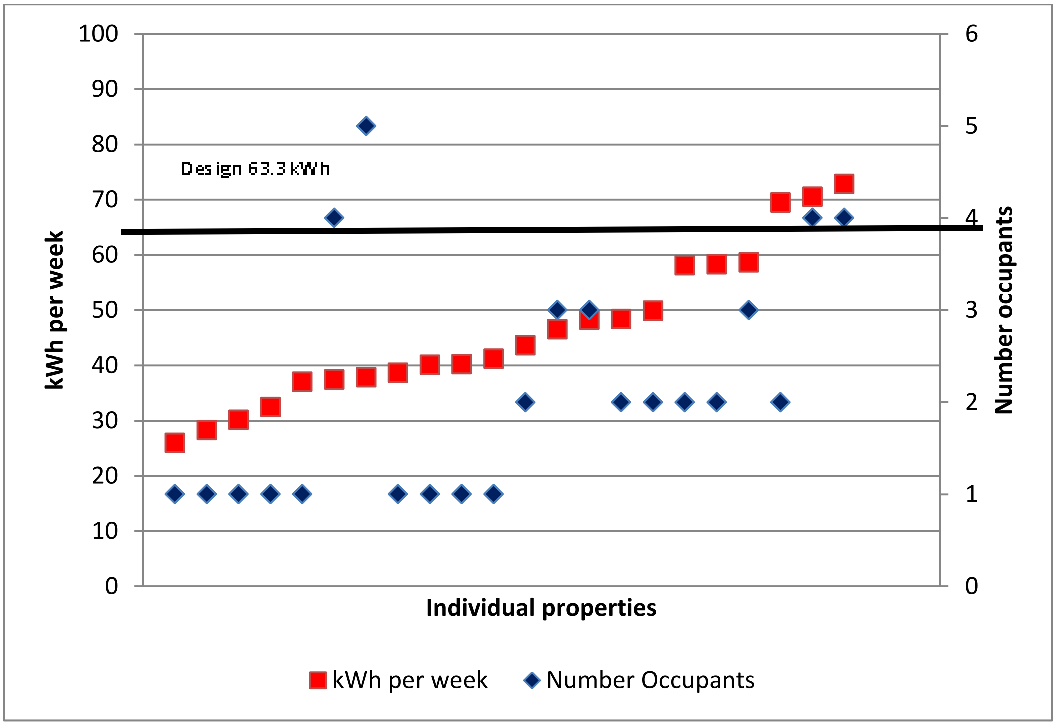


Figure 7.1: BedZED mean electricity consumption compared to number of occupants

As expected, Figure 7.1 illustrates some correlation between the number of occupants and electricity use.

The breakdown of appliances used by the BedZED sample is shown in Figure 7.2. The most popular appliance is a washing machine, followed by a television. "A-rated" white goods were provided as standard in BedZED homes including fridge freezers and washing machines.

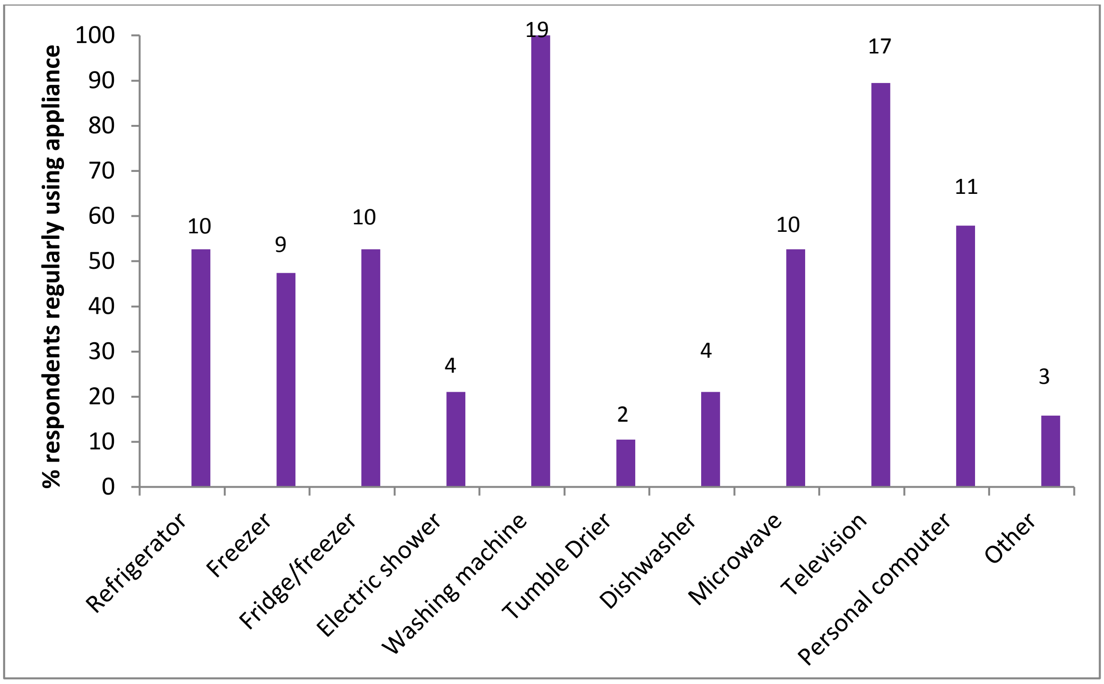


Figure 7.2: Appliance use at BedZED

7.4 Phase 3 Energy Usage at BedZED

For Phase 3, electricity and heat data were analysed for all BedZED dwellings for the two year period from 2011-12 to 2012-13.

7.4.1 Phase 3 Data Issues

Following the completion of Phase 2, some live-work units were converted into dwellings. The data supplied for Phase 3 did not distinguish between live-work units or dwellings. The significance of a change of use from live-work to residential is considered to be that properties were occupied for shorter periods than the original design; live-work units would be expected to be occupied continuously whereas dwellings may be vacant during the day if all occupants were away at school or work.

7.4.2 Phase 3 Energy Usage Results

Table 7.5 summarises heat, electricity and total energy usage per property for Phase 3.

Table 7.5: BedZED Phase 3 Average Energy Usage per property

	Design kWh/annum	2011-12 kWh/annum	2012-13 kWh/annum	Mean kWh/annum	Difference of mean to design
Heat	**4,170**	4,918	5,769	**5,344**	**+28%**
Electricity	**3,290**	2,553	2,740	**2,647**	**-20%**
Total	**7,460**	7,471	8,509	**7,990**	**+7%**

Table 7.5 shows that electricity usage is 20% less than the design (Phase 2 data showed 17% lower than design), heat usage is 28% higher and overall energy usage 7% higher than the design. There is a reasonable level of confidence in these data since the electricity results for Phase 2 and Phase 3 are broadly comparable and the Phase 3 data were used by the energy supplier for billing purposes. The overall energy usage of 7% higher than design is considered to be a successful outcome.

The data shown in Table 7.5 have not been standardised to account for the different sizes of property. Table 7.6 shows the data standardised to m^2.

Table 7.6: BedZED Phase 3 Energy Usage standardised for floor area

	Design $kWh/m^2/annum$	2011-12 $kWh/m^2/annum$	2012-13 $kWh/m^2/annum$	Mean $kWh/m^2/annum$	Difference of mean to design
Heat		76.24	90.72	83.48	
Electricity		40.59	42.77	41.68	
Total	**75**	**116.83**	**133.49**	**125.16**	**+67%**

Table 7.6 gives very different results to the results in Table 7.5 which are not standardised to floor area. Assumptions about property size could be one reason. In the original concept design, a typical BedZED dwelling was assumed to be $100m^2$. This was also the proxy used for the indicative SAP rating. If the $100m^2$ proxy were used for the mean average energy use of 7,990 kwh/annum shown in Table 7.5, this would give a result of 80 $kWh/m^2/annum$, only 7% more than the design of 75 $kWh/m^2/annum$ stated in the concept design documents (Bioregional 1999 p20). However, the difference between the concept design and actual type, number and size of

properties built can be materially different. This is discussed further in section 7.7.1.

The Phase 3 data supplied were not standardised to weather conditions. To assess whether there was any difference between the two years' data and check the reliability of the mean average used above, Table 7.7 shows the data checked against degree days.

Table 7.7: BedZED Phase 3 measured energy usage per degree day

	2011-12	2012-13	Difference	Difference %
Electricity kWh/annum	2,553	2,740	187	+7.3
Heat kWh/annum	4,918	5,769	851	+17.3
Degree days	1,594	2,159		
Electricity kWh/ degree day	1.60	1.27	0.33	-26.0
Heat kWh/degree day	3.09	2.67	0.42	-15.7

Table 7.7 shows that when the data are corrected for degree days, the additional demand for heat in 2012-13 was lower than the colder external temperatures, a reduction of 15% in contrast to the absolute increase in heat demand of 17.3%. Electricity demand is not generally related to external weather conditions but the adjusted data are included here for completeness.

Further analysis was carried out to establish whether there were any differences between property types, standardising data for m^2. Table 7.8 shows the results and these are summarised in Figure 7.3.

Table 7.8: Phase 3 actual energy usage by property type standardised for floor area

Property Size	2011-12 Number Properties	2011-12 kWh/m²/per annum	2012-13 Number Properties	2012-13 kWh/m²/per annum	Mean kWh/m²/per annum
Heat					
1 bedroom	40	86.48	36	108.41	91.03
2 bedrooms	24	92.05	26	84.31	82.28
3 bedrooms	24	45.52	19	66.97	49.04
4 bedrooms	3	59.02	2	81.32	72.04
Electricity					
1 bedroom	40	50.85	36	50.31	52.76
2 bedrooms	24	42.71	26	48.37	56.50
3 bedrooms	24	23.01	23	25.88	24.19
4 bedrooms	3	27.39	2	28.54	31.93
Total Energy					
1 bedroom		137.33		158.72	143.79
2 bedrooms		134.76		132.67	138.78
3 bedrooms		68.53		92.85	73.23
4 bedrooms		86.41		109.86	103.97

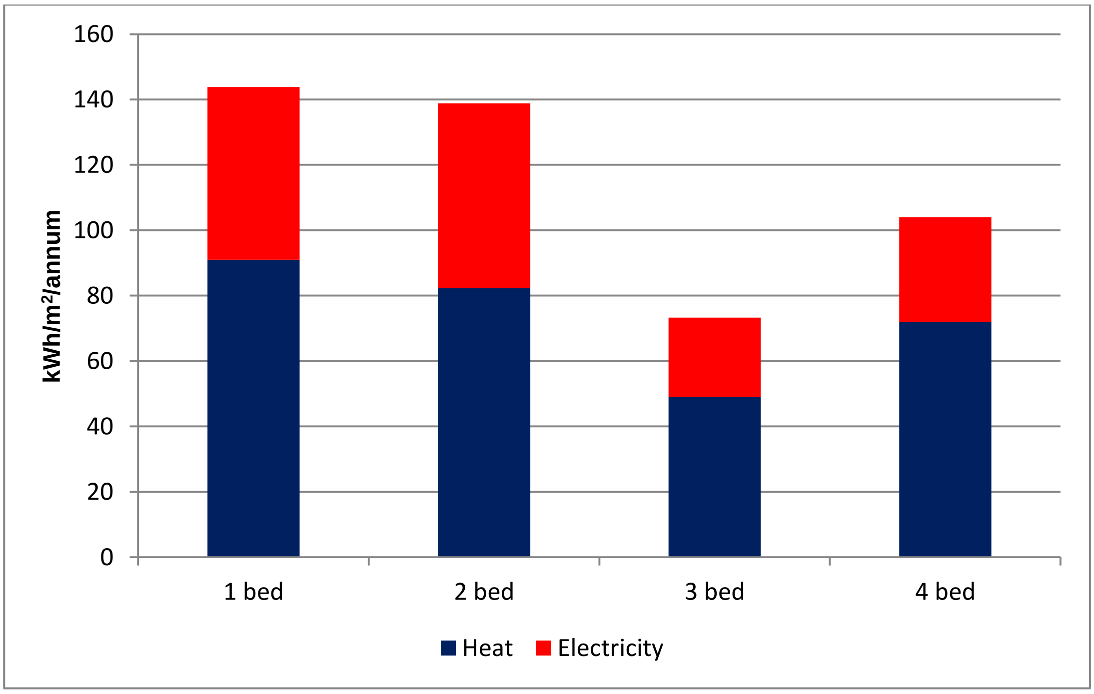


Figure 7.3: Phase 3 energy usage by property type standardised for floor area

It could be argued that the results in Table 7.8 and Figure 7.3 show the impact on energy use of the trend towards smaller households identified in Table 2.1. There is a marked reduction in total energy use by floor area for three- and four-bedroomed properties compared to one- and two-bedroomed properties. However it must be noted that the number of four-bedroomed properties in this sample was very low. The results show the impact of smaller dwellings/smaller households which are far more intensive per m^2 than larger households.

7.5 Overall BedZED Energy Use Summary

Table 7.9 summarises electricity usage for the three phases of this study.

Table 7.9: BedZED Study Electricity Usage for three Phases

	sample size	**kWh/week**
BedZED design		63.3
Phase 1 pre-BedZED	3	130.0
Phase 2 - BedZED	24	52.5
Phase 3 - BedZED	87-91	51.0

The Phase 1 results in Table 7.9 show that for these properties, BedZED comfortably achieved its design intention to reduce electricity consumption by 10%. Phase 2 results are based on all 24 properties included in the BedZED monitoring sample over the near two years' monitoring period. Phase 3 data cover two years' usage and are based on electricity meter readings for the whole development, including some properties that were formerly live-work units. The results of both Phase 2 and 3 confirm that BedZED met the design requirements for electricity use.

Table 7.10 shows heat energy usage for Phases 1 and 3. Heat data was not available during Phase 2.

Table 7.10: BedZED Study Heat Usage for three Phases

	Sample Size	kWh/week
BedZED design		80.2
Phase 1 pre-BedZED	3	175.7
Phase 2 - BedZED	n/a	
Phase 3 - BedZED	83-91	102.8

The results for Phase 3 in Table 7.10 show that BedZED did not achieve the design heat usage of 80.2kWh. However, the higher heat usage is offset in part by the lower electricity consumption. Overall the energy design target for an average dwelling was 7,460 kWh/annum or 143.46 kWh/week. From the Phase 3 data, an average BedZED dwelling achieved 7,990 kWh/annum or 153.8kWh/week suggesting that overall BedZED exceeded the designed energy use by 7%. To put this in context, this is only a third of mean average domestic energy usage of 26,709 kWh in 2011 (Table 2.1).

Analysing the data by floor area suggests that BedZED properties performed worse than the total usage data, see Table 7.11.

Table 7.11: BedZED Total Energy Usage compared to Design, standardised to m^2

	1995 Building Regs	BedZED Design	BedZED Phase 3
Total kWh/m^2/annum Heat and Electricity	163	75	125.2

Table 7.11 shows that, when standardised to m^2, BedZED energy use exceeded the design by 67%, although it performed 23% better than other standard new build properties of the time. As previously discussed, the 75 kWh/m^2/annum design target for energy use at BedZED was based on an indicative property size of 100m^2.

Hodge and Haltrecht's energy usage results compiled seven years after the construction was completed is shown in Table 7.12. This study took meter readings from 56 properties in January and March 2007 and then November and January 2008. Electricity and heat data were compiled for periods of between 126 and 434 days and then aggregated to calculate annual consumption.

Table 7.12: Hodge & Haltrecht BedZED Energy usage

	Mean kWh/dwelling/annum	Mean kWh/m^2/annum
Electricity	2,579	34.4
Heat	3,526	48.0
Total	**6,105**	**82.4**

Source: Hodge & Haltrecht (2009) combined from tables on pp16, 17 & 18

The Hodge results in Table 7.12 show that overall average energy usage at 82.4 kWh/m^2/annum was close to the designed performance of 75 kWh/m^2/annum. Hodge and Haltrecht adjusted the total units of electricity and heat consumed to get a mean average consumption per day and these results were then multiplied by 365 to provide an annual consumption (Hodge & Haltrecht 2009). The results were therefore not corrected for degree days and there is a risk that some of the results were collected principally for the March to November 2007 period, that is, outside the main heating season.

By the time the Hodge study was undertaken, hot water was being supplied by a communal gas-fired boiler and circa 20% of electricity was being generated by the photovoltaics with the remainder being taken from the national grid although there continued to be problems with the meters, some of them being out of action.

Figure 7.4 plots Phase 3 energy usage against design, standardised to m^2, and compared to the Building Regulations standard applicable at to BedZED and the Hodge results.

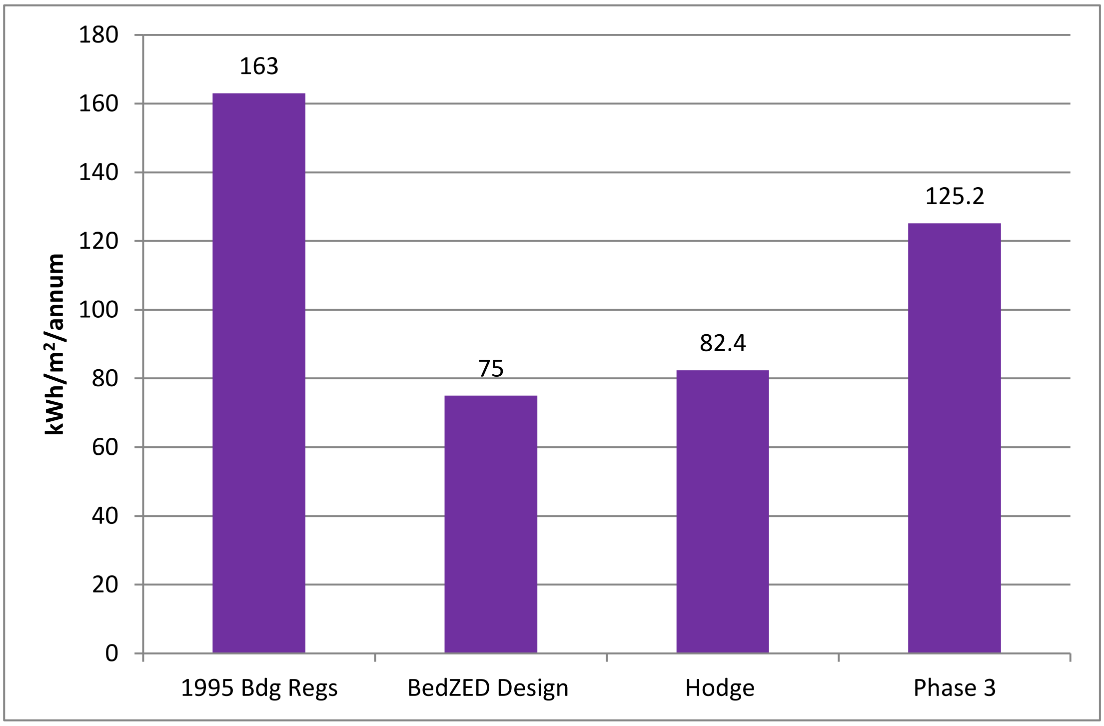


Figure 7.4: Design and actual energy use at BedZED

Figure 7.4 shows that BedZED performed better than the Building Regulations in force at the time of design but it did not meet the design performance of 75kWh/m^2 per annum stated in the design concept documents.

7.6 BedZED Energy Performance Certificates (EPCs)

Energy Performance Certificates (EPCs) were mandated in 2007 for all dwellings sold or rented and comprise two ratings, an energy efficiency rating and an environmental impact rating, which measures CO_2 emissions.

By November 2014, 43 EPCs for BedZED undertaken by 25 different EPC assessors had been uploaded to the national EPC Register, hosted by the Landmark Information Group. This represents approximately half of the original 82 dwellings (some live-work units were subsequently converted to dwellings). A data summary for the 43 EPCs is provided at Table 7.13.

Table 7.13: Summary of BedZED EPCs

	Floor Area	Energy Efficiency Rating		Environmental Impact		Energy Use kWh/m^2		CO_2 emissions tonnes/annum	
	m^2	Current	Potential	Current	Potential	Current	Potential	Current	Potential
Mean	67.5	76.5	78.8	80.1	81.0	175.4	174.5	1.7	1.7
Max	114.0	95.0	100.0	108.0	111.0	412.0	370.0	5.0	4.5
Min	34.0	26.0	32.0	48.0	52.0	34.0	0.0	-0.9	-0.4
Std Dev	24.4	11.2	10.6	12.7	12.1	77.2	84.3	1.2	1.1

An analysis of the certificates shows a surprising variation of ratings, given that BedZED was built to a single design standard. While occupiers may have made some alterations to BedZED properties since moving in, it is not considered likely that occupant alterations would have resulted in such diverse ratings. Figures 7.5 and 7.6 show the energy efficiency and environmental impact ratings respectively for the 43 certificates and Figure 7.7 combines the results into a single chart.

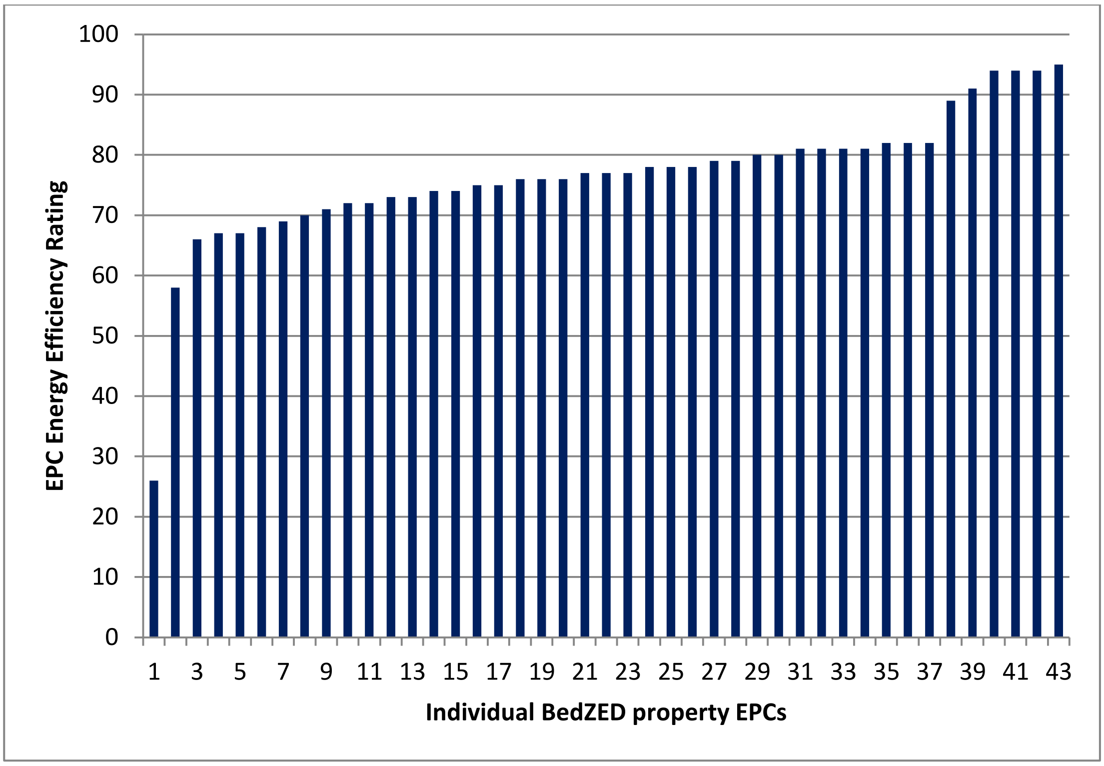


Figure 7.5: Energy Efficiency Ratings from BedZED EPCs

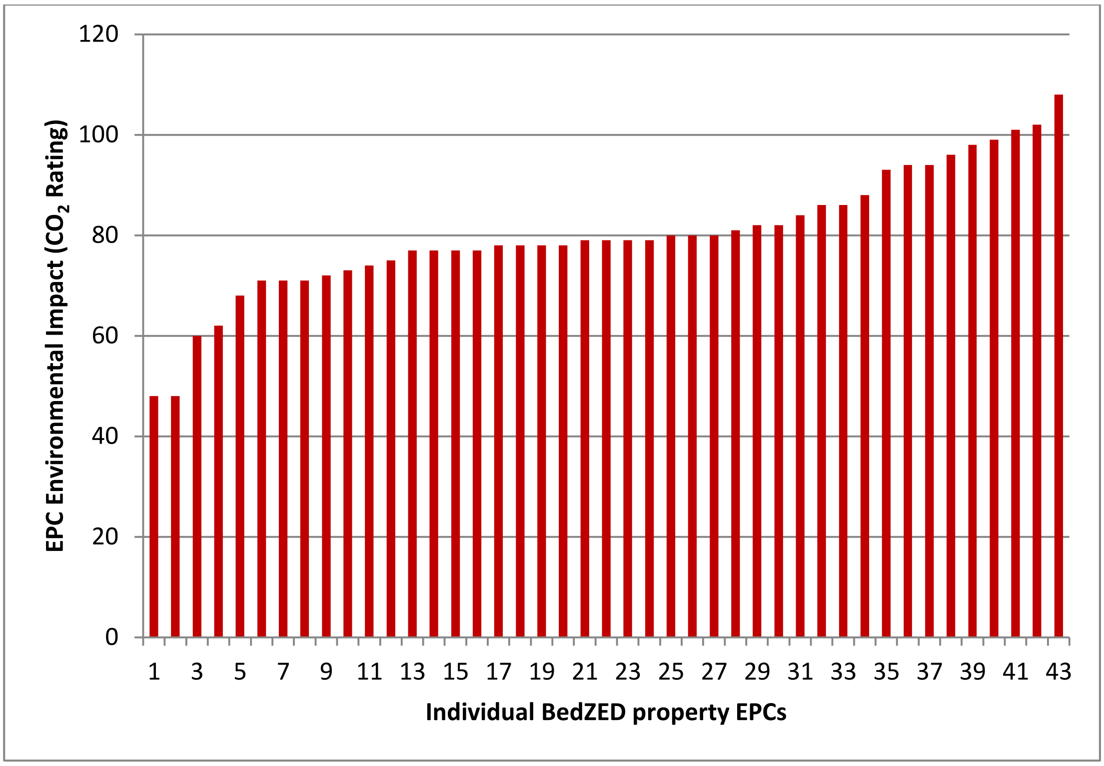


Figure 7.6: Environmental Impact (CO_2) Ratings from BedZED EPCs

Figure 7.5 shows that the lowest energy efficiency rating was 26 and the highest 95. Figure 7.6 shows that Environmental Impact (CO_2) ratings range from 48 to 108. While the distribution of ratings looks broadly similar for both sets of ratings, there is some variation between the two different sets of ratings. Figure 7.7 consolidates the ratings into a single chart and this shows the differences at a property level.

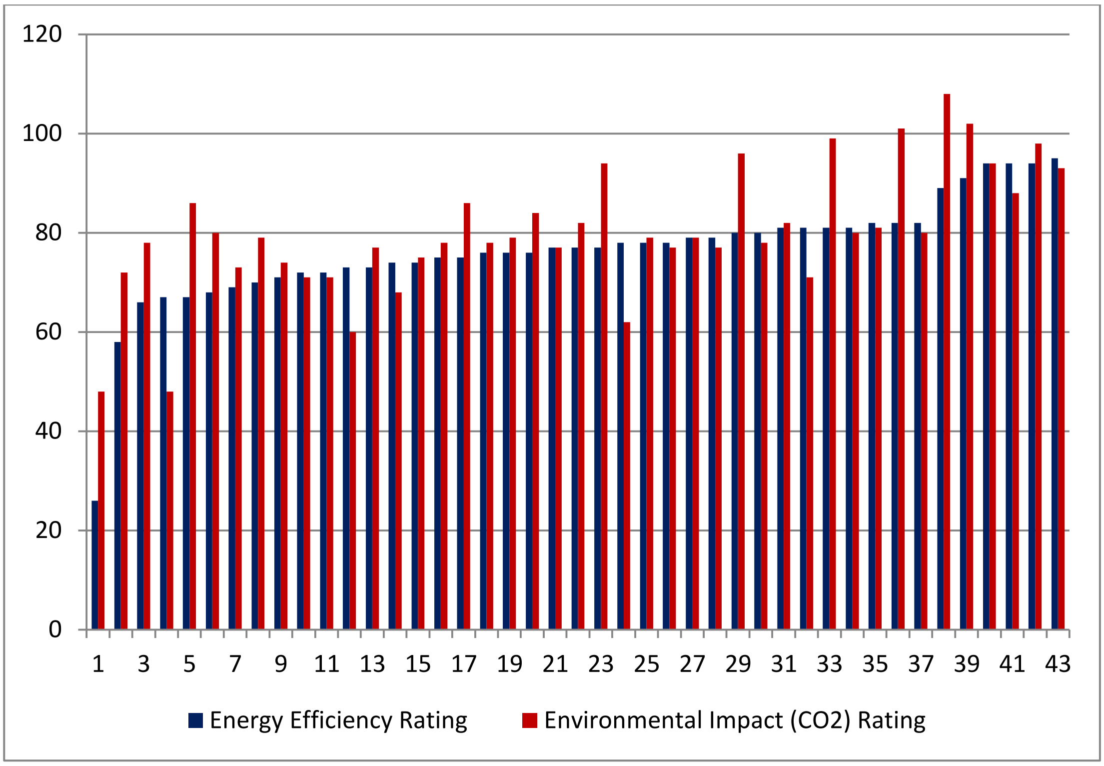


Figure 7.7: Combined Energy Efficiency and Environmental Impact (CO_2) Ratings from BedZED EPCs

From Figure 7.7, it can be seen that, for example, the highest ratings for environmental impact are not the same properties that score highest for energy efficiency. Property 38 has the highest environmental impact rating and property 43 has the highest energy efficiency rating.

To provide some context, the number of new dwellings registered in 2013 (DCLG 2014c) was analysed. Of the 141,467 certificates issued, 68% were given an energy efficiency rating A (the highest rating) or B compared to 30% (13 number) of the BedZED dwellings which were completed in 2002. 83% of the new dwellings registered were given an environmental impact rating based on CO_2 emissions of A (the highest) or B compared to 37% (16 number) of BedZED dwellings. It is worth noting that BedZED would be treated as existing dwellings and not new-build by EPC surveyors.

The overall ratings for the BedZED dwellings are summarised in Table 7.14.

Table 7.14: BedZED EPC Ratings Summary

Energy Efficiency rating	A 92+	B 81-91	C 69-80	D 55-68	E 39-54	F 21-38	G 1-20	Total
Number	**4**	**9**	**24**	**5**	**0**	**1**	**0**	**43**
Environmental Impact rating	A 92+	B 81-91	C 69-80	D 55-68	E 39-54	F 21-38	G 1-20	
Number	**9**	**7**	**22**	**3**	**2**	**0**	**0**	**43**

Variations between assessors' ratings of energy used by BedZED properties were also found. Figure 7.8 shows that the ratings ranged from 34 kWh/m^2/annum to 412 kWh/m^2/annum. The actual kWh/m^2/annum calculated from Phase 3 data and the design kWh/m^2/annum are included by way of comparison.

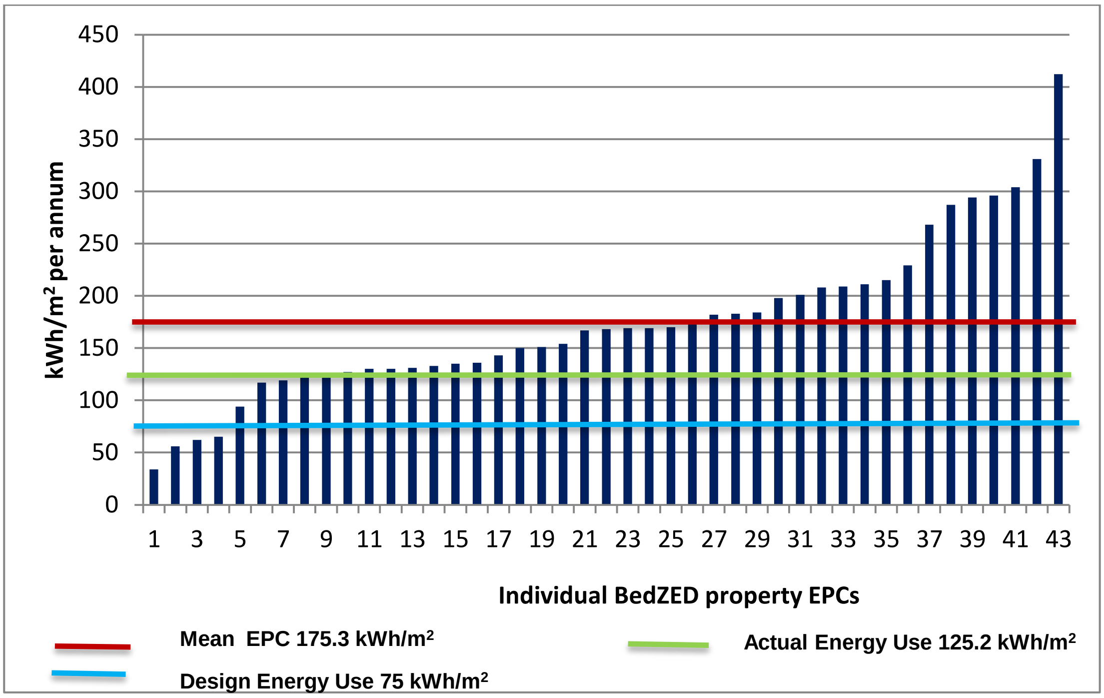


Figure 7.8: Estimated Annual Energy Use from BedZED EPCs

It is interesting that Figure 7.8 shows that the mean EPC rating at 175.3 kWh/m^2/annum is higher than 163 kWh/m^2/annum, the standard produced by new dwellings built to the 1995 Building Regulations in operation at the time BedZED was built. One reason for such variation could be the unique design features of BedZED which energy assessors may not be familiar with, for example, the centralised boilers providing heat principally in the form of hot water and the absence of radiators and traditional controls within the dwellings. For example, EPCs carried out by different assessors were compared for two semi-detached houses with similar floor areas ($81m^2$ and $88m^2$). One assessor calculated the energy use at 412 kWh/m^2/annum (property 43 in Figure 7.8). A second assessor calculated the energy use to be 65 kWh/m^2annum (property 4 in Figure 7.8). If a ±10% tolerance were applied to the EPC estimates of energy use (actual energy use 125 kWh/m^2annum), 11 EPCs are within tolerance, which represents only 26% of the total analysed.

Table 7.15 illustrates a similar variation in the assessment of energy efficiency performance in the component elements of BedZED construction.

Table 7.15: Building Element Energy Efficiency from BedZED EPCs

	1* Very Poor	**2* Poor**	**3* Average**	**4* Good**	**5* Very Good**
Walls				41	2
Roof			14	6	
Windows			9	34	
Main Heating	6	1	2	34	
Main Heating Controls	14	22	3	4	
Hot Water	5	4	8	24	2
Count	**25**	**27**	**36**	**143**	**4**

A more detailed analysis of the description of building elements given in the EPCs highlights considerable variability in element descriptions: ten certificates stated properties were fully triple glazed compared to 33 that stated double glazing. It is surprising that, given that the windows were designed to a very high specification and all windows being triple glazed except the double glazed windows on the southern aspect (average U-value $1.0W/m^2K$) that none of the certificates assessed the windows as Very Good.

Table 7.16 shows the considerable variability in the way in which assessors described the main heating systems in the BedZED properties.

Table 7.16: Description of Main Heating System from BedZED EPCs

Number	Description in EPC
4	No system present, electric heaters assumed)
1	Electric storage heaters
1	Room heaters, electric
2	Boilers and radiators, electric
1	Warm air, electric
24	Community scheme
6	Community scheme with CHP
2	Community scheme with CHP and mains gas
1	Air source heat pump, warm air electric
1	Ground source heat pump, warm air, electric

It is notable that only two assessors specifically cited that the central boiler system uses mains gas although the assessors that produced the 30 EPCS that cite Community Scheme and Community scheme with CHP may have assumed they were gas-fired but they did not select that more detailed description when compiling the EPC. In contrast, nine assessors state that the heating system is electrically powered (the first five descriptions on the list above).

The component with the most varied descriptions in the BedZED EPCs is heating controls. Table 7.17 shows this variability.

Table 7.17: Description of Main Heating Controls from BedZED EPCs

Number	Description in EPC
4	None
1	No time or thermostatic control of room temperature
1	Manual charge control
2	Room thermostats only
3	Programmer and room thermostat
6	Flat rate charging, room thermostat only
7	Flat rate charging, no thermostatic control of room temperature
7	Flat rate charging, programmer and room thermostat
2	Flat rate charging, programmer, no room thermostat
6	Charging system linked to use of community heating, room thermostat only
1	Charging system linked to use of community heating, programmer and room thermostat
3	Unit charging, programmer and TRVs

The absence of a traditional heating system and heating controls is unusual for recently constructed buildings but a simple internet search would quickly provide clues to the unique scheme design.

Another factor that may explain these results is the format of the Reduced Data SAP (RdSAP) method for existing dwellings (DECC 2013c) which is used to calculate EPCs for existing buildings. The fields provided do not lend themselves easily to BedZED element features. For example, in Table S6 Wall U-values in the RdSAP (DECC 2013c p131), the maximum cavity filled thickness is 200mm and the best possible U-value in the whole table is 0.12 $W/m^2/K$ compared to the 300mm filled cavity and 0.1 $W/m^2/K$ of the BedZED wall design. There is a similar challenge with ground floor insulation (Tables S11 and S12), with the best performing choice being 150mm of insulation at a U value of 0.22 $W/m^2/K$ compared to the 0.1 $W/m^2/K$ of the BedZED floor design which is also achieved by 300mm of insulation. And for heating controls, the SAP 2012 guidance directs assessors to Section 9.14 which sets out a series of conditions that must be met for time and temperature zone control. These conditions assume, for example, that if hot water is heated by the same device as space heating, then there are separate controls. It is possible to see that assessors might find it challenging to assess the heating system at BedZED using this standard format.

Eight of the 43 properties were included in the BedZED Phase 2 sample used in this study and the results for these eight properties are summarised in Table 7.18.

Table 7.18: EPCs issued for Phase 2 BedZED properties

Property	Date of Certificate	Total Floor Area m^2	Energy Efficiency Rating	Environmental Impact Rating	Energy Use kWh/m^2	CO_2 emissions tonnes/year
A	29/01/2009	109	81	80	133	2.3
B	23/03/2011	47	82	101	198	-0.1
C	01/12/2011	35	71	74	229	1.6
Q	16/09/2009	67	73	60	331	3.4
S	11/06/2012	58	69	73	182	2
T	25/05/2011	34	73	77	208	1.4
V	19/03/2010	85	58	72	215	2.8
AB	10/01/2013	46	75	86	170	0.9
Mean		**60.1**	**72.8**	**77.9**	**208.3**	**1.8**

Table 7.18 shows a range of energy efficiency ratings from 58 to 82 and energy use from 133 kWh/m^2 to 331 kWh/m^2 for the sample of eight. The mean average energy use for the 43 properties is 175.4 kWh/m^2 and for the sample of eight above it is 208.3 kWh/m^2. This contrasts with the Phase 3 results from this study which show that the overall energy use for BedZED is 125.2 kWh/m^2. The EPCs are overstating the amount of energy used by BedZED dwellings.

There was also some discrepancy between property sizes with the sizes on the EPCs varying by -13 to +20%. This would also affect the calculation of the kWh/m^2, adding to the recurring issue of how property sizes are calculated in energy assessments. The EPC for property B states that the property contributes -0.1 tonnes of CO_2 emission per annum and that the property benefits from biomass community heating and solar PV. This is incorrect as at the time of the EPC, the biomass CHP had been switched to a gas-fired CHP. The surveyor was therefore incorrect in his assumptions.

In conclusion, there is inconsistency between assessors completing EPCs. Many of the surveyors do not view the absence of a conventional space heating system as a positive attribute and score the lack of controls over the heating and hot water systems poorly. While these scores appear to be driven primarily by the way that the EPC standard template is set up, it is interesting to compare these low scores to the BedZED participants' views about their control over heating and hot water systems in the occupancy surveys' results in Chapter 10.

7.7 Energy Usage Discussion

The trend towards smaller households and the potential impact on overall energy demand were discussed in Chapter 2. The analysis of BedZED energy usage illustrates the impact of single person living and that potentially smaller households will not proportionately use less energy per m^2. There are some possible explanations for the difference between the design assumptions and actual usage and these are discussed in the following sections.

7.7.1 Property Sizes

For the initial BedZED energy design, the engineers used a schedule of property areas provided by the architects to calculate energy requirements making high level assumptions about the number of occupants and floor areas. The aim was a realistic average to allow sizing of the plant, pipework, etc (Twinn 2014). It is difficult subsequently to apply these assumptions directly to actual properties and occupants. For example the engineers refer to a flat with a maximum capacity of two people and a predicted number of occupants as one. For this study, this is assumed to be a one-bedroomed flat.

Property sizes are calculated for different purposes. The engineering calculations were to enable the CHP to be sized. Sizes in the architectural drawings needed to be more accurate since these would be used to build the scheme. And properties can be measured in different ways as discussed in Chapter 6, including Net Internal Area (NIA) used for Phase 1 NHER surveys, Gross Internal Area (GIA) used in the architectural drawings and the method used for SAP which is very similar to GIA (but not explicitly described as such).

The different floor areas used for the BedZED scheme are shown in Table 7.19. This also includes the property sizes published in Corbey's 2005 dissertation and included in the accommodation schedule attached at Appendix 1. Corbey's measurements were supplied by BioRegional post-construction. His schedule indicates that the property sizes vary according to the location in the development and they are assumed to be taken from as-built drawings because they are broadly comparable to the construction drawings measurements.

Table 7.19: BedZED floor areas

Property Type	Energy Design Calculations[1] m^2	Construction Drawings[2] GIA m^2	Corbey[3] GIA m^2 Unit sizes
1-bed	48.5	46.28	47.5; 51.9; 53.9; 59.4; 71.6
2-bed	60	64.68	64.5; 68.8; 77.1
3-bed	60; 73.5; 75.5	108.3	100.5; 106.96; 107.1
4-bed	73.5; 75.5	154.5	141.35
Total Residential	**5,278**		**7,802.7**
Office	85	n/a	77.4; 79.9
Total commercial	**1,275**		
Other uses	1.062		1,404.6
Total BedZED	**7,615**		**9,207**

[1]from Arup calculation spreadsheet (Bioregional 1999) based on area schedule from BDA, May 1999
[2]Taken from BDA measurements on construction drawing schedules, October 2001
[3]Taken from Corbey 2005 dissertation, measurement method not specified, assume as-built.

Table 7.19 shows that the original concept energy design calculations for the development were based on a far smaller buildings footprint of 7,615m^2 than the actual built development at 9,207m^2. Although there are differences between the construction drawing measurements and the as-built drawings, the unit sizes are broadly aligned. However when compared with the property sizes assumed for the engineering calculations, there is a considerable variation between the size of the larger dwellings which are understated in the engineering calculations resulting in an under-estimate of the residential footprint of circa 21%. The engineering calculations did include an additional 20% contingency for sizing the CHP and so this is unlikely to have resulted in an undersized CHP system. However, this comparison does illustrate the challenge in producing reliable data about energy use at the early feasibility stage. Then as designs are developed in the detailed design stage, the overall size of buildings and therefore the heat and electricity demand can change considerably from original assumptions at the feasibility stage.

Section 7.5 found that energy usage was broadly in line with design but the usage per m^2 was found to be higher than the design metric of 75 kWh/m^2/annum. That design metric was modelled on a typical dwelling size of 100m^2. It can be seen from Table 7.19 that the total residential floor area of 5,278m^2 used in the energy design calculations was understated since that floor area would equate to 53 dwellings, much lower than the actual 82 dwellings that were built.

The difference between the engineering estimate of size and the others does not explain the higher actual kWh/m^2 compared to design. If anything, the smaller footprint for the engineering calculations would have increased the design kWh/m^2. What this does show is the need to update design targets that are set at an early stage of the design using an indicative number of properties and an indicative dwelling size as the design is developed.

7.7.2 Number of Occupants

The monitoring data and surveys undertaken in Phase 2 were a sample of the whole development, 24 dwellings out of a total of 82. Some information about the number of occupants was collected in the post-occupancy surveys but the information was not comprehensive. However, the Corbey study included the number of occupants at BedZED in 2005 and so his more comprehensive data are compared to the assumptions made in the engineering calculations. The number of occupants is expected to have a direct impact on the amount of hot water consumed and some impact on energy used for appliances. Conversely, fewer occupants than modelled could result in lower internal heat gains requiring booster space heating in the heating season. A comparison of the design assumptions of number of occupants and the actual number of occupants is presented in Table 7.20.

Table 7.20: BedZED number of occupants

Property type	**Energy Design Calculations**[1]	**Corbey**[2]
Residential	213	209
Offices (live-work)	106	33
Other uses	80	24
Total	399	266

[1]from Arup calculation spreadsheet (Bioregional 1999)
[2]from Corbey (2005)

Table 7.20 shows that, by 2005, the actual number of people occupying dwellings at BedZED was broadly in line with the design assumptions; 209 people in occupation compared to the original assumption of 213. However, the number of people occupying live-work units and using the other facilities such as the nursery and offices was considerably lower than the assumptions made at the design stage. While different property uses impact differently on electricity and heat consumption, overall a lower live-work occupancy level would be expected to reduce energy consumption since the units would not be occupied all the time. And a number of the live-work units were converted to dwellings by the time Phase 3 was undertaken.

7.7.3 Occupant Behaviour

Part of the energy strategy for BedZED was to ensure that fuel dials were visible in the dwelling in order to raise awareness of fuel consumption and encourage reduced fuel use. Darby set out a commonly shared view that that providing occupants with feedback about how much energy they use helps to drive energy efficient behaviour. She stated that local displays could give a benefit of improved understanding and control, although this would be partly dependent on the quality of display (Darby 2008).

Figure 7.9 shows the location of the fuel dials in a typical BedZED kitchen. During Phase 2, just electricity readings were available; heat readings were not available owing to the operational issues with the CHP. Even by 2007, in their follow-up study of BedZED Seven Years on, Hodge and Haltrecht (2009) reported that there were problems with the meters within BedZED dwellings.

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Figure 7.9: Fuel dials on display in typical BedZED kitchen

In the Phase 2 post-occupancy survey, BedZED participants were asked whether the fuel dials made a difference to their use of fuel and appliances and the results are in Figure 7.10 and 17 responses were received.

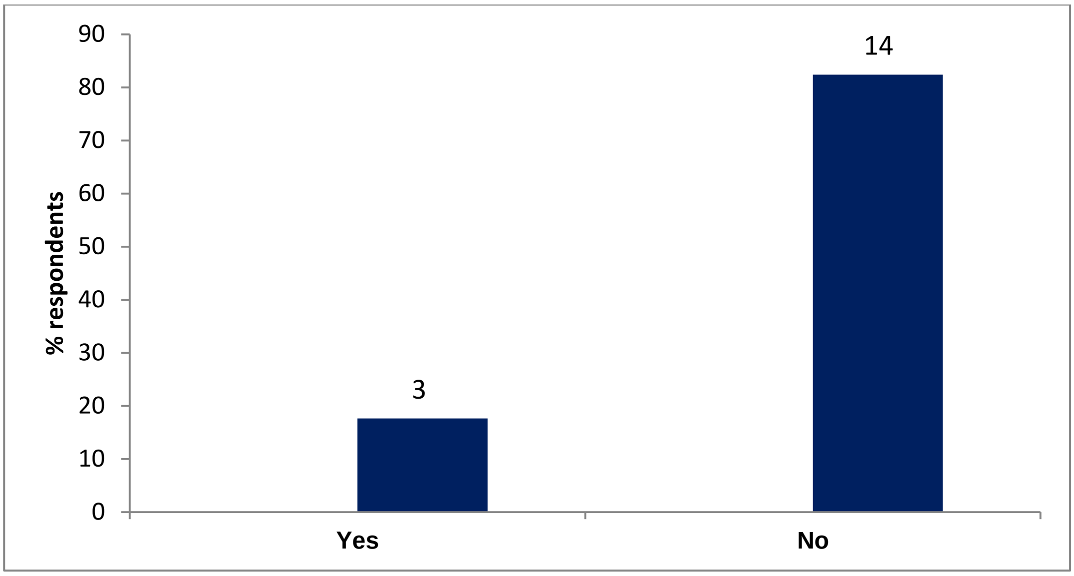

Figure 7.10: BedZED occupant survey: Does having the fuel dials on display make a difference to your use of fuel and appliances?

82% of respondents said that the dials made no difference to their use of fuel and appliances. This seems very high. It could be that, given their decision to move to BedZED in the first place, the participants were already very aware of their energy consumption. One participant stated that the dials were not on display, just accessible and another participant said that the question was not applicable as there were no sub-meters. Another explanation could be that participants were more inclined to take account of their energy use via their bills.

7.8 Energy Usage Conclusions

The results presented in this chapter provide evidence to answer the first three research questions for this study: how do the constructed units perform compared with theoretical design performance; what is the difference if any; and why is there a difference.

BedZED comfortably achieved its aim to reduce electricity usage by 10% compared to standard dwellings, achieving electricity usage of 52.53 kWh/week at BedZED (Table 7.4) compared to 73.67 kWh/week achieved at typical properties built to the 1995 Building Regulations (Table 4.5).

Total energy use was 7% higher than designed at 7,990 kWh per property compared to the design of 7,460 kWh (Section 4.11), principally because of higher than expected heat usage but this is considered to be a successful outcome.

The 125 kWh/m^2/annum achieved at BedZED was considerably higher than the 75 kWh/m^2/annum design target, but lower than the typical new building standard of 163 kWh/m^2/annum of the time. The BedZED total energy usage is broadly in line with the Passivhaus standard of 120 kWh/m^2/annum for total energy demand, discussed in Chapter 2 (Schnieders 2003, Cutland 2012), and is 40% less than the mean average estimates in the BedZED EPCs. The 75 kWh/m^2/annum design target should have been updated as the design was developed and demonstrates the importance of design targets being thoroughly tested and assured and updated during design development. The average 175.3 kWh/m^2/annum recorded by the BedZED EPCs overstates the actual energy use by 40%.

The analysis in this chapter illustrates the sensitivity of real performance data to variables that are unknown at the early design stage of a project when design assumptions have to be made. It also illustrates the importance of analysing the data from a number of perspectives: total usage data are vital but the relative efficiency of usage to property size and number of occupants is also important given the changing demographics discussed in Chapter 2. The effect of external weather conditions is important particularly if the monitoring data are limited to one or two years, since these may not be typical. This analysis illustrates the limitations of data collected over a two year period since trends cannot be determined with such a relatively small dataset.

Chapter 8 Internal Temperatures Results and Analysis

8.1 Introduction

Section 4.20 discussed the original design target for BedZED, which was to achieve an internal temperature of 20ºC. This chapter discusses the results obtained during the Phase 2 monitoring period to help answer the research question of whether the constructed units perform compared to design with regards internal temperatures achieved.

8.2 Winter Internal Temperatures

Typically, housing developments designed with traditional whole house heating systems are designed around the concept of the heating season where the dwelling's heating system operates once external temperatures fall below a certain point. The unmodified heating degree day concept assumes that whole house heating systems will operate once the external temperature falls below 15.5°C (Perry & Hollis 2005). This study examines, inter alia, whether this approach fits with very well insulated homes like BedZED which are designed without standard whole house heating systems and associated thermostatic controls.

8.2.1 BedZED Winter Internal Temperatures

Figures 8.1 and 8.2 show mean internal temperatures recorded in bedrooms and living rooms when the external temperature was 5ºC. Three properties, Z, H and R had additional data loggers in second bedrooms.

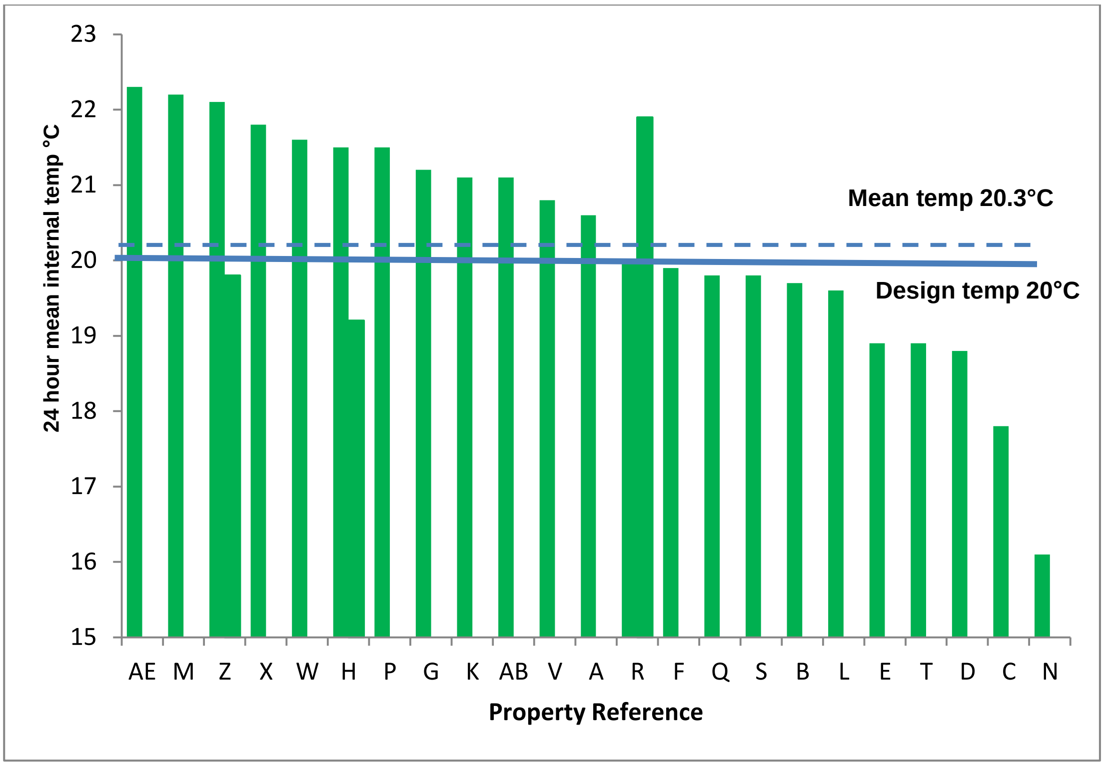

Figure 8.1: Internal bedroom temperatures standardised to external temp of 5°C

Figure 8.1 shows that the design temperature was achieved in 14 bedrooms and not achieved in 12 bedrooms with an overall mean across the sample of 20.3ºC. It is also notable that 13 properties achieved temperatures higher than the design temperature of 20ºC. An analysis of the occupant survey completed at the end of the Phase 2 monitoring period was undertaken to assess whether the higher temperatures were a consequence of occupants using additional heating. However, participants AE, Z, X, W and H did not answer this question and participants M, P, K, V and A stated that they did not use additional forms of heating. Property G stated that they used heating in one bedroom but only while there was a defective skylight. The only participant in the survey who answered this question positively with regards additional heating in bedrooms was property S. They stated that they used additional heating in the bedroom for eight hours a day. At a mean average temperature of 19.8ºC, that is just below the design temperature.

Figure 8.2 shows that the mean temperature achieved in living rooms over the monitoring period when the external temperature was 5ºC was 21.4ºC, which exceeded the design temperature of 20ºC.

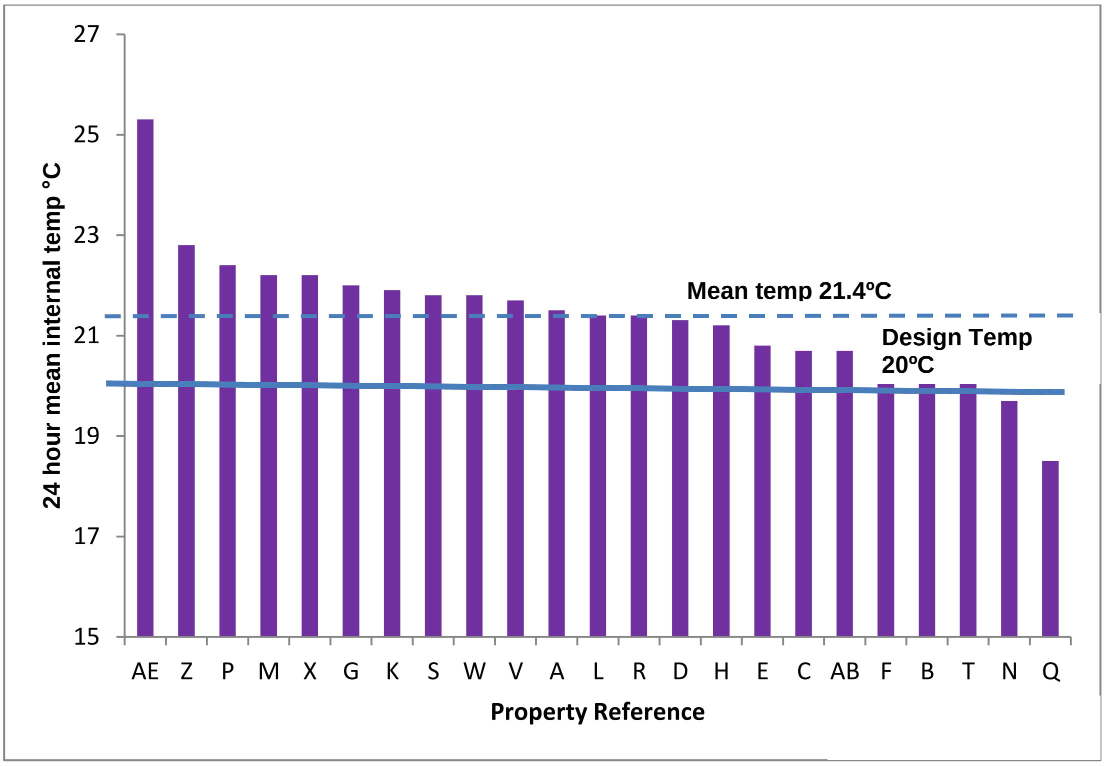

Figure 8.2: Internal living room temperatures standardised to external temp of 5°C

Figure 8.2 shows that the design temperature was achieved in all living rooms apart from two properties. The design temperature was more consistently achieved in the living rooms compared to bedrooms.

Overall, across all the sampled properties, the average temperature achieved in living rooms when the external temperature was 5ºC was 21.4 ºC and the average temperature achieved in bedrooms when the external temperature was 5ºC was 20.3 ºC. BedZED was therefore successful in achieving the design heating temperature in living rooms and bedrooms during the heating season.

Table 8.1 shows the range of average internal temperatures together with the statistical standard deviation and confidence intervals (assuming 95%

confidence level). The standard deviation and confidence interval measures provide a further illustration of the consistency of living room temperatures compared to bedroom temperatures during the heating season.

Table 8.1: Summary of internal temperatures standardised to external temp of 5°C

	Living Room	**Bedroom**
Mean °C	21.4	20.3
Lowest °C	18.5	16.1
Highest °C	25.3	22.3
Median °C	21.4	20.3
Standard Deviation	1.29	1.49
Count	23	26
Confidence Interval 95% ± °C	0.53	0.57

Table 8.1 shows that the range between maximum and minimum in mean temperatures is 6.2ºC for bedrooms and 6.8ºC for living rooms. A one-way ANOVA statistical test was undertaken between mean bedroom and living room temperatures. The resulting p value of .012 demonstrates that the difference between the different room types is significant. Living rooms are likely to have more solar gains since they all faced south and are enclosed by sunspaces which provide a buffer to external temperatures. They may also have had more incidental gains from electrical appliances sited in living rooms which give off heat. Some living rooms are open plan to kitchens and the heat loss from cooking may also be a contributory factor to higher temperatures and greater range of temperatures. Occupancy levels may be higher in living rooms with the corresponding incidental gains.

8.2.2 Comparison of Winter Temperatures at BedZED with other studies

The BedZED winter internal temperature results were compared to results from the 1990 and 2005 Milton Keynes (MK) studies; the Warm Front (WF) programme both pre- and post-intervention and the 2011 Energy Follow Up Study (EFUS); and the Brixton super-insulation programme which had living room data only. The BedZED data were collected exclusively for this study and the comparative data were sourced from the CaRB study. Figure 8.3

compares mean internal temperatures achieved at BedZED with other studies standardised to an external temperature of 5ºC.

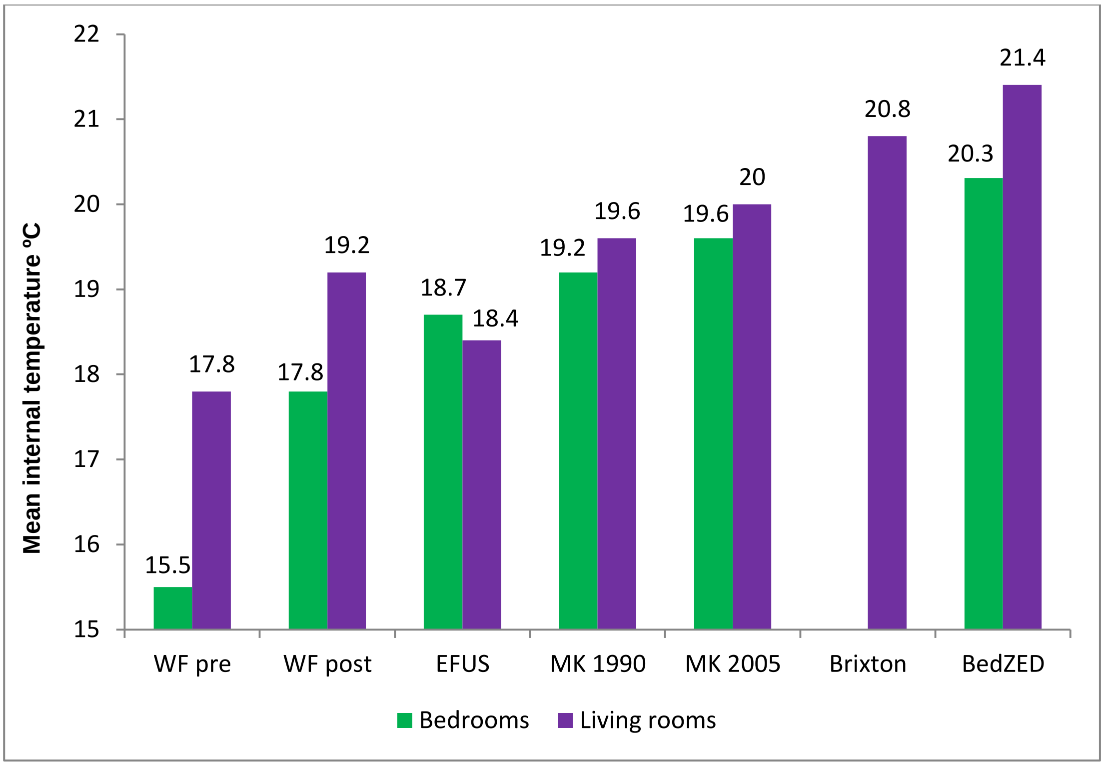

Figure 8.3: Mean internal temperatures across studies standardised to external temperature of 5°C

Figure 8.3 shows that, for both living room and bedroom comparisons, BedZED achieved the highest internal temperatures of the studies. Milton Keynes had been constructed some years before BedZED and did not incorporate the extent of passive design features that BedZED did. Conversely, Milton Keynes was installed with gas heating systems unlike the design approach at BedZED which eliminated the need for conventional heating systems. Warm Front included packages of insulation upgrades and modern heating systems but, as a retrofit project, could not incorporate all the elements of passive design such as the building orientation and construction of a sunspace that were included at BedZED. The Brixton houses were designed as super-insulated dwellings and built in 1991 although a comparison between Brixon (Table 3.2) and BedZED (Table 4.2) shows that BedZED was designed with higher U values.

In summary, the results of this comparison validate the design approach taken at BedZED and demonstrate that the properties performed well in the heating season compared to other energy efficiency interventions.

8.3 Summer Internal Temperatures

As discussed in section 4.20, a specific summer design temperature was not set in the BedZED concept design. In order to analyse the BedZED results, the CIBSE benchmarks of 26°C for bedrooms and 28°C for living rooms are adopted, recognising that the occupied hours data were not available which is required to assess overheating using the CIBSE approach.

The Phase 2 monitoring period included the hot spell of August 2003. Using Wright's definition of the 2003 hot spell to be the 3rd to the 13th August inclusive (Wright 2005), Table 8.2 and Figure 8.4 show the external temperatures recorded at the BedZED weather station during the hot spell period.

Table 8.2: External temperatures °C recorded at BedZED during August 2003 hot spell

Date	3 Aug	4 Aug	5 Aug	6 Aug	7 Aug	8 Aug	9 Aug	10 Aug	11 Aug	12 Aug	13 Aug
Max	30.3	31.1	30.7	35.7	29.5	30.7	34.0	37.0	34.4	31.1	29.5
Min	11.0	14.5	17.1	20.2	18.3	17.1	17.9	17.9	19.4	18.3	17.9
Mean	20.9	22.7	23.5	27.9	24.5	24.4	26.4	27.4	26.6	24.5	23.5

By way of comparison, Met Office records show that the highest temperture recorded in August 2003 was 38.5°C at Brogdale in Kent on 10 August 2003 (Met Office 2011).

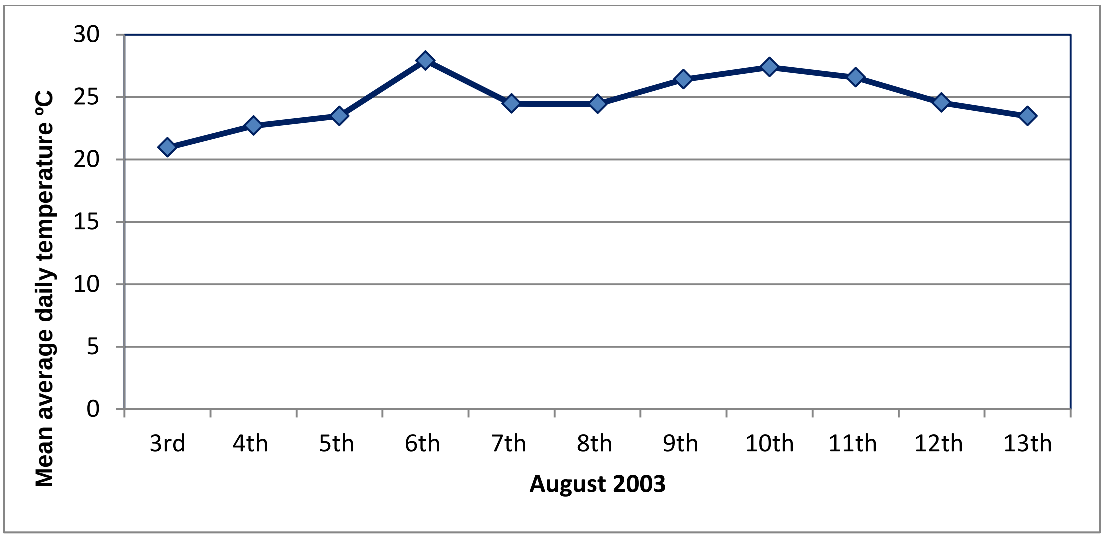

Figure 8.4: Mean external temperatures °C recorded at BedZED during August 2003 hot spell

8.3.1 Summer Temperature Results at external temperature of 20ºC

Figure 8.5 shows BedZED summer mean internal temperature results for living rooms when the external temperature was 20°C.

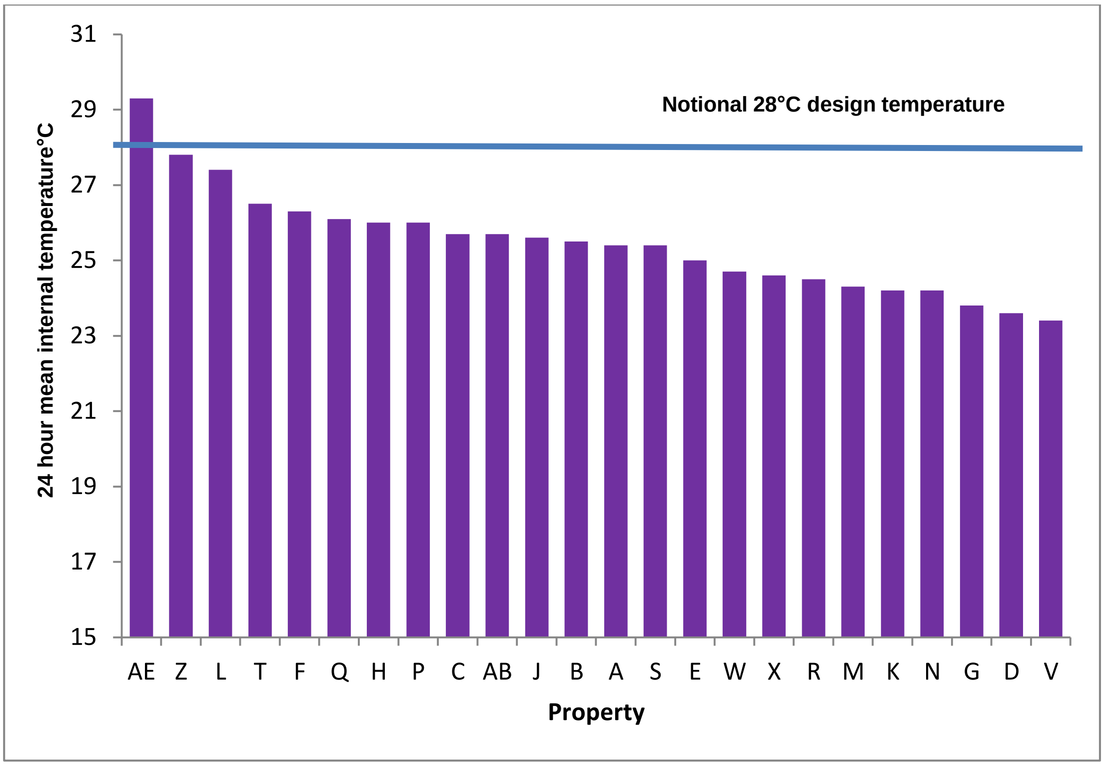

Figure 8.5: Mean living room temperatures standardised to external temp of 20° C

Figure 8.5 shows that all living room temperatures were above the ambient temperature of 20°C by at least 3°C and one property (AE) was 9°C above the ambient temperature. While these results do not exceed the notional design temperature of 28°C except in the case of AE, this is hot.

Figure 8.6 shows BedZED summer mean internal temperature results for bedrooms when the external temperature was 20°C. Property R had an additional data logger in a second bedroom. Data were not available for these periods from other additional bedroom loggers in properties H and Z.

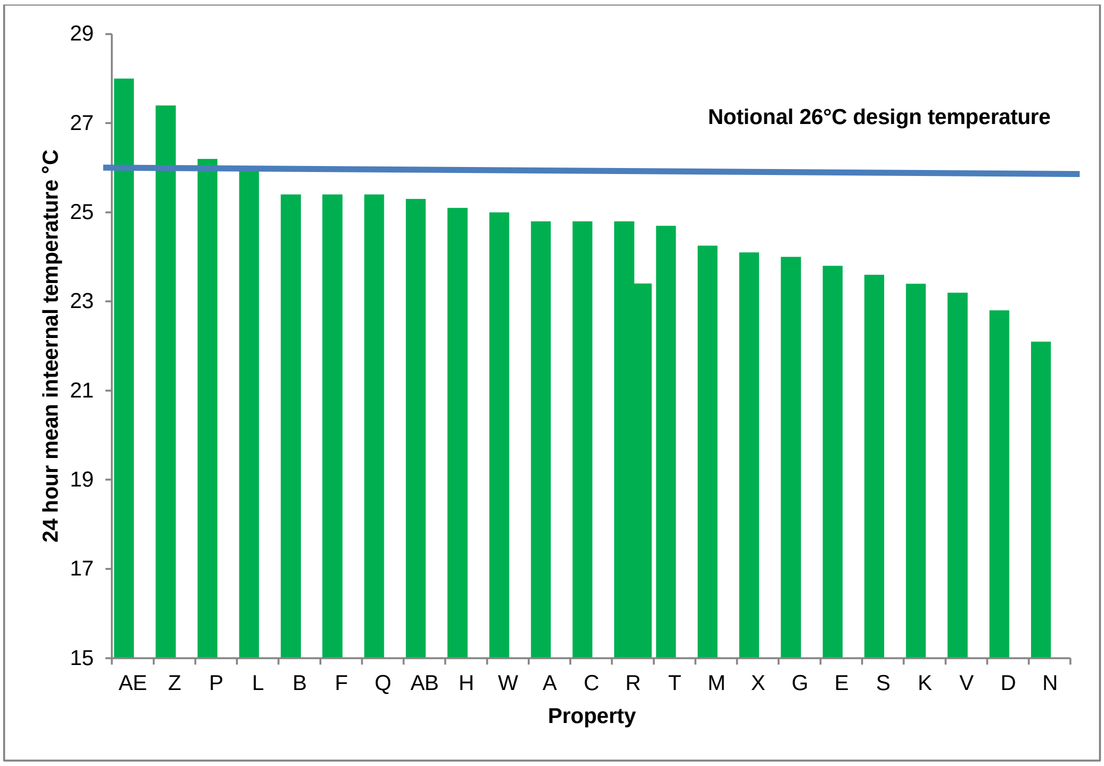

Figure 8.6: Mean bedroom temperatures standardised to external temp of 20°C

Figure 8.6 shows that the ranges between lowest and highest mean temperatures are 5.9ºC for both living rooms and bedrooms. At a mean 20ºC external temperature, three bedrooms (AE, Z and P) exceeded the notional design temperature of 26ºC and one living room (AE) exceeded the notional design temperature of 28ºC. Although slightly cooler than living room temperatures, the notional design temperature for bedrooms is lower, reflecting the need for cooler conditions when sleeping.

Figures 8.5 and 8.6 show that properties AE and Z had the highest mean internal temperatures for both living rooms and bedrooms. Further analysis of source data (drawings, core building worksheet, core occupant worksheet) was undertaken to establish potential reasons for the higher temperatures in these properties. There was no commonality in terms of the type of tenure or location of the property within the block: one property was social housing and the other owner occupied; one property was at the end of terrace, the other was internally sandwiched between other properties. AE was a top floor property but Z was a ground and first floor maisonette.

Post-occupancy surveys were also consulted. The occupant of Property Z did not complete a survey. The occupant of property AE was generally dissatisfied with the heating, hot water and ventilation and reported that it was difficult to operate the heating controls. This occupant further stated that the property was too hot in summer and some rooms too cold in winter. There may be a link between the occupant's difficulty with operating the heating controls, the higher than average temperatures and their dissatisfaction, but firm conclusions cannot be drawn.

8.3.2 Summer Temperature Results at external temperature of 25°C

Figures 8.7 and 8.8 show BedZED mean internal temperature results for bedrooms and living rooms respectively when external temperatures were 25°C.

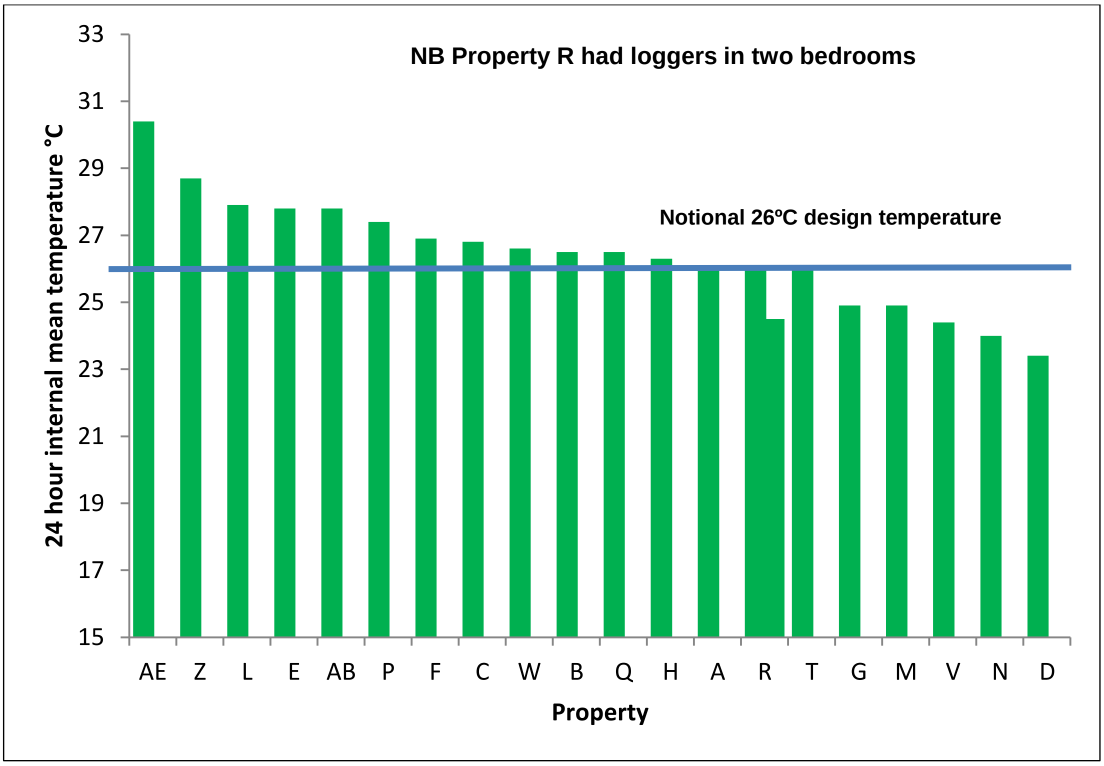

Figure 8.7: Mean bedroom temperatures standardised to external temp of 25°C

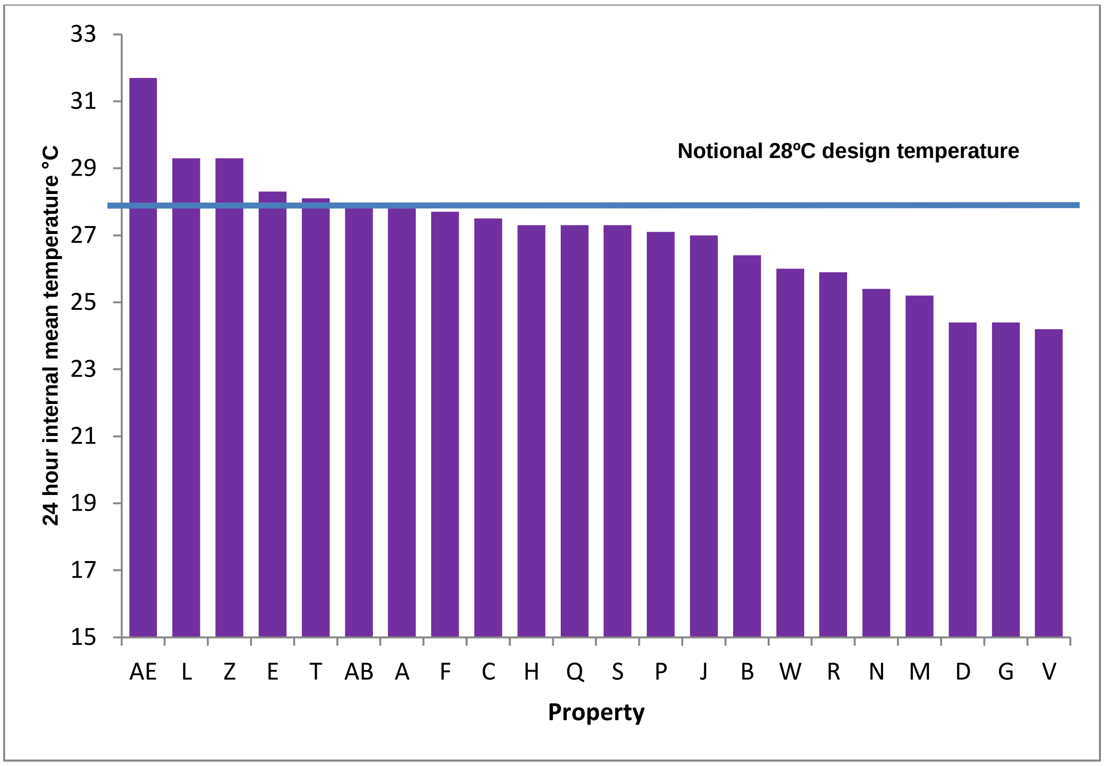

Figure 8.8: Mean living room temperatures standardised to external temperature of 25°C

Figures 8.7 and 8.8 show that at 25°C, the general pattern is that most of the average internal temperatures recorded exceed the external ambient temperature. Of the 21 loggers in bedrooms, 15 recorded mean internal temperatures higher than 25°C. Of the 22 loggers in living rooms, 19 recorded mean internal temperatures higher than 25°C. Applying the notional design temperatures, at 25°C five living rooms exceed 28°C and 15 out of the 21 bedrooms measured exceed 26°C.

Figures 8.7 and 8.8 also show that the properties with higher internal temperatures at external temperatures of 20°C, i.e. properties AE and Z, also have the highest temperatures at 25°C. Similarly, property L has the third highest living room temperature at 20°C and is equal second with Z when external temperatures are 25°C.

Table 8.3 summarises the results from Figures 8.5, 8.6, 8.7 and 8.8.

Table 8.3: Summary of summer internal temperatures at external temperatures of 20ºC and 25ºC compared to notional design standards

External temperature		**20ºC**	**25ºC**
Mean internal temperature °C	Living Room	25.4	27.1
	Bedroom	24.7	26.4
Number properties over CIBSE standard value (% of total)	Living (28ºC)	1 (4%)	5 (23%)
	Bedroom (26ºC)	3 (12.5%)	15 (71%)

One-way ANOVA statistical tests applied to mean bedroom and living room temperatures at 20ºC found no statistical significance difference between the two rooms (p = >0.05) and that the "mean of means" in the above table is representative of the results from each property. These results are different from the heating season results which did show a significant difference between the living room and bedroom internal temperatures.

Overall, in summer conditions, properties perform well against notional design temperatures at 20ºC but bedrooms begin to overheat when the external temperature is 25ºC. Figure 8.9 illustrates how the dwellings perform at a property level. Each data point represents one logger position.

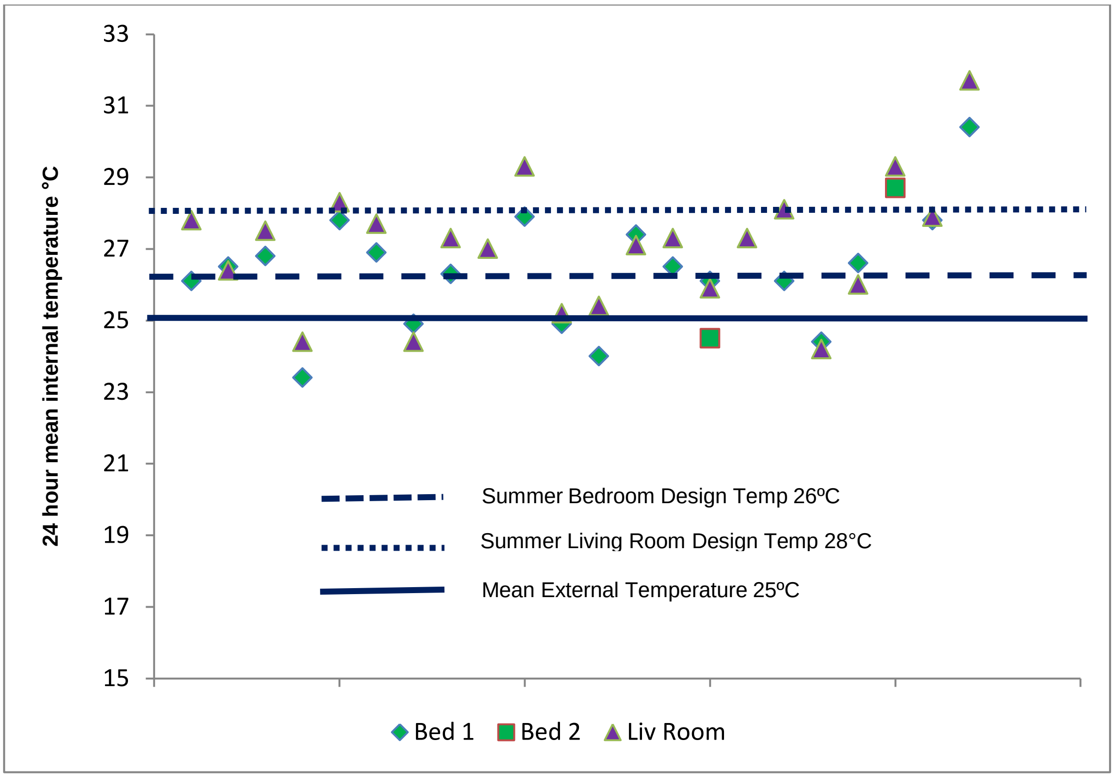

Figure 8.9: Mean average daily internal temperatures standardised to external temperature of 25°C

Further analysis was undertaken to investigate whether the loggers on the top floors of BedZED recorded higher internal temperatures than the loggers on the ground or first (middle) floors, see Figures 8.10 and 8.11.

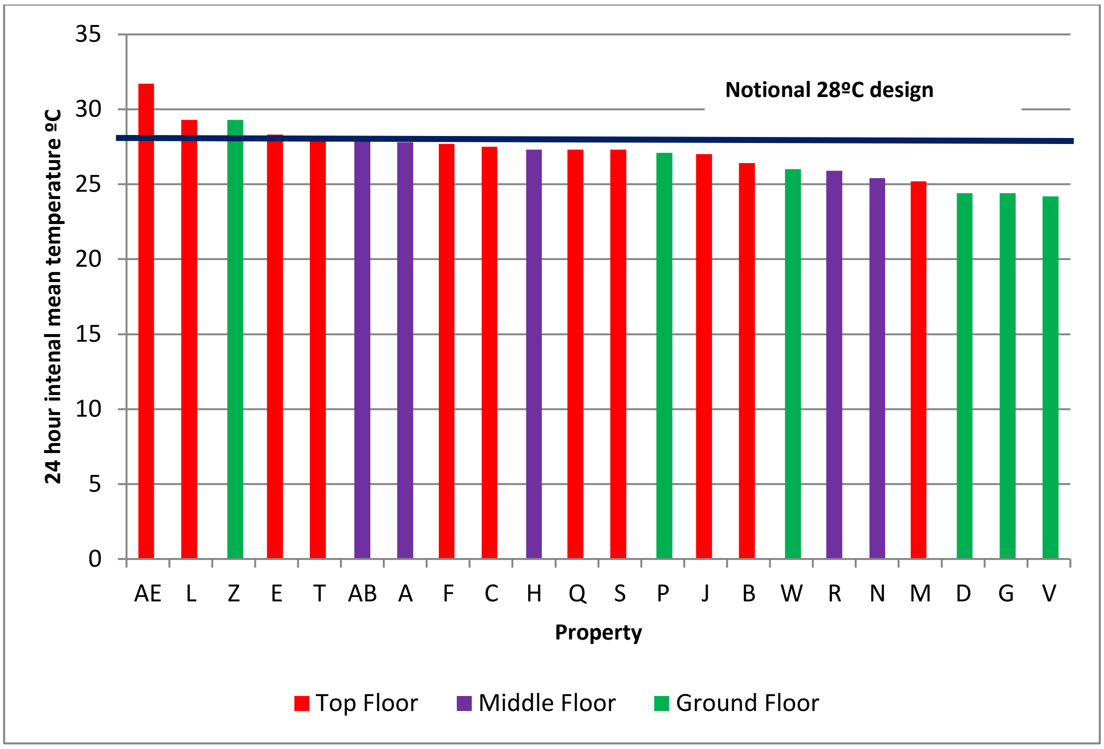

Figure 8.10: Living room temperatures standardised to external temperature of 25°C showing floor location

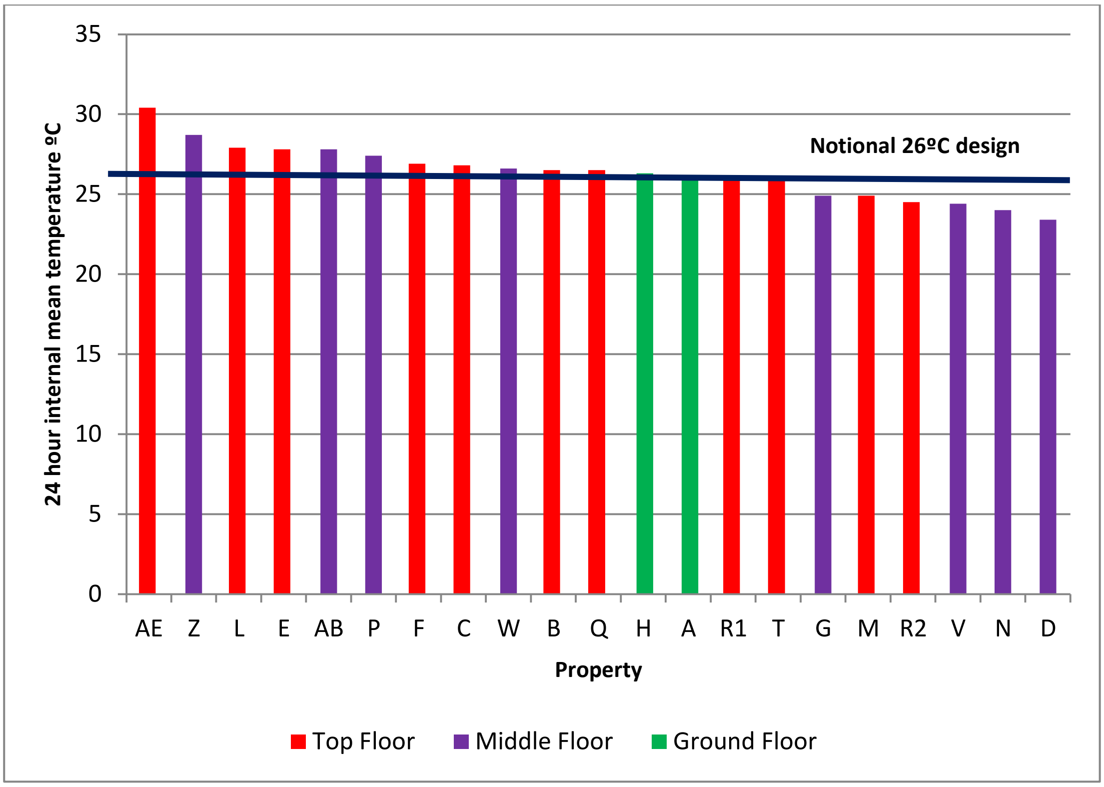

Figure 8.11: Bedroom temperatures standardised to external temperature of 25°C showing floor location

Figures 8.10 and 8.11 do not show a strong correlation between the location of the logger and temperature. Property Z, which has its living room logger sited on the ground floor records the third highest mean average temperature and the three lowest bedroom temperatures (V, N, D) are sited on the first (middle) floor.

As discussed in Chapter 4, the design philosophy for BedZED was that the high mass construction would operate as a heat sink, day time warmth being stored by the structure for slow release at night in the winter and night time cool stored for slow release during the day in summer. The post-occupancy survey aimed to find out how participants used their dwellings and to compare the results of the temperature monitoring with participants' views about summer comfort. This is discussed in more detail in Chapter 10.

In section 8.2.1, it was discussed whether the reason for higher internal temperatures in living rooms in the heating season might be a function of additional solar gain owing to the south facing sunspaces enclosing living rooms. However this does not explain why there is no significant difference in the cooling season also. Other factors may be relevant such as additional ventilation resulting from active window opening by participants. Further data would be required to establish why there is a difference in the heating season but not in the cooling season. This would need to include, for example, more details about occupancy behaviour such as window opening, use of appliances and cooking.

8.3.3 Comparison of BedZED summer temperatures with other studies

Figure 8.12 shows mean internal temperatures in living rooms and bedrooms across studies standardised to an external temperature of 20ºC. The comparison includes BedZED, the two Milton Keynes studies undertaken in 1990 and 2005 and living room data only for the Brixton super-insulated study, bedroom data were not collected.

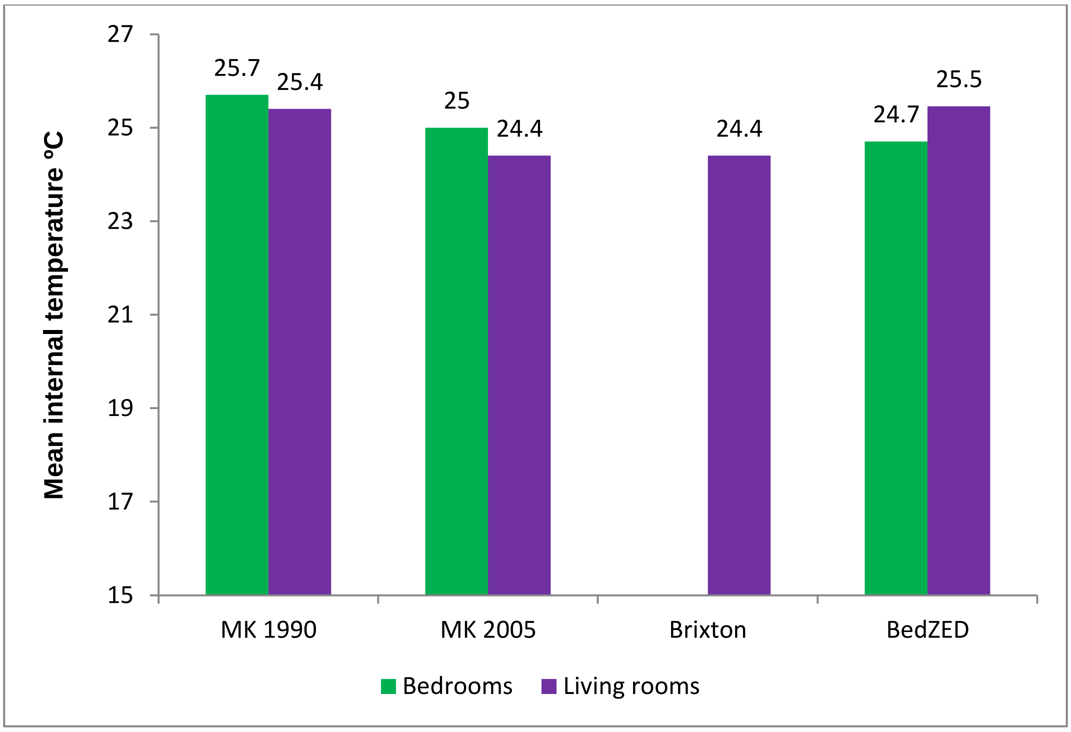

Figure 8.12: Mean internal temperatures across studies standardised to external temperature of 20°C

The comparison shows that at 20ºC, BedZED has the lowest internal bedroom temperature and the highest living room temperature. The higher living room temperatures at BedZED are thought to be attributable to the sunspaces built onto the south facing elevation which also includes the living rooms and participants potentially not optimising ventilation strategies to cool down the internal spaces.

All studies show higher internal temperatures compared to the external ambient temperature of between 5.5ºC for the living room at BedZED to 5.7ºC for the bedroom at Milton Keynes 1990. However, temperatures are so close in range that there cannot be said to be a significant difference.

8.4 Overall Analysis of Internal Temperatures

8.4.1 Performance of BedZED compared to Design

Figure 8.13 summarises the mean internal temperatures in BedZED dwellings when external temperatures are 20ºC and 25ºC and compares with the internal temperatures when external temperatures are 5ºC.

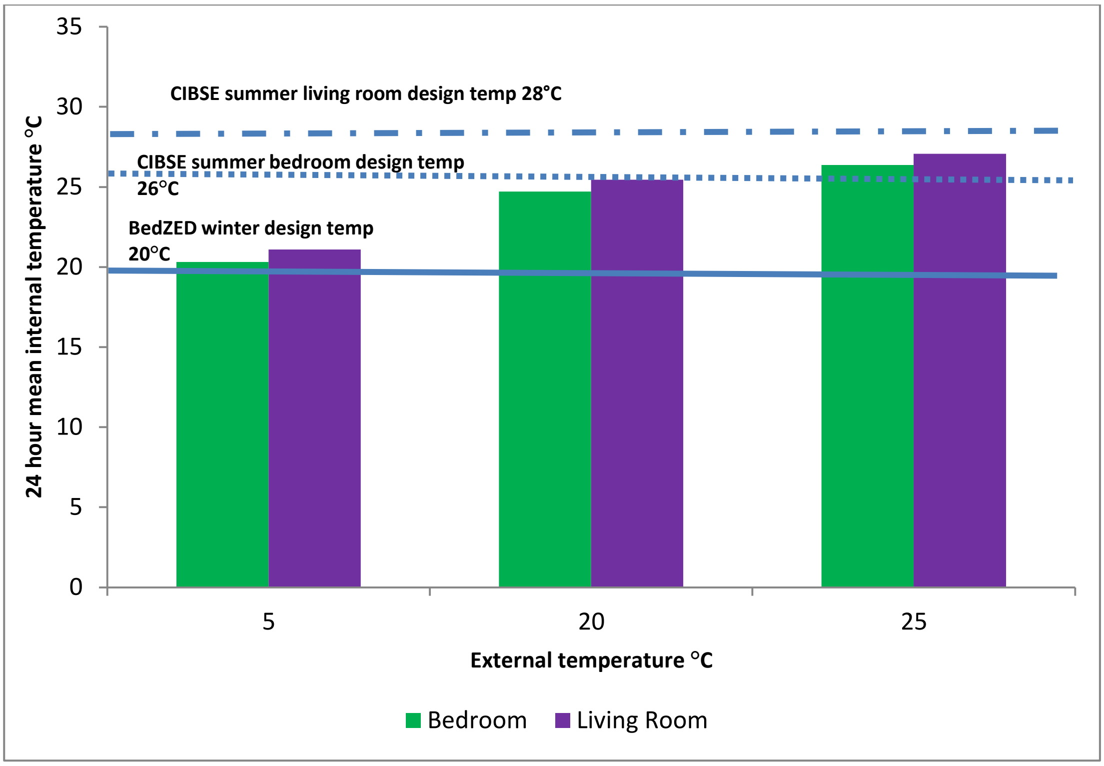

Figure 8.13: Mean Internal Temperatures compared to Design

Figure 8.13 shows that the dwellings perform well according to the winter design temperature but there is potential overheating in bedrooms during summer when daily external temperatures reach 25ºC. With a notional summer design temperature of 26ºC applied, BedZED bedrooms perform well up to external temperatures of 20ºC (mean internal temperature 24.7ºC) but at a 24 hour external temperature of 25ºC, the mean internal temperature increases to 26.4ºC. With a notional summer design temperature of 28ºC, living rooms perform well with a mean internal temperature of 25.5ºC when the external temperature is 20ºC and mean internal temperature of 27.1ºC when the external temperature is 25ºC.

BedZED occupants did complain of overheating during the summer months and the design team visited the site to explain how best to keep properties cool by, for example, opening windows at night but closing during the day (Twinn 2014).

8.4.2 Additional Analysis - Sunspaces and Bathrooms

For a small number of properties, additional internal temperature data were collected for other rooms besides living rooms and bedrooms. Data loggers were installed in sunspaces in properties E and S and in bathrooms in properties H and R. Sunspaces face south and are designed as an integral part of the passive design, acting as a buffer between the outside and the internal areas. Bathrooms are internal to the property and have a fitted towel rail fitted connected to the hot water system. Figure 8.14 shows internal temperatures recorded in sunspaces and compared to living rooms and bedrooms at different external temperatures.

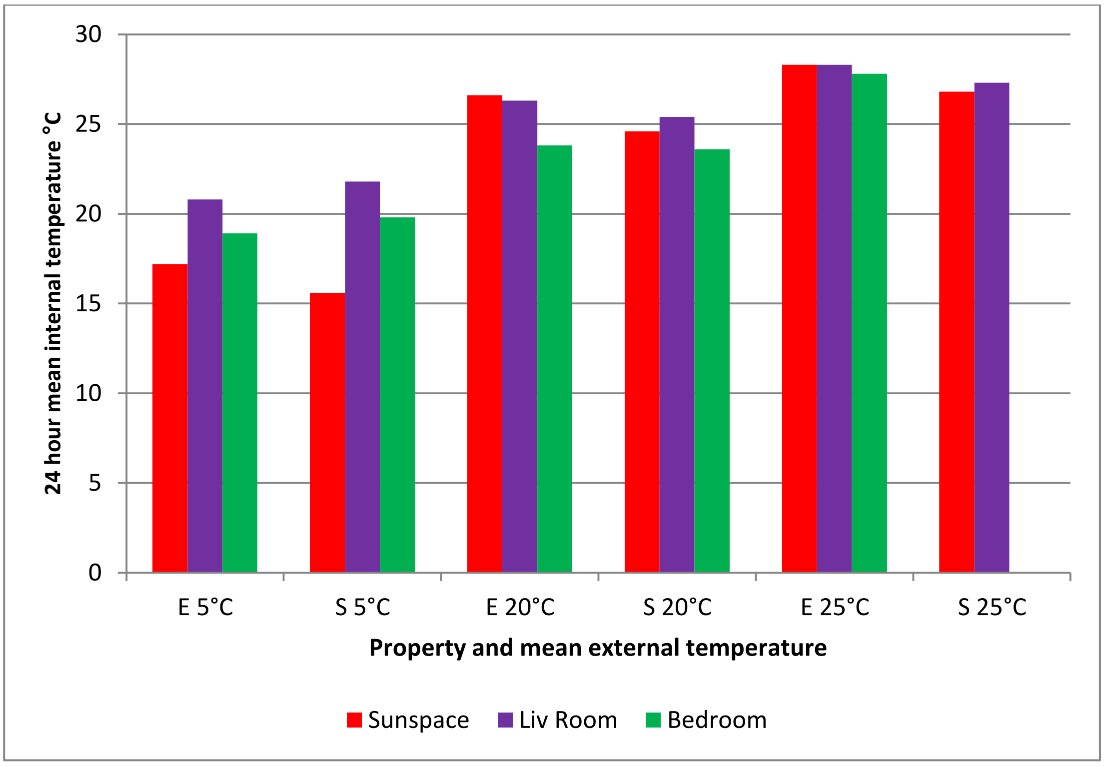

Figure 8.14: Mean internal temperatures in sunspaces for two properties

Figure 8.14 illustrates that when external temperatures are 5°C there is a marked temperature difference between the sunspaces and the living rooms/bedrooms in these two properties confirming the function of the sunspace as a buffer between external and internal temperatures. (N.B. insufficient data were available for temperatures above 20°C for the logger in Property S's bedroom.) From the data available, it can be seen that there is less difference between the sunspace internal temperatures and the temperatures in the living rooms and bedroom at 20°C and above. The sunspace with the higher internal temperature, property E, has lower internal temperatures in the living room and bedroom than property S which has a lower mean temperature in the sunspace but higher temperatures than E in the living room and bedroom. Both properties are the same size and sited on the same floor level of different blocks and all sunspaces face south.

Consulting the Phase 2 post-occupancy survey, both participants said that they found the comfort level of their home in the summer comfortable overall. The participant in property S remarked that the sunspace was too cold in winter whereas the participant in property E did not comment on their sunspace. Other participants who quoted the sunspaces in their post-occupancy survey include occupant B who stated that the sunspace was too cold in winter. Participants G and P state that there was mould growing in the sunspace during the winter which suggests low temperatures and a lack of ventilation. Different approaches to ventilation could account for the different results in the properties which had loggers installed in the sunspaces. It is assumed that participants might not have fully understood the purpose of the sunspace to act as a buffer between external temperatures, both the colder temperatures in the winter and the warmer temperatures in the summer and may have been using the sunspace as an extension of their living space. To be reliable, further research would need to be undertaken to assess temperatures of sunspaces in a larger sample of properties and an assessment of occupants' understanding of the purpose of the sunspaces should also be undertaken at the same time.

Figure 8.15 shows temperature differences in bathrooms, living rooms and bedrooms.

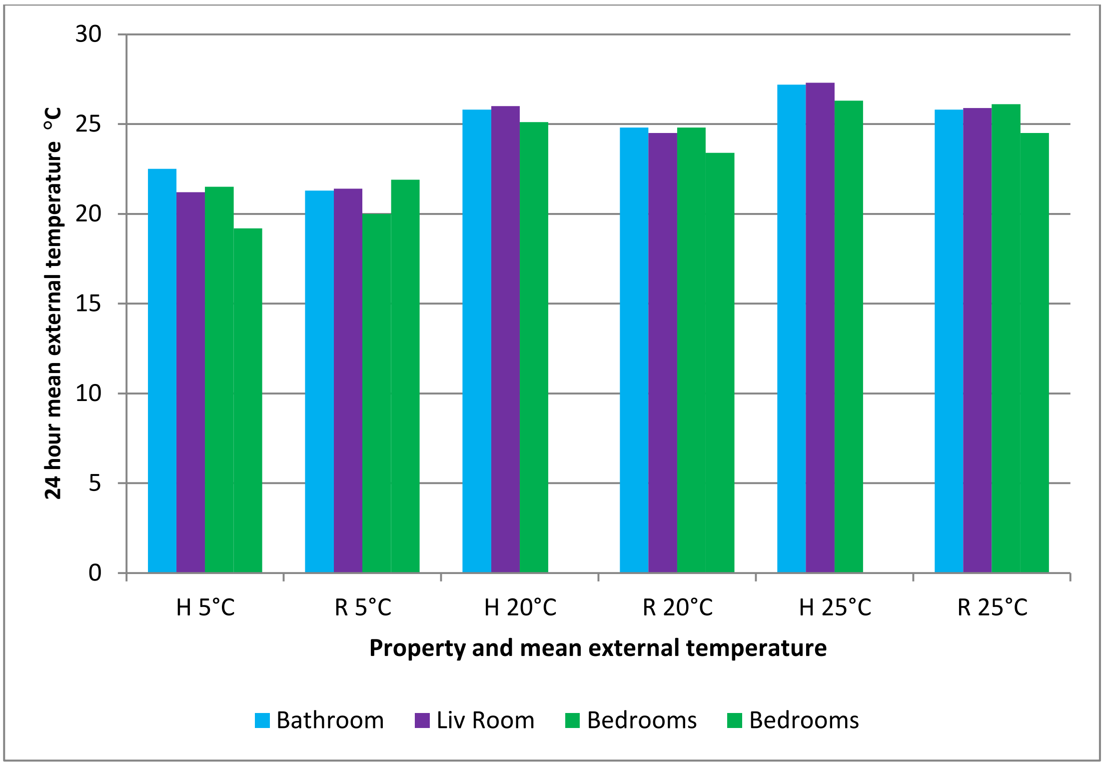

Figure 8.15: Mean internal temperatures in bathrooms for two properties

Figure 8.15 shows that there is little difference between the bathroom and other rooms monitored in properties H and R. The temperatures for all rooms illustrated are higher than the external temperature apart from the second bedroom at property R when mean external temperatures reach 25°C. At BedZED, bathrooms are enclosed rooms with the result that occupants cannot open windows for additional ventilation.

In the Phase 2 post-occupancy survey, ten out of 19 participants stated that their homes were too hot overall, see Table 10.11. While no occupants reported using additional cooling in the bathroom, three participants (J,L,V) stated that it was difficult to control the temperature of the heated towel rail in the bathroom and two participants (F,P) reported that the bathroom was too hot in summer. While the sample of two properties is small, the results for the bathroom temperatures are more consistent than the sunspaces. This could be because the bathrooms at BedZED are internally sited and are not affected by, for example, occupants opening windows and/or the direction of prevailing winds which could impact on the temperatures in the externally located sunspaces.

8.5 Internal Temperature Conclusions

The results presented in this chapter provide evidence to answer the first two research questions for this study: how do the constructed units perform compared with theoretical design performance and what is the difference if any?

The results show that BedZED achieved its 20ºC design temperature in the winter months but overheated in hot weather. Compared to other low energy case studies, BedZED performed better in winter than the other case studies examined with higher temperatures achieved in both bedrooms and living rooms. In summer, BedZED bedrooms were the coolest in the case study comparison but BedZED living rooms the hottest. The higher living room temperatures at BedZED are thought to be attributable to the sunspaces built onto the south facing elevation which also includes the living rooms with participants potentially not optimising ventilation strategies to cool down the internal spaces.

The reasons for the difference in summer temperatures are examined in more detail in Chapter 10 which analyses the results from the occupants' surveys.

Chapter 9 Airtightness Results and Analysis

9.1 Introduction

Achieving designed heat loss and air-tightness standards were important for meeting the overall energy design for BedZED. The more air tight the buildings, the less heat would be lost. The consequence of excessive heat loss would be that internal design temperatures and comfort would not be achieved and occupants might supplement the internal temperature with additional space heating, thus increasing fuel consumption. Conversely, inadequate ventilation could lead to internal air quality problems such as condensation or mould growth within dwellings.

The Energy Saving Trust stated that a ventilation rate (uncontrolled and controlled) of 0.5 to 1.5 air changes per hour for a whole dwelling is good practice to keep indoor relative humidity below 70% which is the trigger point for condensation to occur (Energy Saving Trust 2006).

The BedZED concept design provided for a very high envelope air tightness of 2 air changes per hour (ach) at 50 Pa test pressure (Arup 1999a) and this was carried forward to the air leakage testing specification which set out the maximum permitted air leakage rate as 2 ach at 50 Pa. (Arup 2001).

A wind-assisted passive stack heat recovery ventilation system was installed at BedZED. The aim was that the roof-mounted wind cowls would harness natural wind currents to create air pressure sufficient to provide a healthy fresh air supply to the building with no running energy cost (such as fans or heaters) since heat exchangers in the wind cowls would recover up to 70% of heat from exhaust air and natural pressure differences (wind and/or stack) provide the air movement. BedZED's double and triple-glazed windows (U-value 1.0W/m^{2}K) would also reduce the likelihood of surface condensation.

9.2 Air Tightness Tests carried out at BedZED by others

During the construction of BedZED, Building Sciences Limited (BSL) carried out air leakage pressurisation tests in December 2001 on six completed properties in accordance with CIBSE guidance on testing buildings for air leakage (CIBSE 2000). BSL found results varying from 2.98 to 3.83 ach at a differential pressure of 50 Pa. with a mean average result of 3.28 ach at 50Pa. (Building Sciences Limited 2001). The report identified a number of building snags that needed correcting, in particular missing or poorly applied mastic seals around external doors and windows. No report was available for this study to show whether the air leakage was reduced on completion of all building snagging work.

In 2005, Living Space Sciences carried out five tests on a BedZED property (Dunster 2008). They calculated an air infiltration rate of 2.2 ach at 50 Pa from blower door tests. Using a tracer gas decay measurement test, they determined that the average ventilation rate was 0.11 ach when the ventilation inlet was sealed, rising to 0.45 ach when the ventilation inlet was unsealed. This is a good result and in theory enough to maintain the relative humidity below 70%.

9.3 Infra-Red Thermography and Air Infiltration Tests carried out for this thesis

Air infiltration rate and heat loss tests were conducted specifically for this thesis on one dwelling from the Phase 2 sample. The tests took place after the buildings had been occupied for about two years and after the completion of the temperature and relative humidity monitoring undertaken as part of this study. By this time all construction was completed, the snags identified in the earlier construction stage tests completed by BSL were assumed to have been addressed and the properties assumed to have dried out. Sung H Hong and Dejan Mumovic of UCL conducted infra-red thermography and whole-house air infiltration rate tests to a sample dwelling and provided initial analysis of the the results (Hong and Mumovic 2005). The purpose of the tests was to investigate the building fabric performance of the sample dwelling which was a top storey, end-of-terrace, studio flat with exposed roof. The tests were carried out on 10th December 2004 between the hours of 10:30 to 13:00. These tests and results were produced exclusively for this study and have not been used elsewhere.

Two separate infiltration rate tests were carried out with the four wall openings to the passive stack vent in open and closed conditions using blower door tests. In common with the earlier construction pressure tests undertaken by BSL, the sunspace was excluded from the test. The total tested internal volume was $103.4m^3$.

9.3.1 Results of Infra-Red Thermography Test

The full results are in Appendix 8.

The overall conclusion of the infra-red thermography test was that the building appears to have continuous insulation but with some small areas of detailing that showed some heat loss. These were considered unlikely to be the cause of major heat loss or condensation since the temperature difference was quite small. For example, a small strip of cold area was detected along the ceiling edge above the living room. The reason for this could be cold air ingress from a gap possibly caused by missing edge insulation or a gap between the roof flashing and the edge of the roof concrete slab. The design team were aware of some workmanship issues during the construction period including detailing and missing insulation (Twinn 2014). Unlike the sealants to doors and windows, snags to insulation is much less likely to be picked up during construction snagging owing to the difficulty gaining access once roof and wall finishes are installed.

Generally, the infra-red thermography test showed that there was good insulation throughout. The infra-red camera was also used to detect cold air ingress along window seals while the case study flat was depressurized forcing cold exterior air into the flat. The test result showed very good seal along the joints of window frames to wall and along the casement window to frame. No mould growth was detected in the dwelling and this can be attributed to the high surface of temperature of the walls and the ceilings, the reasonable insulation levels illustrated by the thermography test and the fact that measured ventilation rates with the ventilation system open were close to the designed ventilation rates. Given the improvement between the construction and post-construction air infiltration tests, it is assumed that the workmanship issues identified by the BSL tests were addressed before the properties were handed over.

9.3.2 Results of Air Infiltration Tests

Tests were carried out with passive vents open and closed and with and without pressurisation and the results are shown in Table 9.1.

Table 9.1: Results of Air Infiltration Rate Tests

Passive vent condition	**Closed**	**Open**
Pressurised at 50 pascals (air changes per hour)	2.5	3.1
Background (no pressurisation) (air changes per hour)	0.12	0.16

Source: Hong & Mumovic 2005

The results were that in normal conditions with the passive vents open the property achieved 3.1 ach at 50 Pa. and achieved 2.5 ach at 50 Pa. when the vents were closed.

9.4 Relative Humidity Results

There is a risk with airtight buildings like BedZED that high levels of moisture might accumulate within the dwelling and trigger condensation and mould growth if there is not an effective controlled ventilation strategy such as the one provided by the passive stack ventilation system.

Relative humidity (RH) readings were compiled for this property during Phase 2 monitoring, except for the period October 2003 to January 2004, and the results are presented in Tables 9.2 and 9.3.

Table 9.2: Property B Temperature and RH Results

	Bedroom °C	Living room °C	Bedroom %RH	Living room %RH
Max	38.32	31.93	84.60	80.40
Mean	22.38	21.76	53.05	51.43
Min	12.93	14.47	22.00	25.40
Std. Dev	3.62	3.68	9.53	9.22

Table 9.3: Property B RH Analysis

	Bedroom	Living Room
Number data points	22,626	24,101
Number data points over 70%	507	411
% data points over 70% RH	2.24	1.71

The results show a very similar RH in the bedroom and the living room with the mean RH being 53% and 52% respectively. The RH was over 70% (often regarded as a critical RH for mould growth) in the bedroom for only 2.2% of the time during the monitoring period and 1.7% of time in the living room. The highest RH readings tended to occur in the evening and the morning. Since the occupant was generally out at work during the day this is in line with expectations; the higher RH readings are likely to have occurred when the occupant was cooking or showering. The low RH is consistent with the lack of condensation in this property observed during the infra-red thermography tests in Appendix 8, the reasonably high internal temperatures and the air tightness tests which evidence that the ventilation stacks are working properly. An interrogation of the results of the occupant survey completed for this property at the end of Phase 2 also shows that this participant did not report condensation in their property.

9.5 Comparison of Air Infiltration Tests

Table 9.4 compares the results from all air infiltration tests with the original design intent.

Table 9.4: BedZED Air Infiltration Test Results compared to Design

	Date	ach at 50 Pa
Design[1]	1999	2
Construction Testing[2]	2001	3.28
Phase 2 Sampled Property[3]	2004/05	2.5
Additional Post-Occupancy Testing[4]	2005/08	2.2

Sources: [1]Arup 1999b, 2001; [2]Building Sciences Ltd 2001; [3]Hong & Mumovic 2005; [4]Living Space Sciences, Dunster 2008

The BSL tests carried out during construction indicated that some sealants around external doors and windows needed to be addressed. In the sampled property tested for this thesis, the infrared camera was used to detect cold air ingress along window seals while the dwelling was depressurized forcing cold exterior air into the property. The test result showed very good seal along the joints of window frames to wall and along the casement window to frame. Effective snagging might account for the improved results between the construction testing and the two sets of post–occupancy tests.

Compared to the design target of a maximum of 2 ach at 50 Pa., the results of the two sets of tests carried out after construction completion at 2.5 and 2.2 ach show that BedZED broadly achieved air infiltration rates close to the design and showed an improvement since the tests carried out during the construction period.

9.6 Air Tightness Conclusions

The results presented in this chapter provide evidence to answer the first two research questions for this study: how do the constructed units perform compared with theoretical design performance and what is the difference if any.

At 2.5 ach at 50 Pa., BedZED broadly achieved its designed air tightness level of 2 ach at 50 Pa. The sampled dwelling showed good air tightness and minimum heat loss from background air infiltration. The RH results demonstrate that the ventilation was operating effectively. Additional RH results are included in Chapter 10 which discusses results from the occupants' surveys and reports from those survey participants that reported condensation in their homes.

Chapter 10 Occupant Survey Results

10.1 Introduction

The results from occupant surveys presented in this chapter provide evidence to answer the final research question for this study: have participants changed how they use energy at home as a result of moving to the new development?

The Phase 1 occupant survey was conducted at the end of the Phase 1 monitoring period prior to participants moving to BedZED. The Phase 2 survey was conducted at the end of the Phase 2 monitoring period after participants had lived at BedZED for almost two years. The occupant survey questionnaires are in Appendix 3 and 4. The number of participants in each survey is summarised in Table 10.1 with the full list in Table 6.6.

Table 10.1: Number of participants completing Phases 1 and 2 occupant surveys

	Phase 1	**Phase 2**
Participants	14	24
Surveys Completed	11	19

Not all participants answered every question in both surveys.

10.2 Participant Profiles

Table 10.2 compares the age profile of participants who took part in the two occupancy surveys although not all Phase 2 participants answered this question (12 out of 19). In Phase 1, 10% of occupants in the sampled households were under 5 years of age with 19% in the Phase 2 occupancy survey. It is not possible to draw conclusions from the different age profiles in these two surveys given the two year time lapse between the surveys and potential change in household make-up although there were no participants that were over 65 years of age in either survey.

Table 10.2: Number and age of participants in Phases 1 and 2 occupant surveys

Age Group	Phase 1 Survey	Phase 2 Survey
Under 5	2	4
6-15	1	1
16-25	2	4
26-35	8	7
36-45	7	3
46-55	1	1
56-65	0	1
Over 65	0	0
Total occupants in scope	**21**	**21**
% under 5	**10**	**19**
% over 65	**0**	**0**
Total number of responses to question	**11**	**12**

Table 10.3 shows the results to the survey question about the times of day that participants occupied their homes. For this question, ten participants responded to the Phase 1 survey although one participant (J) stated that since she worked a night shift, she did not complete the times that she was at home.

Table 10.3: Time of day that dwellings are occupied from Phases 1 and 2 occupant surveys

	Phase 1 Adults	Phase 1 Children	Phase 2 Adults	Phase 2 Children
total daytime (morning, lunch, afternoon)	9	6	25	12
total evening (evening and night)	18	4	38	14
% daytime	33*	60	40	46
% evening	66*	40	60	54
Total responses	**11**		**19**	

*rounding

10.3 Occupant Survey Results

Table 10.4 shows results for a question about the number of electrical appliances used by the household.

Table 10.4: Electrical appliances used by households, Phases 1 and 2

Appliance	Phase 1	Phase 2
Refrigerator	5	10
Freezer	3	9
Fridge/freezer	6	10
Electric shower	2	4
Washing machine	9	19
Tumble Drier	2	2
Dishwasher	1	4
Microwave	7	10
Television	14	17
Personal computer	7	11
Other	2	3
Total appliances	58	99
Appliances per household	5.3	5.2
Total number of responses to question	**11**	**19**

Table 10.5 shows the extent of low energy light bulb use and in which rooms. BedZED was fitted out with low energy lamps when occupants moved in and the purpose of this question was to establish whether participants in the study already used low energy light bulbs and also whether they would continue to do so, two years in, in the Phase 2 survey. Since this study was completed, all light bulbs sold in the UK are low energy.

Table 10.5: Low energy light bulbs, Phases 1 and 2

	Phase 1	Phase 2
None	6	0
1 room	4	0
2 rooms	1	0
3 rooms	0	3
4 rooms	0	3
More than 4 rooms	0	13
Total number of responses to question	**11**	**19**

Table 10.6 shows how easy or not participants found the heating controls to use. Participants were asked to score the ease of use on a range of 1 to 5, with 1 being easy and 5 being very difficult. The additional answer of "not applicable" was introduced for the Phase 2 survey to assess whether BedZED residents considered whether they did have control over their heating systems, given the fairly prescriptive design of the system.

Table 10.6: Ease of heating controls operation, Phases 1 and 2

		Phase 1	Phase 2
1	Easy	8	2
2	Fairly easy	1	1
3	OK	1	4
4	Difficult	0	2
5	Very difficult	1	5
	Not applicable		2
Total number of responses to question		**11**	**16**

A similar question was asked about how easy occupants found it to use the hot water controls, and, as with the question about heating controls, an additional "not applicable" answer was also included in the Phase 2 survey. The results are in Table 10.7.

Table 10.7: Ease of hot water controls operation, Phases 1 and 2

		Phase 1	Phase 2
1	Easy	9	3
2	Fairly easy		2
3	OK	2	5
4	Difficult		2
5	Very difficult		4
	Not applicable		2
Total number of responses to question		**11**	**18**

Participants were asked about the effectiveness of the controls to maintain comfortable temperatures in their home. An additional option of "not applicable" was included for the Phase 2 survey. The results are shown in Table 10.8.

Table 10.8: Effectiveness of controls at maintaining comfortable temperatures, Phases 1 and 2

	Phase 1	**Phase 2**
Ineffective	0	3
Fairly ineffective	4	6
Fairly effective	6	2
Effective	1	3
Not applicable		4
Total number of responses to question	**11**	**18**

Table 10.8 shows that nine out of 18 participants rate the controls ineffective or fairly ineffective at maintaining comfortable temperatures with only five participants rating the controls effective or fairly effective and four stating that the question was not applicable.

Participants were asked how they would describe the comfort level of their home during winter and the results are shown in Table 10.9.

Table 10.9: Comfort levels during winter, Phases 1 and 2

	Phase 1	**Phase 2**
Hot overall	0	2
Comfortable	5	8
Certain rooms too hot/cold	3	8
Cold overall	3	0
Other	0	1
Total number of responses to question	**11**	**19**

The "other" response came from participant L who said that the home was OK if sunny, but otherwise a bit cold in living/sleeping space.

Participants were asked if they used any form of additional heating, such as electric fan heaters, and if so where. The results for this question are at Table 10.10.

Table 10.10: Additional heating use, Phases 1 and 2

	Phase 1	**Phase 2**
Living Room	2	4
Kitchen	0	0
Bathroom	3	0
Bedrooms	3	2
Other	0	2
None	0	9
Total number of responses to question	**8**	**17**

The BedZED dwellings were thermostatically controlled albeit not via a traditional wall thermostat. The trickle fan was considered by some to be too noisy and so they used standalone electric fans instead. In their 2009 study, Hodge and Haltrecht found that 39% of BedZED households used electric fans on occasion for between one and two months of the year and 42% used some additional electric heating on average during the coldest two months of the year. This does not imply that residents were using fans/heaters consistently during that time - it could be only for an hour or two on the very hottest/coldest days of the year. This aligns with the findings of post occupancy survey carried out for this research.

Participants were not asked directly about comfort levels in the summer in the Phase 1 pre-occupancy survey because it was not anticipated that summer comfort would be an issue at BedZED. When there were reports of overheating during the hot spell in summer 2003 an additional question about summer comfort was included in the Phase 2 post-occupancy survey and the results included in Table 10.11.

Table 10.11: Comfort levels during summer, Phase 2

	Responses
Hot overall	10
Comfortable	5
Certain rooms too hot/cold	4
Cold overall	
Other	
Total number of responses to question	**19**

Figure 10.1 shows that over 50% of survey participants found their properties hot overall and less than 30% find their homes comfortable during the summer. These findings that more participants find their home comfortable in winter than in summer align with the findings of the Mlecnik 2012 study discussed in Chapter 2.

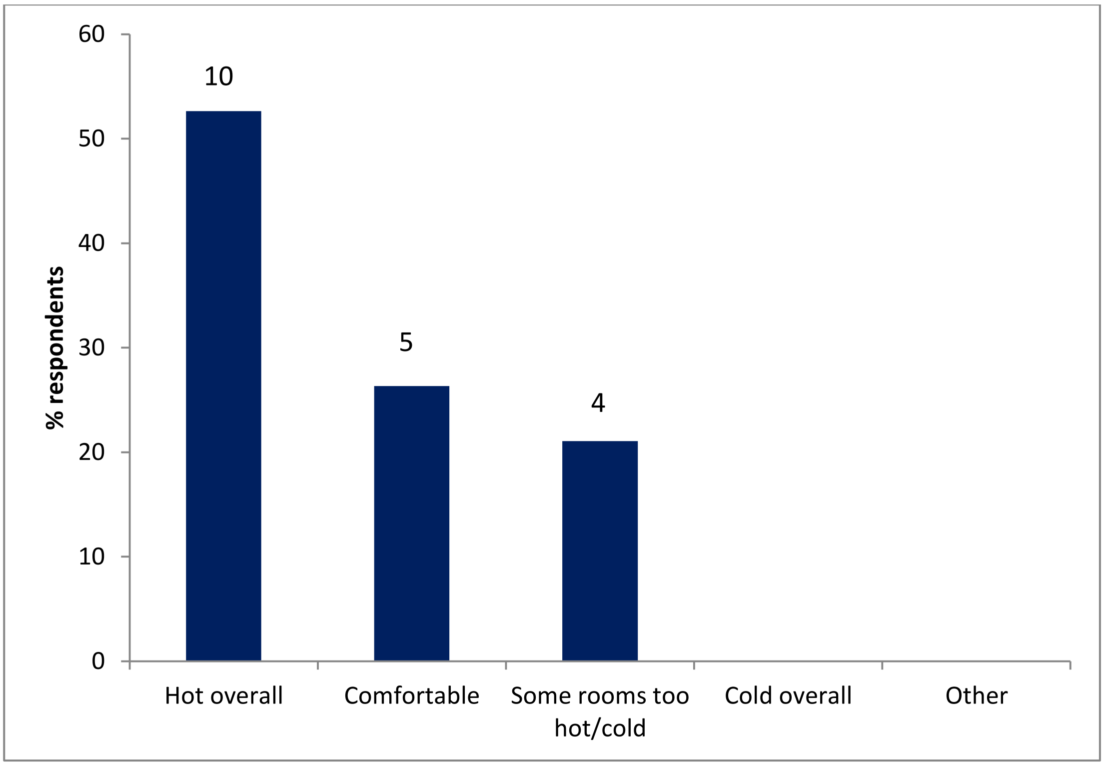

Figure 10.1: Phase 2 occupant survey: comfort level of your home during the summer

A follow on question asked which rooms were too hot or cold. The four participants who answered this question stated that the living room, bedroom and sunspace (B); bedrooms (D), bathroom (F) and all rooms except north facing bedrooms (R) were too hot.

In the Phase 2 survey, an additional question asked occupants whether they used any additional forms of cooling such as fans or air conditioning units and the results are shown in Table 10.12. Of the 18 participants who answered this question, three reported that they used additional cooling in more than one room.

Table 10.12: Additional cooling, Phase 2

Living Room	3
Kitchen	1
Bathroom	0
Bedrooms	7
Other	1
None	10
Total number of responses to question	**18**

Figure 10.2 shows that more than half of the participants who responded to this question (ten out of 18) did not use additional forms of cooling.

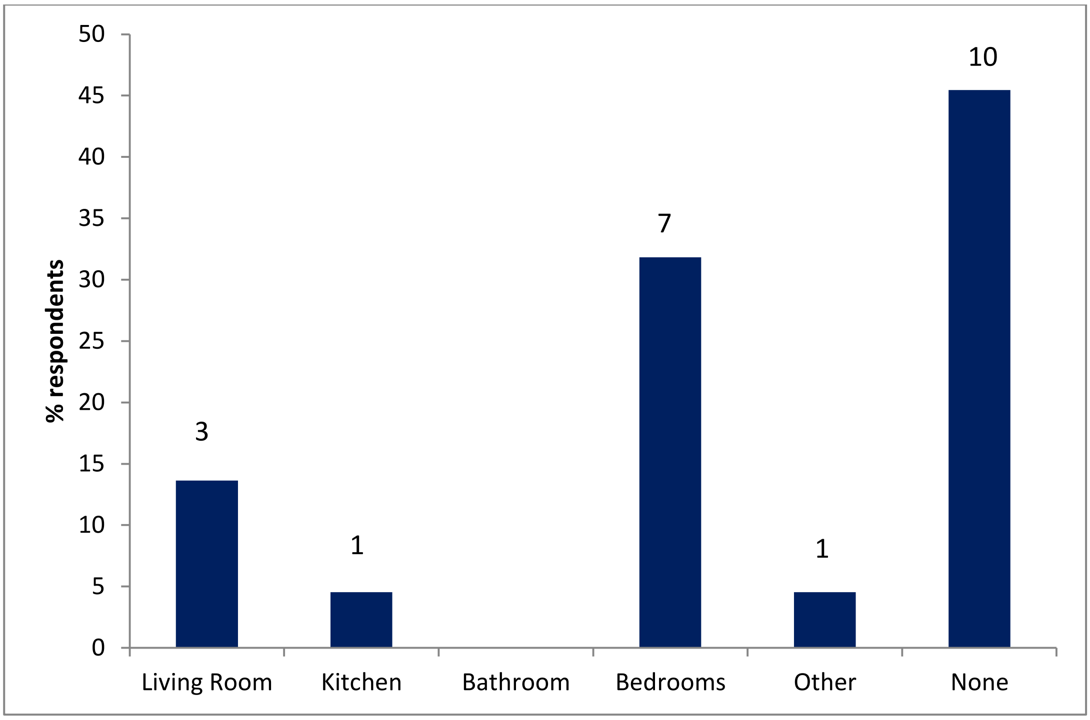

Figure 10.2: Phase 2 occupant survey: additional cooling

In total eight participants said that they did use additional cooling, some cited more than one location (hence the total number of twelve positive responses in Figure 10.2). These participants said that they used it for varying amounts during the year including two hours a day (property K), 3-4 hours (J) and 6-8 hours (P) in the living room. Property K used cooling in the kitchen for two hours a day. Participants used additional cooling mostly in bedrooms ranging from one hour a day (T), two hours (K), three to four hours (J), eight hours (L) and twelve hours (AE). One occupant (A) had cooling on 24 hours a day set to very low but it is not clear whether this is the sunspace or the hall. No one stated that they cooled the bathrooms despite the heated towel rail in the bathroom specifically cited as an issue by F, J and L (discussed in section 8.4.2).

In contrast, ten participants said that they did not use any additional cooling. These responses are consistent with the earlier analyses of internal temperatures, which showed that properties AE, Z and L experienced the highest temperatures (occupant Z did not complete the post-occupancy survey). Occupants were not asked whether they did not use additional cooling because the temperature was tolerable or because they were adhering to the zero energy ethos of the BedZED development and striving to minimise the use of additional electrical appliances. So it is not clear whether this participant response would be replicable on a larger scale or whether a larger population would be more inclined to use cooling during hot spells.

Following the occupation of BedZED and the initial feedback about summer temperatures, participants were additionally asked in the Phase 2 survey whether they opened windows to try and control the temperature of their home and the results are at Table 10.13.

Table 10.13: Window opening to control temperature, Phase 2

	Responses
Yes	19
No	0
Total number of responses to question	**19**

All 19 participants confirmed that they opened windows to control the temperature. This was part of the passive design principles for BedZED and the Residents' Manual explains that the dwellings should be ventilated at night during the summer so that the heat absorbed by the high mass structure can be removed and the property cooled for the next day. However, occupants were not asked when they opened their windows to cool their properties; they may have been opening them during the day which would not have had the same cooling effect and potentially contributing to the higher internal temperatures recorded.

In both surveys, participants were asked about the effectiveness of their ventilation system to remove moisture and odours from their homes. Six participants from Phase 1 said they had ventilation systems. The results are at Table 10.14.

Table 10.14: Effectiveness of ventilation system, Phases 1 and 2

	Phase 1	**Phase 2**
Yes	5	10
No	1	8
Total number of responses to question	**6**	**18**

Almost half of the respondents did not think the ventilation system at BedZED was effective at removing moisture and smells. Two participants in the Phase 2 survey provided additional comments; one stated that the ventilation system brought the smell of a neighbour's cigarettes into their home (anon) and the second (AE) that the bathroom fan did not always work.

A further question asked participants whether they opened windows to improve air quality and the results are at Table 10.15.

Table 10.15: Window opening for air quality improvement, Phases 1 and 2

	Phase 1	**Phase 2**
Yes	10	16
No	1	3
Total number of responses to question	**11**	**19**

Participants were asked whether their hot water system provided enough hot water and the results are at Table 10.16. Two of the 18 Phase 2 participants who answered this question commented that there was sometimes not enough hot water, but they had selected "yes" overall in their answer.

Table 10.16: Adequacy of hot water, Phases 1 and 2

	Phase 1	**Phase 2**
Yes	9	18
No	2	0
Total number of responses to question	**11**	**18**

Participants were asked if they knew how much their fuel bills were per annum and the results are at Table 10.17. One participant (M) was unable to answer this in Phase 1 as the cost was included in their rent. Over a third of participants in the Phase 2 survey did not know what their fuel was costing them at BedZED. This was because there were operational problems with the CHP and with billing arrangements during the first two years.

Table 10.17: Awareness of fuel bills, Phases 1 and 2

	Phase 1	**Phase 2**
Yes	6	11
No	2	7
Other	1	1
Total number of responses to question	**9**	**19**

The final part of the occupancy survey was a series of questions related to participants' health, preferences and overall satisfaction with the systems in their homes. Participants were asked whether anyone in their household had asthma or similar health problem that could be associated with the living environment. The Phase 1 results for this question are at Table 10.18.

Table 10.18: Phase 1 Incidence of health problems associated with the living environment

	Responses
Yes	4
No	7
Total number of responses to question	**11**

For Phase 2, the question was slightly amended to assess whether there were any new cases of health problems related to the living environment. The results for this question are at Table 10.19. Of the two participants who said that their household was affected, one (G) cited noise transference between properties and the second (AE) said that their asthma had got worse.

Table 10.19: Phase 2 Incidence of health problems associated with the living environment experienced for the first time

	Responses
Yes	2
No	19
Total number of responses to question	**19**

Participants were asked whether there was any condensation or mould growth in their homes. The results for both Phases are at Table 10.20 and are discussed in more detail in section 10.5.

Table 10.20: Condensation, Phases 1 and 2

	Phase 1	**Phase 2**
Yes	6	6
No	5	12
Total number of responses to question	**11**	**18**

Participants were asked about their clothing weight preferences during winter and the results are at Table 10.21.

Table 10.21: Winter clothing weight preferences, Phases 1 and 2

	Phase 1	**Phase 2**
Just a thin layer, eg T-shirt, shirt, blouse	3	6
Medium layers, eg T-shirt/shirt + thin sweater/cardigan	4	9
Heavy layers, eg T-shirt/shirt + heavy sweater/fleece	4	4
Total number of responses to question	**11**	**19**

Participants were asked how satisfied overall they were with the heating, hot water and ventilation in their home according to a five-point range from Very Good to Very Poor. The results for both Phases are at Table 10.22.

Table 10.22: Satisfaction with heating, hot water and ventilation, Phases 1 and 2

	Phase 1	**Phase 2**
Very good		4
Good	4	7
OK	4	3
Poor	2	1
Very poor	1	2
Total number of responses to question	**11**	**17**

Two participants in Phase 2 did not answer the question about overall satisfaction. One (anon) cited a range of issues relating to the CHP not working and overheating in the bedroom (as a consequence of blocking up vents to prevent cigarette smoke coming in from a neighbour's property). The other participant who did not answer the question did not provide any comment.

10.4 Comparison of Occupant Survey Results with Internal Temperature Results

A comparison was undertaken between winter living room temperatures and participants' overall level of satisfaction with their heating, hot water and ventilation. Where this question was answered, the results are plotted on Figure 10.3 and this illustrates how this compares with the standardised internal temperatures in living rooms in the heating season.

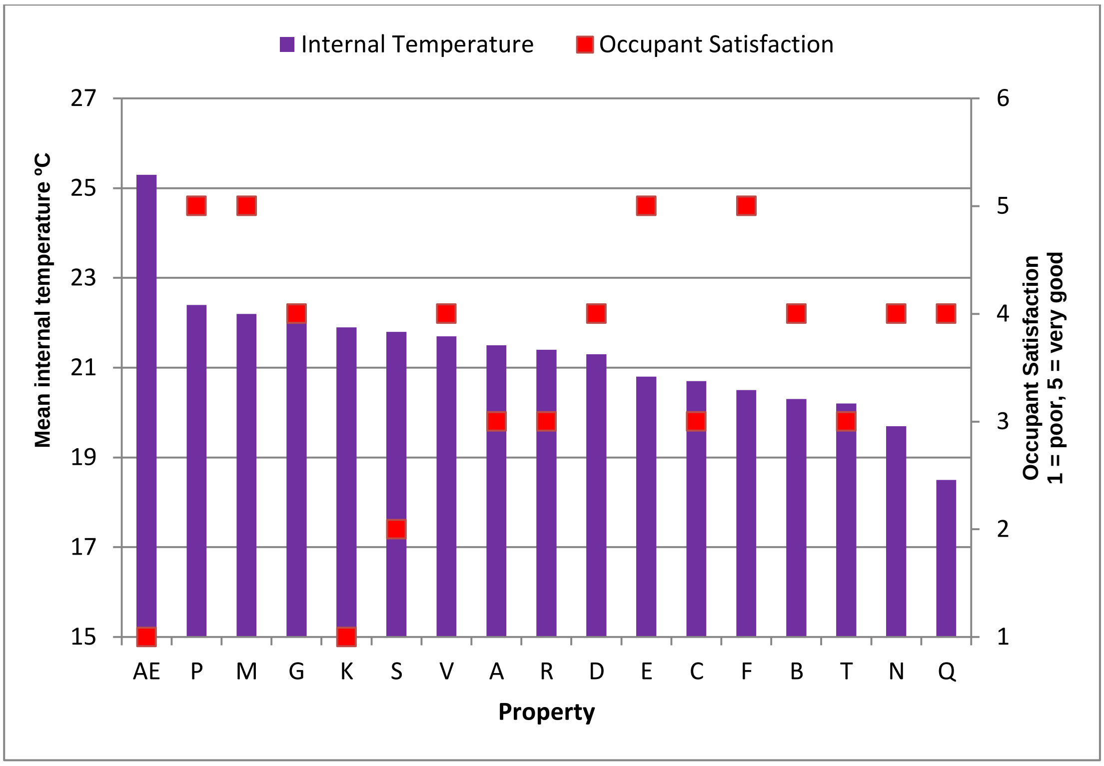

Figure 10.3: Comparison of internal living room temperatures standardised to external temp of 5°C with overall occupant satisfaction levels with heating, hot water and ventilation

Figure 10.3 shows that 14 participants were satisfied with the heating, hot water and ventilation compared to 3 that were dissatisfied.

There does not appear to be a correlation between the internal temperatures during the heating season and overall satisfaction. Participants P, M, E and F said that they were very satisfied and their properties ranked 3rd, 4th, 16th and 19th warmest in the sample. Conversely, participants AE and K said that they were very dissatisfied and their properties ranked 1st and 5th warmest in the sample and their properties achieved the design temperature of 20ºC. The cause for their dissatisfaction must lie elsewhere. In a further question about how easy it was to operate the control systems for heating and hot water, occupant AE said that they found them “difficult” and occupant K said they found them “very difficult”. This could be a contributory factor to their dissatisfaction.

Another reason might be that the two participants were used to keeping their homes at much higher temperatures than BedZED but since neither occupant took part in Phase 1, it is not possible to make a comparison of internal temperatures. However, occupant K did provide additional comments at the end of the post-occupancy survey. They said “I would love the temperature of the flat to be lower inside when it’s warm/hot outside. Sometimes the heat is unbearable.” K’s dissatisfaction with internal temperatures appears to be more aligned with summer temperatures than the winter temperatures shown in Figure 10.3. Finally, AE was a social housing tenant. In Chapter 6, it was suggested that social housing tenants might have provided a control study if a large enough number had agreed to participate (section 6.4) since they had less choice about moving to BedZED compared to owner occupiers. While it is not possible to draw conclusions from a single property, it is notable that AE experiences the highest internal temperatures and the lowest satisfaction rating.

A comparison was undertaken of occupants’ overall satisfaction with the heating, hot water and ventilation when external temperatures were 25°C. The results for satisfaction and living room temperatures are shown in Figure 10.4 and for satisfaction and bedroom temperatures in Figure 10.5.

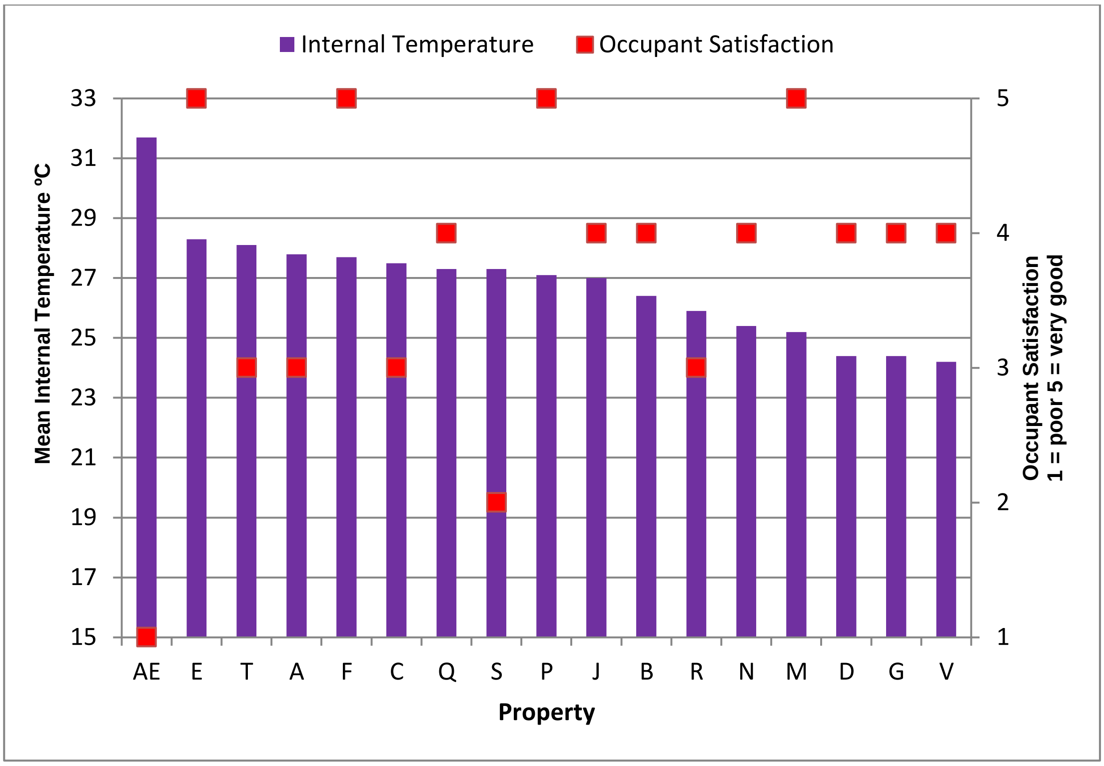

Figure 10.4: Comparison of living room temperatures standardised to external temperature of 25°C with results of overall occupant satisfaction with heating, hot water and ventilation

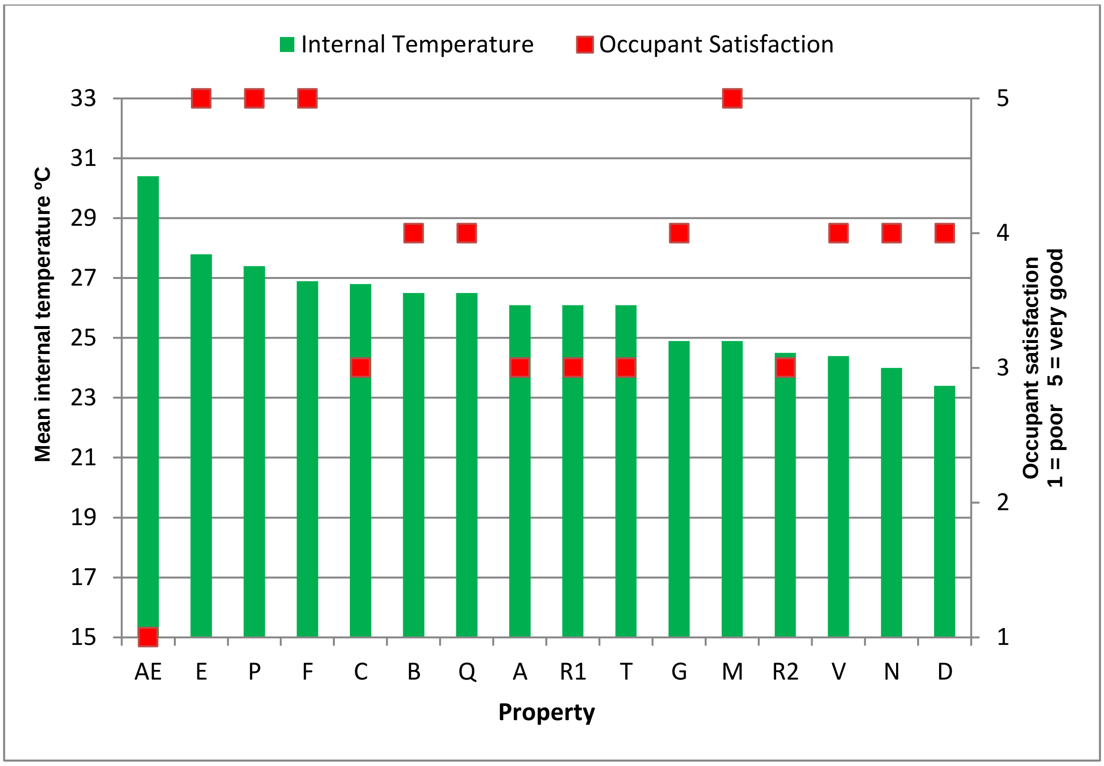

Figure 10.5: Comparison of bedroom temperatures standardised to external temperature of 25°C with results of overall occupant satisfaction with heating, hot water and ventilation

There is no clear correlation between internal summer temperatures and participants' overall satisfaction with the heating, hot water and ventilation.

In line with the literature, the participants' response to overheating seems to be more a problem in bedrooms than living rooms, with seven participants installing cooling (e.g. fans or air conditioning units) in bedrooms compared to three in the living room. CIBSE guidance on summer comfort sets lower operative and peak temperatures for bedrooms compared to other rooms in dwellings. As discussed, overheating is considered to be more of an issue during the night because of the impact on sleep patterns.

A subsequent survey of BedZED residents in 2007 by Goh & Sibley (2008) found that over half (56%) of BedZED residents thought their homes too hot in the summer, shown in Table 10.23. That larger survey corroborates the results of this study with regards summer temperatures.

Table 10.23: Goh and Sibley BedZED Occupant Survey Results

Scale	**Too cold**			**Just right**			**Too hot**
Scale	1	2	3	4	5	6	7
Winter months %			20	44	20		
Summer months %				10		56	

Notes:
71 households (86.6% of total households) took part
30% respondents use electrical fan on average for 1-2 months
42% respondents use electrical heater on average for 1-2 months

Source: Table 5, Goh & Sibley (2008)

Goh & Sibley attributed summer overheating to the fact that the excess heat from the hot water cylinder and the towel rail in the bathroom were not locally controlled. They also speculated whether households used the windows and sunspace to cool dwellings as originally intended in the design.

71% of the 71 households surveyed by Goh and Sibley had installed curtains or blinds in sunspaces albeit primarily for privacy reasons. In their thermal simulation study of nine UK dwellings, He, Young, Pathan et al (2005) found that the provision of window blinds and a large roof overhang to provide solar shading had little effect on passive cooling techniques, reducing cooling demand by only 2%. However the use of window opening regimes for late evening and early mornings produced a 90% reduction in demand for cooling. They attribute the reason for this to thermal storage effects of structure and to the time lag associated with this, so the previous evening's cooling load will carry forward to the next day.

In his 2008 book, the BedZED architect Bill Dunster stated that "regrettable cost savings were made by the client to omit opening roof lights on the top floor sunspaces, making it harder to ventilate warm air build up". He noted that the problem of ventilating warm air build up is not experienced in the lower maisonettes, where a combination of low level windows and doors and high level tilt turn windows provide good cross ventilation. The literature discussed earlier in this chapter points towards active window opening as the most effective method of managing overheating. The decision to omit opening roof lights may have contributed to the reports of overheating in some properties. That said, all participants surveyed in this study confirmed that they opened windows to control the temperature of their home and this is illustrated in Figure 10.6.

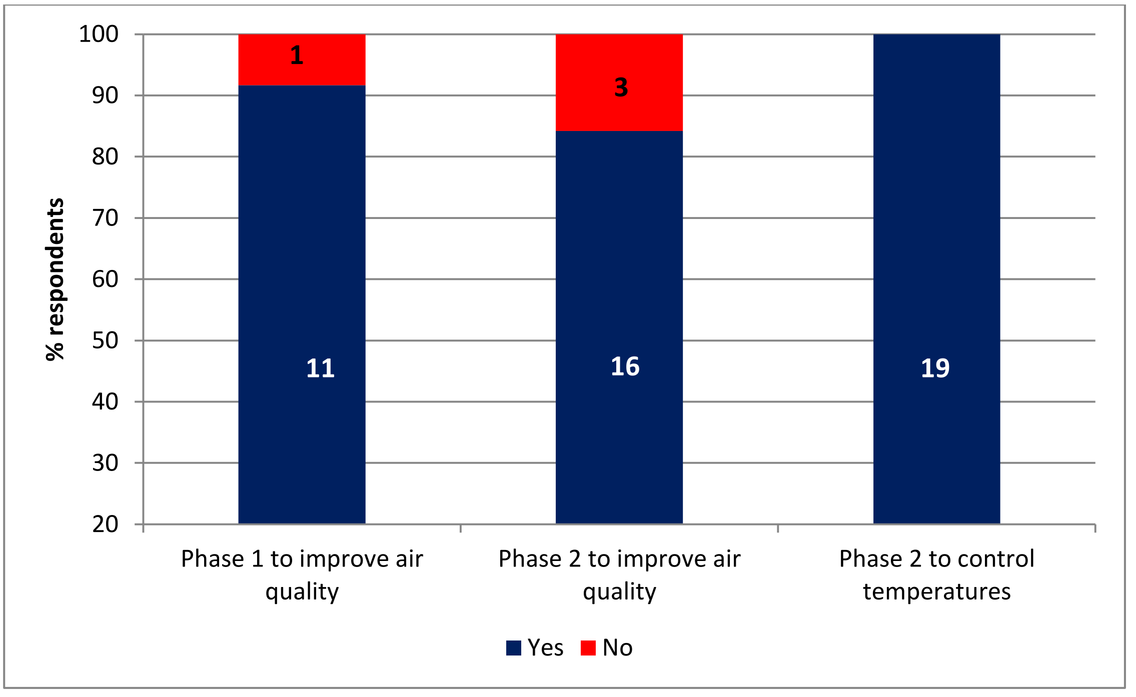

Figure 10.6: Phase 1 and 2 Occupant Surveys - Window Opening

The three Phase 2 participants in Figure 10.6 who did not open windows to control air quality, also stated that there was no condensation or mould growth in their homes. All three households comprised one occupant only, which may also have been a factor.

The occupancy surveys carried out for this thesis did not explore the time of day when occupants opened windows but in his thesis, Corbey recorded anecdotal evidence from BedZED occupants about overheating. He noted that operating the window units takes a degree of learning, in that on very hot days the best way of keeping the unit cool is to ventilate the sunspace and shut the internal door from the sunspace to the dwelling (Corbey 2005).

The BedZED energy engineer took part in meetings with BedZED residents and reported that there was not enough understanding about how to deal with overheating. He reported that residents were extending their living area into the sunspace and leaving the door between the dwelling and the sunspace permanently open with the result that, when the sunspace heated up from solar gain, so did the living space and after a few days the dwelling mass heated up. Thermal inertia then meant that it would take time before internal temperatures reduced. He advised that sunspaces should be kept closed during the day and their windows opened. At night, all windows could be opened to cool down the whole dwelling (Twinn 2014).

The BedZED Residents Manual provided guidance for occupants in its troubleshooting section which recommends that during very hot windless days, windows should be closed during the day and opened during the cooler evening and early morning so that room surfaces are cooled ready for the following day (Peabody Trust 2002). Based on Corbey's findings and correspondence from the project team energy engineer (Twinn 2014), it is clear that optimum window opening during hot spells was not fully understood by occupants.

10.5 Comparison of Occupant Survey Results with RH Results

Section 9.4 found no condensation in the sampled BedZED property tested for air infiltration and infra-red thermography as part of this study. However, an analysis of the Phase 2 survey results for condensation shown in Table 10.20 provides a different perspective. This analysis is presented in Figure 10.7 and shows that 33% of participants who answered this question said that there was condensation or mould in their home.

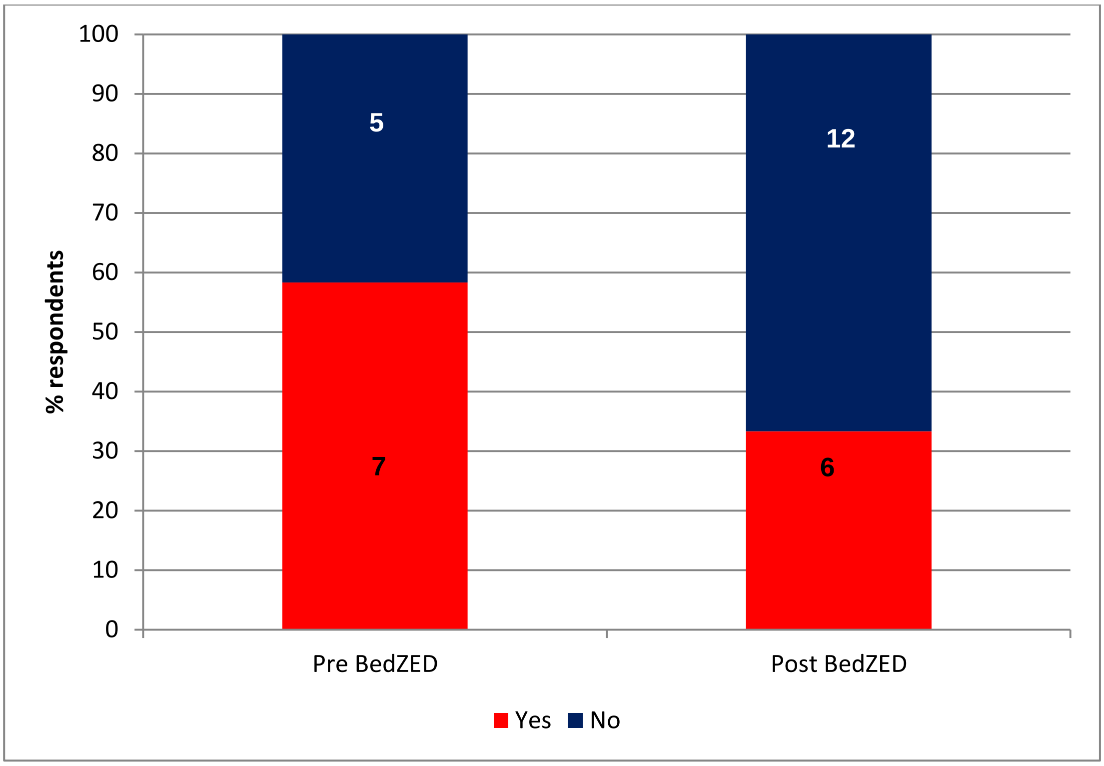

Figure 10.7: Phase 1 and 2 Occupant Surveys – Condensation

33% seems high for new properties. NHBC state that:

> "Condensation is common in new and newly converted homes while construction materials dry out. If allowed to persist it can sometimes cause mould on walls and ceilings" (NHBC 2014).

The post-occupancy survey was undertaken in June 2004, some two years after construction completion and it was expected by that time that the properties would be fully dried out. The air tightness tests discussed in Chapter 9 found high levels of air tightness in the sampled property which could lead to condensation in the absence of a controlled ventilation strategy.

Participants' responses to the Phase 2 occupancy survey show that the new dwellings suffer from less condensation than their former homes which is to be expected given that they are newly built and in excess of minimum building regulations applying at the time. However, the reported incidence of condensation or mould in six out of 18 homes is high.

Analysis of comments provided by three of the six respondents to this question provides further insights. Occupant V states that the problem is condensation dripping from the roof lights. This could be condensation but is more likely to be penetrating dampness from poor sealants in the roof light units, an issue raised by Occupant G in response to a different question. The other two participants who provided comments to this question stated that the condensation was in the sunspace and occurred in winter when the area was sealed up. Occupant P reported having to open up the exterior windows to allow more ventilation into the sunspace and this would have partially negated the buffering effect of the conservatory. Another occupant highlighted a general ventilation issue; in response to the question about whether the ventilation system was effective, they (anon) stated that they had blocked up the vent because they were getting the smell of cigarettes from their neighbour's property. While this occupant did not report condensation or mould in their property, blocking up the vents should affect the ventilation of their dwelling and could create the conditions for condensation. If the tracer gas measurements in one property were representative of the stock then blocking the vents will reduce the ventilation by about a quarter: from 0.45 to 0.11 ach.

The relative humidity (RH) readings for Phase 2 were analysed for the six properties that reported condensation (C, G, P, S, V, T) plus the property that had the airtightness survey conducted as part of this study (B), already reported in Chapter 9 but included here for comparison. The results are shown in Table 10.24.

Table 10.24: RH Results, Phase 2

Property		Bedroom % RH	Living room % RH	Sunspace % RH
B	**Max**	84.60	80.40	
	Mean	53.05	51.43	
	Min	22.00	25.40	
	Std. Dev	9.53	9.22	
	% > 70%RH	**2.24**	**1.71**	
C	**Max**	93.80	88.40	
	Mean	53.81	50.97	
	Min	23.60	23.20	
	Std. Dev	11.78	10.15	
	% > 70%RH	**9.48**	**3.25**	
G	**Max**	85.70	96.20	
	Mean	54.87	51.43	
	Min	24.30	24.20	
	Std. Dev	9.23	9.34	
	% > 70%RH	**6.88**	**2.49**	
P	**Max**	99.00	99.00	
	Mean	59.21	60.29	
	Min	23.30	24.80	
	Std. Dev	9.58	7.67	
	% > 70%RH	**14.99**	**10.74**	
S	**Max**	96.30	99.00	100.00
	Mean	56.64	55.10	59.27
	Min	23.80	22.70	21.80
	Std. Dev	10.71	12.17	15.79
	% > 70%RH	**13.64**	**11.56**	**30.42**
T	**Max**	81.40	84.40	
	Mean	49.21	45.57	
	Min	24.80	23.20	
	Std. Dev	8.21	8.11	
	% > 70%RH	**0.43**	**0.11**	
V	**Max**	77.10	78.60	
	Mean	50.69	49.80	
	Min	24.50	25.90	
	Std. Dev	7.79	6.51	
	% > 70%RH	**0.10**	**0.04**	

Table 10.24 shows that property B does not exhibit excessive RH with the overall property exceeding 70% RH between 1.7% and 2.2% of the total monitoring period which aligns with the conditions observed in the air-tightness survey discussed in Chapter 9. The results for properties T and V show low levels of RH with readings exceeding 70% only occurring 0.04% to 0.4% of the time. Participant V commented in the occupant survey that the condensation was dripping from the roof lights. It is likely that this dampness was more likely to be a consequence of water penetration from the roof lights than condensation and this accords with the RH results. Participant T offered no additional comments.

Higher levels of humidity were found in properties P and S with 10% of readings for bedrooms and living rooms exceeding 70% RH over the monitoring period and 30% of sunspace readings exceeding 70% RH. This accords with property P's comments about black mould in the sunspace. It is assumed that these participants did not understand how to ventilate their properties. The Residents Manual (Peabody Trust 2002) provides guidance on how occupants should ventilate their homes although there is no specific guidance on the sunspace. In all cases, moisture levels are higher in bedrooms than living rooms.

A comparison of the incidence of RH readings higher than 70% for Property B and the six properties that reported condensation is in Table 10.25.

Table 10.25: RH Comparison, Phase 2

% > 70%RH	**Bedroom % RH**	**Living room % RH**
Mean (C,G,P,S,T,V)	7.59	4.70
Property B	2.24	1.71

Table 10.25 shows that the properties reporting condensation are between 2.7 and 3.3 times more likely to experience RH levels higher than 70%, supporting the observations from the occupant survey.

When asked about draughts, the proportion of participants experiencing draughts since moving to BedZED reduced, illustrated in Figure 10.8.

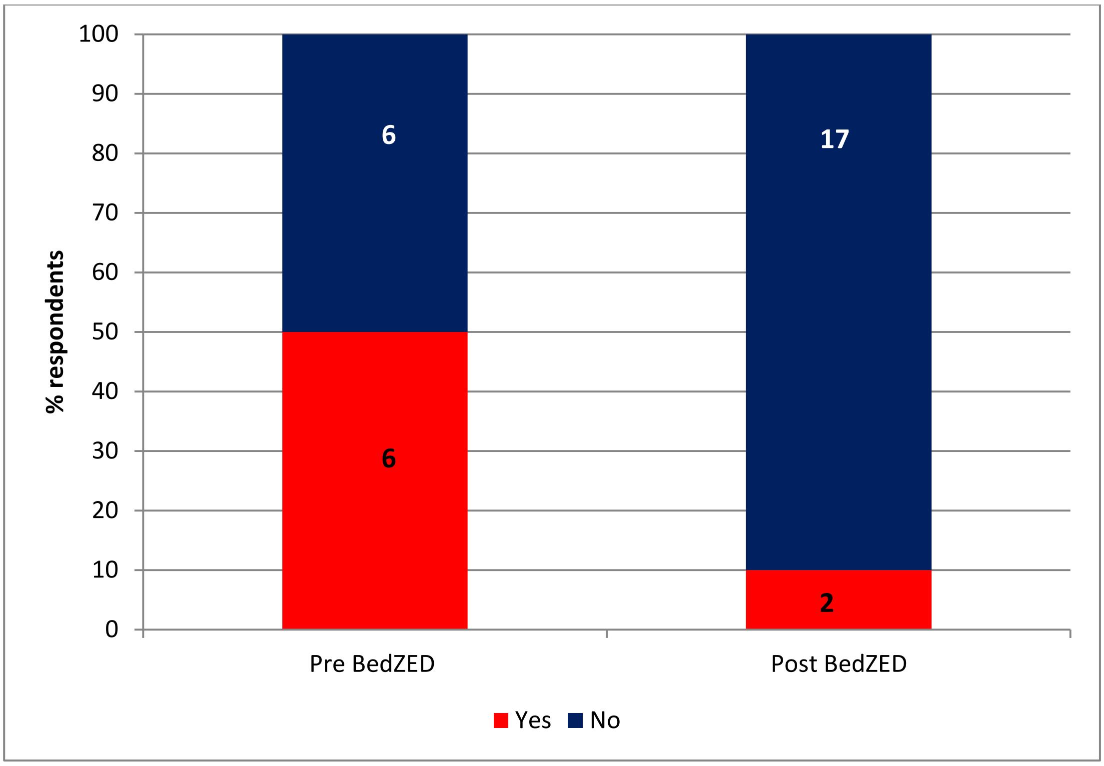

Figure 10.8: Phase 1 and 2 Occupant Surveys - Draughts

Analysing the responses to the Phase 1 survey half said that the draughts came from windows, three of the six also said that the draughts came through doorways. In the Phase 2 survey, the faulty window seals were raised by participants V and G. Given the high levels of air-tightness at BedZED, it is surprising that two participants stated that they did experience draughts. One of these (G) also reported faulty window seals which could explain the draughts and the same participant reported condensation in the sunspace which they addressed by opening the exterior windows. Again, this could account for draughts.

10.6 Occupant Surveys Conclusions

The results presented in this chapter provide insights into the human factors relevant to the study and help to answer the final research question which is “have participants changed how they use energy at home as a result of moving to the new development?”

Overall, 82% of survey participants rated the heating, hot water and ventilation as OK, good or very good (Table 10.22). The surveys show a higher level of satisfaction with the winter temperatures achieved at BedZED (42% selecting “comfortable”, Table 10.9) and a lower level of satisfaction with summer temperatures (26%, Table 10.11). The surveys provide an insight into the reasons for occupants’ dissatisfaction. 44% of participants who answered this question stated that they found the heating controls “difficult” or “very difficult” to operate and a further 13% stated that the question was not applicable (Table 10.6), indicating a low level of confidence in the BedZED occupants that they can operate their heating controls effectively.

Given the air tightness of BedZED, a good ventilation system is essential to provide fresh air and remove moisture. However the occupant survey results indicate that almost half of the respondents did not think the ventilation system at BedZED was effective at removing moisture and smells (Table 10.14). The survey shows that all participants employed active window opening to control the temperature of their home but the internal temperature results during hot spells indicate overheating and the results of the occupants’ surveys indicate that less than 30% find their homes comfortable during the summer (Figure 10.1). Other studies suggest that this is partly attributable to a lack of understanding on when to open windows to achieve optimum cooling.

These findings are further tested in Chapter 12 with the longitudinal study which directly compares the same sample of occupants in Phase 1 and Phase 2.

Chapter 11 Changes to BedZED during the Development Process

11.1 Introduction

This chapter refers to project source documents and discusses changes made to the design during the development and occupation phases which may have impacted on the actual performance of the BedZED properties in use. The results of this analysis help to answer the first three research questions for this study: how do the constructed units perform compared with theoretical design performance; what is the difference if any; and why is there a difference.

11.2 Changes during the Construction phase

A review of the available project documentation did not highlight any major changes to the design or the components that would have affected the performance of the dwellings in use (Peabody Trust 1999-2000). For example, the August 1999 project design meeting discussed the design of the airing cupboard and the trade-off between insulating the hot water cylinder compared to reducing the effectiveness of the cupboard as a clothes dryer, with a view to installing uninsulated cylinders (Peabody Trust 1999-2000). However this was not permitted under the Building Regulations and insulated cylinders were installed.

Of more concern was workmanship on site. In correspondence, the energy engineer stated that he had been made aware in retrospect of instances where wall insulation had been missed, finned tube heaters being missed out and other workmanship concerns that may have adversely affected the energy performance (Twinn 2014).

The infra-red thermography test discussed in Chapter 9 provides some evidence of insulation detailing issues at wall and ceiling junctions although these issues did not affect the thermal performance in the tested dwelling.

11.3 Changes during the Operational phase

The CHP plant was designed to provide all heat and electricity to BedZED properties with a connection to the national grid for import and export in the event of under-supply or over-supply. The design had assumed that 100% of the site electricity requirements for power to buildings would be met by the CHP together with the hot water demand for washing. Back-up supply arrangements were to draw power from the national grid for individual immersion heaters within dwellings.

The performance of the CHP was inconsistent. The CHP plant installed at BedZED was a prototype designed by the supplier and was fully automated with daily automatic start-up and shut down and automatic de-ashing. Plant maintenance was expected to be weekly for routine checks with scheduled maintenance carried out quarterly. However, a number of problems arose in the operation of the plant. These included the design of new untested equipment such as the automatic ash removal and the reliability of some equipment that needed to operate continuously such as the woodchip grabber and slide valves. The main issue that affected the operation was tar condensing from the wood gas, exacerbated by cooling of the plant during the nightly shut down (Hodge & Haltrecht 2009, Twinn 2014).

Lazarus stated that during the first winter of occupation, 2002-03, the CHP and heating system were still being commissioned and that this affected the supply of hot water to properties and so the contribution of incidental gains toward the space heating (Lazarus 2003).

Hodge and Haltrecht stated that the CHP never consistently reached the design outputs (Hodge & Haltrecht 2009).

After completion of Phase 2 of this thesis, Peabody Trust de-commissioned the biomass system and installed centralised gas boilers to provide heat for the district hot water system.

The issues with the operation of the CHP were discussed in Chapter 7 since this resulted in heat energy data not being available for the Phase 2 monitoring period.

11.4 Zero Energy and Renewables

A key element of the BedZED design was that the scheme would be zero energy. Inherent to this was that the development would be self-sufficient in non-carbon energy. Renewable energy would be provided from the biomass CHP and from photovoltaic (PV) panels.

The monitoring undertaken for this thesis did not include an assessment of the PV panels. Other sources have been consulted to assess this and are discussed in Chapter 4.

At its conception, the project had been called Beddington Zero Energy Development, abbreviated to BedZED. Later, the full name of the project was changed to Beddington Zero (Fossil) Energy Development. It is assumed that the name change was to make clear that BedZED would use energy and was not autonomous but that the energy used would be renewable and not fossil fuels. Other work presented in section 4.21.2 shows that the renewable energy from PV at BedZED was approximately a third of the designed output. More significantly, the failure of the biomass CHP, which was to play a significant role in the zero carbon nature of BedZED, meant that the renewable energy design was not achieved.

11.5 Development Process Conclusions

The evidence in this chapter shows that the failure of the biomass CHP in the operational phase resulted in the zero carbon design not being achieved. The system was a prototype system which the manufacturer and operator was unable to make fully operational. By the operational stage with BedZED fully inhabited, it would have been very difficult to replace the failed biomass

CHP with another experimental system and the decision was taken to use a tried and tested method in the form of gas-fired boilers.

There is some evidence that workmanship issues on site during the construction phase may have compromised the thermal performance of the units as constructed. This is corroborated in part from the infra-red thermography survey carried out on a sample dwelling for this study and discussed in section 9.3.1. However, there is also evidence that the air-tightness performance improved between the construction air-tightness tests and the post-completion tests (Table 9.4), suggesting that some of these construction issues had been addressed prior to handover of the completed properties.

Chapter 12 Longitudinal Study

12.1 Introduction

A unique feature of this study was the inclusion of a measurement phase prior to participants taking up residence in BedZED. The purpose of this was to track over time occupant behaviour and assess whether it changed as a result of moving into the new dwelling. This chapter provides evidence for the fifth research question for this study: have participants changed how they use energy at home as a result of moving to the new development?

The longitudinal study set a baseline for participants' behaviour and preferences, before they moved to the new BedZED dwellings. It also aimed to assess how participants responded to the improved energy efficiency of their new homes: do they benefit from the improved energy efficiency by maintaining internal temperatures at the levels of their previous dwellings or do they "take back" the improvements in energy efficiency in some way by, say, wearing lighter clothes in winter as a consequence of higher internal temperatures?

This chapter compares the actual performance of BedZED dwellings in use (Phase 2) with the performance of dwellings occupied prior to moving to BedZED (Phase 1) by comparing actual internal temperatures and energy used and an evaluation of occupant responses in two surveys.

Phase 1 comprised three elements: an NHER survey, an occupant survey and temperature monitoring. The participants and properties included in these elements vary from element to element depending on the occupant's particular circumstances. The reasons for not completing one element were varied: some participants were staying in shared households or hostels/hotels where it was not practical to carry out temperature monitoring or to relate the monitoring back to the specific participants who moved into BedZED; other participants were unable to take part owing to short timescales between exchanging contracts on a BedZED property and moving in; other participants in the main Phase 2 monitoring were unwilling to take part until they moved in.

Table 12.1 summarises the participants in each of the Phase 1 cohorts. Full details are in Table 6.1.

Table 12.1: Phase 1 Cohorts

Cohort 1 Building	B	D	F	J			N	P	Q	R	S	V	X	AB
Cohort 2 Monitoring	B		F		L	M	N	P	Q	R	S	V		AB
Cohort 3 Survey	B		F	J		M	N	P	Q	R	S	V		
All cohorts	**B**		**F**				**N**	**P**	**Q**	**R**	**S**	**V**		

To ensure consistency in data analysis, individual comparisons between Phase 1 and Phase 2 are made according to the relevant cohort and not to the Phase 1 sample as a whole.

The whole Phase 1 sample comprised 14 households prior to moving to BedZED. Cohort 1 comprised participants who had an NHER survey completed for their pre-BedZED dwelling. In total, twelve NHER surveys were completed on pre-BedZED homes and the NHER surveyor also calculated indicative SAP equivalent score using SAP v9.6. Cohort 2 comprised 11 participants who had data loggers installed in living rooms and bedrooms collecting temperature and RH monitoring at 30 minute intervals for a period of approximately four to six weeks. Cohort 3 comprised ten participants who completed the occupancy survey. One of the participants (AB) did not complete the survey at the end of Phase 2 and therefore the AB occupant survey results are not included in the longitudinal comparison.

12.2 Building Analysis

Table 12.2 shows the range of different age and constructions of the pre-BedZED dwellings contrasting with the BedZED dwellings that were all constructed to the same design and standards. The pre-BedZED properties were distributed across the full range of dwelling ages. Half of the dwellings were built post-1982 and so would have been built with some insulation.

Table 12.2: Construction date for Phase 1 dwellings

Age of construction	Number of dwellings
pre-1900	1
1900-29	2
1930-49	1
1950-65	1
1966-76	1
1982-90	2
1991-95	2
1995+	2

A comparison of Phase 1 (pre-BedZED) and Phase 2 (BedZED) buildings surveyed in Cohort 1 is provided at Table 12.3.

Table 12.3: Cohort 1 building comparison

Property	SAP	£/yr energy (NHER)	Heat Loss[a] (U-value) W/m^2K	pre-BZ m^2 NIA	BZ m^2 GIA	BZ m^2 NIA (proxy)	% change in property size
B	50.0	290	0.6	29.8	46.3	39.4	32.1
D	29.0	611	1.8	53.0	108.7	92.4	74.4
F	55.0	272	0.8	31.3	46.3	39.4	25.8
J	40.0	310	2.3	53.4	46.3	39.4	-26.3
N	35.0	459	2.3	52.3	61.9	52.6	0.7
P	61.0	392	0.6	56.5	108.7	92.4	63.5
Q	58.0	322	0.8	37.7	69.5	59.1	56.7
R	51.0	713	1.6	100.9	154.5	131.3	30.2
S	66.0	391	1.7	59.4	69.5	59.1	-0.5
V	29.0	466	1.1	49.5	108.7	92.4	86.7
X	61.0	273	0.73	32.33	108.7	92.4	185.8
AB	68	242	0.95	34.34	46.1	39.2	14.1
Mean	**50.3**	**392.5**	**1.3**	**49.2**	**81.3**	**69.1**	**45.3**

[a]Average U-value of property from NHER survey

Table 12.3 illustrates that the mean average SAP of the pre-BedZED cohort was 50.3. By comparison, the SAP score calculated in 1999 by Arup for Building Regulations approval for a generic two-storey BedZED dwelling of 100m^2 was 150, reported as 100 in line with SAP reporting protocols (Arup, 1999b). This compared to an average SAP for English housing of 46.7 in 2001 (DCLG 2013). So the previous dwellings occupied by the BedZED residents who took part in this study were only slightly higher scoring on the SAP rating scale than the English average and the highest scoring being property AB with a SAP of 68.

Of particular interest is the finding that, with only two exceptions (J,S) the majority of this group moved into larger properties than before, a mean increase in property size from 49m^2 to 69m^2 and an overall increase in floor area of 45%. By way of comparison, the national average property size of 87m^2 at the time being even higher than this BedZED cohort (DCLG 2006b). For this cohort of participants, there is a clear trend towards larger properties as discussed in Chapter 2. Other things being equal, additional floor area would be expected to lead to higher overall energy usage as a function of increased demand for space heating.

12.3 Comparison of Internal Temperatures

For the pre-BedZED Phase 1 dwellings, data were collected in 2002 for periods between one and twelve weeks with a mean period of 8½ weeks. Phase 2 monitoring at the BedZED properties took place over 23 months. Phase 1 data were principally collected over the cooler months of the year and it is possible to compare the performance of the pre- and post-BedZED dwellings when external temperatures were 5°C. However there was insufficient monitoring data collected during the warmer months to compare the two Phases at higher external temperatures. Cohort 2 (properties B,F,L,M,N,P,Q,R,S,V,AB) provides a direct comparison of pre- and post-BedZED internal temperatures.

Internal temperature comparisons are shown in Figures 12.1 and 12.2 for bedrooms and living rooms respectively.

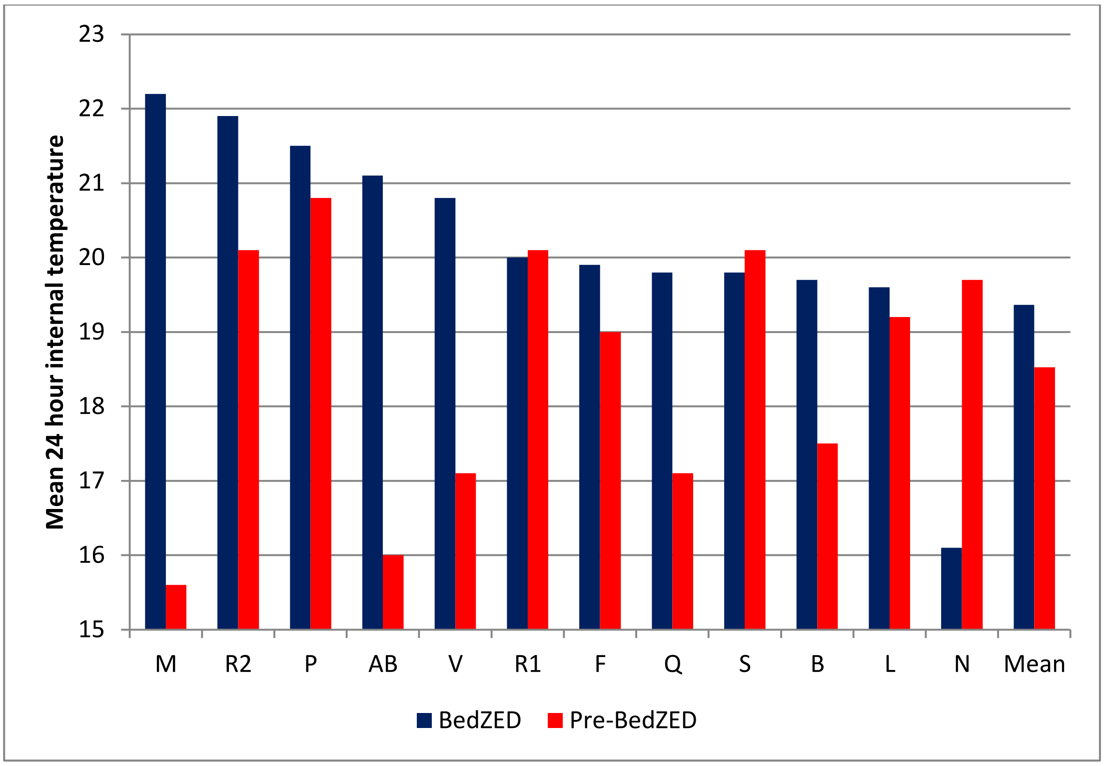

Figure 12.1: Comparison of bedroom temperatures Phases 1 and 2 standardised to external temperature of 5°C

Figure 12.1 shows mean bedroom temperatures when external temperatures were 5ºC during Phase 1 (pre-BedZED) and Phase 2 (BedZED) for Cohort 2. All properties that had measurements for both phases experienced higher internal temperatures at BedZED apart from properties N, R and S. The difference in internal temperatures between Phases 1 and 2 ranges from -+3.6ºC (N) to -6.6ºC (M), with a mean difference of +0.8ºC.

The participant in property N experienced a reduction of 3.6ºC at BedZED compared to their former home. They moved from an older flat conversion built between 1900 and 1920 with a SAP rating of 35. The pre-BedZED property was 52.3m^2 NIA which broadly equates to the 61.9m^2 GIA BedZED flat assuming that the NIA/GIA efficiency ratio of the pre-BedZED property was 85% (see discussion of NIA/GIA in Chapter 6). In their former home, the participant of property N spent about £200-300 per annum on energy bills compared to £300-400 at BedZED. They rated their overall satisfaction with the heating, hot water and ventilation at their former home as "poor" compared to a rating of "good" at BedZED. In both occupancy surveys, they stated that they wore heavy clothing indoors during the winter. It is interesting that they are paying about £100 per annum more for energy at BedZED, experiencing lower internal temperatures and are more satisfied overall with the heating, hot water and ventilation.

The participant in property S experienced a reduced internal temperature at BedZED of 0.3ºC compared to their former home. They had previously lived in a flat built between 1966-76 with a SAP rating of 66 and which measured 59.4m^2 NIA or 68.3m^2 GIA assuming that NIA/GIA efficiency ratio of the pre-BedZED property was 85% (as above) and which broadly equates to the new BedZED flat which measured 69.5m^2 GIA. At their previous home, the participant in property S assessed their heating, hot water and ventilation as "OK". They reported that their living room was too cold in winter. At BedZED, they reported that the overall heating, hot water and ventilation were "poor". Here they found the bedrooms too cold in winter. The mean internal temperature recorded in their previous property was 20.1 ºC and at BedZED was 19.8ºC, that is, just below the design temperature of 20ºC. They also report that they wear medium weight clothing indoors in winter compared to the thin layers at their previous home. The participant did not answer the question on energy costs for BedZED and so no comparison can be drawn about costs. The reason for their dissatisfaction could be attributed to the fact that the bedroom does not achieve the design temperature and this could have affected the participants' comfort despite them wearing heavier clothing after moving into BedZED.

Occupant M experienced the biggest improvement in internal temperatures, increasing from 15.6ºC in their former home to 22.2ºC at BedZED. They rated the heating, hot water and ventilation at BedZED as Very Good (the highest rating) and stated that they wore thin layers at BedZED compared to medium layers previously.

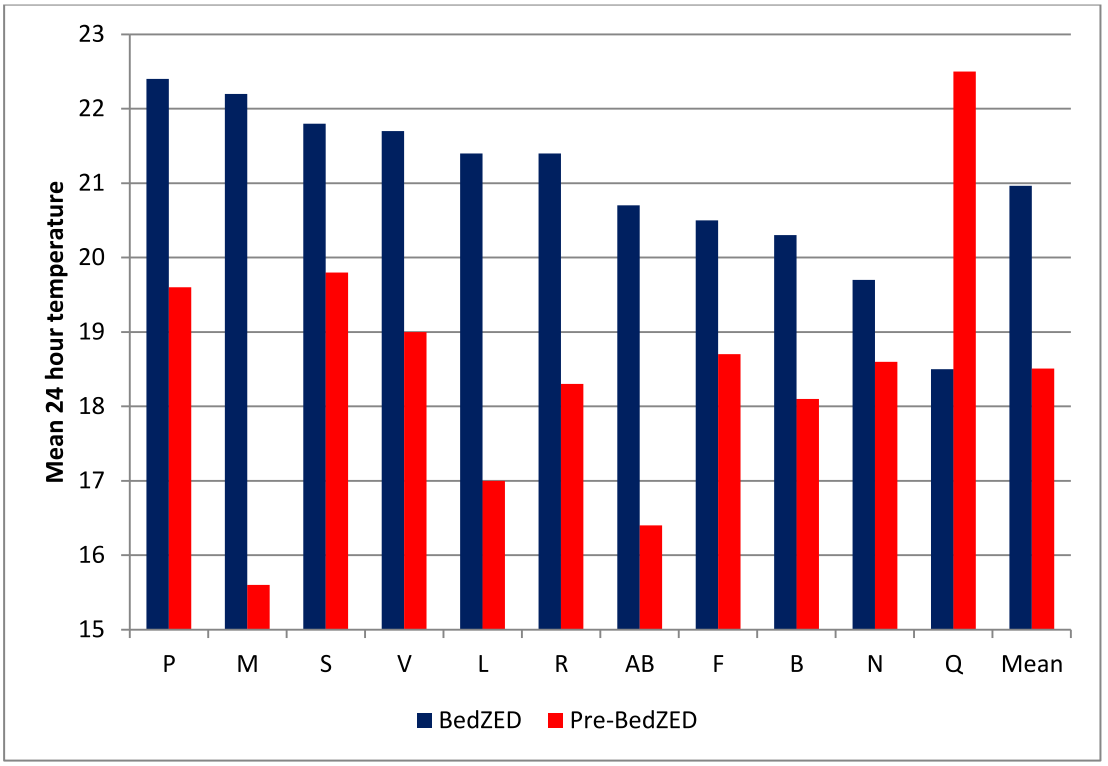

Figure 12.2: Comparison of living room temperatures Phases 1 and 2 standardised to external temperature of 5°C

Figure 12.2 shows mean living room temperatures when the external temperature was 5ºC during Phase 1 (pre-BedZED) and Phase 2 (BedZED). All properties recorded higher mean living room temperatures at BedZED apart from Property Q. The difference in internal temperatures between Phases 1 and 2 ranges from -4ºC to 6.6ºC, with a mean difference of 2.5ºC, higher than the 0.8ºC increase for bedroom temperatures.

The mean internal temperature of the living room during Phase 1 for Property Q was 22.5ºC compared to 18.5ºC, at BedZED. Property Q was built in 1995 and had a SAP rating of 58. Reviewing occupant Q's responses to the occupant survey at the end of Phase 2, they stated that they were satisfied overall with the heating and hot water at BedZED. They reported some concern about winter temperatures but this appears to be confined to the sunspace (which was not designed as a living space) and the occupant also reported that they used a back-up space heater for about two hours a day in the winter months. Their previous home had been a flat built around 1995 with electric space heating. This would have been relatively well-insulated, likely to have been built to the 1985 Building Regulations. They report that their annual energy costs at BedZED are about £200-£300 which was the same cost range that they reported in the Phase 1 survey based on their previous home. The principal change for this occupant between the two surveys is that they report that they now wear medium-weight clothing in the winter compared to just a thin layer at their previous home. This could account for the reduced internal temperature but overall satisfaction with BedZED. They also appear to have gained additional floor area in their new home. Although still a two-bedroomed flat, their floor area has increased from 37.7m^2 NIA to 69.5m^2 GIA, an increase of approximately 38% (assuming NIA/GIA efficiency ratio of 85%, as above). This may have also contributed to their overall satisfaction since they were paying the same energy costs for more space albeit they had to adapt their behaviour through the clothes they wore in response to the internal temperature.

Figures 12.1 and 12.2, plotting bedroom and living room temperatures for both the BedZED and pre-BedZED properties, show little correlation. For example, the warmest BedZED property was not the warmest pre-BedZED property and the coldest BedZED property was not the coldest pre-BedZED property. This suggests that internal temperature is not a simple variable selected by the participants but the result of a more complex interaction between fabric, services and occupants. Love (2014) found that retro-fitting better insulation to existing dwellings resulted in higher temperatures and shorter heating times. She concluded that the increased temperatures were a result of better thermal efficiency of the building fabric rather than occupant behaviour change because temperatures were higher when the heating was off. It is seen later in the chapter that BedZED participants did not consider that they could control the services within their homes.

Table 12.4 summarises the changes in internal temperatures between Phases 1 and 2 Cohort 2 for bedrooms and living rooms.

Table 12.4: Summary of changes to internal temperatures Phases 1 and 2 standardised to external temperature of 5°C

	Min °C	**Max °C**	**Mean °C**	**Range °C**	**σ**
Bedroom					
Pre-BedZED	15.6	20.8	18.5	4.8	1.78
BedZED	16.1	22.2	19.4	6.1	1.58
Change	**+0.5**	**+1.4**	**+0.8**		
Living Room					
Pre-BedZED	15.6	22.5	18.5	6.9	1.86
BedZED	18.5	22.4	21.0	3.9	1.17
Change	**+2.9**	**-0.1**	**+2.5**		

The comparison in Table 12.4 shows variation of internal temperatures between BedZED and pre-BedZED properties. Across the whole cohort, the range is highest for pre-BedZED living rooms and lowest for BedZED living rooms. The greatest change in mean internal temperature is BedZED living rooms which increase by 2.5ºC. The sample included in this cohort of 11 properties (12 loggers because property R had loggers in two bedrooms) is smaller than the total Phase 2 sample and includes six properties that had mean internal temperatures below the design temperature of 20ºC.

As expected, the standard deviations illustrate that the mean internal BedZED temperatures are more consistent than the pre-BedZED properties, particularly living rooms. BedZED properties are constructed to the same design and by the same constructor and demonstrate a more consistent environment than the variety of design and age of the pre-BedZED dwellings. Additionally, BedZED temperature data were collected over a longer period.

Turning to occupants' satisfaction with internal temperatures, the occupant survey asked a range of questions about heating, hot water and ventilation. The main line of inquiry was how BedZED dwellings performed during the heating season given that the dwellings did not have a typical central heating system. For consistency, data presented in the following charts (Figures 12.3 – 12.8) were based on Cohort 3 responses only, that is, the ten participants who took part in both pre- and post-occupancy surveys (properties B,F,J,M,N,P,Q,R,S,V)

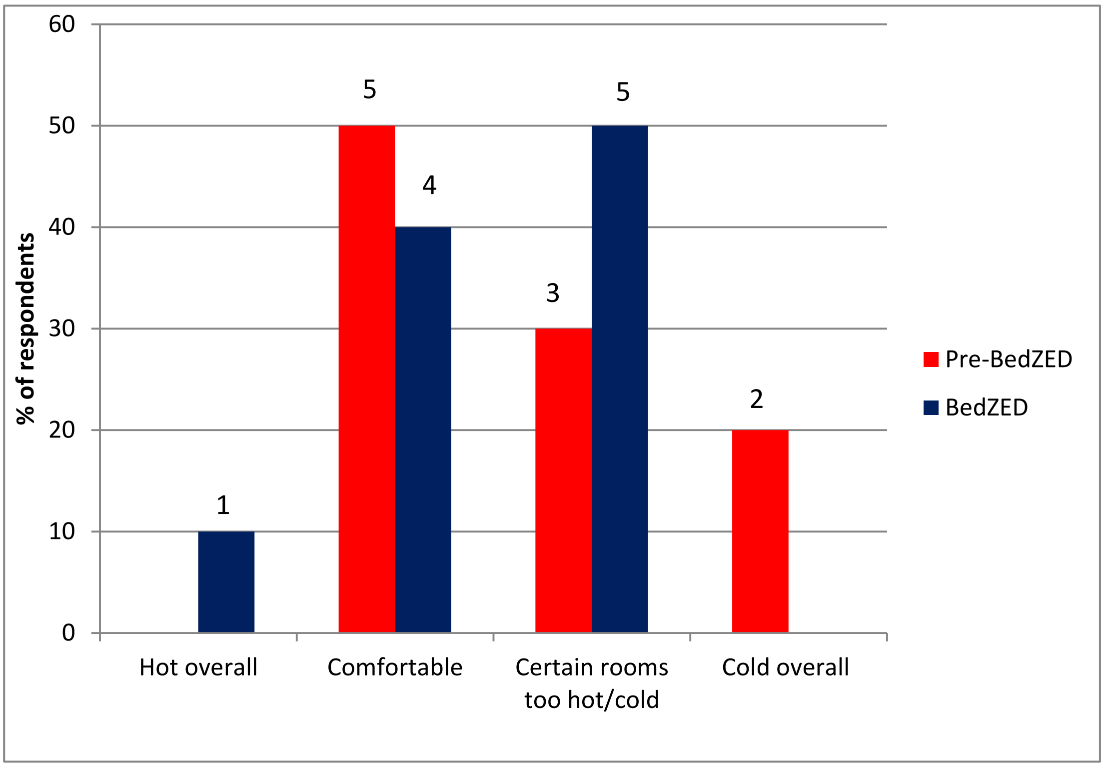

Figure 12.3: Occupant surveys: How would you describe the comfort level of your home during the winter?

Two participants found their pre-BedZED properties cold overall while no one at BedZED found their property cold overall. One BedZED occupant (P) found their property hot overall in the winter. However, a larger number of participants found that certain rooms were too hot or cold at BedZED compared to previously. The explanations given are variously that the living room (B,J,R), sunspace (Q,S) and bedrooms (R,S) are too cold. It is notable that two respondents cited the sunspace as too cold because the sunspace was not designed to be used for living space during the winter months.

Figures 12.1 and 12.2 show that winter BedZED internal temperatures were higher than this cohort's previous homes. However, Figure 12.3 shows that only 40% find the winter temperatures comfortable. This demonstrates the difference between actual measured readings and occupants' expectations of comfort, particularly in a new dwelling.

Section 4.15 described how the space heating and control system at BedZED differs from other dwellings with traditional central heating systems and thermostatic controls that are visible in the living space and directly adjusted by the occupants. Given the complexity of adjusting the controls at BedZED, a more likely action to increase internal temperatures above the design temperature would be for the occupants to use additional space heaters. A number indicated that they did so in the Phase 2 post-occupancy survey although the original design assumed that occupants would only do this if babies or the elderly were living there.

To examine this in more detail, Figure 12.4 shows how effective cohort 3 considered the controls to be at maintaining comfortable temperatures in the home.

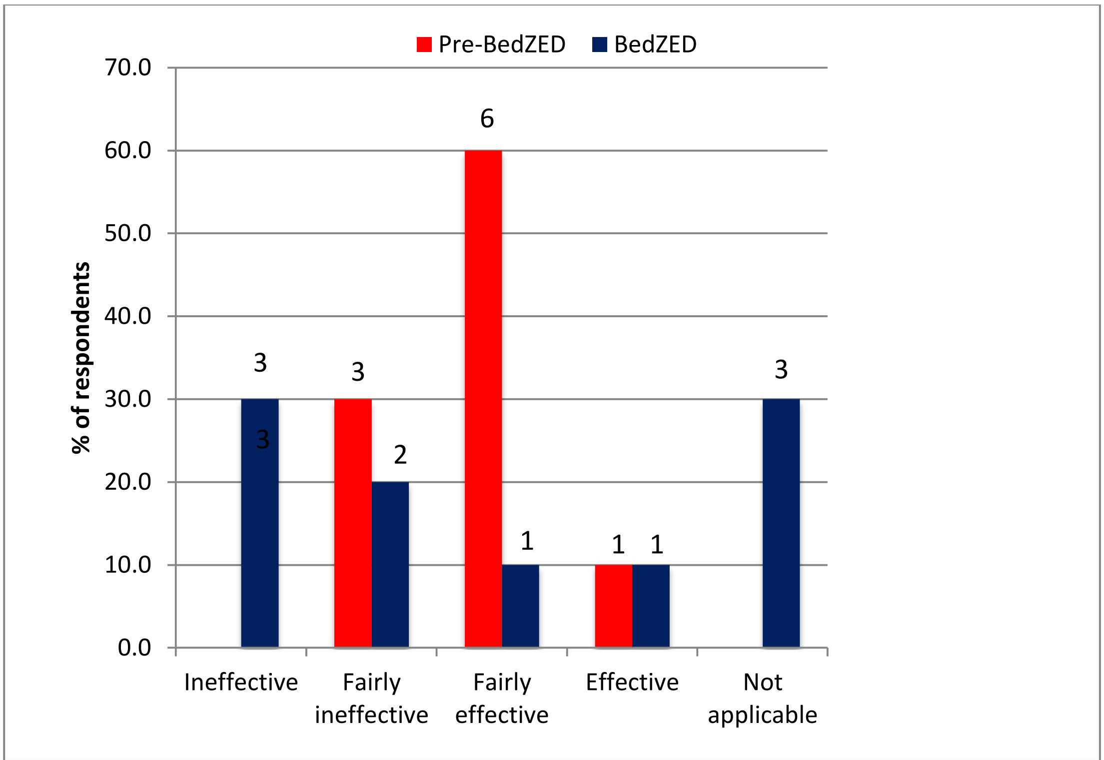

Figure 12.4: Occupant surveys: How effective are the controls at maintaining comfortable temperatures in the home?

Figure 12.4 shows that five participants said that the BedZED controls were ineffective or fairly ineffective, three said that the question was not applicable and two said that they were effective or fairly effective. Overall 50% of BedZED participants rated the controls fairly ineffective or worse compared to the 30% of the same group of participants before they moved into BedZED.

The “Not Applicable” answer was not supplied in the survey, and so it is interesting that three BedZED respondents stated that this question was not applicable to them. This suggests a lack of awareness that the controls could be adjusted. A further question about the ease of operation of the controls at BedZED suggests that the participants did not find the controls easy to operate. These results are shown in Figure 12.5.

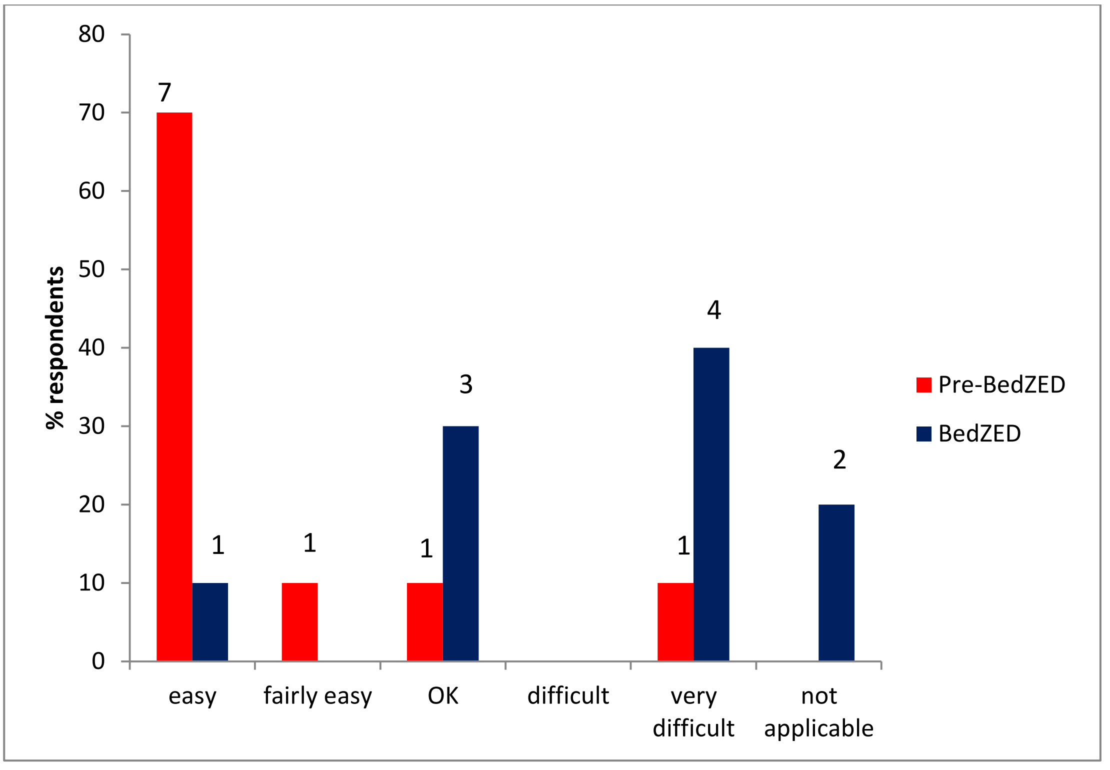

Figure 12.5: Occupant surveys: How easy do you find it to operate the heating controls?

Despite the variety of properties in the pre-BedZED sample, it is notable that Figure 12.5 shows that 80% of respondents found the controls easy or fairly easy to operate in their previous homes compared with only 10% at BedZED.

6 of the 10 respondents found the BedZED controls difficult to adjust or considered the question to be irrelevant.

The comments provided to this question from the whole Phase 2 sample (i.e. not only confined to this longitudinal sample of ten participants) are also informative here. One respondent said that they had not received full operating manuals for the thermostatic controls; another occupant said that "there aren't really any controls". No explanatory comments were received from participants F and P who stated that the question was not applicable although the controls on the heated towel rail and the hot water cylinder indirectly control the waste heat from both and which constitute some of the incidental gains that provide space heating at BedZED. The BedZED Residents' Manual (Peabody Trust 2002) provides information about all these controls but it is not known whether the respondents of this survey had read and understood the manual. In conclusion, this suggests a missed opportunity to provide additional information to BedZED occupants about how to get the best out of their homes, particularly given the innovative design of the heating system.

Turning to the provision of additional space heating, participants were asked whether they used any supplementary heating and the results are in Figure 12.6.

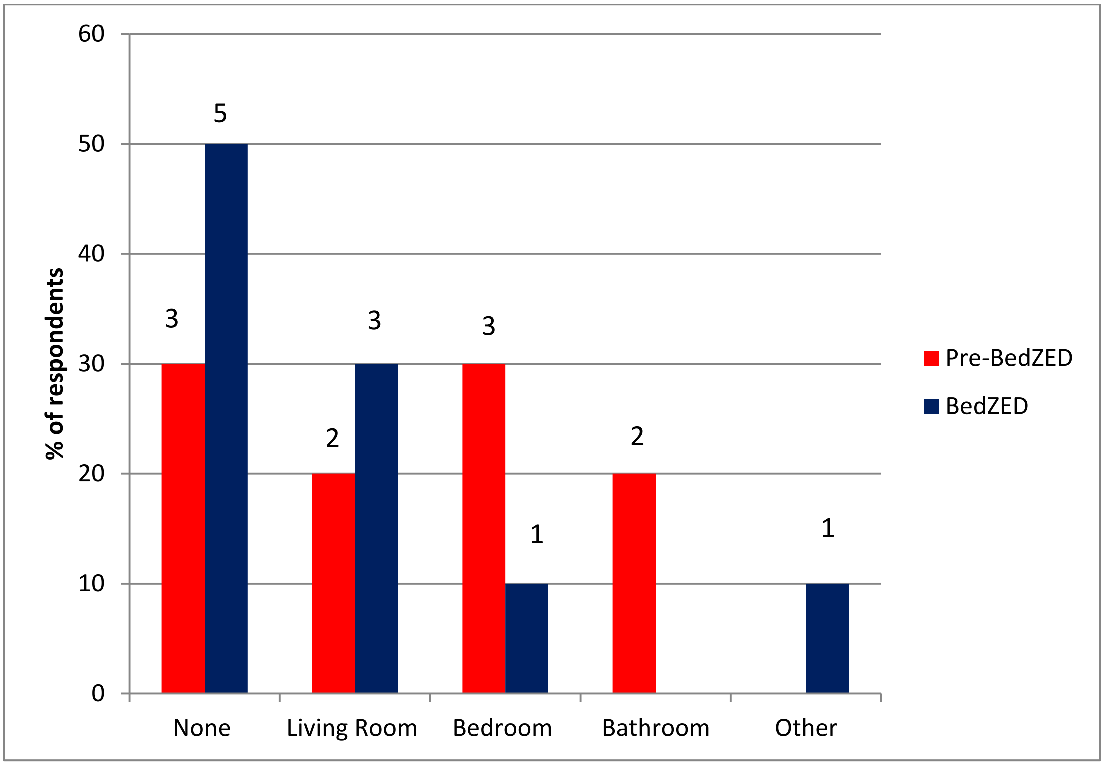

Figure 12.6: Occupant surveys: Do you use any additional form of heating?

For their pre-BedZED dwelling, one participant (S) said that they had additional heating in the bedroom and bathroom, however the incidence has only been included once in the above table (recorded against bedrooms). It is interesting that three respondents said they used additional heating in BedZED living rooms compared with only two in the pre-BedZED properties and Table 12.4 showed that the BedZED living room temperatures were 2.5°C higher than previous living rooms and BedZED bedrooms 0.8°C higher than previous bedrooms. Some of this gain will have resulted from the additional space heating but overall there are fewer participants (five) using additional space heating at BedZED than before (seven). However, it had been assumed that BedZED occupants would not use any supplementary space heating unless there were babies or elderly people living at the property.

Figures 12.7 and 12.8 compare mean internal living room temperatures to SAP ratings and mean average U-values of the pre-BedZED properties in Phase 1 Cohort 1 dwellings respectively for which data were available (properties B,F,J,N,P,Q,R,S,V,AB) to establish whether there is a correlation between the building design and actual temperatures measured. Each data point represents one property.

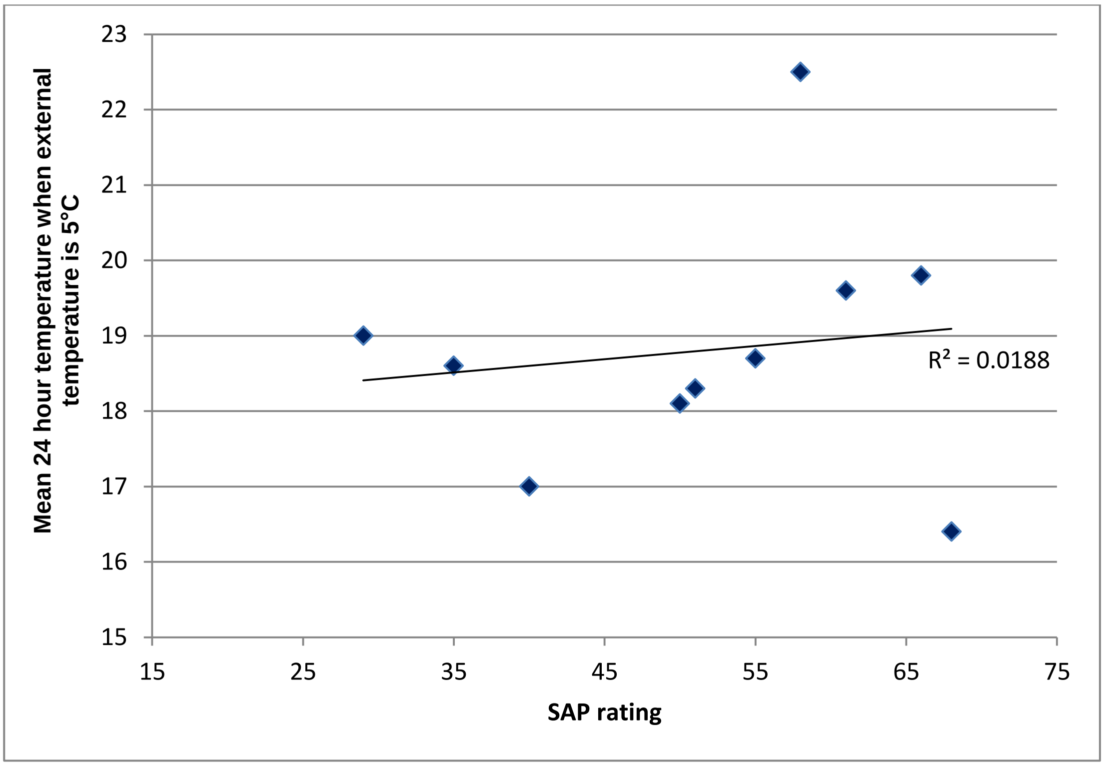

Figure 12.7: Phase 1 dwellings - Living Room Temperatures compared to SAP

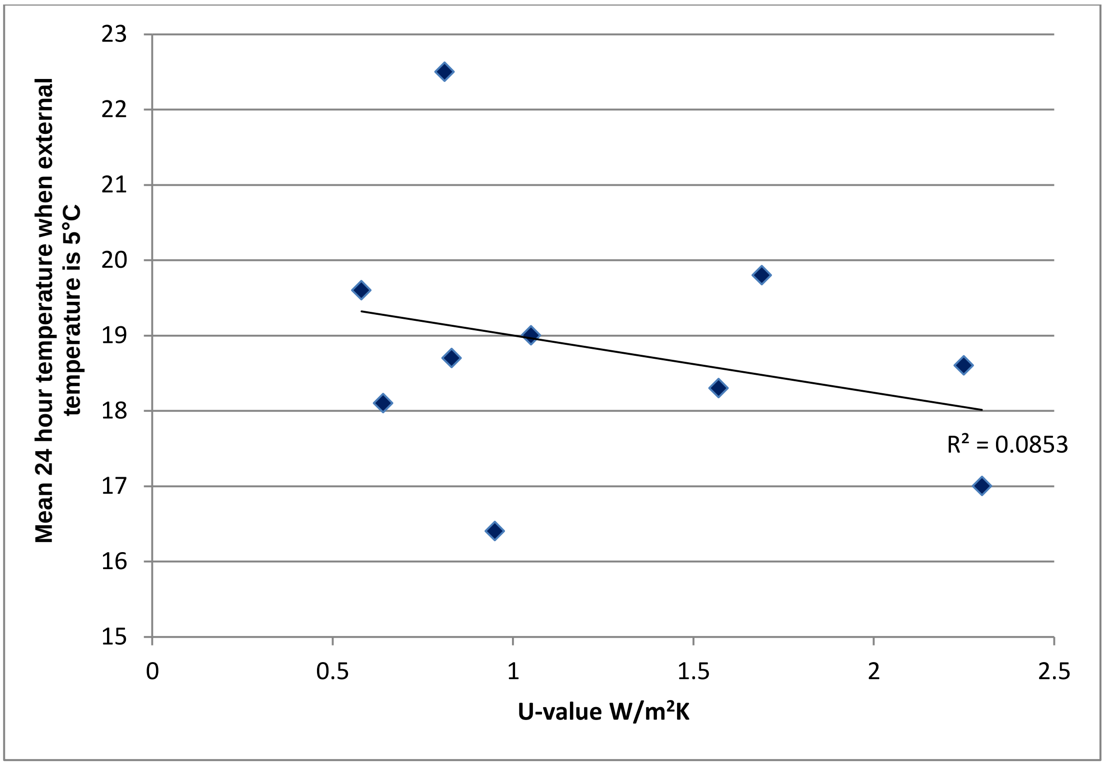

Figure 12.8: Phase 1 dwellings: Living Room Temperatures compared to mean U-values

The line of best fit illustrates that the dwellings with higher SAP ratings have circa 0.6°C higher internal temperatures and that properties with the lowest U-value have circa 1.6°C higher temperatures. The charts indicate that no linear relationship exists between the internal temperature in the pre-BedZED properties and U-value (R^2 = 0.085) or SAP (R^2 = 0.019). The range of internal temperatures observed is 5°C, from 15.8°C to 20.8°C. For example, Property AB had the highest SAP rating of 68 and an internal mean temperature of 16.4°C. Property V has the lowest SAP rating of 29 and internal mean temperature of 19°C. The occupant of property V stated in the Phase 1 (pre-BedZED) survey that they used additional heating in the bedroom for short periods of an hour during cold spells. The results of this analysis provide some insight into the behaviour of the BedZED participants and what they think about their previous dwellings. With only one pre-BedZED property (Q) maintaining a 24-hour mean internal temperature of over 20ºC, these temperatures are not excessive for the winter months.

The R^2 values are very low and no firm conclusions can be drawn from the comparisons of Phase 1 temperatures with the building design/fabric. The poor correlation coefficients for the plots are indicative that there may be an effect but it is a weak relationship given the small sample size

The Warm Front retro-fit study of circa 1,600 dwellings did find a relationship between dwelling heat transfer characteristics and internal temperatures. Following energy efficiency improvements to dwellings, internal temperatures increased as occupants took back some of the improvement in the form of higher internal temperatures (Hamilton, Davies, Ridley et al 2011). This would not seem to apply to the BedZED study because the participants surveyed did not seem to be confident in the operation of the heating controls.

12.4 Comparison of Energy Usage

Energy usage data were collected for seven dwellings in the Phase 1 dwellings but lack of sub-metering meant that it was not possible to exclude heat usage data from dwellings which were electrically heated. Table 12.5 compares the electricity usage for two properties, D and R, across Phases 1 and 2. D and R were selected for this comparison because their pre-BedZED properties had heat provided by gas and so the electricity usage figures for the two Phases are consistent.

Table 12.5: Comparison of Electricity Usage during Phases 1 and 2

	Phase 1	**Phase 2**	% reduction
	kWh/week	kWh/week	
D	101.50	71.12	30
R	253.15	146.69	42

For Phase 2, property R had sub-meters fitted and used approximately 12% of total electricity on heat for immersion heaters, therefore the Phase 2 usage for R has been reduced by 12% (see Table 7.3). Property D did not have sub-meters installed in Phase 2 and the usage has therefore been adjusted in line with Table 7.4, i.e. the electricity usage reduced by 18%. Table 12.5 shows that these two households significantly reduced their electricity usage when they moved to BedZED. A-rated low energy white goods were installed as standard at all BedZED properties as well as low energy lamps in light fittings.

In both cases, participants D and R had moved into larger properties at BedZED. While increased floor area is more likely to affect heat requirements, it could also affect electricity consumption, particularly lighting but also appliance use if the move were accompanied by an increase in the size of the household. Accordingly, table 12.6 standardises electricity usage data for property size and shows that when usage is standardised to floor area, both households reduced their electricity use by over 50% on moving to BedZED.

Table 12.6: Adjusted Comparison of Electricity Usage during Phases 1 and 2

	Phase 1	**Phase 2**	% reduction
	kWh/m^2/week	kWh/m^2/week	
D	1.67	0.8	53
R	2.18	1.1	51

The number of appliances used by D is not known and it is therefore not possible to assess whether there is any change in the number of appliances. Occupant R used 9 appliances in Phase 1 and 8 in Phase 2. This appears to be because they no longer have an oil-filled panel radiator.

In summary, the comparison shows that these households reduced their electricity consumption when they moved to BedZED. It shows that if the results from these two properties were representative, that the original design aim to reduce electricity consumption at BedZED by 10% was comfortably achieved.

12.5 Occupant Behaviour

In their post-occupancy evaluation of an EcoHomes “excellent” case study, Gill, Tierney, Pegg et al (2010) found that energy-efficiency behaviours account for 51% and 37% of the variance between dwellings in heat and electricity consumption respectively. The comparison of occupant behaviour between Phases 1 and 2 of this study aimed to find out whether participants actively changed their behaviour to increase efficient energy use at BedZED.

In both surveys, participants were asked about how much clothing they normally wore in the home in winter in order to assess whether they changed their behaviour when they moved to BedZED. For example, if internal temperatures were lower, were participants adding extra layers of clothing or were they using additional heating and would either of these scenarios result in lower satisfaction levels? The question asked "How much clothing do you normally wear in the home in winter?" and the choice of responses was:

- Just a thin layer, e.g. T-shirt, shirt or blouse
- Medium layers, e.g. T-shirt/shirt and thin sweater/cardigan
- Heavy layers, e.g. T-shirt/shirt and heavy sweater/fleece.

The results are in Figure 12.9.

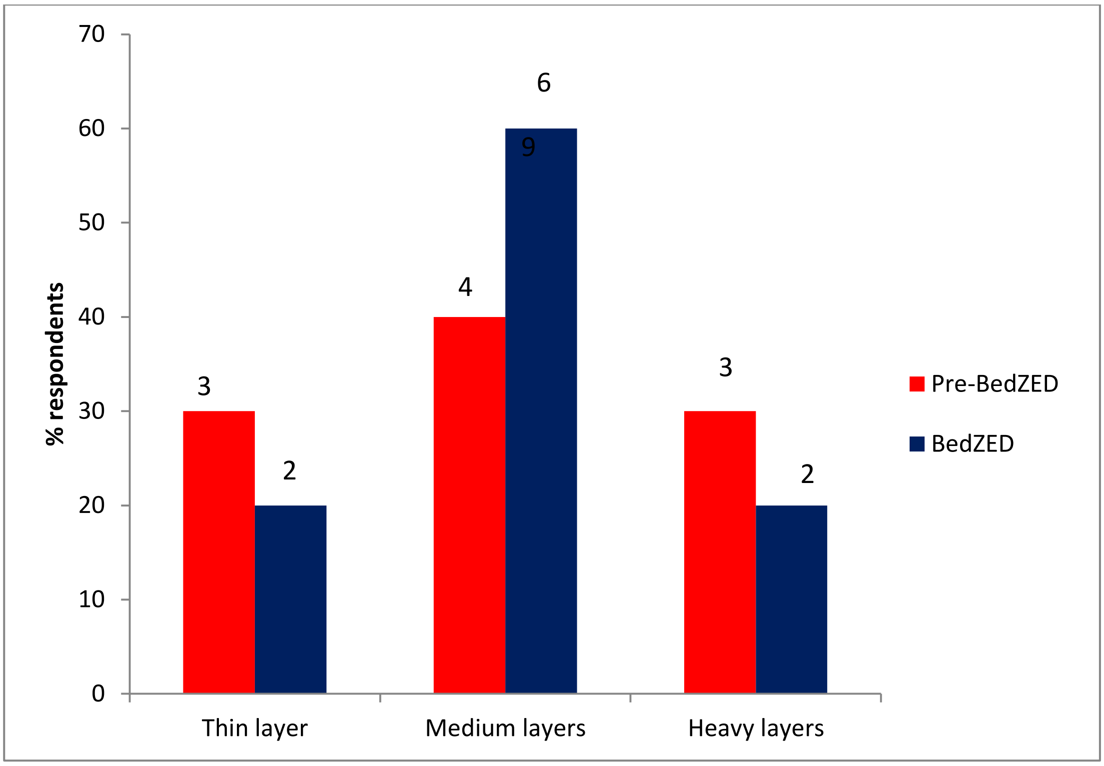

Figure 12.9: Occupant surveys: How much clothing do you normally wear in the home in winter?

Figure 12.9 shows a shift of one person towards medium-weight clothing from thin layers but it also shows a shift of one person from heavier-weight clothing to medium-weight. One occupant (B) has been classified in the medium weight bracket although they also responded positively to the heavy layers question stating that they wear a fleece indoors during cold spells. If that response had been included in the heavy layers category instead of medium layers, the chart would have shown a positive shift towards wearing heavier-weight clothes indoors.

With this small sample, it would be unreliable to conclude that BedZED participants "took back" the improved environmental conditions by reducing clothing layers rather than reducing their heating requirements further. And we have seen from the questions about controls, that the BedZED participants found it difficult to operate the heating (and hot water) controls. The nature of the heating controls at BedZED was such that occupants were not expected to regularly adjust temperature settings.

12.6 Overall Satisfaction with Heating, Hot water and Ventilation

In both Phases, participants were asked about how satisfied they were with the heating, hot water and ventilation in their home. The results are presented in Figure 12.10.

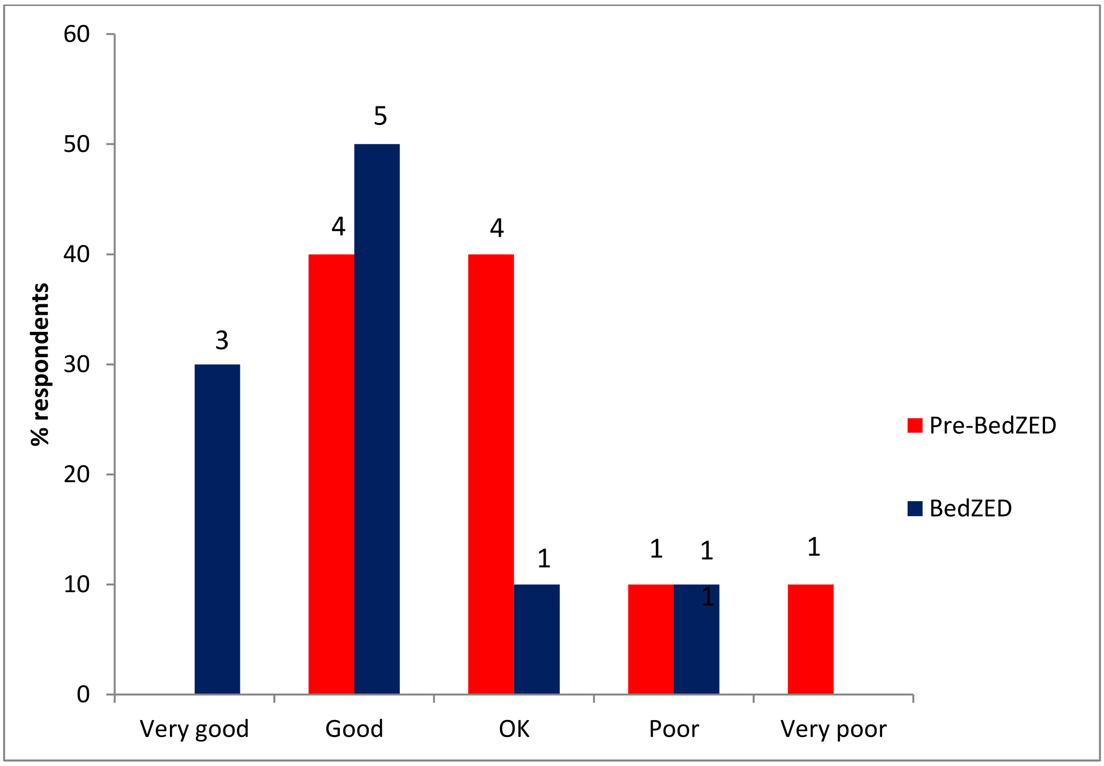

Figure 12.10: Occupant surveys: How satisfied are you with the heating, hot water and ventilation in your home?

Overall, responses show that the majority is satisfied with the heating, hot water and ventilation in their properties with 80% saying that the systems are good or very good. In comparison, only 40% rated their pre-BedZED properties as good. There is a clear trend towards more satisfaction with the heating, hot water and ventilation than previously. One respondent (R) stated that they were "not very satisfied but it was OK" and cited the fact that the CHP was not working. This response was allocated to the "OK" category. There were no other comments provided by other respondents to this question although some of the general responses at the end of the survey are informative. Two respondents cite summer overheating as an issue (B,J) and two respondents say that they would like more control over the temperature (R,V).

12.7 Ventilation and Condensation

Participants were asked whether there was any condensation or mould growth in their home before and after moving to BedZED and the results are in Figure 12.11.

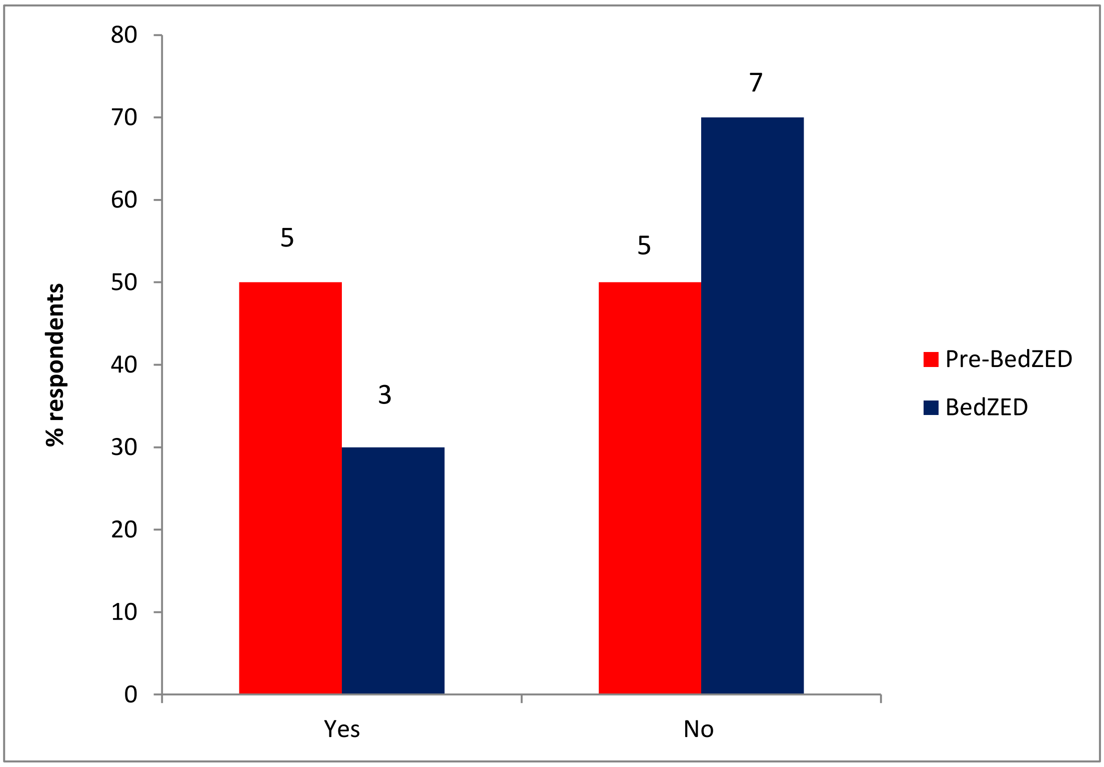

Figure 12.11: Occupant surveys: Is there any condensation or mould in your home?

Figure 12.11 shows that BedZED dwellings suffered from less condensation than participants' former homes with just three participants (P, S, V) reporting condensation or mould in the BedZED dwellings compared to five in pre-BedZED dwellings. The overall improvement in reduced condensation was to be expected given that the BedZED properties are newly built and well insulated. It is surprising that the number of positive responses to this question for the BedZED homes was as high as three out of the sample of ten. A more detailed analysis of all participants who reported condensation in their property, not just cohort 3 for the longitudinal study, is in section 10.5.

In both surveys participants were asked whether they opened windows to improve air quality and the results are presented in Figure 12.12.

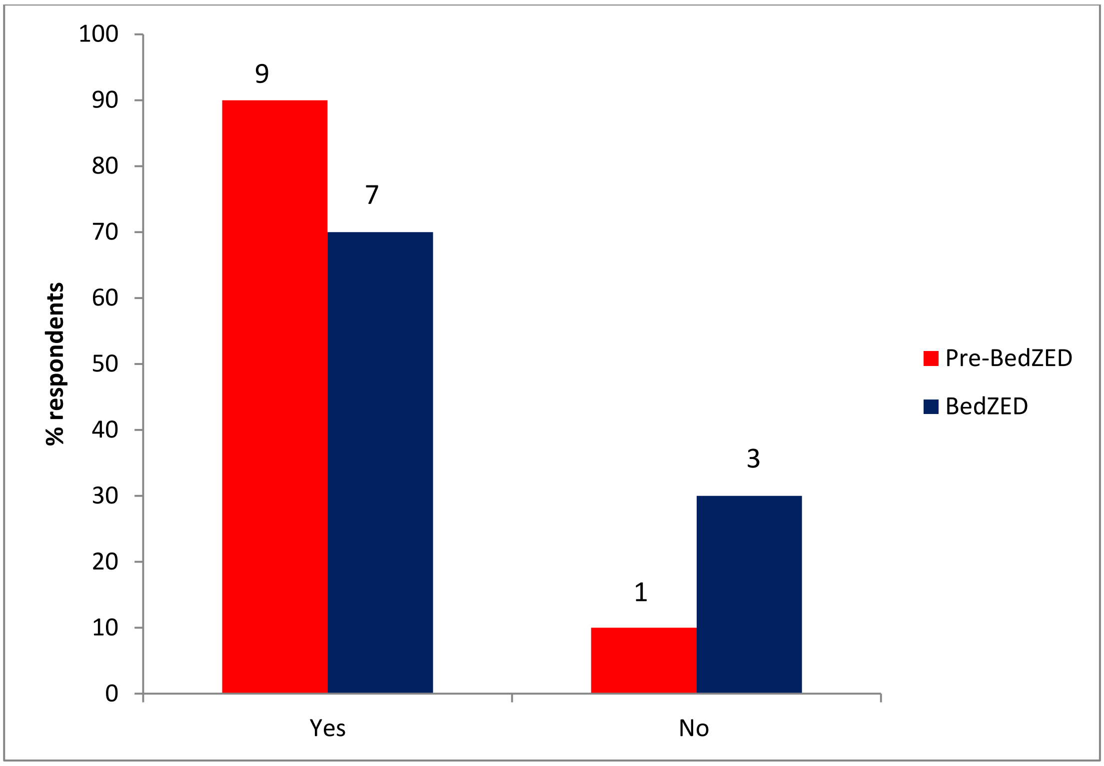

Figure 12.12: Occupant surveys: Do you open windows to improve air quality?

90% of respondents said that they opened windows for fresh air in the pre-BedZED dwellings compared to 70% of the BedZED survey. As a very airtight design, the ventilation strategy for BedZED was a combination of passive stack ventilators to exhaust local moisture and pollutants and occupant controlled window opening. It is therefore surprising that 30% of the sample is not opening windows for fresh air at BedZED and that previous window-opening behaviour had changed. Specific questions were not asked about the passive vents, but one of the reasons for less window-opening could be that the passive vents were effective in exhausting stale air. Another reason could be the reduction in condensation compared to previously.

Since air-tightness is an important element of the building design for BedZED participants were also asked about the draughtiness of their homes in both surveys and the results presented in Figure 12.13.

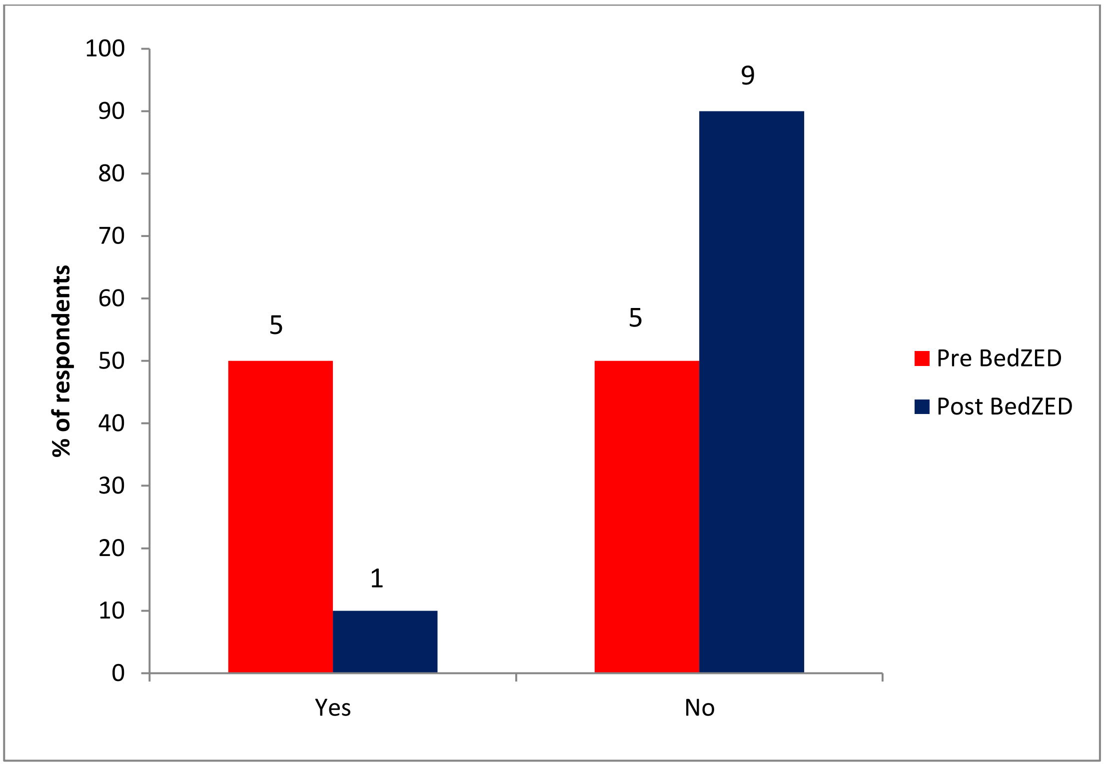

Figure 12.13: Occupant surveys: Do you consider your home to be draughty?

There is a clear reduction in the incidence of draughts in the BedZED survey compared to the pre-BedZED survey. The pre-BedZED properties were of varying ages and standards of construction and half were reported to be draughty by the participants surveyed. In the post-occupancy survey, only one participant (S) out of the ten reported that their BedZED dwelling is draughty and the cause of the draughts is the windows. No further explanation is offered although an occupant not included in this longitudinal comparison, (G), cited problems with seals to roof lights. It is not clear whether this snagging issue was also the cause of the draughts experienced by occupant S.

12.8 Health

Before moving to BedZED, participants were asked if there was any instance of asthma or similar health problem that could be associated with the living environment. For the post-occupancy survey, participants were asked whether, since moving to BedZED, anyone in the household had experienced asthma or similar health problem for the first time that might be associated with the living environment. The results of both questions are plotted in Figure 12.14.

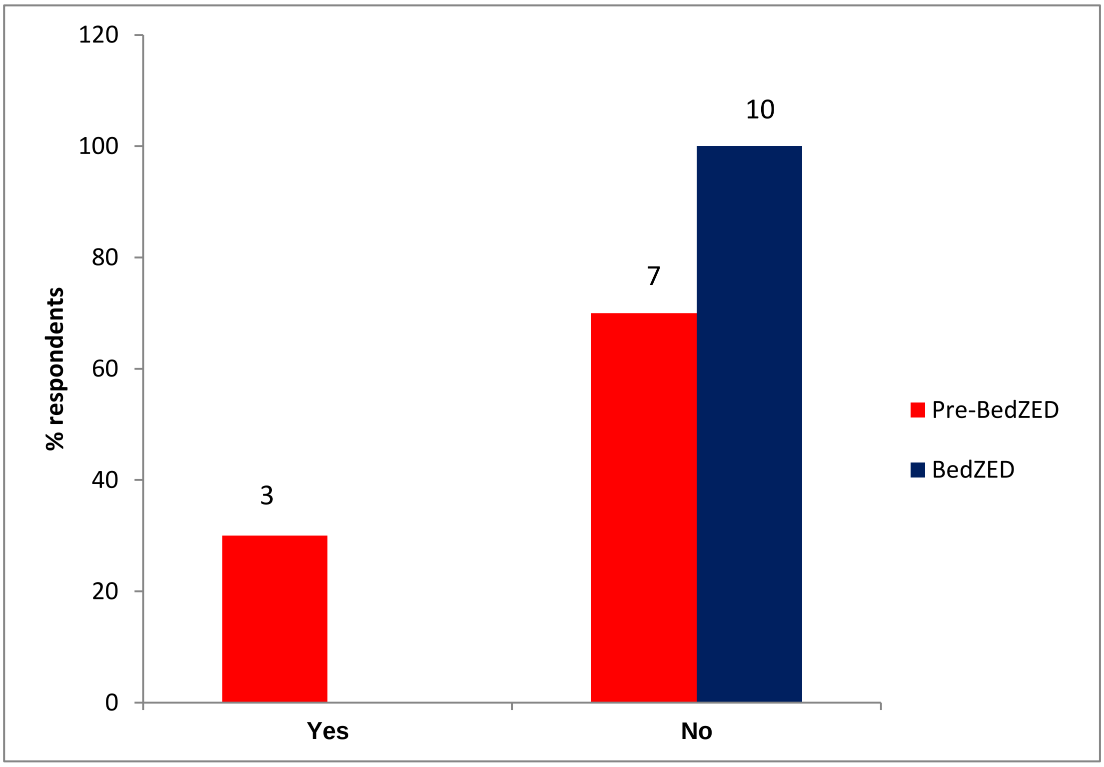

Figure 12.14: Occupant surveys: Have you experienced asthma or a similar health problem either in your previous home or for the first time in BedZED?

The question in the second survey did not check whether pre-existing conditions were still experienced or had ceased. The three respondents that reported issues (B,J,M) in the first survey that included asthma, bronchitis and dust allergy may have continued to suffer from these conditions in BedZED. However the results show that no occupant experienced new illnesses that could be attributed to the dwelling. Although not included in the longitudinal sample, one occupant (G) cited noise transference owing to poor acoustic insulation between dwellings and said that this was affecting their sleep and their general health overall.

It would have been useful to know whether any of the participants in the first survey who reported some health problems had experienced any change in those problems. However this question was not put to participants.

12.9 Energy Bills

In both surveys, participants were asked about their fuel bills, whether they were aware of how much they were spending on fuel and the actual amount that they spent. The results are in Figure 12.15.

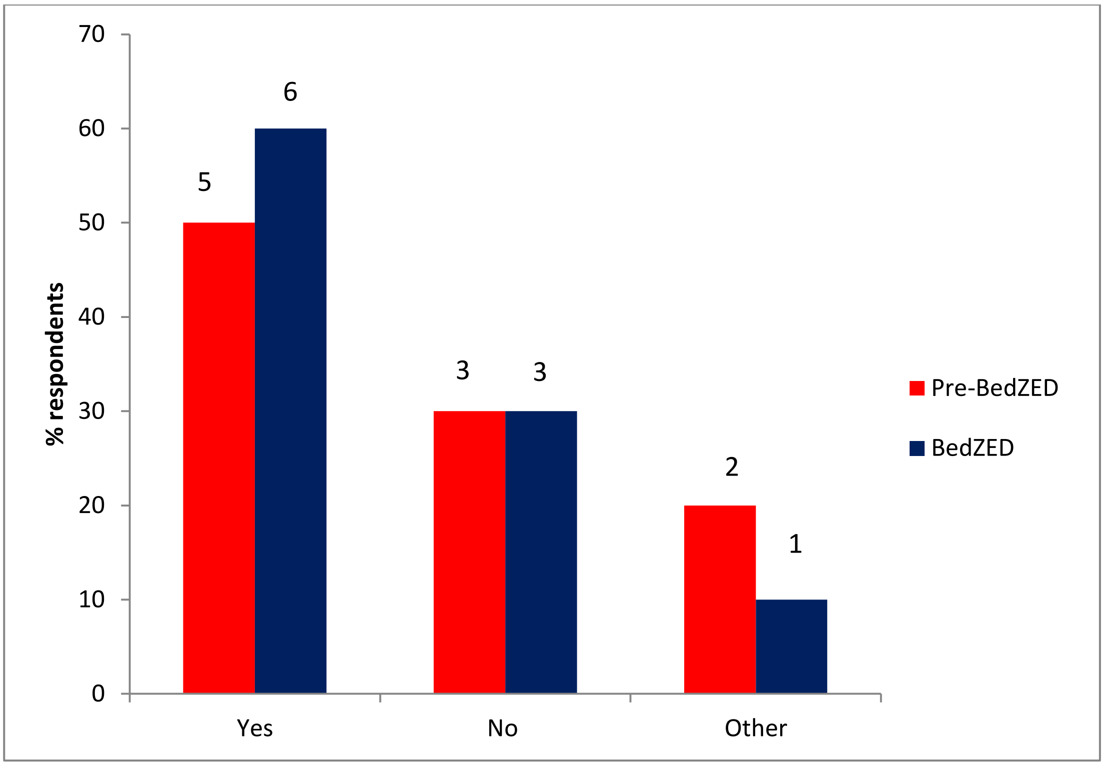

Figure 12.15: Occupant surveys: Do you know how much your annual fuel bills are?

The reason why one participant (P) was unsure about their bills in the pre-BedZED dwelling was because fuel costs were included in their rent. Occupant P did not answer the question in the post-occupancy survey and so was allocated to the "other" category to maintain the integrity of the comparative sample sizes. It is difficult to draw direct comparisons between pre- and post-BedZED occupancy because BedZED bills were for electricity, heat and also water charges, whereas prior to BedZED, bills could have included gas bills as well as electricity but did not include water bills. What is striking about this comparison is that six BedZED participants said that they were clear about how much their bills were when at the time there were issues with the operation of the CHP system serving the development. More responses would have been expected like that from occupant R who answered “other” to this question in the Phase 2 survey, stating that they were aware of their fuel bills when they first moved in but they had subsequently become confusing.

12.10 Appliance Use

Figure 12.16 shows the number of electrical appliances in each dwelling for each Phase. The purpose of this comparison was to see if the move to BedZED prompted changes in the number of electrical appliances used.

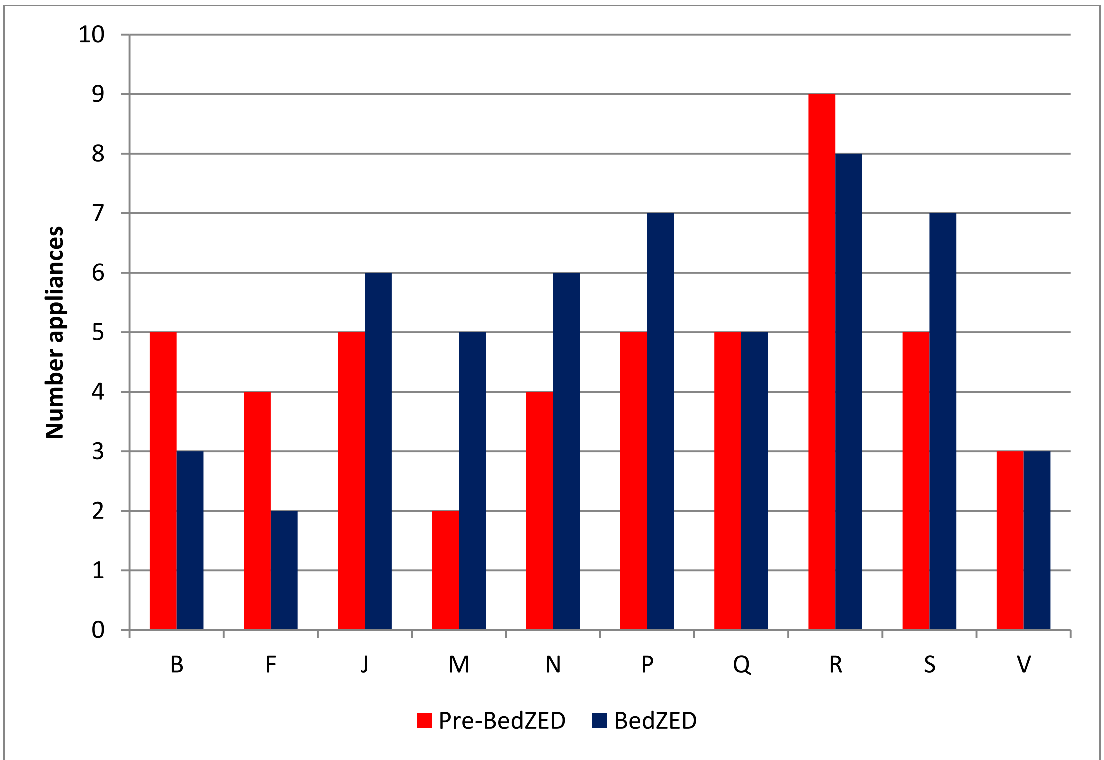

Figure 12.16: Occupant survey - number of appliances

There was an increase in the total number of appliances used at BedZED by the longitudinal cohort from 47 to 52. At an individual dwelling level, five participants increased the number of appliances used, three reduced the number and two were unchanged. The biggest change was occupant M who increased from only two appliances (a fridge and a TV) to five appliances.

12.11 Longitudinal Study Conclusions

The purpose of this chapter was to provide evidence to answer the fifth research question for this study: have participants changed how they use energy at home as a result of moving to the new development?

At the time of the study, this was the first longitudinal study of a group of occupants moving from older dwellings to new built dwellings. The main conclusion is that, on average, across the longitudinal cohort, the new BedZED homes were 2.5°C warmer in the living rooms and 0.8°C warmer in the bedrooms at an external temperature of 5°C compared to previous homes. The proportions of this rise attributable to a direct “comfort taking” is difficult to judge particularly given the participants’ reports that they do not consider they can easily control internal temperatures. Participants’ overall satisfaction with the heating, hot water and ventilation increased from 40% in their former homes to 80% at BedZED.

The higher temperatures are in large part due to the design of the property and its systems which made it difficult for the participants to maintain higher or lower temperatures than the design temperature. BedZED participants were less satisfied with their ability to control the heating, hot water and ventilation than in their previous homes. Some participants adjusted clothing to compensate and others relied on pro-active window opening which was part of the overall design philosophy. People do like to be able to control the heating and ventilation in their homes. Better induction and information about how to do so in passively-designed dwellings like BedZED is important since control in these properties will require different behaviours to a traditionally heated dwelling with room thermostats.

BedZED properties used less electricity than previous dwellings although this is based on a small sample of two participants. BedZED properties suffered from less condensation and mould than the previous properties but the level experienced was still at an unacceptable level for new properties.

A further finding of the longitudinal study is that most of the participants included in the sample moved into a larger property at BedZED with an overall increase in property footprint size of 45%. While the design of BedZED reduced overall energy use compared to other newly built properties (see Chapter 7), if this trend for larger properties were extrapolated nationally the increase in energy use from larger dwelling footprints could offset energy savings made from efficient design. That said, the average size of BedZED properties was lower than the national average.

Chapter 13 Discussion

13.1 Introduction

The hypothesis for this study is "There is a performance gap between predicted and actual energy performance in low energy dwellings and this is due to occupant behaviour". To test this hypothesis on the BedZED case study, the following research questions were set:

- How do the constructed units perform compared with the theoretical design performance?
- What is the difference, if any, between the constructed units and the units as designed?
- Why is there a difference?
- What conclusions can be drawn about this and can the energy model or design practices be changed to reflect this?
- Have participants changed how they use energy at home as a result of moving to the new development?

Energy modelling of building components and technologies normally assumes perfect quality control during the manufacture and construction of buildings and predictable use of the finished products by users. As buildings become progressively more energy efficient any discrepancy between modelling and actual energy used becomes more important. Energy modelling does not predict design changes that are made during construction but these changes can have a significant effect on the performance of the completed system. Additionally, energy modelling makes assumptions about occupant behaviours and human factors, which can also affect the performance of the completed system. These assumptions are normally based on limited or historical empirical evidence. However, this comparison does illustrate the challenge in producing reliable data about energy use at the early feasibility stage. Then as designs are developed in the detailed design stage, the overall size of buildings and therefore the heat and electricity demand can change considerably from original assumptions at the feasibility stage. .

The results and analysis in Chapters 7 – 12 identify differences in the performance of the BedZED dwellings compared to design and differences in how the study participants used their BedZED dwellings compared to their previous homes. This chapter discusses the key differences in the context of the research questions.

13.2 Energy Usage

The results presented in Chapter 7 show that BedZED achieved its aim to reduce electricity usage by 10% compared to standard dwellings. Total energy use was 7% higher than designed, principally because of higher than expected heat usage, but overall this is considered to be a successful outcome.

BedZED did not meet its ambitious overall design target of 75 kWh/m^2/annum, the 125 kWh/m^2/annum achieved at BedZED being considerably higher than the 75 kWh/m^2/annum design target, but much lower than the typical new building standard of 163 kWh/m^2/annum of the time. However, the BedZED total energy usage is broadly in line with the Passivhaus standard of 120 kWh/m^2/annum for total energy demand described in Chapter 2 (Schnieders 2003, Cutland 2012).

13.3 Modelling and Measurement

The 75 kWh/m^2/annum design target was based on a notional dwelling size of 100m^2 at the concept design stage. The overall footprint for BedZED at 7,615m^2, which was used to calculate the site energy requirements and size the CHP at the feasibility stage, was built out at 9,207m^2, some 21% higher. Given that the actual energy use is broadly in line with design (+7%) and the floor area of BedZED considerably higher than design (+21%) it is concluded that the 75 kWh/m^2/annum design target should have been updated as the design was developed.

The research questions are founded on a comparison between theory and practice and key to this comparison is how measurement systems are deployed. With regards to the fourth research question, this research has identified a number of areas where the use of energy models and design practices can be changed to effect improvements in the delivery of low energy dwellings. This includes the method used to measure floor area; the assumptions made about floor area during the different stages of design (feasibility, outline and detailed design); and the assumptions made by surveyors when completing EPCs.

There were three different measurement systems for property sizes used in the study, all of them standard methods: the method used in SAP; NIA used in NHER surveys and GIA used in the architectural drawings. It is not possible to directly convert from one measurement system to another although there are industry rules-of-thumb and they were used in this study. It is recommended that energy models use consistent methods of measurement in future to simplify energy analysis and reduce room for error.

The change in the overall footprint size of the BedZED scheme illustrates the dynamic nature of the design development process. It is typical for a scheme to be changed from inception to construction as a consequence of, for example, planning, funding or technical constraints. It is therefore important for the original energy models to be updated as the design is developed to ensure that the design targets will still be met.

While the kWh/m^2/annum metric is a useful way of comparing the energy use of different schemes on a like-for-like basis, it does not account for the different intensity of use between different sized households. Figure 7.3 shows that smaller dwellings (one- and two-bedroomed properties) have a higher kWh/m^2/annum than larger dwellings (three- and four-bedroomed properties), illustrating the greater intensity of energy use by smaller households. Table 2.1 presents data relating to population size, household size and energy use by household. It shows that the number of households is increasing faster than the population but that energy use by households is falling in relative terms.

A basic parameter for normalising energy use is property size and yet the different methods of calculating floor area have proved a challenge in compiling these data. This highlights the problem in determining the performance gap between theory and practice.

13.4 Adjusting for External Weather Conditions

The raw data collected in Phase 3 suggest a trend towards increasing heat demand but when corrected to external temperatures using degree day data, the trend reverses, thus illustrating the difficulties of interpreting actual performance against design; the design target has to be normative whereas real data fluctuates according to weather and occupancy. For measurement of actual performance to be useful, it should take account of the external weather conditions during the monitoring period so that data from one season can be meaningfully compared to other seasons' data. There are standard methods for correcting data for weather fluctuations but these are not routinely applied to domestic properties and are more complex in very low energy properties.

13.5 Winter Temperatures

BedZED achieved its winter design temperature of 20°C and performed best out of the low energy case studies analysed both for living rooms and bedrooms. There is evidence that some occupants used supplementary heating in winter but it is not possible to distinguish whether this was solely when the CHP was non-operational. The Phase 2 study sample was asked a number of questions about the heating and hot water in BedZED. To the very specific question about the comfort level of their home during winter

(Table 10.9), eight out of the 19 participants who answered the question chose Comfortable. A further eight chose “certain rooms too hot/cold”, two chose “hot overall” and one (L) chose “other” stating that it was OK if sunny but otherwise a bit cold in the living/sleeping space. Other respondents quoted some rooms being too cold for example, the sunspace (Q) and the rear bedroom (V).

It is interesting that the monitoring data show that there was no performance gap in the mean average temperature of BedZED dwellings compared to design but that the study participants have a different perception. This highlights the difference between statistical averages and how people actually experience comfort. In their answers to the survey, participants highlight the cold spots (and hot spots) in their home but the questionnaire requires them to select an overall (mean average) response.

13.6 Summer Temperatures

BedZED overheated in summer. Although a specific design target for summer was not set, analysis of mean average temperatures during summer months and a hot spell shows evidence of overheating. At 20°C external temperature, all BedZED living rooms in the Phase 2 sample experienced temperatures of between 3°C and 9°C higher than the external ambient temperature. Of the 19 survey participants who answered the question about how comfortable they found their home during the summer, five said they found it comfortable overall but with some caveats (E stated that the bedrooms got too hot and V stated that the living room got too hot). The other 14 participants stated that it was too hot overall or certain parts of the property were too hot. However, for context, BedZED bedrooms performed better in hot weather compared to other low energy case studies analysed.

Design may play a part in the reasons for overheating. Hot water pipes from the CHP were run underneath dwellings where practical in order to reduce the heat losses between the CHP and the dwellings with any pipeline heat losses inside buildings treated as incidental gains. While this is beneficial during colder temperatures, it could contribute to overheating during hot spells.

Another cause of the overheating could be a lack of understanding of how to operate the (at the time) novel dwelling with passive design features in particular, window opening. The literature highlights the importance of window opening to reduce overheating. For this study, while all participants surveyed confirmed that they opened windows to control temperatures, there is some evidence that BedZED residents did not fully understand how to get the best performance out of their homes in summer, in particular the use of the sunspace as a buffer rather than a living space and the need to open windows at night to cool down dwellings rather than during the day.

13.7 Human Factors

The variability of human response to comfort is illustrated by the comparison of internal temperatures and occupant satisfaction levels. For the winter temperatures, it was expected that there would be a correlation between temperatures that achieved the winter design target and overall satisfaction with heating and other systems, see Figure 10.3. A correlation was also expected between the summer high temperatures and overall satisfaction with heating and other systems, see Figures 10.4 and 10.5. However there is no correlation between these measures.

There was clear dissatisfaction with the heating controls. Although the controls enabled the BedZED properties to achieve the design temperature in the winter months, survey participants expressed dissatisfaction with the ability of the controls to maintain comfortable temperatures (Figure 12.4) and the ease of operating the controls (Figure 12.5). The longitudinal study is useful here because it clearly shows that the survey participants recognised that their BedZED homes were warmer in winter than their previous homes (Figure 12.3). But the survey participants rated the effectiveness of the BedZED controls to heat their home (Figure 12.4) and the ease of operation (Figure 12.5) more poorly than the controls at their previous homes. The final question about survey participants' overall satisfaction with the heating, hot water and ventilation (Figure 12.10) highlights that the majority (80%) of the longitudinal cohort rated these systems "Good" or "Very Good" at BedZED compared with only 40% for their previous homes. It can be concluded that the BedZED participants did not like the lack of personalisation in the form of room thermostats that the BedZED controls assumed and which are now standard for most UK dwellings.

At the time that BedZED was built, the average UK dwelling air infiltration rate was 13.1 ach at 50 Pa. (Stephen 1998) and for newer properties, built between 1987 and 1994, the average air infiltration was 9.6 ach at 50 Pa. (Stephen 2000). At 2.5 ach at 50 Pa, BedZED displayed a good level of airtightness, an important facet of the low energy passive design. A good ventilation system is essential to provide fresh air and remove moisture and the results of the airtightness test carried out for this study supports the findings of other studies that the ventilation system is effective (Table 9.1). However the occupant survey results indicate that almost half of the participants who answered this question did not think the ventilation system at BedZED was effective at removing moisture and smells. The survey also shows that all participants employed active window opening to control the temperature of their home but the internal temperature results during hot spells indicate overheating. Other studies suggest that this is partly attributable to a lack of understanding on when to open windows to achieve optimum cooling. Taken together, these results indicate a gap between actual measured performance and occupant perception.

There were reports by some of the participants that their homes suffered from condensation. This was not borne out by the RH readings for those properties (Table 10.24) except for property S that reported condensation in the sunspace. The passive ventilation system did not extend into the sunspaces and occupants would need to actively ventilate the sunspace, for example by opening windows, to reduce condensation. Participants G, P and S reported that condensation was a problem in the sunspace, and of these three, only property S had a data logger installed in the sunspace and this did record humidity levels conducive to condensation. It can therefore be assumed that other occupants actively ventilated the sunspace to control condensation.

It is interesting that the majority of survey participants said that the fuel dials on display in kitchens to raise awareness of energy usage made no difference to their behaviour (Figure 7.10) because this is contrary to the literature (Darby 2008).

13.8 Design Changes during the Development Process

The principal design change during the BedZED development process was the failure of the biomass CHP in the operational phase. This meant that the CHP, which was to provide zero carbon energy to the development, did not achieve its initial aim to be zero carbon. The designed contribution from renewables, both biomass and PV, did not happen in practice and there are many lessons to be learned for future zero carbon regulations if the UK is to achieve its planned targets for carbon emissions in new buildings. If such properties are to secure and maintain market value, changes are required to the design, construction, operation and assessment of such buildings.

13.9 Zero Energy or Low Energy?

In a paper on domestic energy use and carbon emissions scenarios to 2050, Utley and Shorrock (2005) stated that the ultimate goal is to achieve a carbon neutral dwelling. Energy consumption should be as low as possible and properties well insulated so that as little heat as possible is lost from the structure. So was BedZED zero energy, zero carbon or low energy?

At its conception, the project had been called Beddington Zero Energy Development, abbreviated to BedZED. Later, the full name of the project was changed to Beddington Zero (Fossil) Energy Development presumably to reflect the use of renewable energy rather than fossil fuels and/or grid electricity.

It can be argued that the Zero (fossil) Energy Development name more accurately reflects the aim of the project, which was to not use fossil fuels rather than wholly eliminate the use of energy. However, the operational failure of the biomass CHP and the conversion to gas meant that the majority of energy used by the scheme was in fact fossil fuel.

The literature review in Chapter 2 discusses the taxonomy for developments which include renewable energy production. There is presently a debate as to whether it is preferable to connect such buildings to the national grid or for them to remain “autonomous”. In the case of BedZED, it can be seen that BedZED could not have been autonomous even if the CHP had been successful since it was always planned to connect BedZED to the national grid and supply and draw down grid energy according to fluctuations in site energy demand. In their review of the scheme seven years after the buildings were completed, Hodge and Haltrecht stated (2009) that it is not sensible to say that all energy should be generated on-site in all cases. It may be more practical and efficient for developers to focus on reducing the demand for energy in their developments and to source the energy required from renewable energy sources from the grid.

In summary, BedZED was not Zero Energy or Zero (fossil) Energy. However, the actual energy use is very close to the Passivhaus standard and therefore BedZED can be described as a low-energy building.

While the literature review in Chapter 2 found some confusion over definitions of zero-energy buildings, it also found an increasing confidence on the part of industry to apply zero-energy and low-energy principles and technologies through the increasing number of such houses already built from which to draw upon both in the UK and overseas.

13.10 Limitations of SAP models

The study challenges were not limited to the performance data collected. Despite the improvements made to the SAP rating methodology during this research period, it continues to have some limitations when applied to low energy schemes like BedZED. Some of the original constraints of the early method that did not, for instance, model thermal mass have now been addressed. However the use of the RdSAP for producing EPCs for existing buildings does not fit well with existing low energy buildings. It is essential that these limitations are addressed if low energy buildings are to maintain their marketability in future.

13.11 EPCs

The EPC assessments carried out at BedZED were inconsistent and understated the low energy nature of the dwellings leading to potentially unreliable labelling of low energy buildings. It was striking that from the 43 EPCs assessed for BedZED, the mean average energy usage was predicted to be 175 kWh/m^2/annum compared to the actual 125 kWh/m^2/annum, providing evidence of a performance gap between actual and reported benefits in BedZED EPCs.

In addition to the need for the RdSAP to be reviewed, the skills of EPC assessors when rating very energy efficient buildings are found to be inconsistent. There is a need for more guidance and training for EPC assessors on the assessment of low energy buildings. Occupants who may have purchased a low energy BedZED property on the assumption of its low energy credentials might find their premium eroded by a poor EPC rating and this in turn could undermine the Government's policy of zero carbon buildings.

13.12 Longitudinal Study

The longitudinal occupant study enabled a further dimension to be applied to the performance data analysed for Phase 2.

The BedZED dwellings included in this study achieved higher winter temperatures than participants' previous homes, BedZED living rooms were

2.5°C warmer and bedrooms 0.8°C warmer on average than the participants' previous homes. Participants' overall satisfaction with the heating, hot water and ventilation increased from 40% in their former homes to 80% at BedZED.

The proportions of this increased internal temperature rise that can be attributed to a direct "comfort taking" is difficult to judge given the participants' views that they do not consider they can easily control internal temperatures. This is in large part due to the fact that the design of the heating controls at BedZED were quite prescriptive and it was difficult for participants to maintain higher or lower temperatures than the design temperature. This is reflected in answers to the question about participants' ability to control the heating, hot water and ventilation at BedZED and in their previous homes. The comparison of Phase 1 and Phase 2 answers to this question (Figure 12.5) shows that participants were less satisfied with the controls at BedZED than formerly. Some participants adjusted clothing to compensate although there was not a noticeable trend or change in people's clothing habits. Some participants relied on pro-active window opening to control temperatures although the latter was part of the overall design philosophy. People do like to be able to control the heating and ventilation in their homes. Better induction and information about how to do so in passively-designed dwellings like BedZED is important since control in these properties will require different behaviours to a traditionally heated dwelling with room thermostats.

BedZED properties used less electricity than previous dwellings although this is based on a small sample of only two participants. BedZED properties suffered from less condensation and mould than the previous properties but the level reported was still at an unacceptable level for new properties.

The most significant finding of the longitudinal study is that most of the sampled participants moved into a larger property at BedZED with an overall increase in property size of 45%. That said, the average size of BedZED properties was lower than the national average. If this trend for larger properties were extrapolated nationally the increase in energy use from larger dwelling footprints has to the potential to offset energy savings made from more efficient design.

13.13 Data

Answering the research questions required reliable data to enable the comparison between that which was designed or modelled and the actual performance. The challenge of interpreting actual energy usage from suppliers' data for Phase 3 of this study illustrates the need for a more consistent approach. Data were supplied in a mixture of actual and estimated consumption and Data Protection legislation prevented it being compared to data collected for the sampled properties in the earlier phase. Despite the fact that the data were also used for billing purposes, there was difficulty obtaining consistent energy usage data for the BedZED scheme with the result that one year's data were not used in the study.

13.14 Discussion Conclusions

This chapter discussed the results presented in chapters 7 – 12 in order to answer the research questions. The first two research questions relate to the difference, if any, between the completed BedZED units compared to the theoretical design.

Evidence has been supplied to show that the constructed units performed according to the design on the key criteria of winter comfort, energy use and airtightness. The units overheated in hot spells but did not perform significantly worse than other low energy dwellings and the principal cause of overheating is considered to be attributable to occupants not fully understanding how to ventilate their homes optimally to cool them down. Occupants were dissatisfied with the controls on their heating and hot water systems and it is considered that this is because the controls were not designed for the personalisation of comfort that most people now expect in modern dwellings through, e.g., room thermostats.

13.15 Hypothesis Conclusion

The hypothesis for this study is "There is a performance gap between predicted and actual energy performance in low energy dwellings and this is due to occupant behaviour". The study finds that there is a performance gap in the following areas and for the following reasons:

BedZED dwellings overheated in hot temperatures and this is attributed principally to the occupants' lack of understanding about how to cool their properties.

Actual energy use was broadly in line with the design although there was a performance gap in the energy forecasts calculated by EPC assessors using RdSAP software. The reason for this gap is thought to be due to the inflexibility of the RdSAP tool in its application for very low energy buildings like BedZED and also a lack of awareness by the EPC assessors about the nature and design of low energy buildings like BedZED which resulted in them overstating the energy usage.

There is a performance gap between the prescriptive design of the heating system controls and the expectations of occupants who are used to more personalised control of their living environment.

Chapter 14 Conclusions

14.1 Introduction

This research consists of a detailed case study of 24 dwellings in a zero-energy development. Data collected included energy usage, internal temperatures, air-tightness, RH readings, occupancy surveys and EPCs issued at the point of sale/rental. The unique feature of the study was the longitudinal aspect; the three phases of data collection and analysis that span the full property life cycle of design, construction, occupation and point of sale provide a rich source of information about BedZED. This chapter contains the main conclusions from the study.

14.2 Principal Conclusions

The study found evidence of a performance gap between predicted and measured energy performance but the gap was not as expected. The literature relating to performance gaps finds that actual energy performance is often significantly higher than standardised and theoretical performance (Burman, Mumovic & Kimpian 2014). For BedZED, the actual energy usage was broadly in line with design with overall energy use 7% higher than the original concept design. However, the predicted energy usage in EPCs carried out on almost half of the BedZED properties that have been let or sold since 2008 is over-estimated by 40% compared to the measured results. This is an important finding because it has the potential to undermine the contribution that low energy properties can make to achieving the Government's statutory requirement to reduce carbon emissions by 80% by 2050 as set out in the 2008 Climate Change Act.

If we are to achieve the scale of carbon reduction required by 2050, then energy usage data need to be more readily available to researchers in a consistent format. Suppliers' energy data compiled for Phase 3 of the study and discussed in Chapter 7 were difficult to interpret and required significant cleaning firstly by the landlord and then by the author. The data were supplied in a mixture of actual and estimated consumption, which limited its reliability in the data analysis. Supplier data have the potential to be a comprehensive source of data for future studies but there is still work to be done to ensure that data are captured consistently to enable such analysis.

BedZED achieved its design temperature during the heating season. BedZED was the first large-scale housing development in the UK to be constructed without dedicated central heating systems but with a requirement to achieve a consistent level of comfort in the heating season. This is an important finding that demonstrates housing can be built without whole house heating systems and can perform to modern comfort expectations in the heating season.

BedZED bedrooms overheated in hot weather. Living rooms were hotter than other case studies. Given that a unique feature of BedZED was that whole house heating was not installed, it is understandable why the focus was on achieving the design temperature during the heating season. The risk is that occupants will be more inclined to use mechanical cooling in future hotter summers. At the time that BedZED was conceived, summer overheating was not a major consideration for UK housing design. The engineers did model both summer and winter temperatures in their pre-construction energy modelling but a summer design temperature was not explicitly stated in the concept design for BedZED. In future designers should set a cooling season design temperature and model the effects of hot spells. The 1995 Building Regulations in force during the design and construction phase of BedZED did not require designers to limit the effect of heat gains in the summer but the current edition of the Regulations does require dwellings to have appropriate passive control measures to limit the effect of heat gains on internal temperatures in the summer. It encourages the use of window sizing, solar shading and high thermal capacity but does not prohibit the use of mechanical cooling (HMG 2014).

This research found that the overheating might be partly explained by participants not fully understanding how to cool their properties. It is ironic that these early adopters of low carbon lifestyles may in fact be the greatest losers if the rest of the world does not follow their lead. These occupants live in properties that tend to overheat when the world does get warmer yet these properties use less energy than other properties and so contribute less to climate change.

The predicted rise in global temperatures and the health impacts of summer hot spells mean that overheating is now an issue of concern for designers. Since hot spells are likely to become more frequent as a consequence of climate change, modelling should take account of hot spells as part of designers' adaptive strategy to ensure that dwellings will maintain a reasonable level of comfort during cooling seasons without having to resort to mechanical solutions. This needs to take account of the fact that UK residents need to be briefed about how to use high-mass dwellings in hot weather in order to minimise overheating and how to use sunspaces to optimise comfortable conditions in the home.

BedZED achieved a good standard of air tightness, broadly in line with design and good compared with other new properties built at the time. However, reports of condensation and mould are of concern. All participants opened windows regularly and there is no evidence that the passive vents did not operate correctly. The incidents of mould and condensation recorded by participants in this study are partly related to construction snags and partly a lack of guidance on ventilating the sunspaces, which did not have passive vents installed. It is essential that future projects have sufficient site quality control to ensure that buildings are built as designed and any workmanship issues rectified during construction. It is also essential that occupants are provided with guidance about ventilating the sunspaces.

BedZED did not achieve its original design philosophy of zero energy nor its subsequent zero (fossil) energy ambition. The principal reason for this is because the prototype biomass CHP system could not be made to be operational and had to be switched to gas-fired boilers. The secondary reason, from the literature studied, is that the renewable energy from the installed solar PV was less than expected. This has important lessons for the

Climate Change Act requirements to reduce carbon emissions and the 2010 recast of the Energy Performance of Buildings Directive, which requires all new buildings to be nearly zero energy by 2020. The latest version of the Building Regulations (HMG 2014) has set only modest improvements for increased efficiency in the Conservation of Fuel and Power.

The construction industry does not use consistent measurement systems in modelling and monitoring, making comparisons difficult. There were three different measurement systems for property sizes used in the study: the method used in SAP; NIA used in the NHER surveys; and GIA used in architectural drawings. However it is not possible to directly convert from one measurement system to another although there are industry rules of thumb that have been applied in this study. Designers and energy modellers should use consistent methods of measurement recommended by the RICS when modelling low energy designs and these calculations should be updated when the design is changed. This would ensure that future schemes are modelled consistently and would facilitate subsequent monitoring and comparison. The application of Building Information Modelling to future schemes will enable consistent measurement approaches throughout the whole development lifecycle of buildings.

It is important for designers of low energy, air-tight buildings to take account of human factors. People like to have more personal control over the temperature of their homes than the standard BedZED design gave them. Study participants were not wholly clear about how to get the best out of their innovatively designed homes. They did not feel confident in controlling the heating and hot water systems or the different practices that are required for a low energy dwelling, such as the use of the sunspace as a buffer rather than a living space, and the need to open windows at night in hot weather to cool down dwellings rather than during the day. This demonstrated how design assumptions about occupant performance may cause different results in actual performance during occupation. These practices, which are typical in Mediterranean countries, need to be better explained to residents moving into super-insulated dwellings like BedZED who may not be familiar with such approaches. As new technologies are introduced such as super-insulation, use of sunspaces and conservatories as buffer zones, custom and practice may not change immediately resulting in problems such as overheating.

Modelling makes assumptions about human factors but these cannot be fully predicted. Participants were broadly satisfied with the heating, hot water and ventilation but less satisfied with the controls for these systems than their previous dwellings. The fuel dials put on display in kitchens to raise awareness of energy usage made no difference to the behaviour of the majority of BedZED residents. In Chapter 12, evidence is provided that participants found it harder to use the heating controls at BedZED than their former properties. The BedZED Residents' Handbook does explain how to get the best out of the heating and hot water systems but BedZED was unusual for a modern development in that it did not have conventional wall thermostats which most occupants now take for granted and which offer personalised control of the living space. This finding is supported by the EPC reports for BedZED properties completed by independent surveyors who mostly rated the heating controls at BedZED as poor. It is clear that for innovative buildings like BedZED that additional guidance and familiarisation is required both for occupants moving into them and for professionals in the field.

It is important for energy models to be updated during the development process. The difference between very initial assumptions about the footprint size of BedZED at the initial outline design stage and the constructed footprint was around 21%. Although engineering design does build in significant sizing margins, it is preferable to update energy models as the detailed design is developed to ensure that the design assumptions underpinning the scheme remain relevant. There appeared to be no provision in the delivery phase of the BedZED project to formally review and update original design assumptions. This could have provided assurance that design changes did not adversely impact on the project aims.

Despite improvements to the SAP rating tool over the lifetime of this study, there are still improvements required to ensure that it is suitable for use on low energy buildings like BedZED. The inconsistent Energy Performance Certificates gives cause for concern given the importance of zero carbon dwellings as a way of meeting the Government's climate change commitments. EPCs are a mandatory requirement for a property purchase or rental and may inform the purchaser's decision. The use of the RdSAP template to produce EPCs does not lend itself fully to low energy buildings like BedZED and should be further adapted in the light of the Government's aim to build zero carbon buildings, e.g. to include options such as super-insulation for walls and floors. Surveyors carrying out EPC inspections using the RdSAP tool need more guidance and training on the tool's application to low energy buildings like BedZED.

The literature review in Chapter 2 discussed increased overall demand for energy resulting from a growing population of smaller households. Since the Government's carbon reduction targets are absolute reduction targets, energy efficiency interventions will need to be even more effective in order to counter the growth in the number of households. There is not year clear evidence whether the size of dwellings is reducing commensurate to reducing household size nationally but the BedZED longitudinal study found that residents increased their footprint by some 45% when they moved to BedZED. If the BedZED trend were replicated nationally without a corresponding move towards much more low energy dwellings, this could have significant policy implications since the total amount of floor space per person would increase and the associated energy requirements with it.

If the Government is going to succeed in meeting its carbon reduction targets, it is essential that a common definition is adopted for low energy buildings that factor in the requirement for zero carbon. The Building Regulations should play a key role here.

The benefit of a consistent approach to compiling data from different energy monitoring studies is illustrated by the comparisons in this study between

BedZED and other studies using the protocols developed for the CaRB study. This provided a broader context for the BedZED results and will enable further consistent comparisons with other studies in the future.

Chapter 15 Limitations of the Study and Future Work

BedZED was a unique design and its relevance to other new-build developments may be limited. The applicability of this case study to the wider housing stock is likely to be limited given the small sample size and its unique features. There is a risk that the first occupants who moved into BedZED were more likely to be evangelical about the design and ethos of the development and may not be representative of the general population. Participating in the study was voluntary and all participants included in the study were self-selected. There is therefore a risk of “self-selection” bias in the results.

Although electricity readings at a property level were available, it was not possible to compile a full dataset for heat energy use in Phase 2 because the CHP was not fully operational and CHP energy readings were not available. This meant that it was not possible to compile a holistic assessment of all energy use in Phase 2 and complete a full longitudinal comparison for the energy use for Phases 1 and 2. Phase 3 data for the whole BedZED development enabled an assessment of energy use but since this was not provided at a property level, it was not possible to complete that part of the longitudinal study.

This study benefited from a rich dataset but the Phase 2 monitoring period encountered some data loss because participants were sometimes unable to provide access for data downloads. A remotely accessible monitoring system integrated into individual dwellings was not practical for this study given timescales and other constraints but this would have provided a more comprehensive dataset, eliminating the need for appointments to download data from loggers which resulted in up to 25% of the potential BedZED dataset being lost. Timescales also limited the Phase 1 data collection phase and also the opportunity to pilot the occupant survey. Nonetheless, the data that were collected provides a rich set of measurements that has been analysed for this development and which can be used for comparative purposes with other studies.

Very little information was collected about occupancy patterns within dwellings. More detail about when the dwelling was occupied would have enabled more analysis of energy usage and comfort conditions. Later studies have attempted to capture this information (eg Love 2014) and although in its infancy and with its own challenges, this approach is recommended for future studies.

It would be useful to examine in more detail the relationship between the high mass/low U-value construction and summer overheating and window-opening behaviour. This study found that BedZED was prone to overheating during hot spells and that occupant behaviour may be a factor. It would be useful to conduct a controlled study during a future hot spell to test the benefits of controlled window opening on internal temperatures. Such a study should also record occupancy levels in line with CIBSE guidance.

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Appendix 1: BedZED Accommodation Schedule

Source: Corbey 2005

Housetype	Unit size		Address	People	Adults	Children
3 bed maisonette	106.96	1	Dunster Way			0
3 bed maisonette	106.96	2	Dunster Way	4	2	2
3 bed maisonette	106.96	3	Dunster Way	4	2	2
3 bed maisonette	106.96	4	Dunster Way	4	2	2
3 bed maisonette	106.96	5	Dunster Way	2	2	0
3 bed maisonette	106.96	6	Dunster Way	2	2	0
3 bed maisonette	106.96	7	Dunster Way	4	2	2
3 bed maisonette	106.96	8	Dunster Way	2	2	0
3 bed maisonette	106.96	9	Dunster Way	2	2	0
3 bed maisonette	106.96	10	Dunster Way	2	2	0
3 bed maisonette	106.96	11	Dunster Way	2	2	0
1 bed flat	51.9	12	Dunster Way	3	2	1
1 bed flat	51.9	13	Dunster Way	1	1	0
workspace	79.9	14	Dunster Way	1	1	0
workspace	79.9	15	Dunster Way	1	1	0
1 bed flat	51.9	16	Dunster Way	2	2	0
1 bed flat	51.9	17	Dunster Way	1	1	0
workspace	79.9	18	Dunster Way	1	1	0
workspace	79.9	19	Dunster Way	1	1	0
1 bed flat	51.9	20	Dunster Way	1	1	0
1 bed flat	51.9	21	Dunster Way	2	2	0
workspace	79.9	22	Dunster Way	2	2	0
workspace	79.9	23	Dunster Way	1	1	0
2 bed flat	64.5	24	Dunster Way	2	2	0
1 bed flat	51.9	25	Dunster Way	1	1	0
workspace	79.9	26	Dunster Way	1	1	0
workspace	79.9	27	Dunster Way	1	1	0
1 bed flat	51.9	28	Dunster Way	1	1	0
1 bed flat	51.9	29	Dunster Way	1	1	0
workspace	79.9	30	Dunster Way	2	2	0
workspace	79.9	31	Dunster Way	1	1	0
1 bed flat	51.9	32	Dunster Way	1	1	0
1 bed flat	51.9	33	Dunster Way	2	2	0
1 bed flat	59.4	1	Helios Road	2	2	0
4 bed maisonette	141.35	2	Helios Road	4	3	1
1/2 bed flat	59.4	3.1	Helios Road	3	2	1
1/2 bed flat	59.4	3.2	Helios Road	3	2	1
2 bed flat	68.8	3.3	Helios Road	2	1	1
2 bed flat	68.8	3.4	Helios Road	2	2	0
2 bed flat	77.1	3.5	Helios Road	1	1	0
2 bed flat	77.1	3.6	Helios Road	3	2	1
1/2 bed flat	59.4	4.1	Helios Road	4	2	2
1/2 bed flat	59.4	4.2	Helios Road	1	1	0
2 bed flat	68.8	4.3	Helios Road	2	2	0
2 bed flat	68.8	4.4	Helios Road	3	2	1
2 bed flat	77.1	4.5	Helios Road	3	2	1
2 bed flat	77.1	4.6	Helios Road	4	2	2
4 bed townhouse	141.35	5	Helios Road	2	2	0
4 bed townhouse	141.35	6	Helios Road	2	2	0
4 bed townhouse	141.35	7	Helios Road	4	2	2
4 bed townhouse	141.35	8	Helios Road	4	2	2
workspace	79.9	9	Helios Road	2	2	0
workspace	77.4	10	Helios Road	1	1	0
3 bed maisonette	106.96	11	Helios Road	2	2	0
3 bed maisonette	106.96	12	Helios Road	4	2	2
3 bed maisonette	106.96	13	Helios Road	4	2	2
3 bed maisonette	106.96	14	Helios Road	4	2	2
3 bed maisonette	106.96	15	Helios Road	2	2	0
3 bed maisonette	106.96	16	Helios Road	1	1	0
3 bed maisonette	106.96	17	Helios Road	4	2	2
3 bed maisonette	106.96	18	Helios Road	2	1	1
3 bed maisonette	106.96	19	Helios Road	3	3	0
3 bed maisonette	106.96	20	Helios Road	5	2	3
3 bed maisonette	106.96	21	Helios Road	3	2	1
3 bed maisonette	106.96	22	Helios Road	2	2	0
1 bed flat	51.9	1	Oak Walk	1	1	0
1 bed flat	51.9	2	Oak Walk	1	1	0
workspace	79.9	3	Oak Walk	1	1	0
workspace	79.9	4	Oak Walk			
1 bed flat	51.9	5	Oak Walk	1	1	0
1 bed flat	51.9	6	Oak Walk	1	1	0
workspace	79.9	7	Oak Walk	2	2	0
workspace	79.9	8	Oak Walk	2	2	0
1 bed flat	51.9	9	Oak Walk	1	1	0
1 bed flat	51.9	10	Oak Walk	1	1	0
live work	79.9	11	Oak Walk	4	4	0
2 bed flat	107.1	12	Oak Walk	3	2	1
1 bed flat	51.9	13	Oak Walk	1	1	0
1 bed flat	51.9	14	Oak Walk	1	1	0
1 bed flat	51.9	15	Oak Walk	1	1	0
1 bed flat	47.5	1	Sandmartin Way	1	1	0
3 bed flat	100.5	2	Sandmartin Way	6	3	3
1 bed flat	100.5	3	Sandmartin Way	1	1	0
1 bed flat	49.3	4	Sandmartin Way	1	1	0
1 bed flat	53.9	5	Sandmartin Way	3	1	2
1 bed flat	53.9	6	Sandmartin Way	1	1	0
1 bed flat	53.9	7	Sandmartin Way	1	1	0
1 bed flat	53.9	8	Sandmartin Way	2	2	0
1 bed flat	53.9	9	Sandmartin Way	1	1	0
1 bed flat	53.9	10	Sandmartin Way	1	1	0
1 bed flat	71.6	11	Sandmartin Way	2	2	0
1 bed flat	71.6	12	Sandmartin Way	2	2	0
1 bed flat	69.1	13	Sandmartin Way	2	2	0
2 bed flat	59.4	14	Sandmartin Way	3	3	0
2 bed flat	59.4	15	Sandmartin Way	2	1	1
2 bed flat	59.4	16	Sandmartin Way	4	3	1
2 bed flat	59.4	17	Sandmartin Way	4	2	2
2 bed flat	59.4	18	Sandmartin Way	2	1	1
2 bed flat	59.4	19	Sandmartin Way	3	2	1
Total Residential	**7802.73**			**209**	**160**	**49**
Nursery	706.2	20	Sandmartin Way	15	5	10
CHP enclosure		21	Sandmartin Way	2	2	0
GWTP enclosure		22	Sandmartin Way			
Offices	75	23	Sandmartin Way	2	2	0
Changing facilities		24	Sandmartin Way			
Clubhouse	156	25	Sandmartin Way	5	5	0
Offices	77.4	23	Helios Road	4	4	0
Offices	390	24	Helios Road	29	29	
Total Commercial	**1404.6**			**57**	**47**	**10**
TOTAL BEDZED	**9207.33**			**266**	**207**	**59**
Source: Corbey 2005						

Appendix 2: CHP Sizing Calculation

Source: Bioregional 1999

BEDZED SITE DISTRICT HEATING REQUIREMENTS

ASSUMPTIONS

CHP runs	17	hours/day
Heat distribution losses	20	%
Elec distribution losses	5	%
additional gains (flat)	3.5	W/m²
additional gains (office)	8	W/m²

HOT WATER & HEATING

			W	kWh/annum
1 person	130	litres hot water/day	348	3045
2 people	141		377	3302
3 people	165		441	3864
4 people	187		500	4380
office	0.67	litres/m²	0.043	kWh/m²
shop	1.6	litres/m²	0.103	
nursery	1.6	litres/m²	0.103	
clubhouse	25	6 mins shower	810	litres/day
healthy	3.1	litres/m²	0.199	
delta T	55	°C		

ELECTRICITY USE

1 person flat	2247	kWh/annum
2 person flat	2596	
3 person mais	3298	
4 person house	3533	
office	54	kWh/m²/annum
shop	396	
nursery	20	
clubhouse	74	
healthy	44	

								Hot water			Extra heat			Electric kWh annual			
DWELLINGS		maximum people	predicted people	unit floor area m²	number of units	predicted total people	total floor area m²	per day per unit litres	hot water per day litres	energy per day MJ	extra heat from towel rail + HW cylinder + pipework etc over 24 hrs W/m²	W	MJ	per unit kWh	all units kWh	MJ	per day
BLOCK A	Flat	2	1	48.5	6	6	291	130	780	180	3.5	170	88	2596	15576	153.6	
	Maisonette	4	3	75.5	6	18	453	165	990	229	3.5	264	137	3533	21198	209.1	
BLOCK B	Flat	2	2	48.5	6	12	291	141	846	195	3.5	170	88	2596	15576	153.6	
	Maisonette	4	4	75.5	6	24	453	187	1122	259	3.5	264	137	3533	21198	209.1	
BLOCK C	Flat	2	1	48.5	6	6	291	130	780	180	3.5	170	88	2596	15576	153.6	
	Maisonette	4	3	75.5	6	18	453	165	990	229	3.5	264	137	3533	21198	209.1	
BLOCK D	Flat	2	2	48.5	5	10	242.5	141	705	163	3.5	170	73	2596	12980	128	
	Maisonette	4	4	75.5	5	20	377.5	187	935	216	3.5	264	114	3533	17665	174.2	
BLOCK E	Maisonette	3	2	62	4	8	248	141	564	130	3.5	217	75	3298	13192	130.1	
	Maisonette	4	3	75.5	4	12	302	165	660	152	3.5	264	91	3533	14132	139.4	
BLOCK F	Flat	3	2	60	5	10	300	141	705	163	3.5	210	91	3298	16490	162.7	
	Flat	3	3	60	5	15	300	165	825	191	3.5	210	91	3298	16490	162.7	
	Flat	3	2	60	5	10	300	141	705	163	3.5	210	91	3298	16490	162.7	
BLOCK G	Maisonette	4	3	75.5	5	15	377.5	165	825	191	3.5	264	114	3533	17665	174.2	
	Maisonette	4	4	75.5	5	20	377.5	187	935	216	3.5	264	114	3533	17665	174.2	
	Flat	4	3	73.5	3	9	220.5	165	495	114	3.5	257	67	3533	10599	104.5	
					82	**213**	**5278**			**2971**			**1596**			**2601**	
OFFICES																	
BLOCK A	Unit	7.1		85	6	42.5	510	57	341.7	79	8	680	353	4590	27540	271.6	
BLOCK B	Unit	7.1		85	6	42.5	510	57	341.7	79	8	680	353	4590	27540	271.6	
BLOCK C	Unit	7.1		85	3	21.3	255	57	170.85	39	8	680	176	4590	13770	135.8	
					15	**106.3**	**1275**			**197**			**881**			**679**	
OTHER																	
Shop				342	1	20	342	547	547.2	126	8	2736	236	135432	135432	1335.8	
Nursery				170	1	20	170	272	272	63	8	1360	118	3400	3400	33.5	
Club House				110	1	10	110	810	810	187	8	880	76	8140	8140	80.3	
Healthy Living Centre				440	1	30	440	1364	1364	315	8	3520	304	19360	19360	190.9	
					4	**80**	**1062**			**691**			**734**			**1641**	
Streetlights		35	nr	400	W	14	hours/day									**706**	
Floodlights		8		5000	W	1									498872	**144**	
RW pumps		6		500	W	2								losses	24943.6	**22**	
Heating pumps		1		500	W	17								10%design	49887.2	**31**	
										3860		**+**	**3211**		573703		
TOTALS					**101**	**399**	**7615**			**7071**						**5822**	**MJ/day**
					units	people	area			total heat							

over CHP hours	115.5	kW
TOTAL HEAT	115.5	kW
losses	23.1	kW
10% design margin	13.9	kW
CHP HEAT REQD from heat exchanger	**153**	**kW**

over CHP hours	95.1	kW
TOTAL ELEC	95.1	kW
losses	4.8	kW
10% design margin	10	kW
CHP ELEC REQD output	**110**	**kW**

Appendix 3: Phase 1 Questionnaire (pre-BedZED)

PRE-OCCUPANCY QUESTIONNAIRE

Name ______________________________

Address ______________________________

1 Household Details

1.1 Number of people in the household

Under 5	☐	36-45	☐
6-15	☐	46-55	☐
16-25	☐	56-65	☐
26-35	☐	Over 65	☐

1.2 Please indicate what times the home is occupied and by whom

	Adults		Children
morning	☐	morning	☐
lunch	☐	lunch	☐
afternoon	☐	afternoon	☐
evening	☐	evening	☐
night	☐	night	☐

1.3 Please tick all appliances that you regularly use at home and provide energy rating symbol A-G if known, and estimate of number of loads per week.

		Energy Rating	Number loads per week
Refrigerator	☐	☐	
Freezer	☐	☐	
Fridge/freezer	☐	☐	
Electric shower	☐	☐	
Washing machine	☐	☐	☐
Tumble Drier	☐	☐	☐
Dishwasher	☐	☐	☐
Microwave	☐	☐	
Television	☐	☐	
Personal computer	☐	☐	
Other	☐	☐	

1.4 Do you use low-energy lightbulbs? If yes, please indicate which rooms

None	☐	Living Room	☐
Kitchen	☐	Dining Room	☐
Hallway	☐	Bedrooms	☐
Bathroom	☐	Other	☐

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1.5 Please indicate the type of fuel used for cooking

Electricity	☐	Other	☐	Solid Fuel	☐

2 Heating System

2.1 How easy do you find it to operate the control systems for the heating and hot water?
Rating: 1-5, 1 = easy, 5 = very difficult

Heating				Hot Water
☐	1	easy	1	☐
☐	2	fairly easy	2	☐
☐	3	OK	3	☐
☐	4	difficult	4	☐
☐	5	very difficult	5	☐

2.2 How effective are the controls at maintaining comfortable temperatures in the home?

Ineffective	☐
Fairly ineffective	☐
Fairly effective	☐
Effective	☐

2.3 What are the current settings on your room thermostat and hot water thermostat?

Heating °C

Hot water °C

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2.4 How often do you adjust these controls?

Every 6 months	☐
Every 3 months	☐
Every month	☐
Every week	☐
Every day	☐

2.5 How would you describe the comfort level of your home during the winter?

Hot overall	☐	Cold overall	☐
Comfortable	☐	Other	☐
Certain rooms too hot/cold	☐		

2.6 If certain rooms are too hot or cold, please indicate which ones

Too hot		Too cold	
Kitchen	☐	Kitchen	☐
Living Room	☐	Living Room	☐
Bathroom	☐	Bathroom	☐
Dining Room	☐	Dining Room	☐
Bedrooms	☐	Bedrooms	☐
Sunspace	☐	Sunspace	☐

2.7 Do you use any additional form of heating (eg electric fan heater). If so, where and how long per day

		Hours per day
Living Room	☐	________
Kitchen	☐	________
Bathroom	☐	________
Bedrooms	☐	________
Other	☐	________

3 Hot Water System

3.1 Does the hot water system provide enough hot water when you require it?

Yes ☐
No ☐

3.2 If no, do you use another source for hot water? eg kettle

____

3.3 Is the temperature of the hot water comfortable?

Too hot ☐
OK ☐
Too cold ☐

3.4 If the water is too hot or too cold, have you tried to adjust the temperature?

Yes ☐
No ☐

4 Fuel Costs

3 1 2

4.1 Do you know how much your gas/electricity bills are per annum?

Yes ☐
No ☐

4.2 If yes, how much on average?

Less than £100 ☐
£100-£200 ☐
£200-300 ☐
£300-400 ☐
Greater than £400 ☐

4.3 Please provide a copy of your gas and electricity bills for the last year

5 Ventilation

5.1 Do you have a mechanical ventilation system? Eg extract fans?

Yes ☐
No ☐

5.2 If yes, is it effective at removing steam and odours from the home?

Yes ☐
No ☐

5.3 Do you open windows to improve air quality?

Yes ☐
No ☐

5.4 Would you consider your home to be draughty?

Yes ☐
No ☐

5.5 If yes, which part of your home do the draughts typically come from?

Windows ☐
Doors ☐
Other ____________________

6 Other

6.1 Has there been any instance of asthma or similar health problem that could be associated with the living environment?

Yes ☐
No ☐

6.2 Is there any condensation or mould growth in the home?

Yes ☐
No ☐

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6.3 On the whole, how satisfied are you with the heating, hot water and ventilation in your present home?

Very good ☐ Poor ☐
Good ☐ Very poor ☐
OK ☐ Other ____________________

6.4 How much clothing do you normally wear in the home in winter?

Just a thin layer, e.g. T-shirt, shirt, blouse ☐
Medium layers, e.g. T-shirt/shirt + thin sweater/cardigan ☐
Heavy layers, e.g. T-shirt/shirt + heavy sweater/fleece ☐

Appendix 4: Phase 2 Questionnaire (post-BedZED)

POST-OCCUPANCY QUESTIONNAIRE

	Name	______________________________					
	Address	______________________________ ______________					
	Prop Ref	________________________					
1	**Household Details**						
1.1	Number of people in the household						
	Under 5	☐	36-45	☐			
	6-15	☐	46-55	☐			
	16-25	☐	56-65	☐			
	26-35	☐	Over 65	☐			
1.2	Please indicate what times the home is occupied and by whom						
	Adults		Children				
	morning	☐	morning	☐			
	lunch	☐	lunch	☐			
	afternoon	☐	afternoon	☐			
	evening	☐	evening	☐			
	night	☐	night	☐			
1.3	Please tick all appliances that you regularly use at home and provide energy rating symbol A-G						
	if known, and estimate of number of loads per week. NB applied supplied as fitted to BZ properties						
	are A rated - only need to check that the resident has not changed appliances during occupation						
					Energy Rating		Number loads per week
	Refrigerator		☐		☐		
	Freezer		☐		☐		
	Fridge/freezer		☐		☐		
	Electric shower		☐		☐		
	Washing machine		☐		☐		☐
	Tumble Drier		☐		☐		☐
	Dishwasher		☐		☐		☐
	Microwave		☐		☐		
	Television		☐		☐		
	Personal computer		☐		☐		
	Other		☐		☐		
1.4	Do you use low-energy lightbulbs? If yes, please indicate which rooms						
	None	☐	Living Room	☐			

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	Kitchen	☐	Dining Room	☐			
	Hallway	☐	Bedrooms	☐			
	Bathroom	☐	Other	☐			
1.5	Please indicate the type of fuel used for cooking						
	Electricity	☐	Other	☐	If other, state type_______________________ _______		
	[There is only electricity at BZ, so there shouldn't be other options]						
2	**Heating System**						
2.1	How easy do you find it to operate the control systems for the heating and hot water?						
	Rating: 1-5, 1 = easy, 5 = very difficult						
	Heating				Hot Water		
	☐	1	easy	1	☐		
	☐	2	fairly easy	2	☐		
	☐	3	OK	3	☐		
	☐	4	difficult	4	☐		
	☐	5	very difficult	5	☐		
2.2	How effective are the controls at maintaining comfortable temperatures in the home?						
	Ineffective		☐				
	Fairly ineffective		☐				
	Fairly effective		☐				
	Effective		☐				
2.3	What are the current settings on your room thermostat and hot water thermostat?		___				
	Heating		°C				
	Hot water		°C				
2.4	How often do you adjust these controls?						
	Every 6 months		☐				
	Every 3 months		☐				
	Every month		☐				
	Every week		☐				
	Every day		☐				
2.5	How would you describe the comfort level of your home during the winter?						
	Hot overall		☐	Cold overall	☐		
	Comfortable		☐	Other	☐		
	Certain rooms too hot/cold		☐				

2.6	If certain rooms are too hot or cold, please indicate which ones						
	Too hot			Too cold			
	Kitchen	☐		Kitchen	☐		
	Living Room	☐		Living Room	☐		
	Bathroom	☐		Bathroom	☐		
	Dining Room	☐		Dining Room	☐		
	Bedrooms	☐		Bedrooms	☐		
	Sunspace	☐		Sunspace	☐		
2.7	How would you describe the comfort level of your home during the summer?						
	Hot overall		☐	Cold overall	☐		
	Comfortable		☐	Other	☐		
	Certain rooms too hot/cold		☐				
2.8	If certain rooms are too hot or cold, please indicate which ones						
	Too hot			Too cold			
	Kitchen	☐		Kitchen	☐		
	Living Room	☐		Living Room	☐		
	Bathroom	☐		Bathroom	☐		
	Dining Room	☐		Dining Room	☐		
	Bedrooms	☐		Bedrooms	☐		
	Sunspace	☐		Sunspace	☐		
2.9	Do you use any additional form of heating (eg electric fan heater). If so, where and how long per day						
				Hours per day			
	Living Room	☐		________			
	Kitchen	☐		________			
	Bathroom	☐		________			
	Bedrooms	☐		________			
	Other	☐		________			
2.10	Do you use any additional form of cooling (eg fans or air conditioning units). If so, where						
	and for how long per day						
				Hours per day			
	Living Room	☐		________			
	Kitchen	☐		________			
	Bathroom	☐		________			
	Bedrooms	☐		________			
	Other	☐		________			
3	**Hot Water System**						
3.1	Does the hot water system provide enough hot water when you require it?						

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	Yes	☐
	No	☐
3.2	If no, do you use another source for hot water? eg kettle	
	____	
3.3	Is the temperature of the hot water comfortable?	
	Too hot	☐
	OK	☐
	Too cold	☐
3.4	If the water is too hot or too cold, have you tried to adjust the temperature?	
	Yes	☐
	No	☐
4	**Fuel Costs**	
4.1	Do you know how much your electricity bills are per annum?	
	Yes	☐
	No	☐
4.2	If yes, how much on average?	
	Less than £100	☐
	£100-£200	☐
	£200-300	☐
	£300-400	☐
	Greater than £400	☐
4.3	Do you think having the fuel dials on display makes a difference to your use of fuel and appliances?	
	Yes	☐
	No	☐
5	**Ventilation**	
5.1	Do you find the ventilation system is effective? eg by removing steam and cooking smells?	
	Yes	☐
	No	☐
5.2	Do you open windows to improve air quality? for example to remove steam or cooking smells?	
	Yes	☐
	No	☐
5.3	Do you open windows to try and control the temperature of your home?	
	Yes	☐
	No	☐
5.4	Would you consider your home to be draughty?	

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	Yes	☐					
	No	☐					
5.5	If yes, which part of your home do the draughts typically come from?						
	Windows	☐					
	Doors	☐					
	Other	________________________________					
6	**Other**						
6.1	Since moving to BedZED, has any member of your household experienced any instance of asthma						
	or similar health problem for the first time that might be associated with the living environment?						
	Yes	☐					
	No	☐					
6.2	If yes, please state____						
	____ ___						
6.3	Is there any condensation or mould growth in the home?						
	Yes	☐					
	No	☐					
6.4	On the whole, how satisfied are you with the heating, hot water and ventilation in your present home?						
	Very good	☐	Poor	☐			
	Good	☐	Very poor	☐			
	OK	☐	Other	________________________			
6.5	How much clothing do you normally wear in the home in winter?						
	Just a thin layer, eg T-shirt, shirt, blouse					☐	
	Medium layers, eg T-shirt/shirt + thin sweater/cardigan					☐	
	Heavy layers, eg T-shirt/shirt + heavy sweater/fleece					☐	
Thank you for your time. Are there any other comments that you would like to add?							

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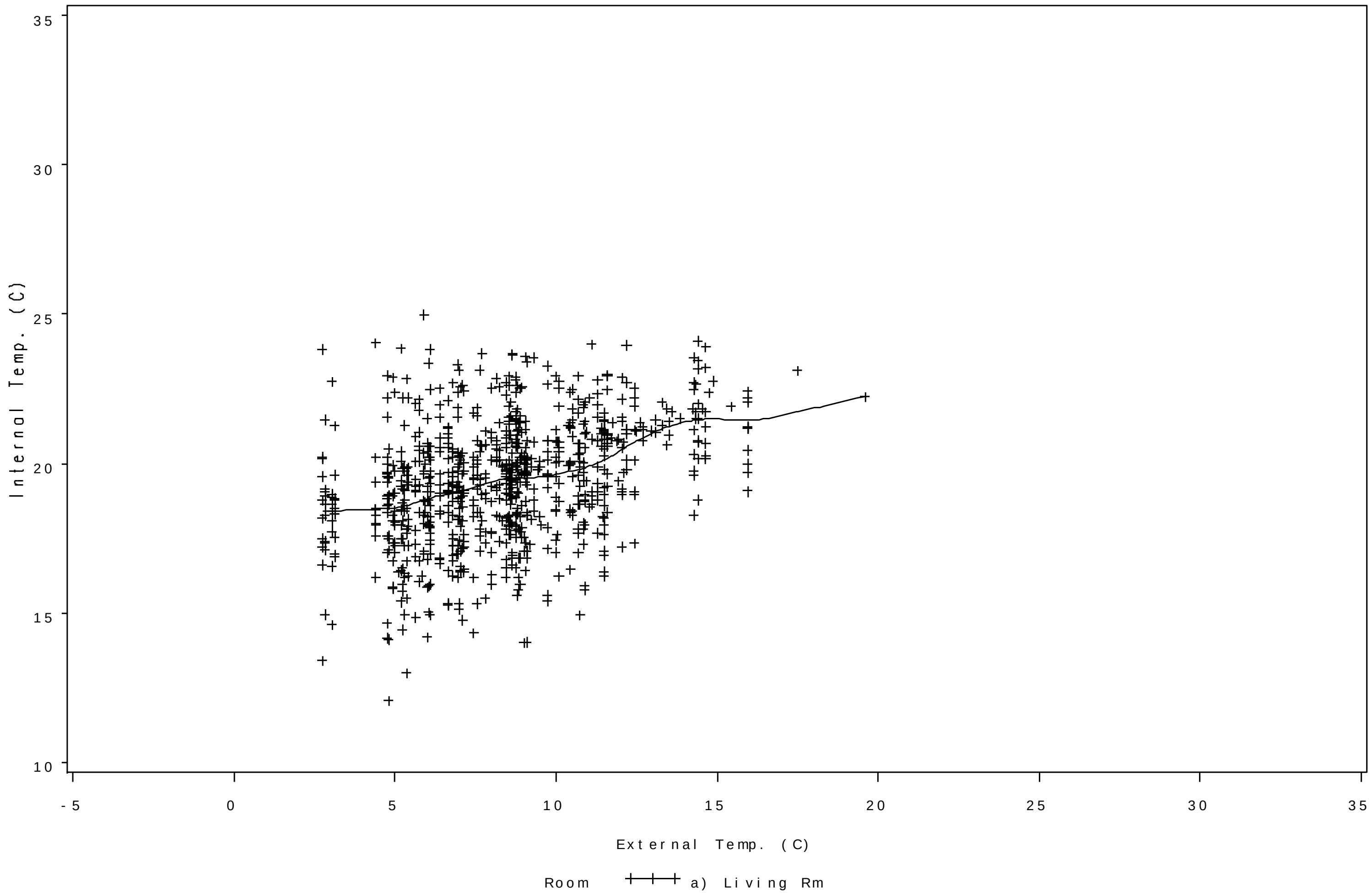
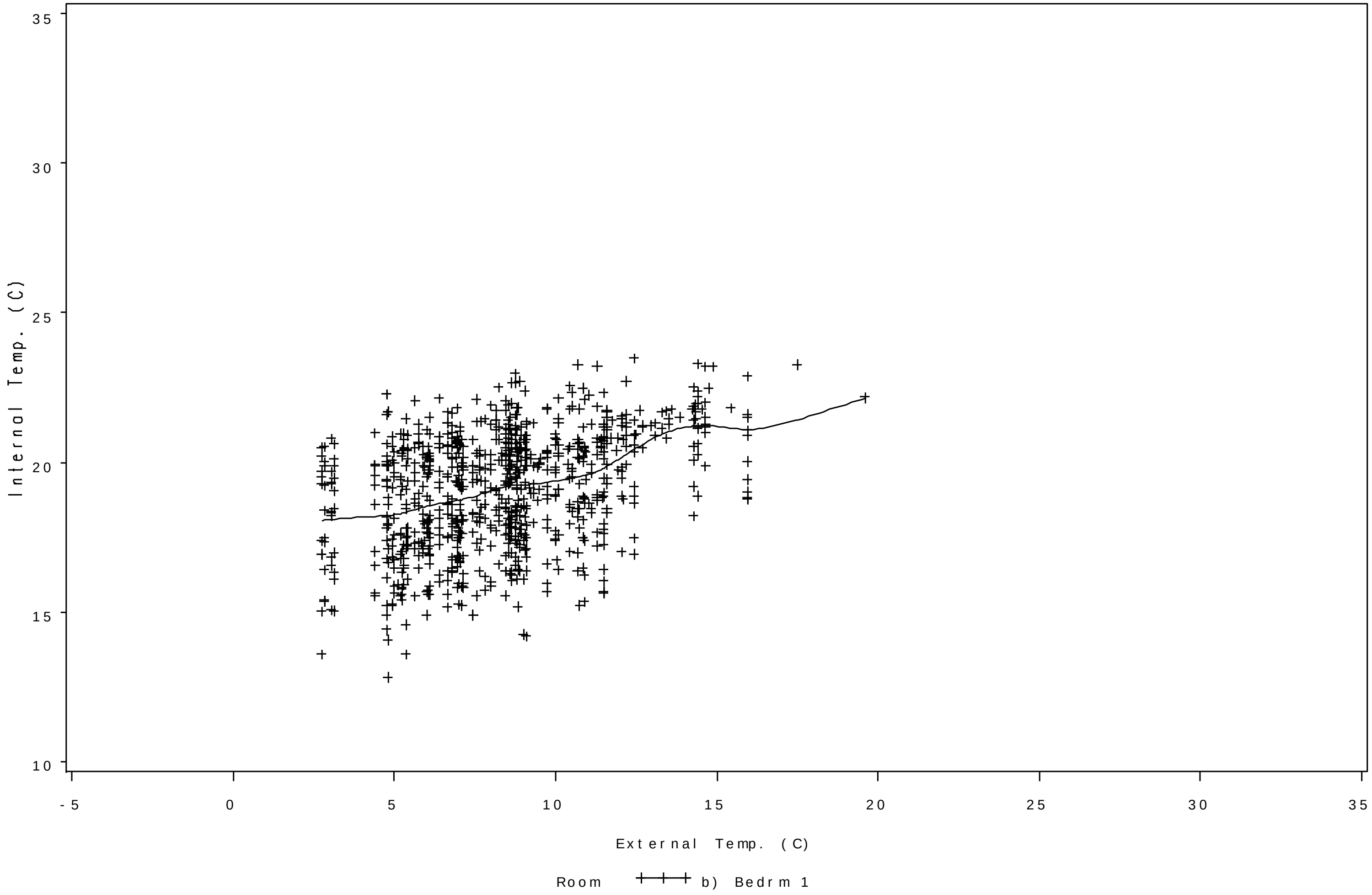
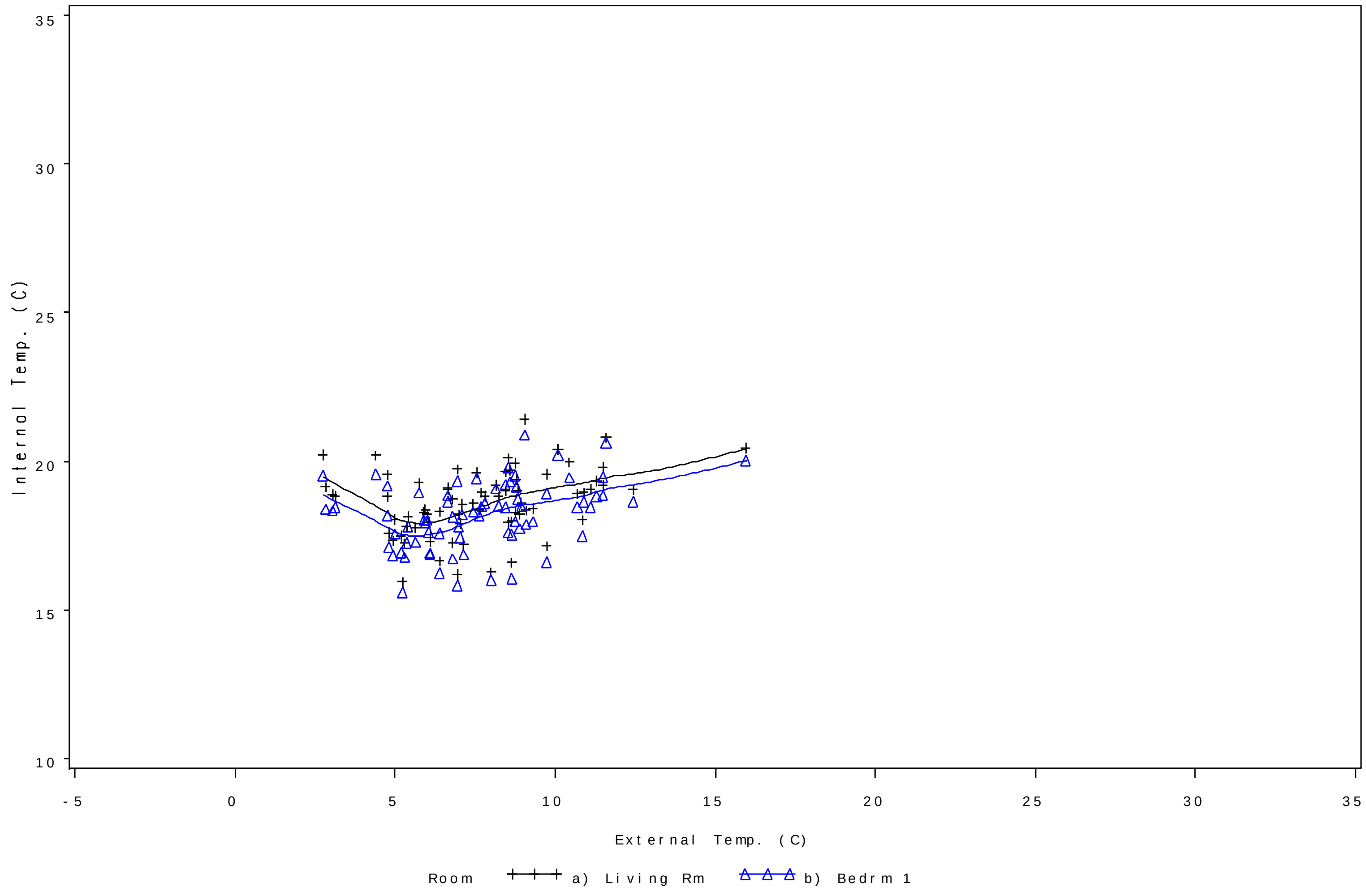
BedZED Phase 1: All Dwellings – Living Rooms

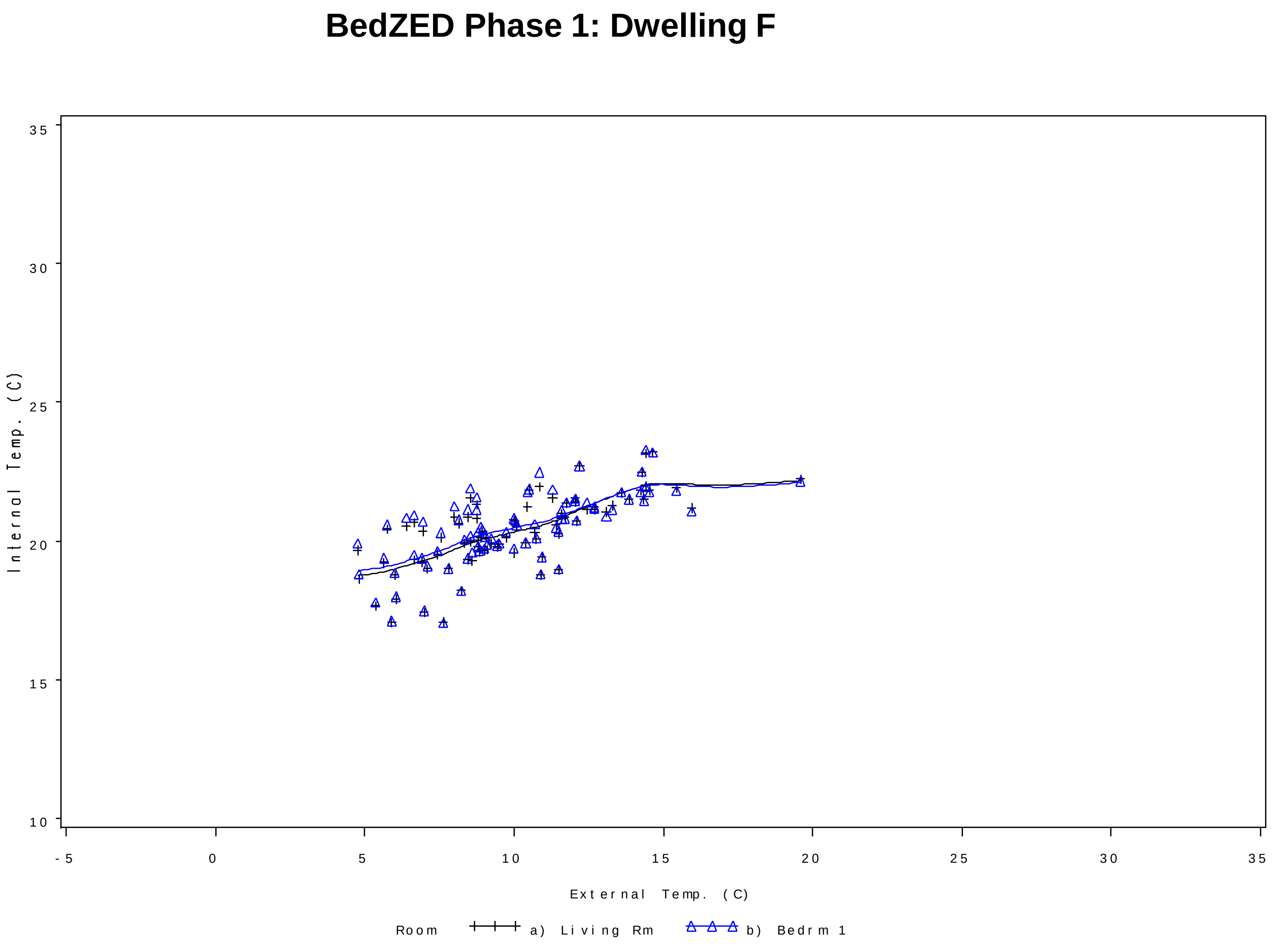


BedZED Phase 1: All Dwellings – Bedrooms

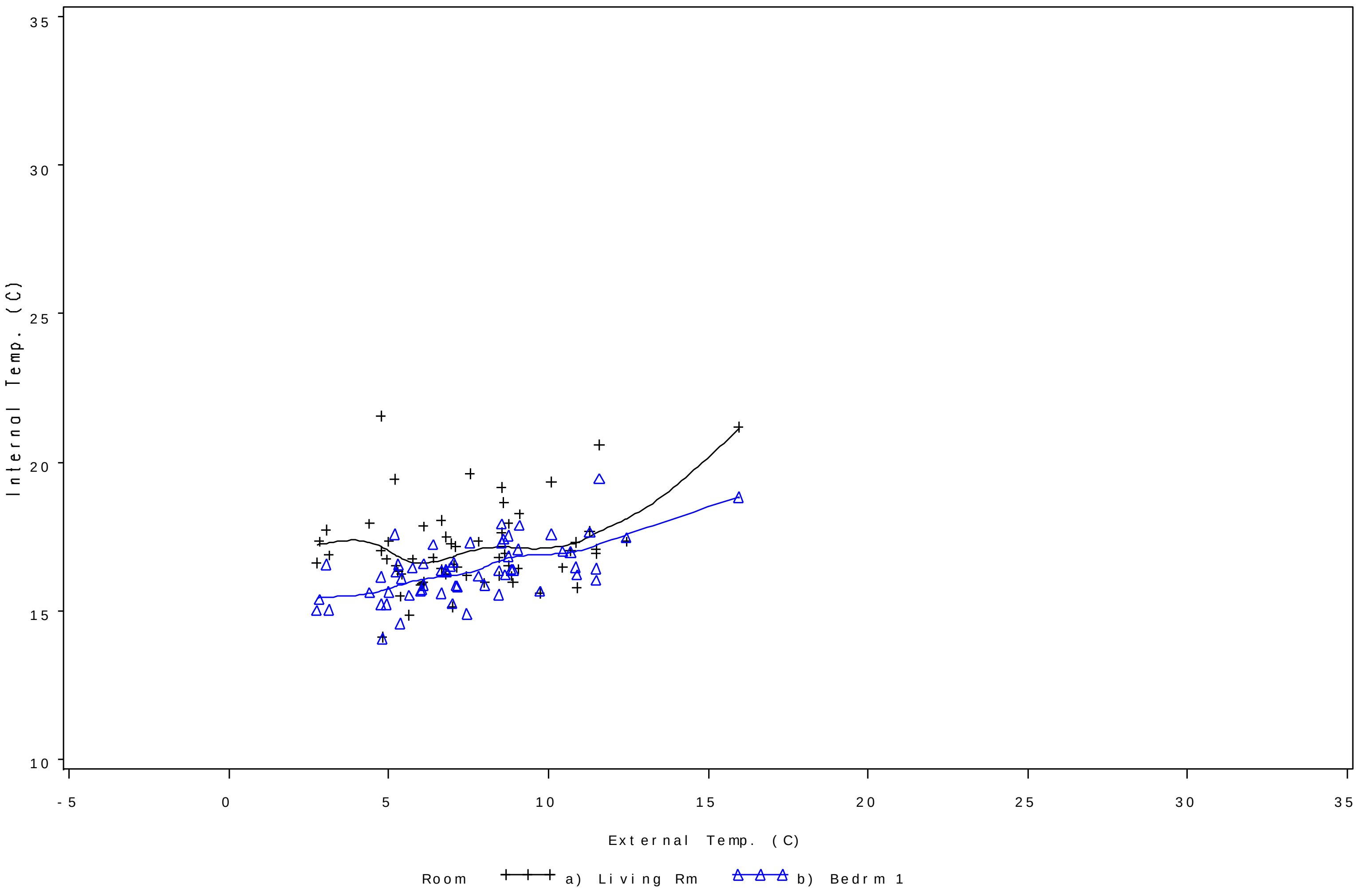


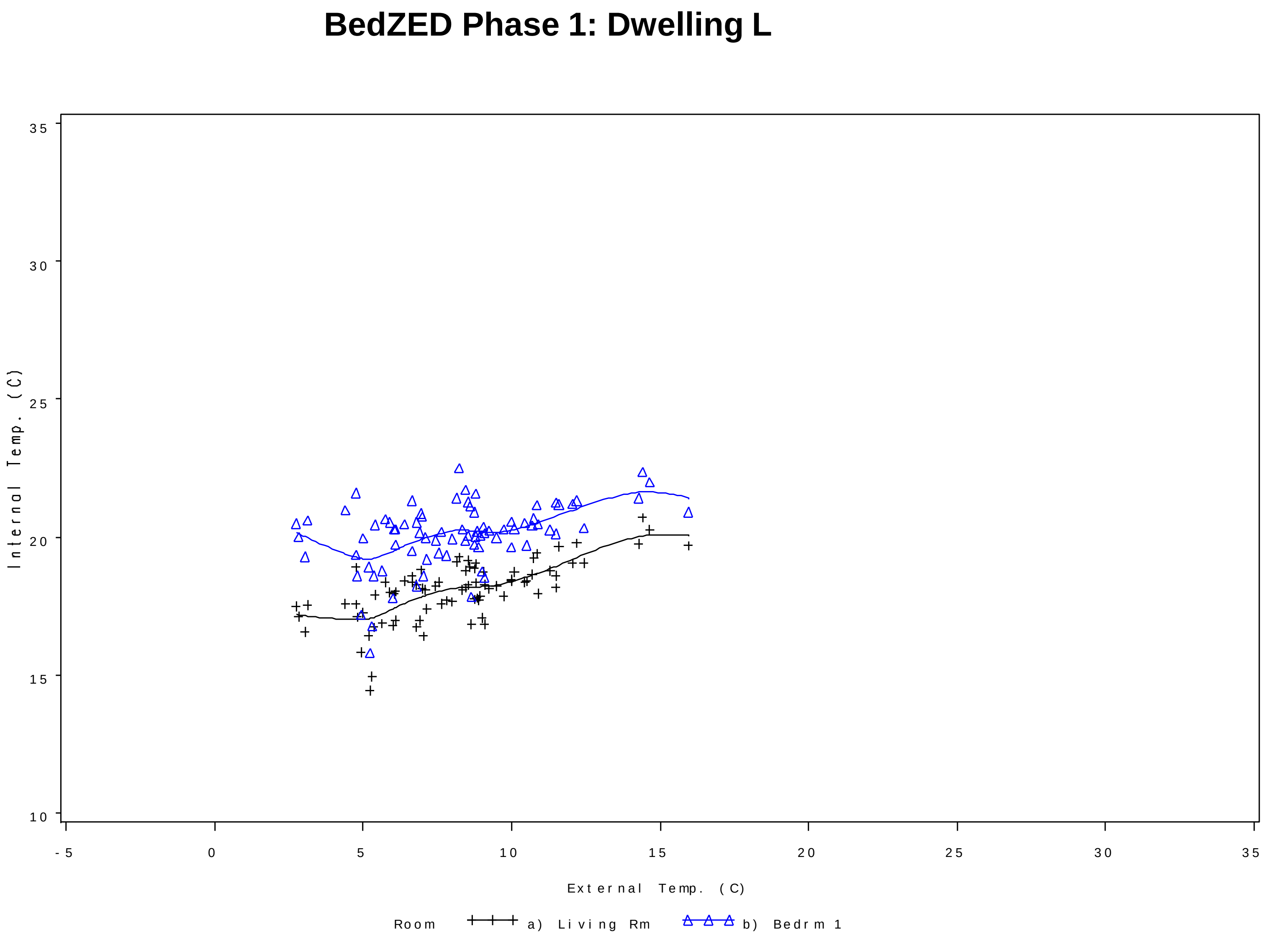
BedZED Phase 1: Dwelling B




BedZED Phase 1: Dwelling F
Internal Temp. (C)
35
30
25
20
15
10
-5
0
5
10
15
20
25
30
35
External Temp. (C)
Room
a) Living Rm
b) Bedrm 1

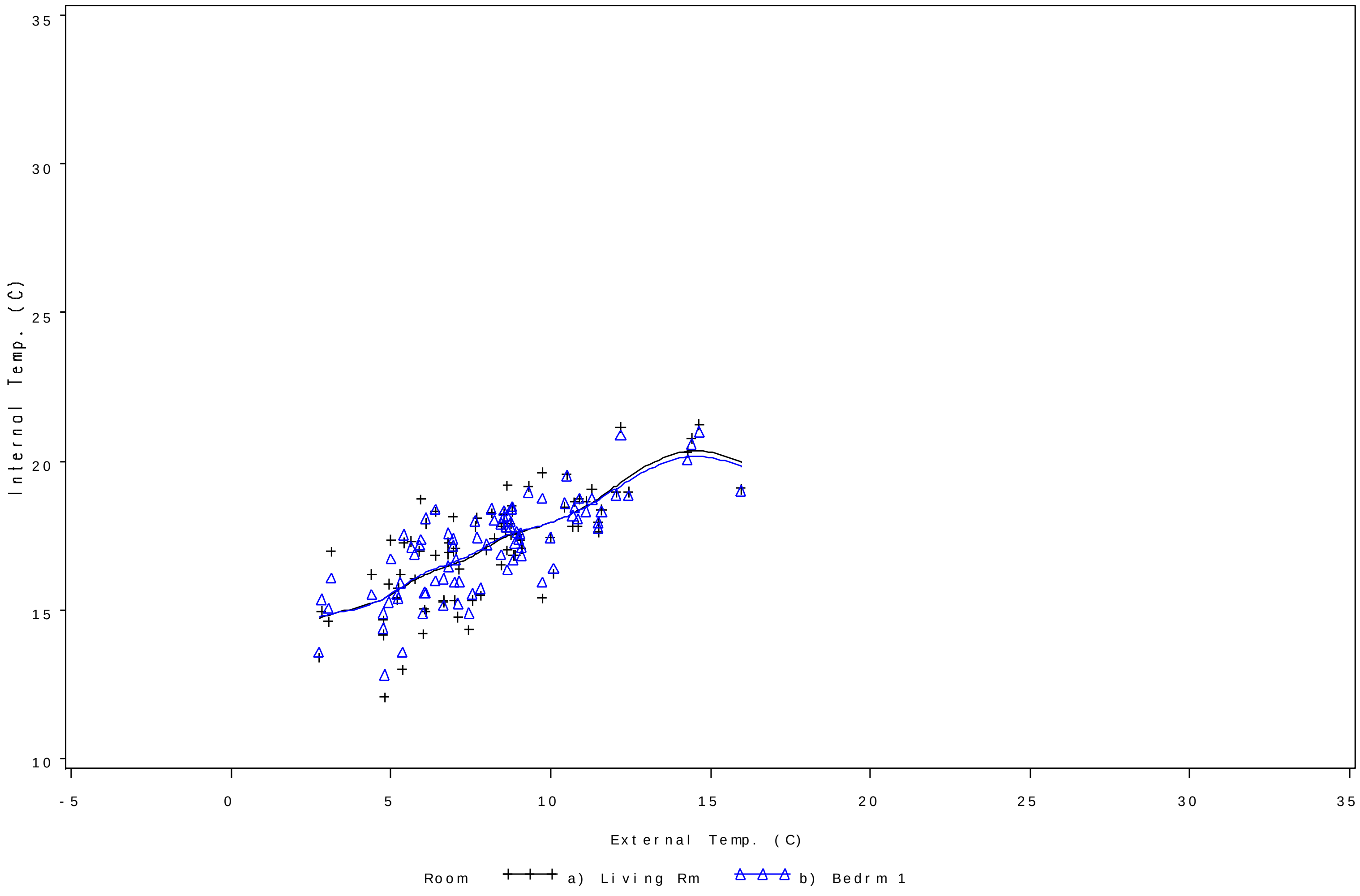
BedZED Phase 1: Dwelling J



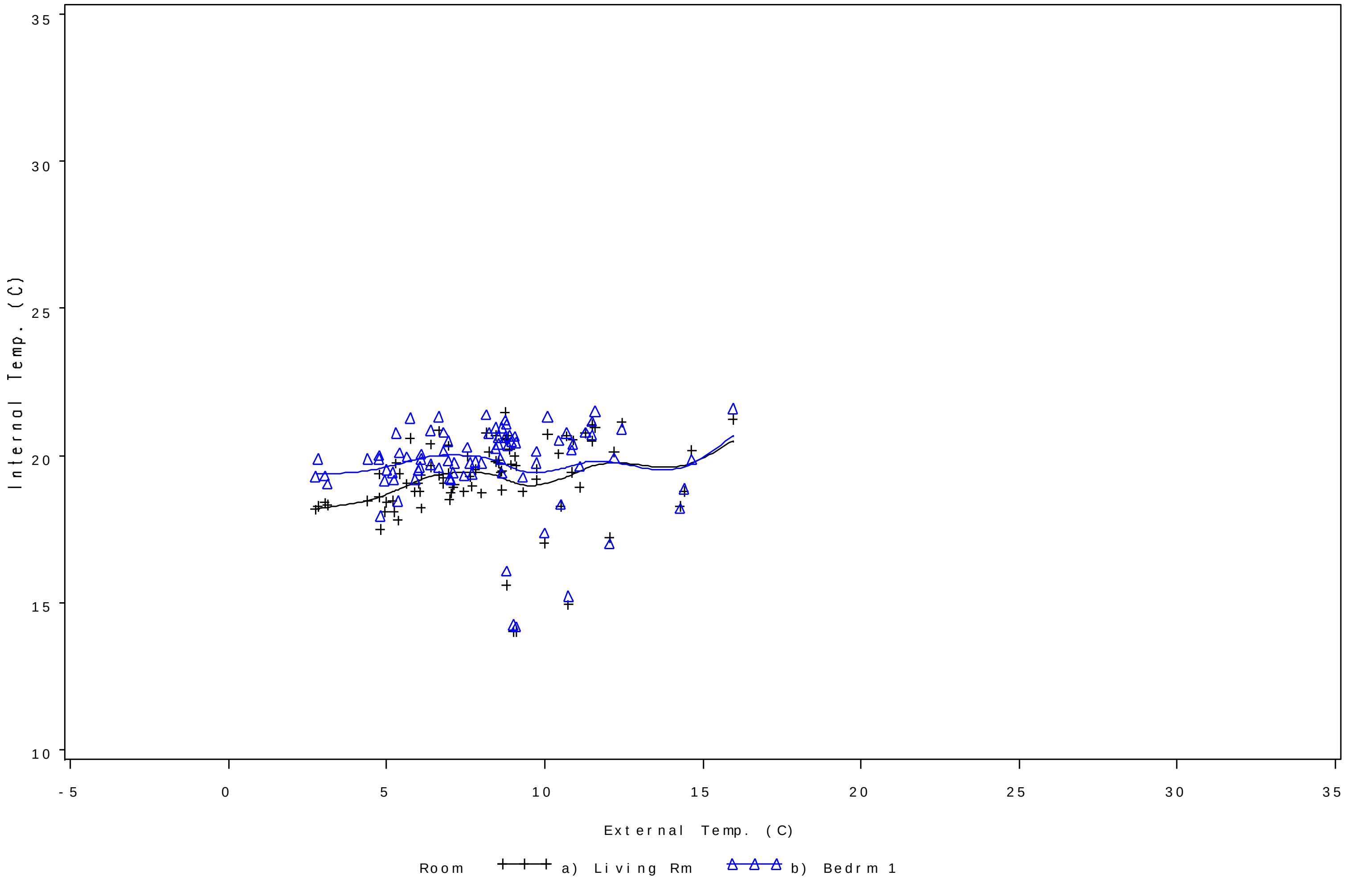


BedZED Phase 1: Dwelling L
Internal Temp. (C)
35
30
25
20
15
10
-5
0
5
10
15
20
25
30
35
External Temp. (C)
Room
a) Living Rm
b) Bedrm 1

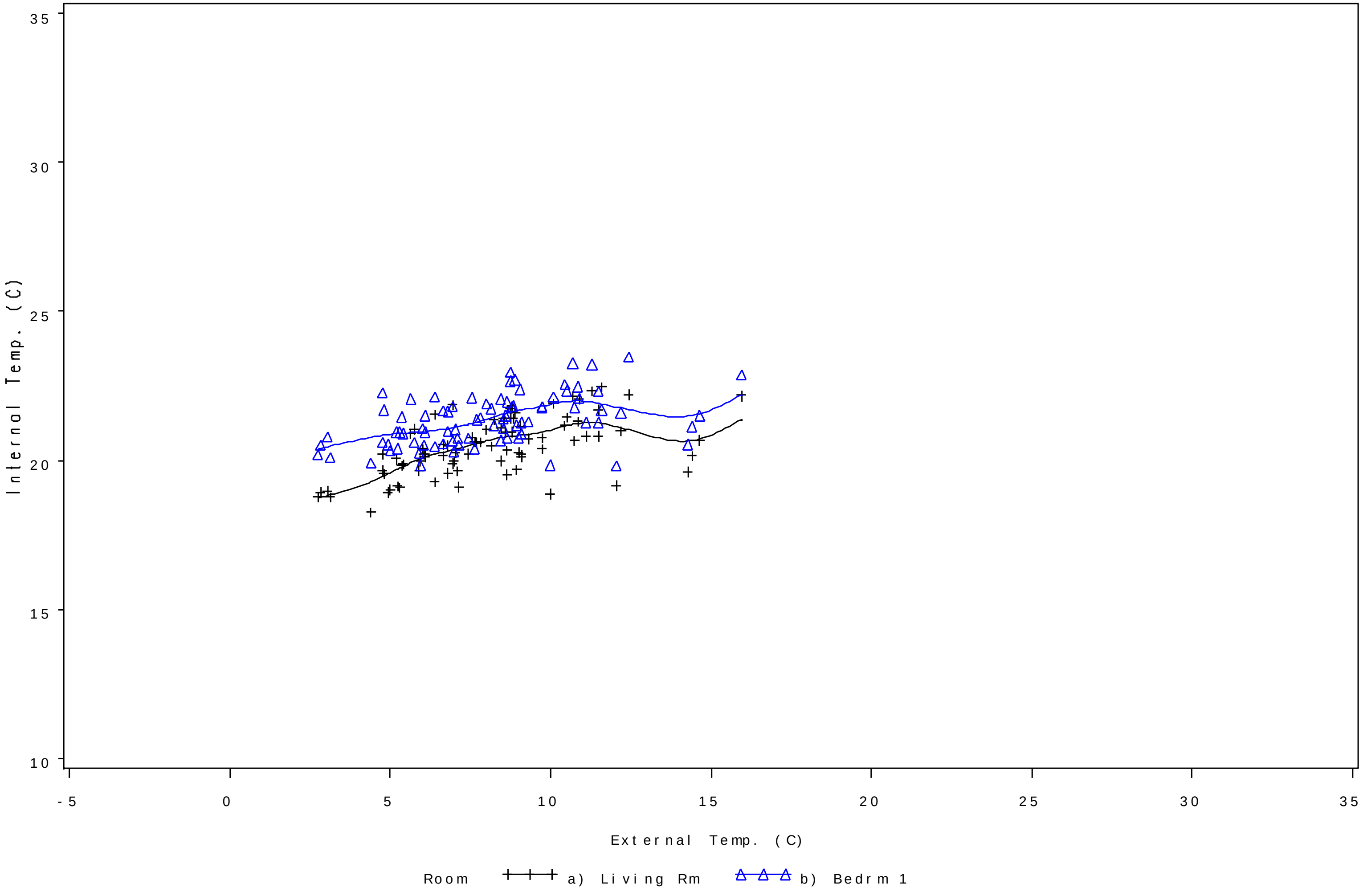
BedZED Phase 1: Dwelling M



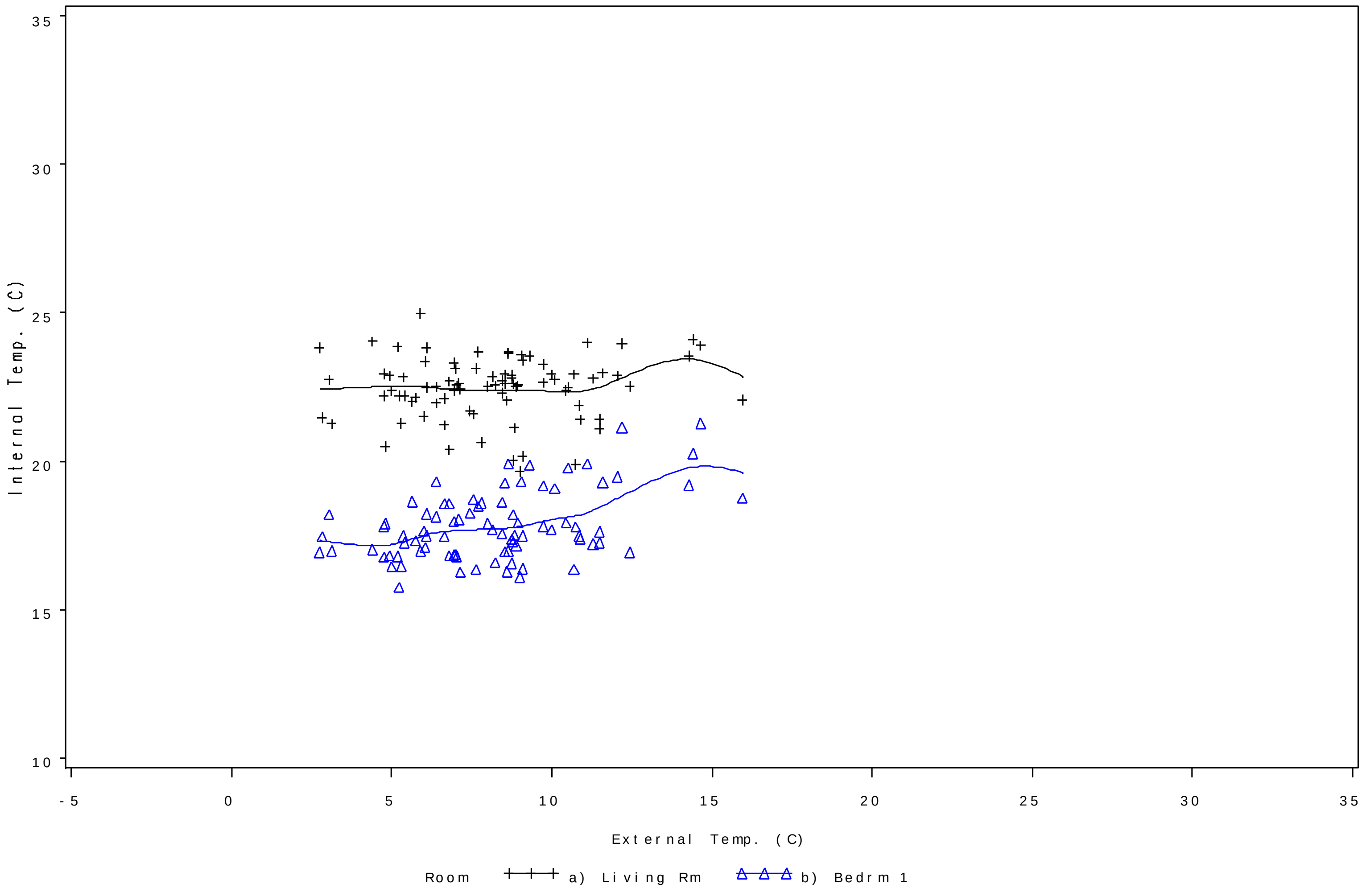
BedZED Phase 1: Dwelling N



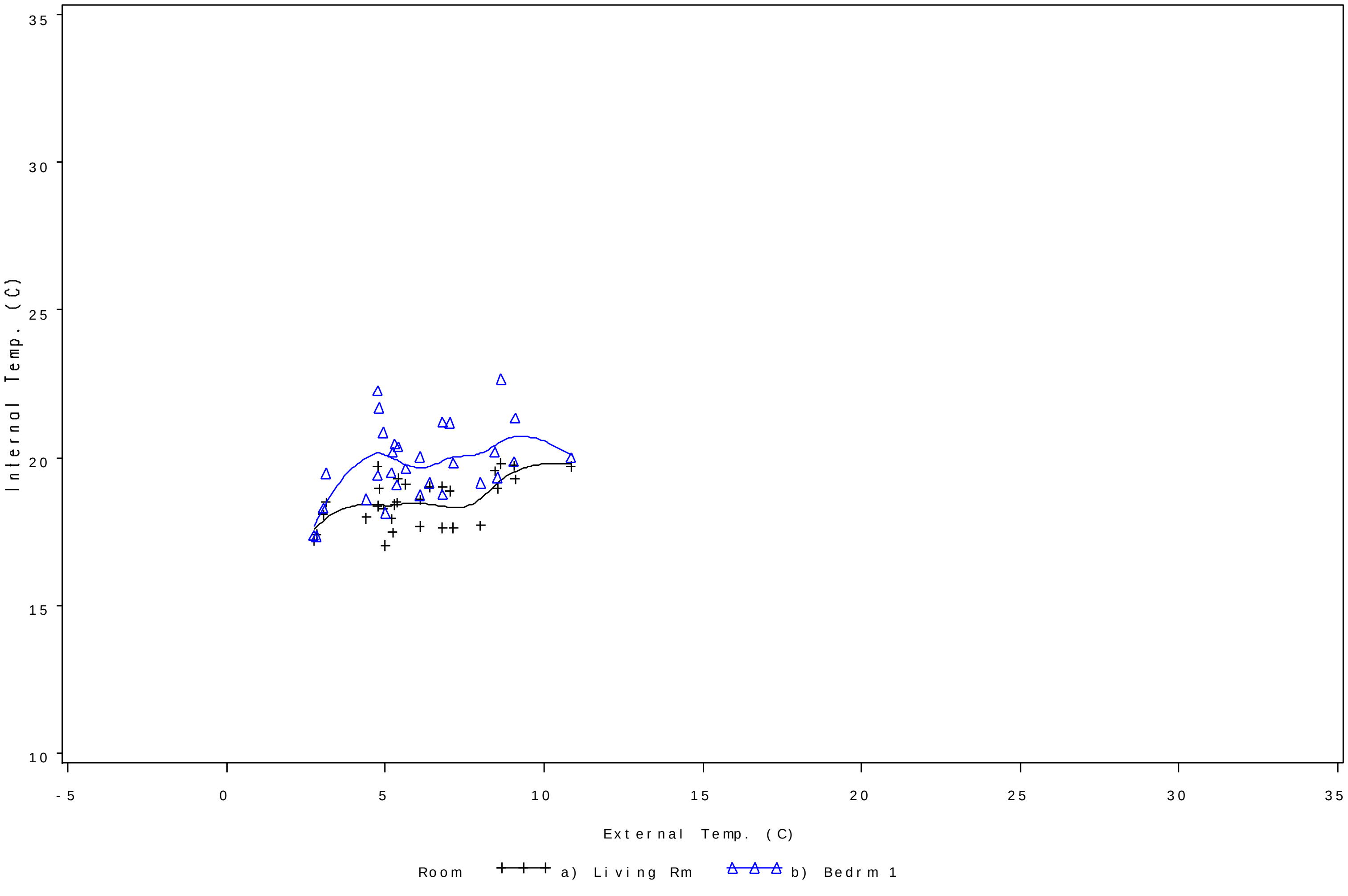
BedZED Phase 1: Dwelling P



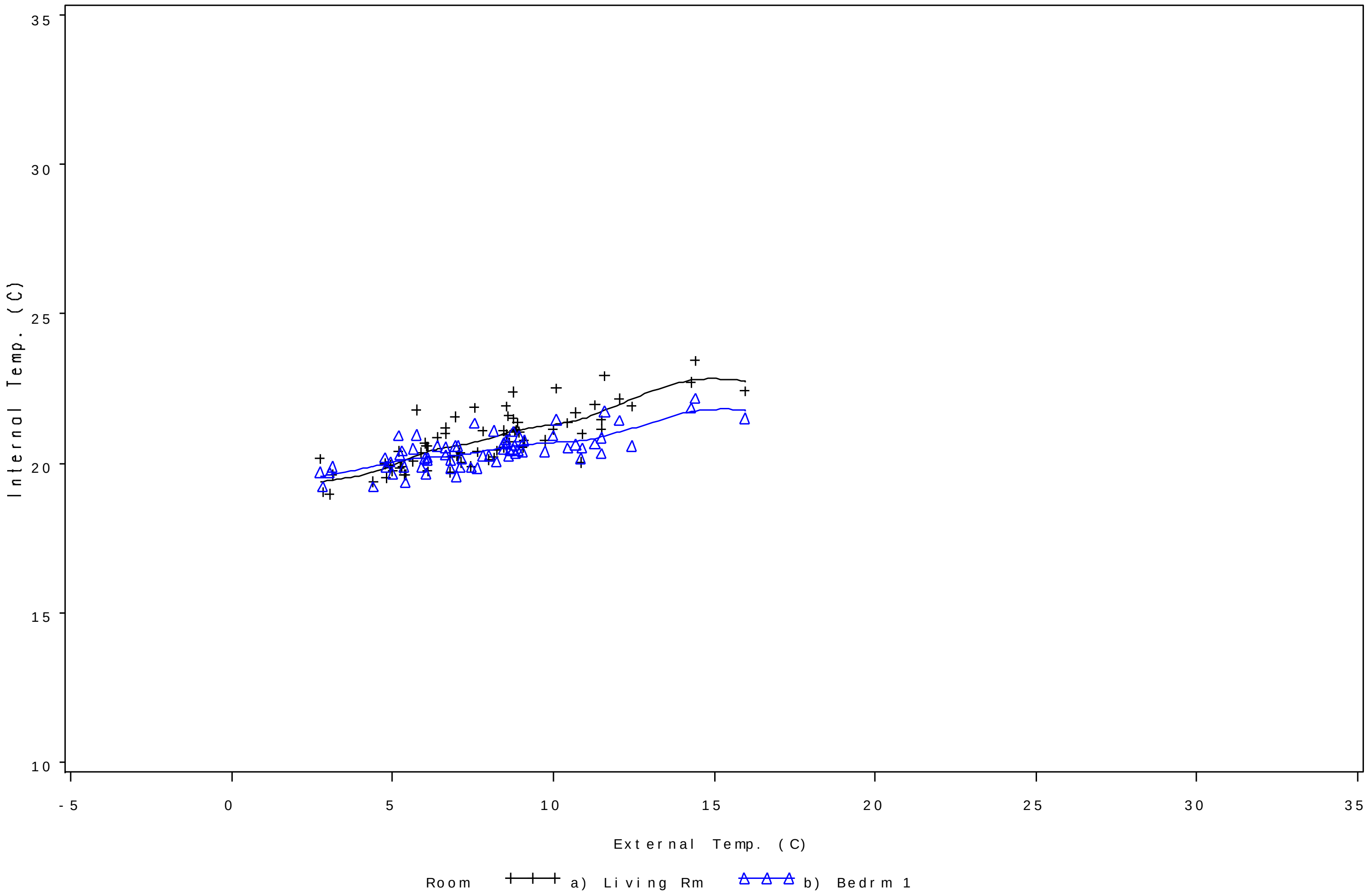
BedZED Phase 1: Dwelling Q



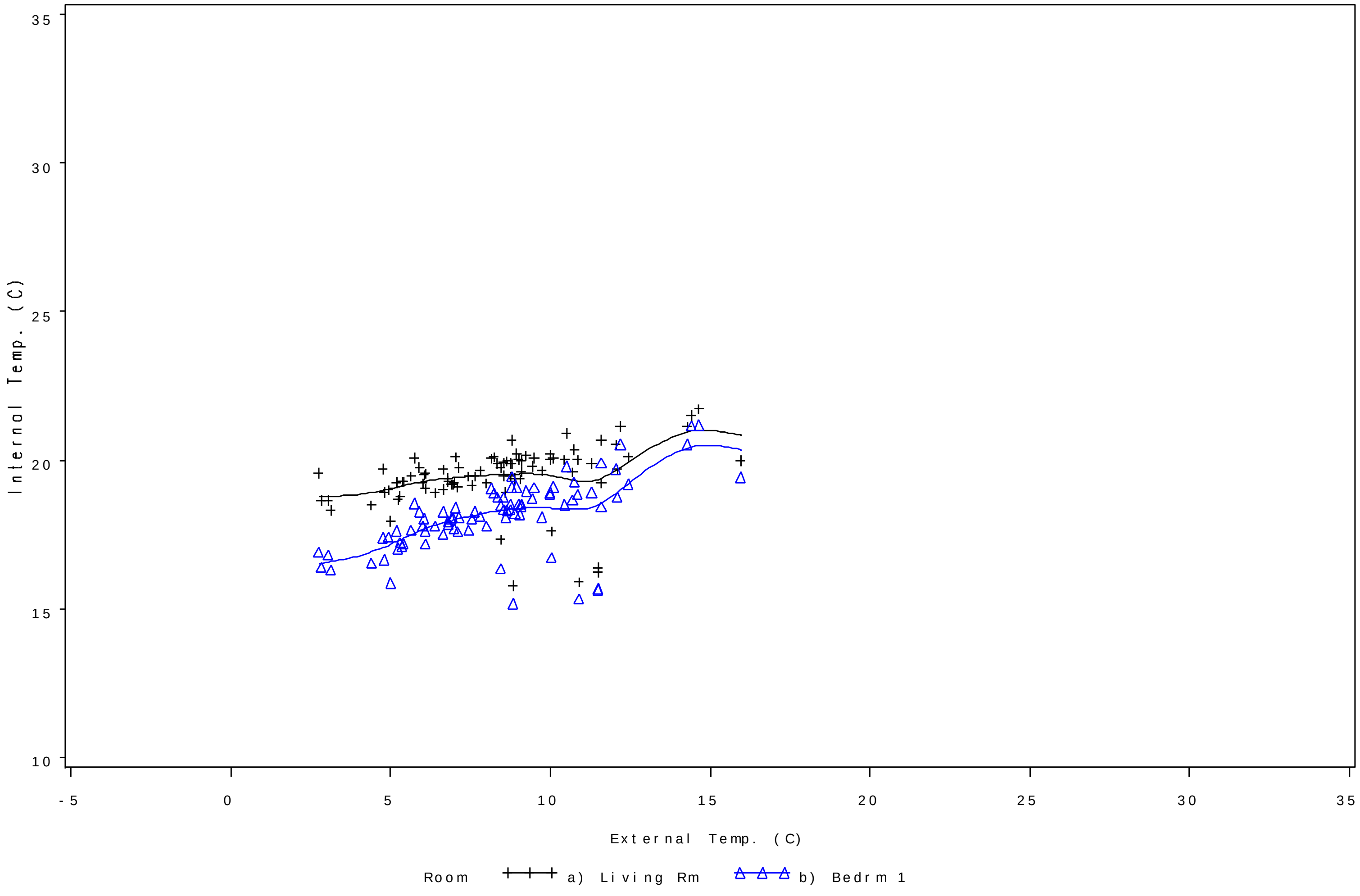
BedZED Phase 1: Dwelling R



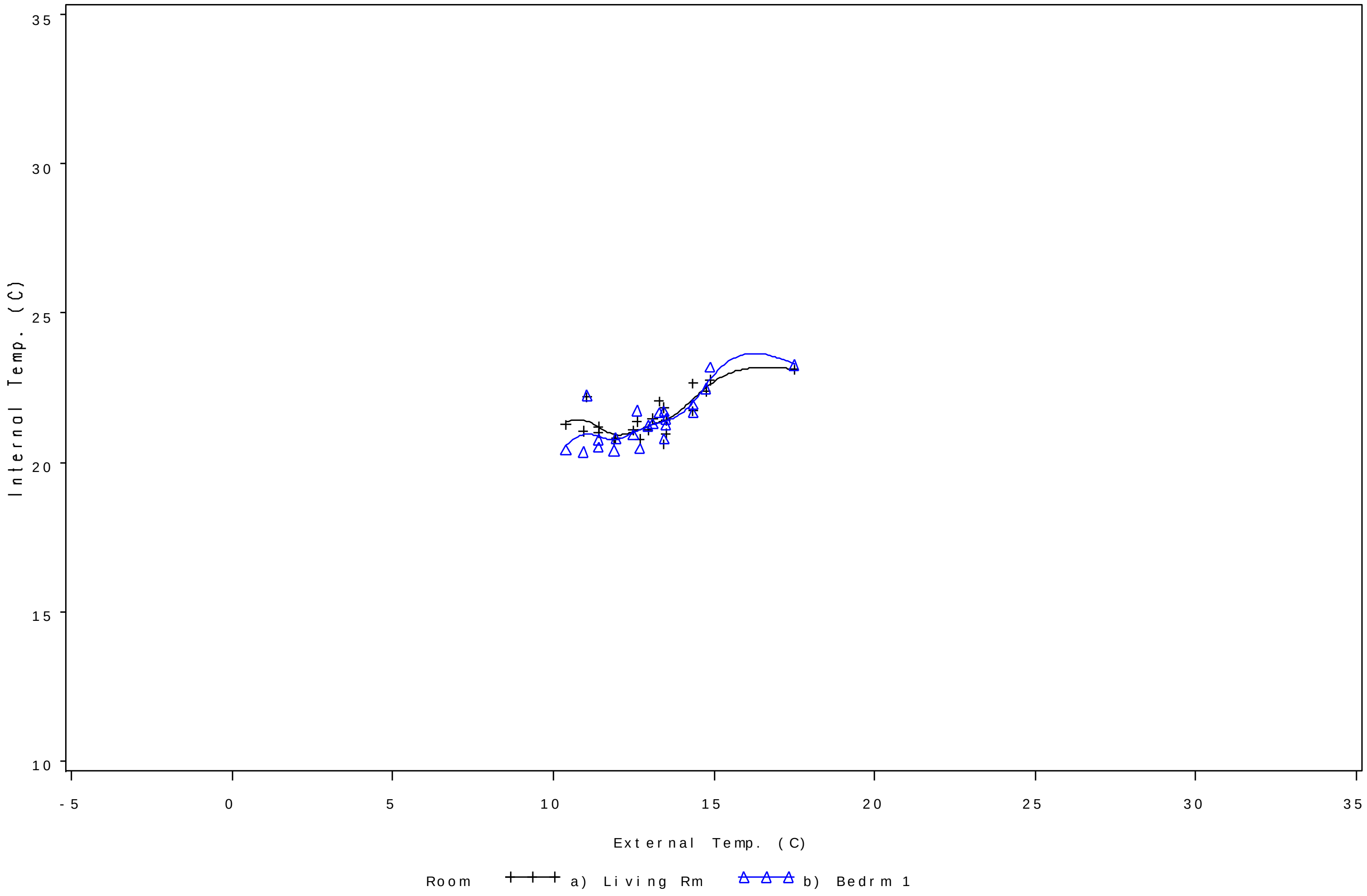
BedZED Phase 1: Dwelling S



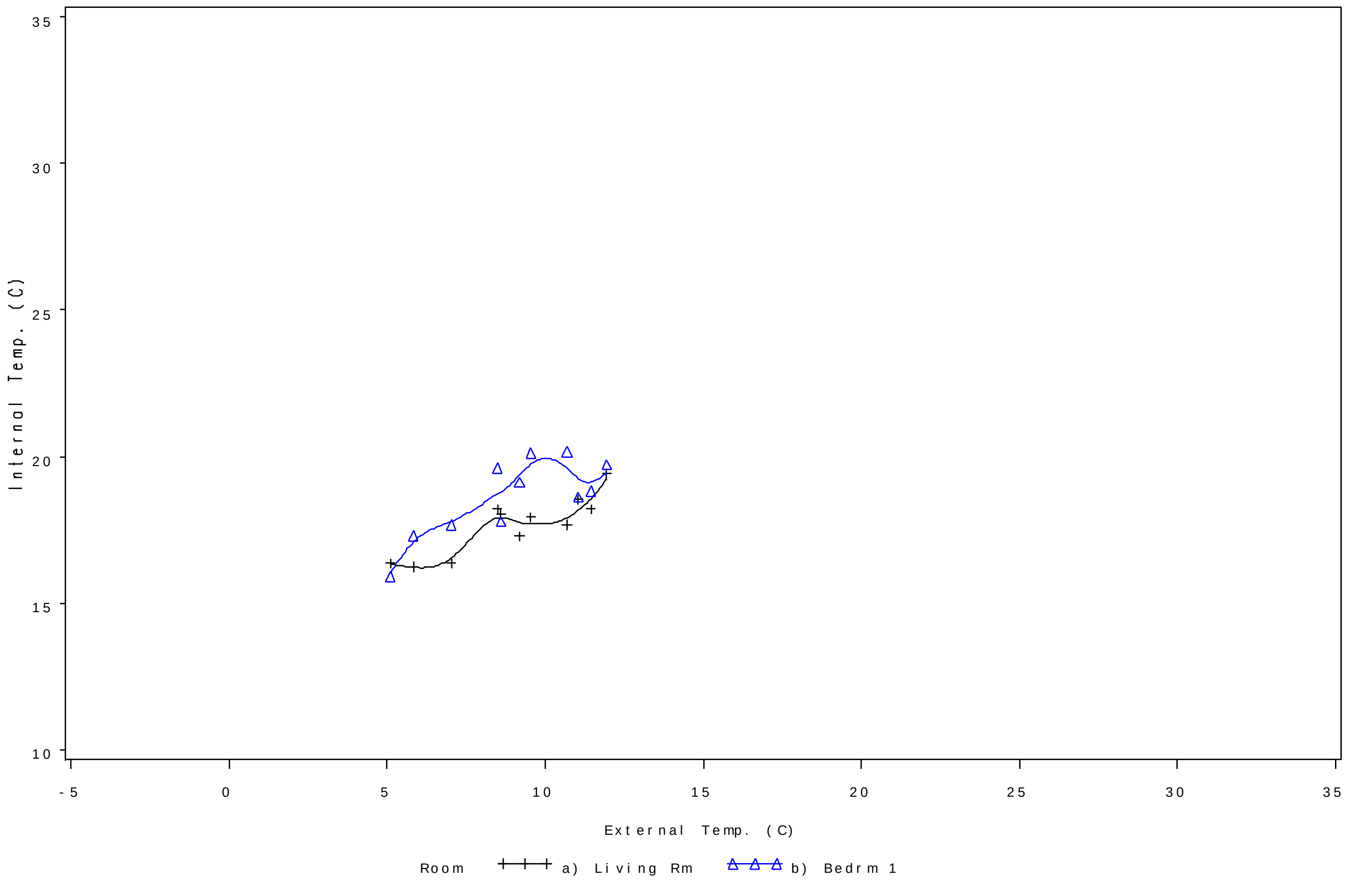
BedZED Phase 1: Dwelling V



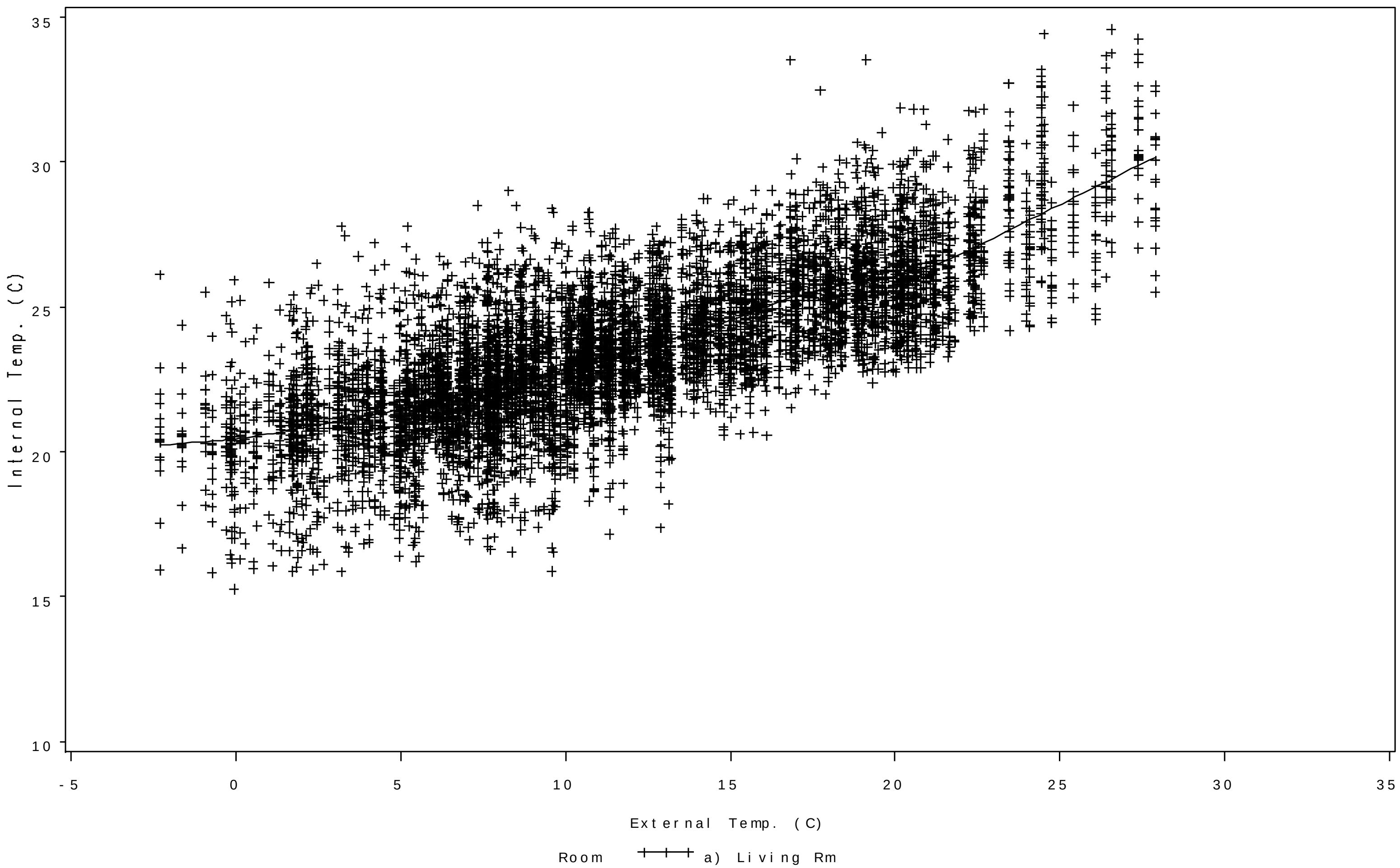
BedZED Phase 1: Dwelling X



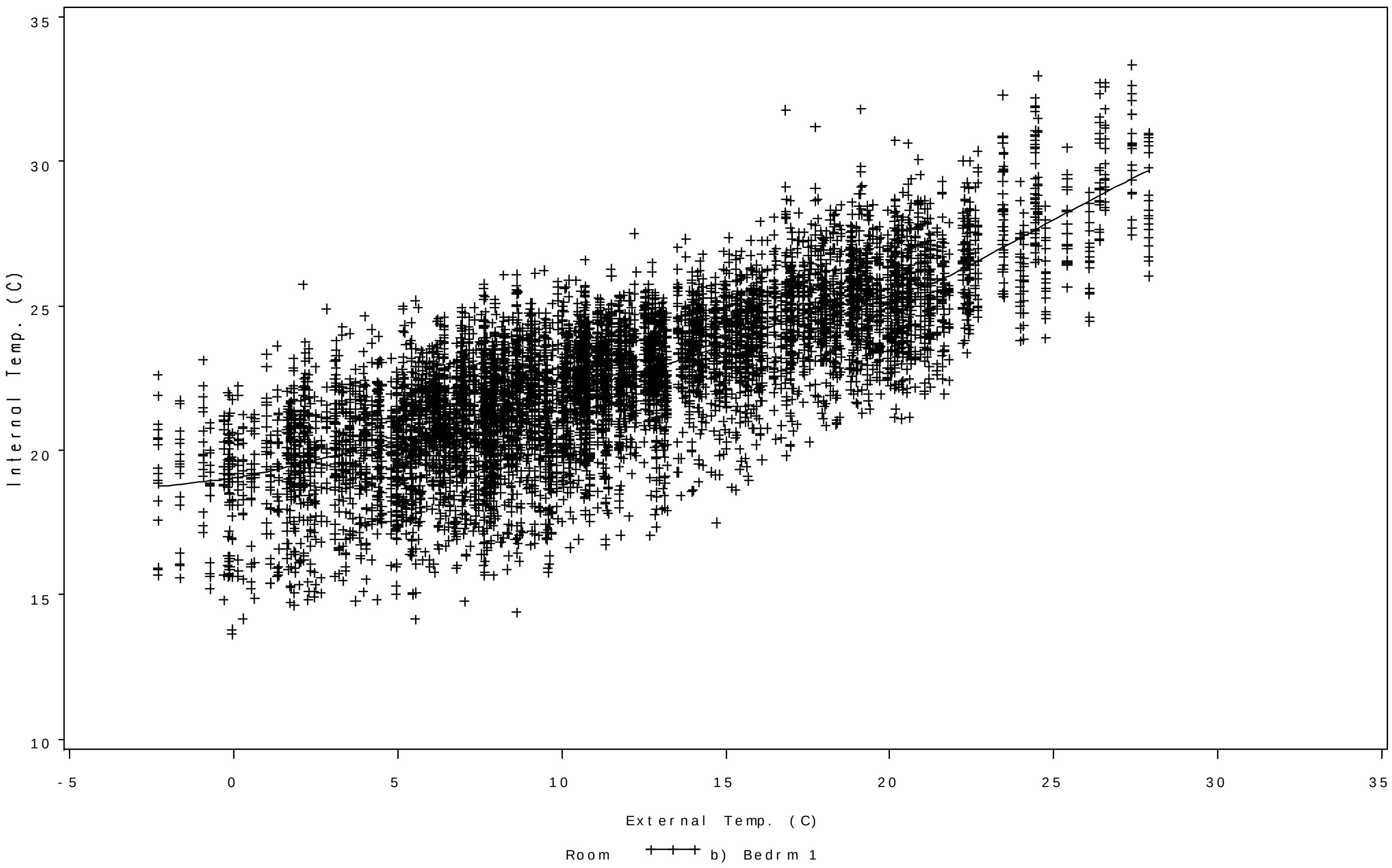
BedZED Phase 1: Dwelling AB



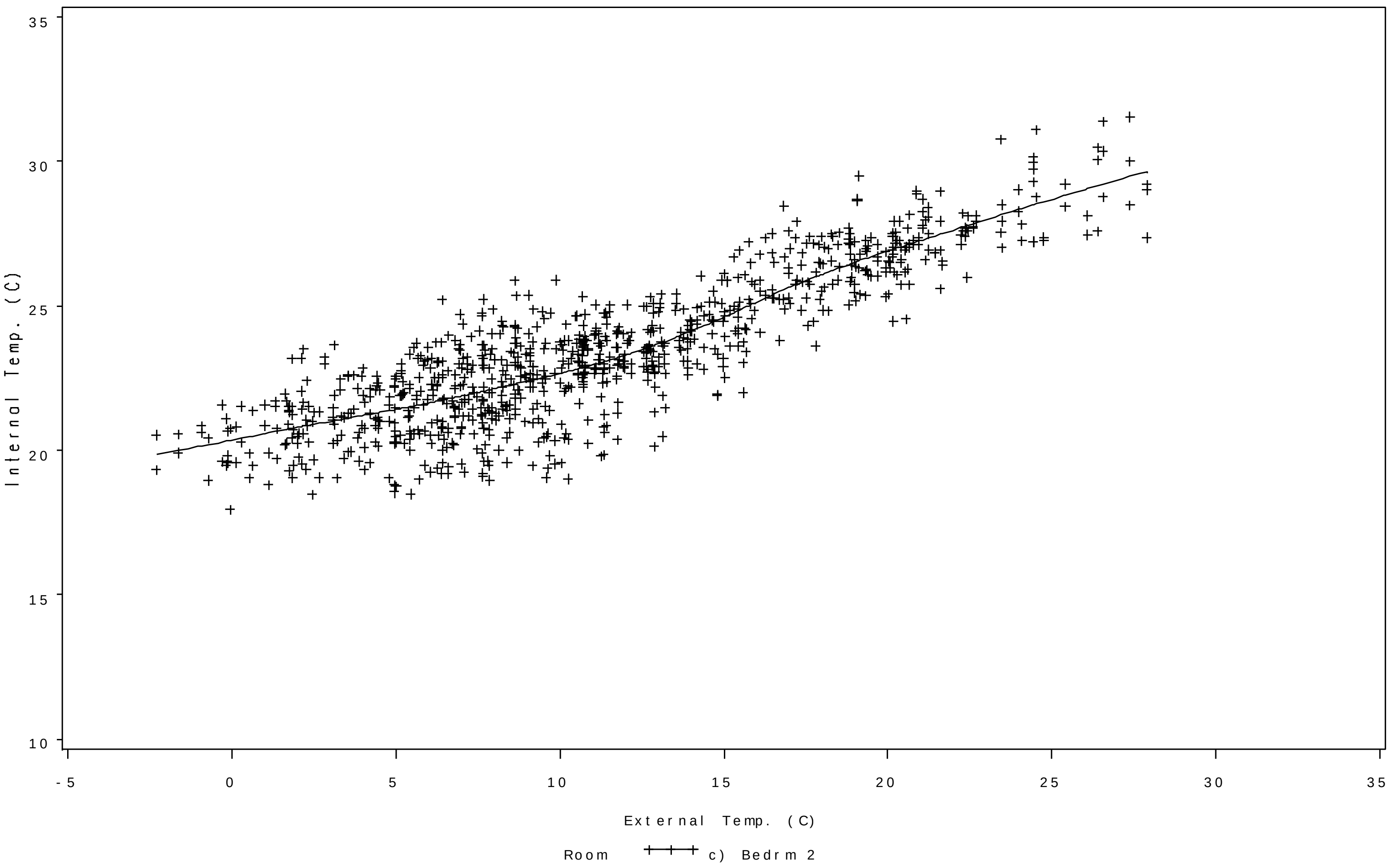
BedZED Phase 2: All Dwellings – Living Rooms



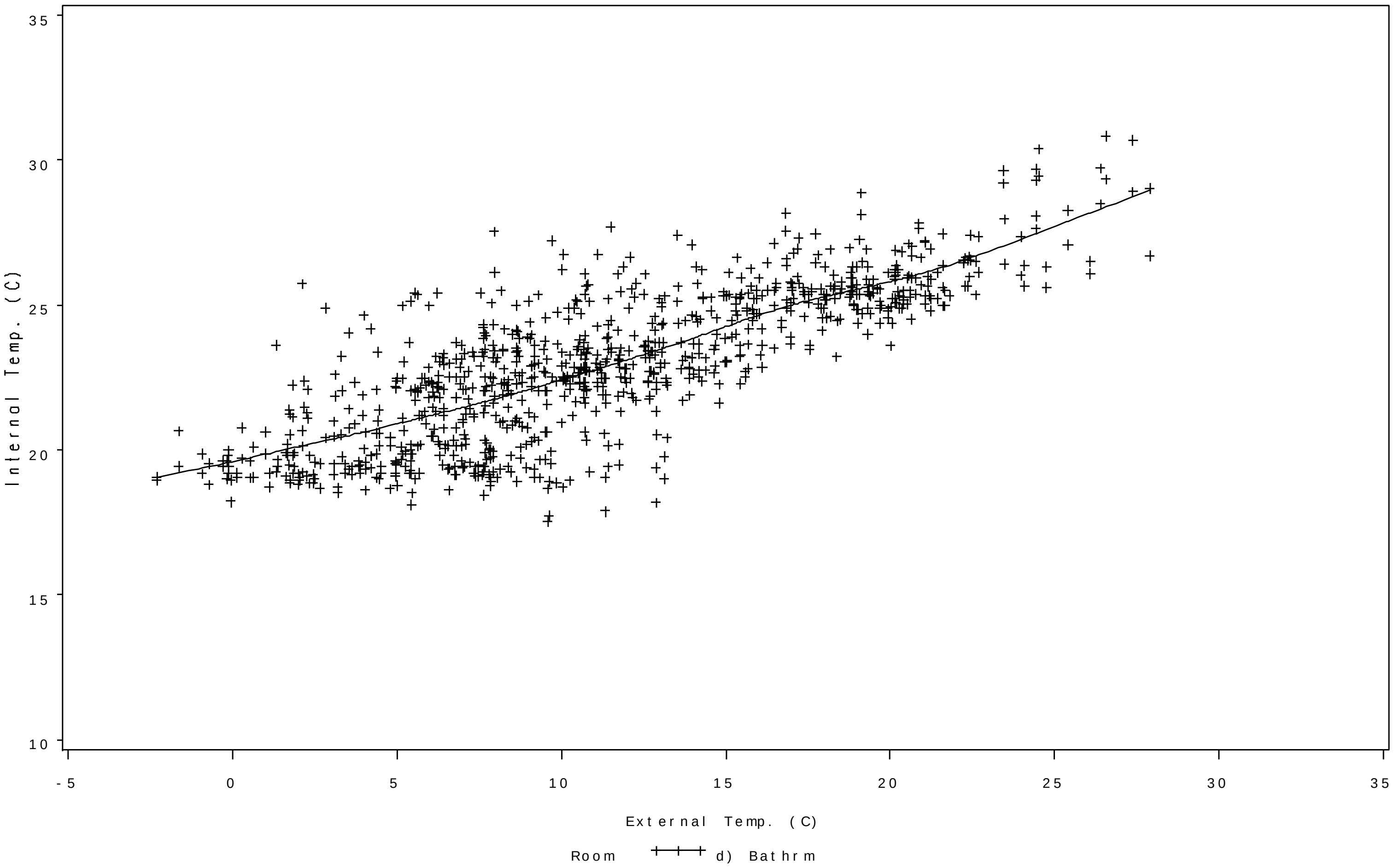
BedZED Phase 2: All Dwellings – Bedroom 1



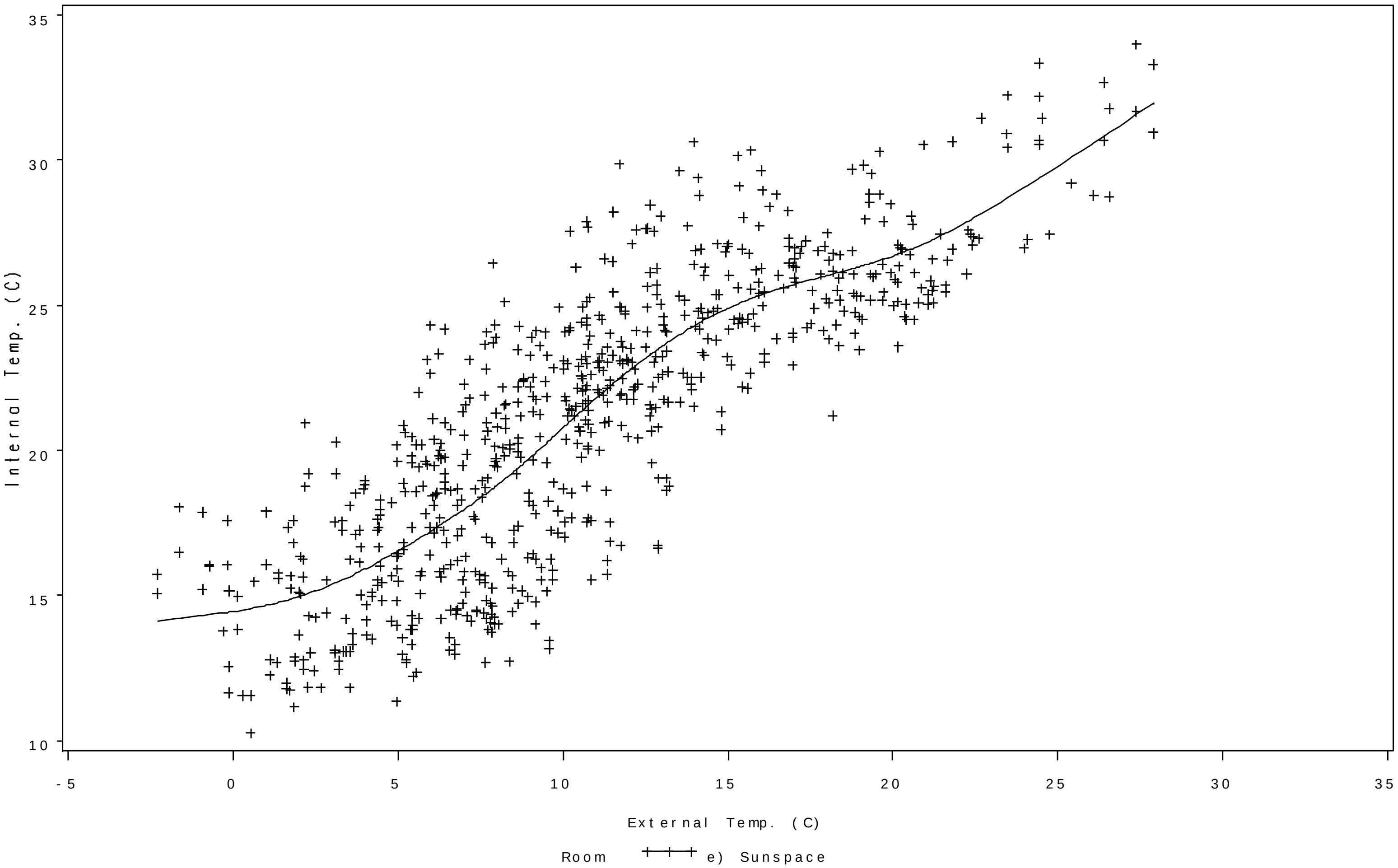
BedZED Phase 2: All Dwellings – Bedroom 2



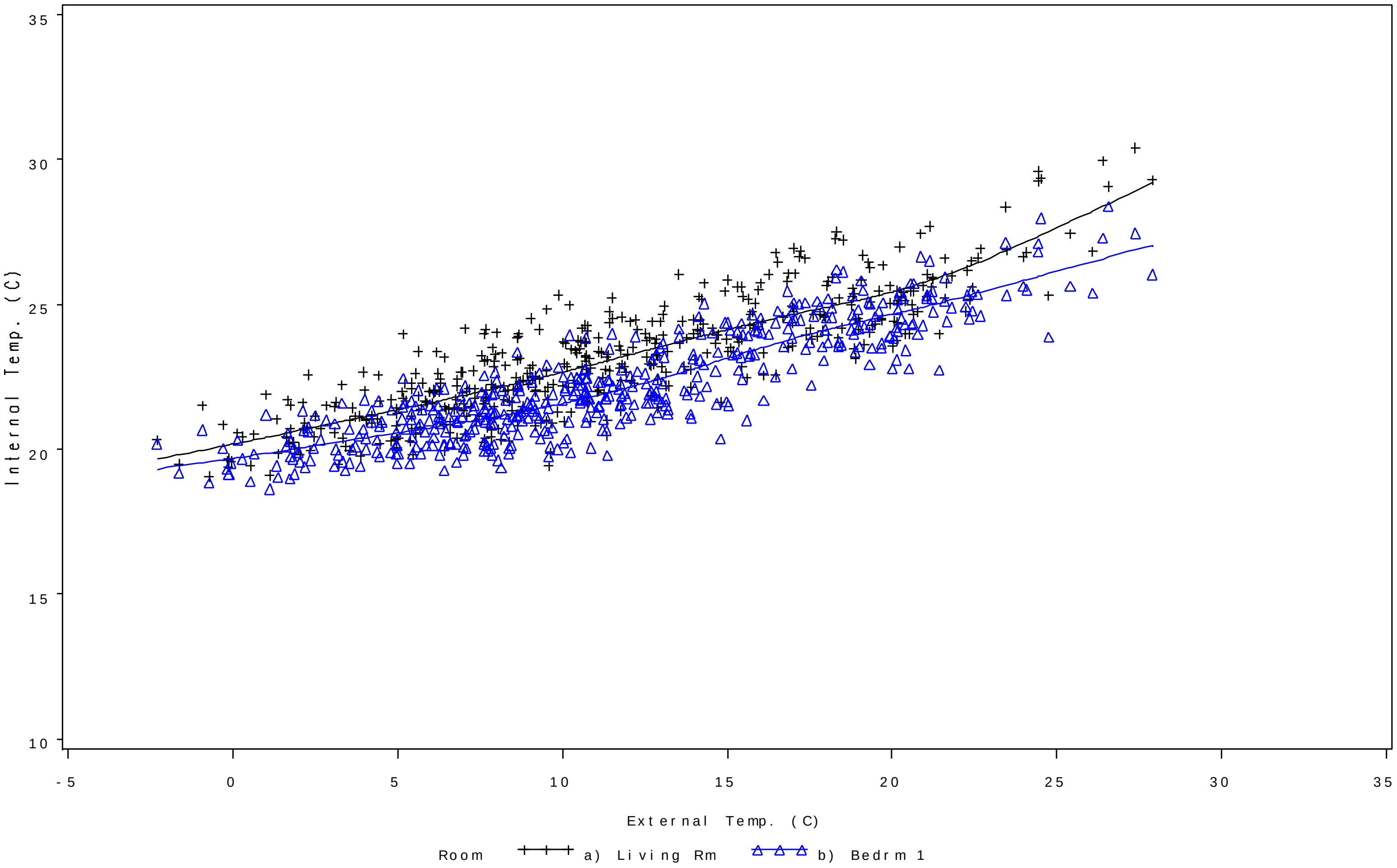
BedZED Phase 2: All Dwellings – Bathrooms



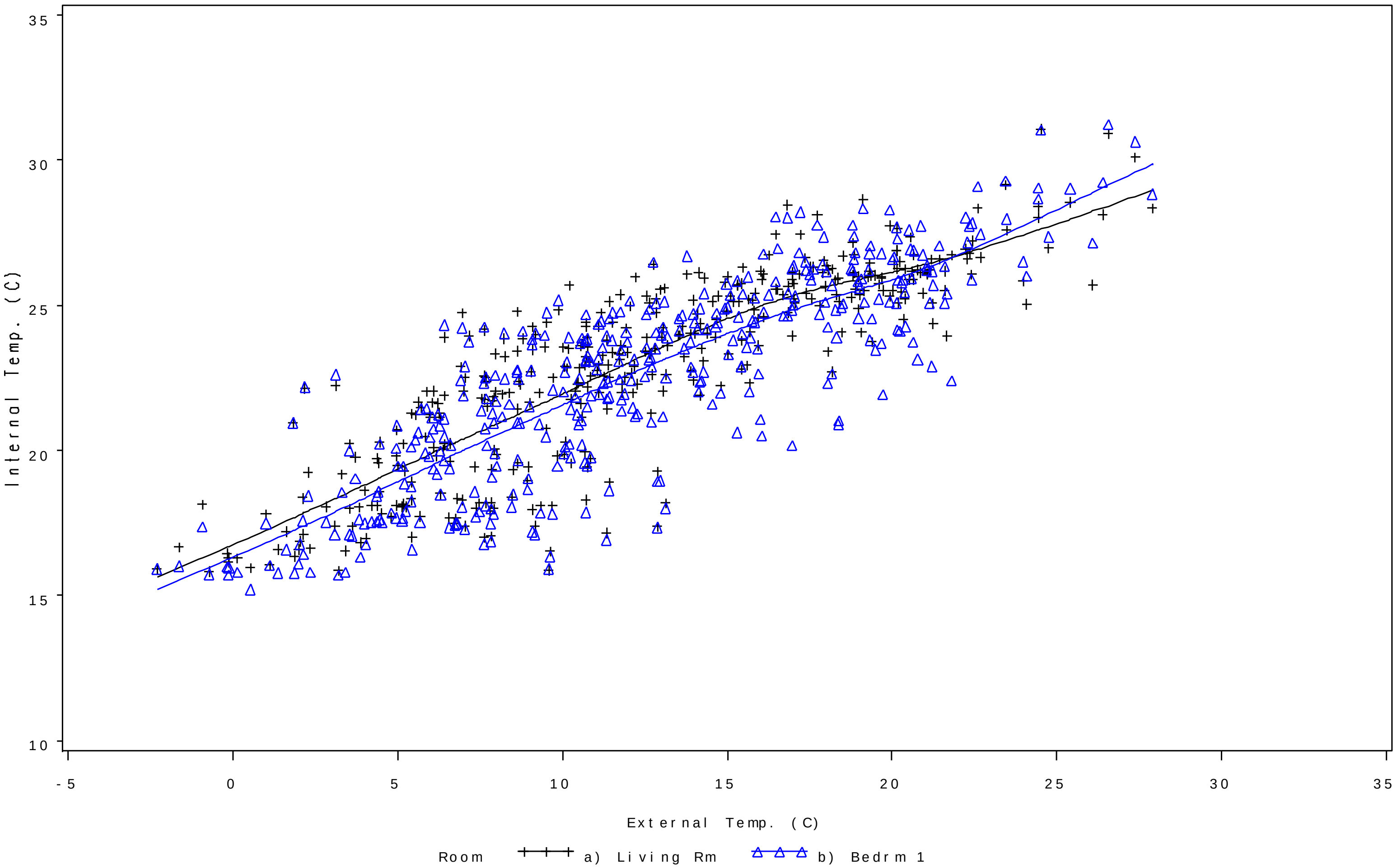
BedZED Phase 1: All Dwellings – Sunspaces



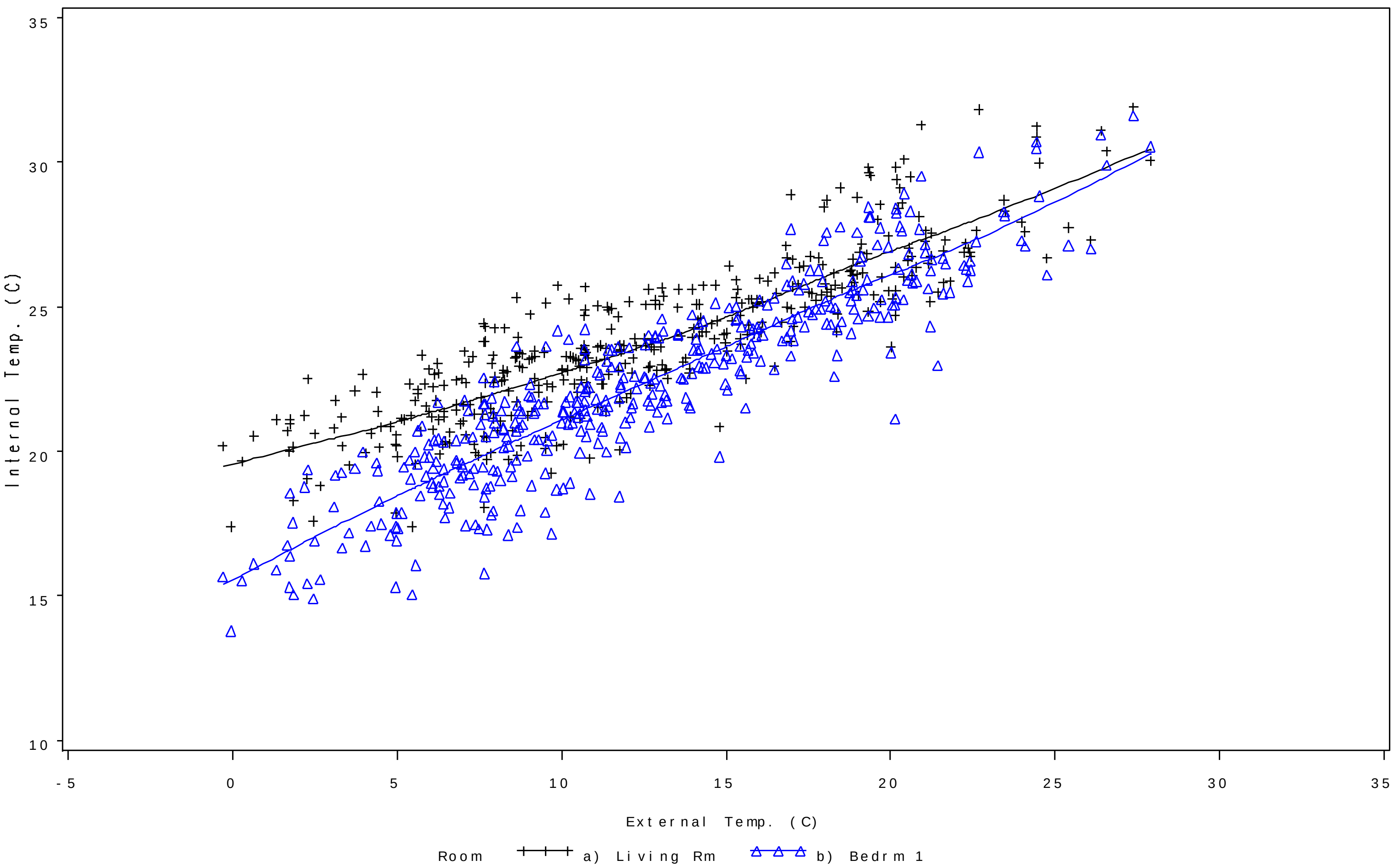
BedZED Phase 2: Dwelling A



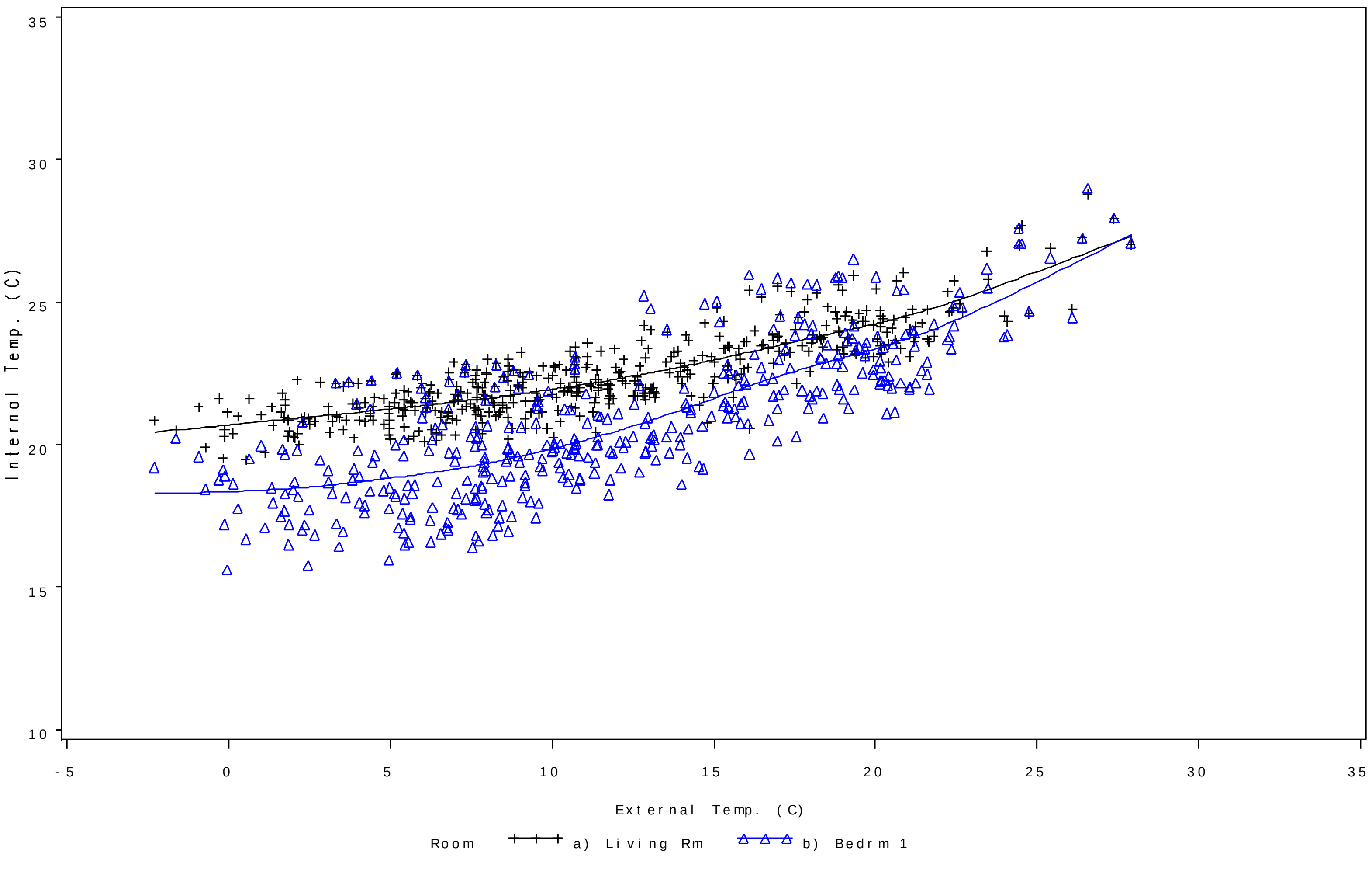
BedZED Phase 2: Dwelling B



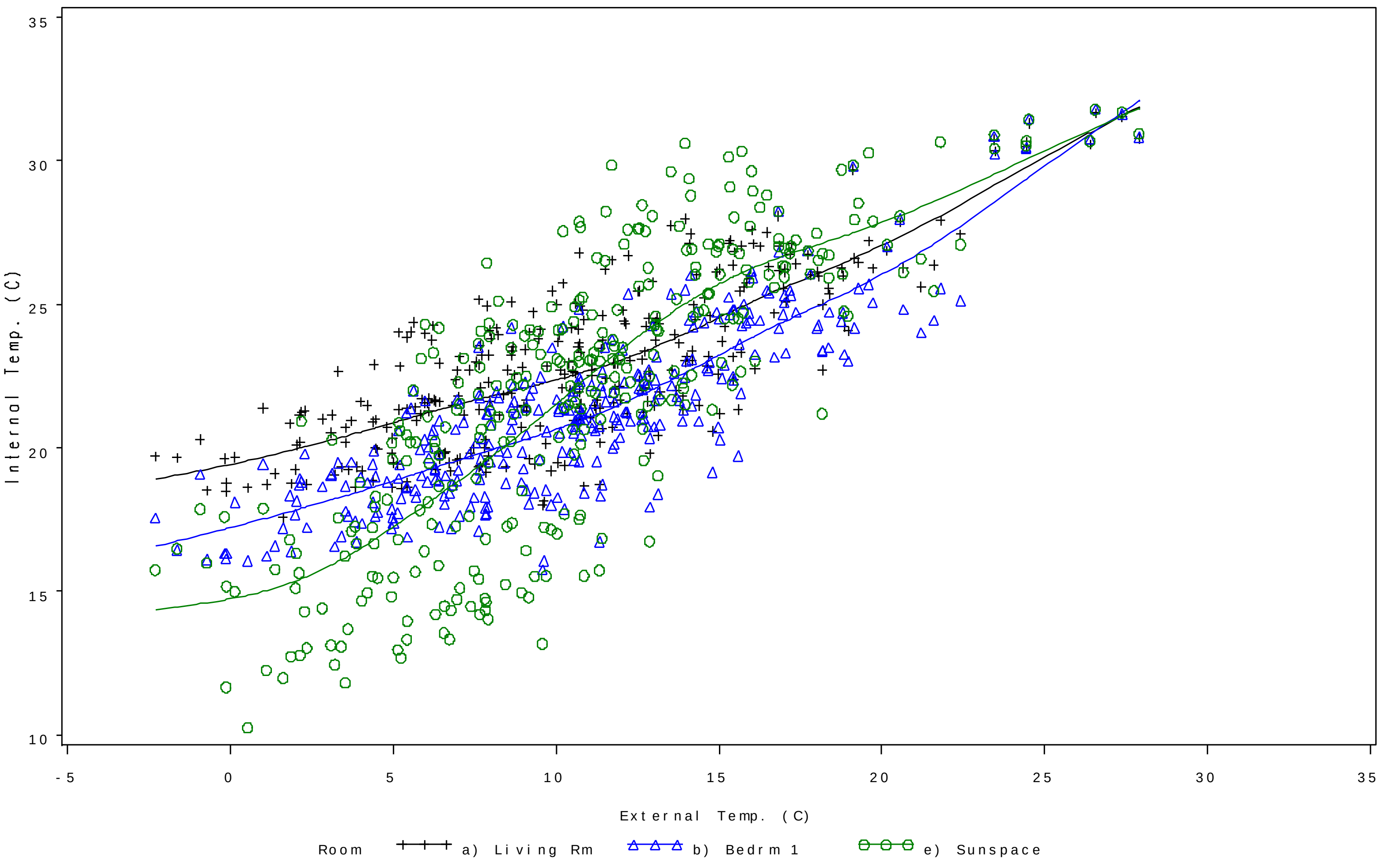
BedZED Phase 2: Dwelling C



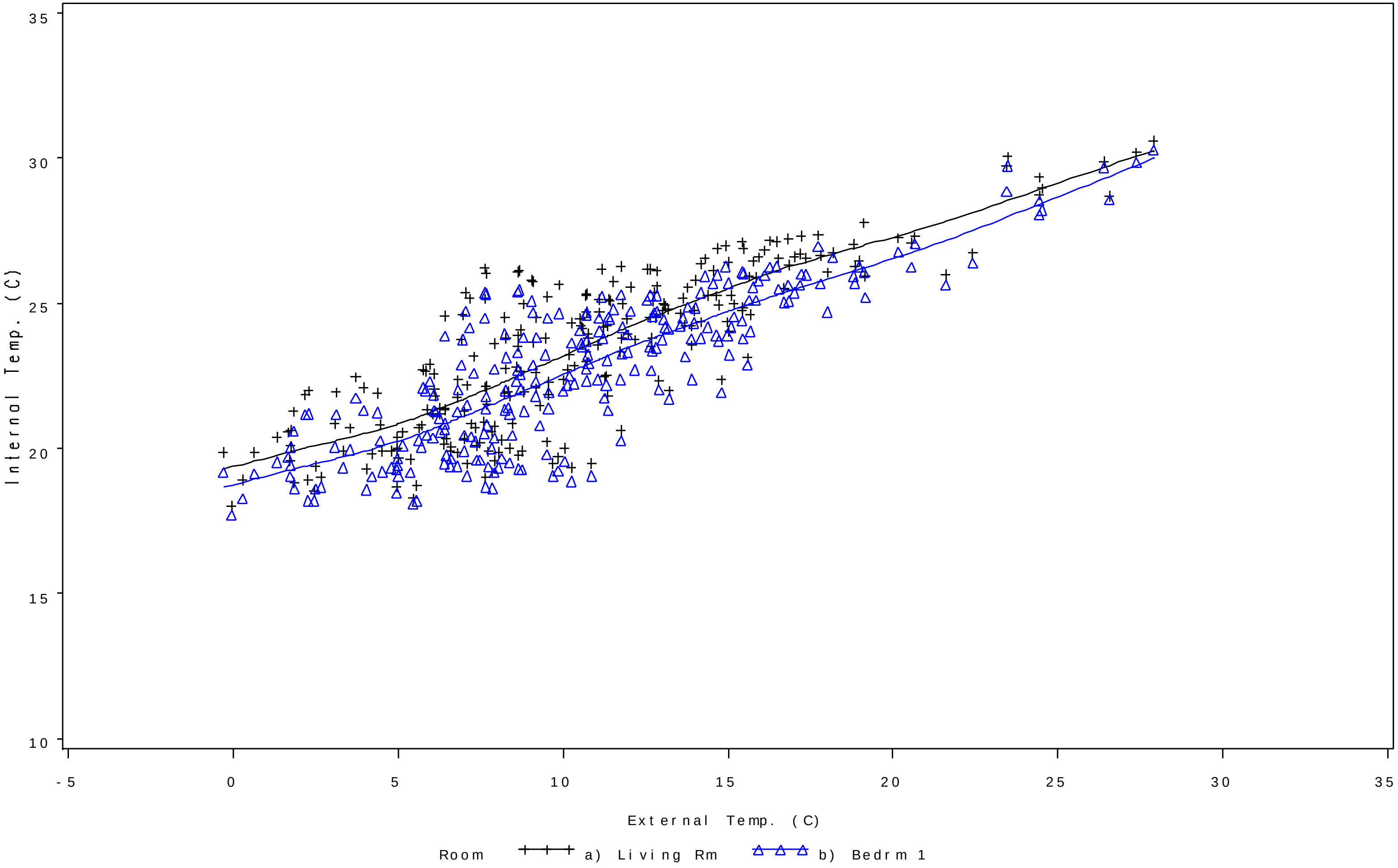
BedZED Phase 2: Dwelling D



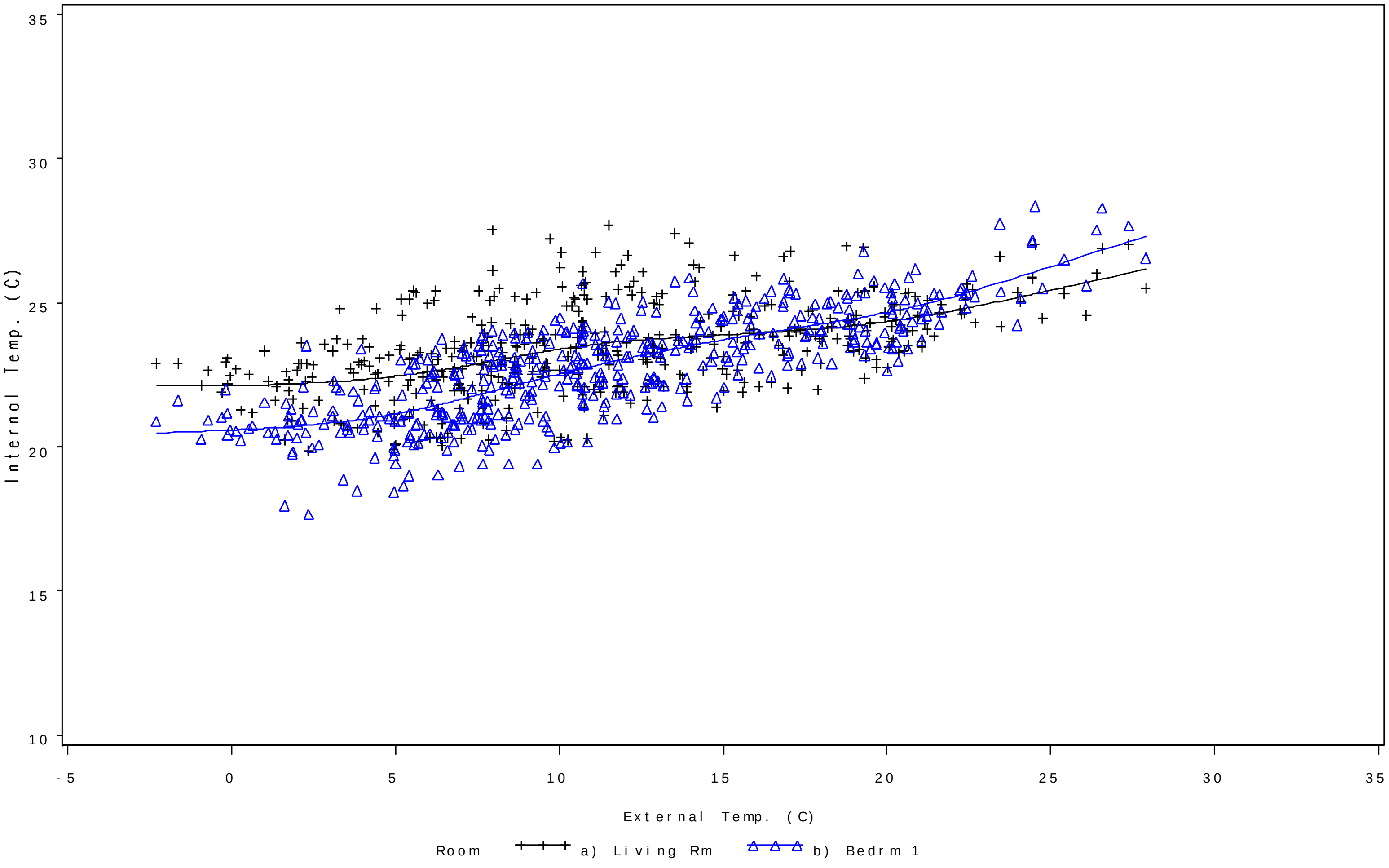
BedZED Phase 2: Dwelling E



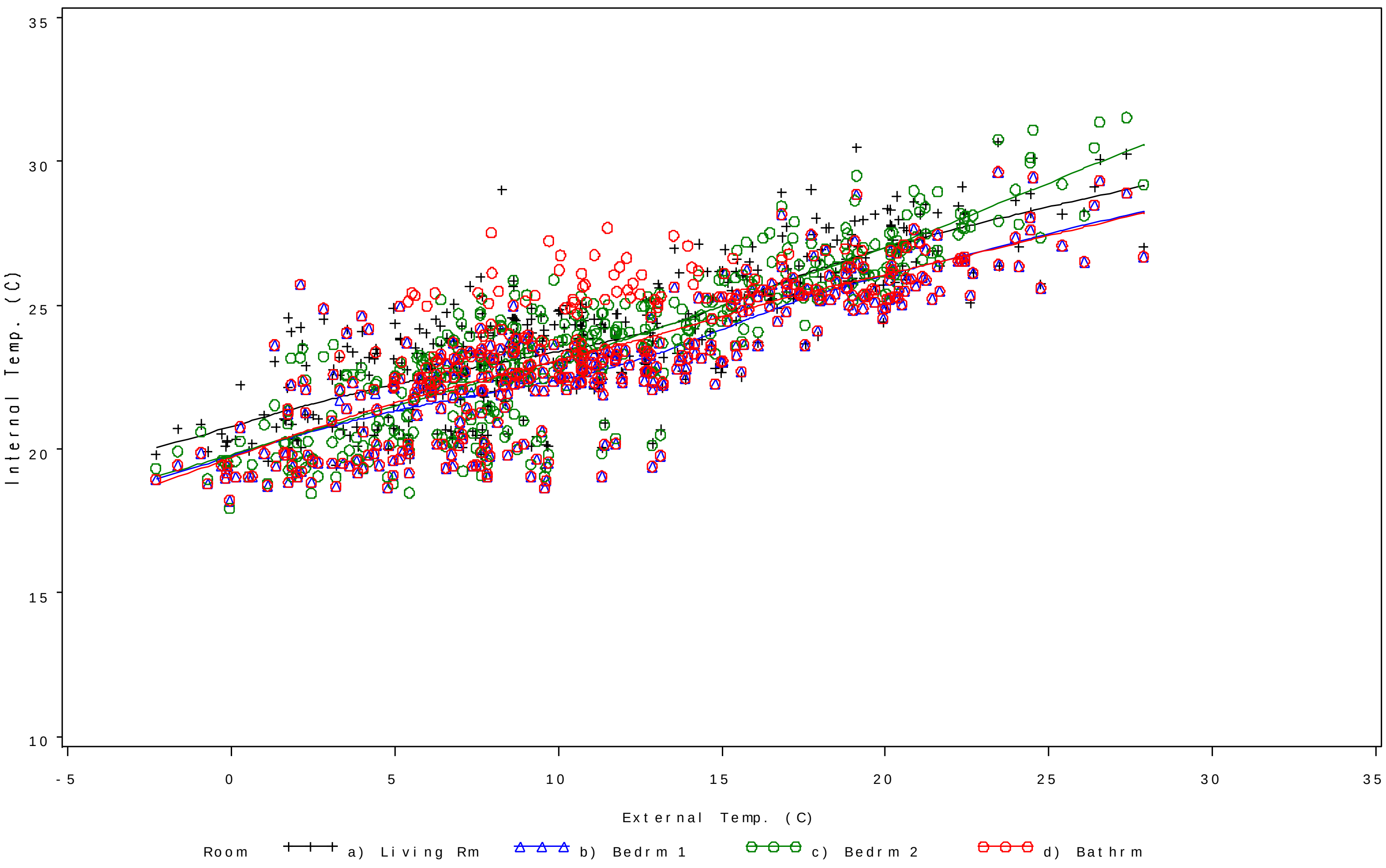
BedZED Phase 2: Dwelling F



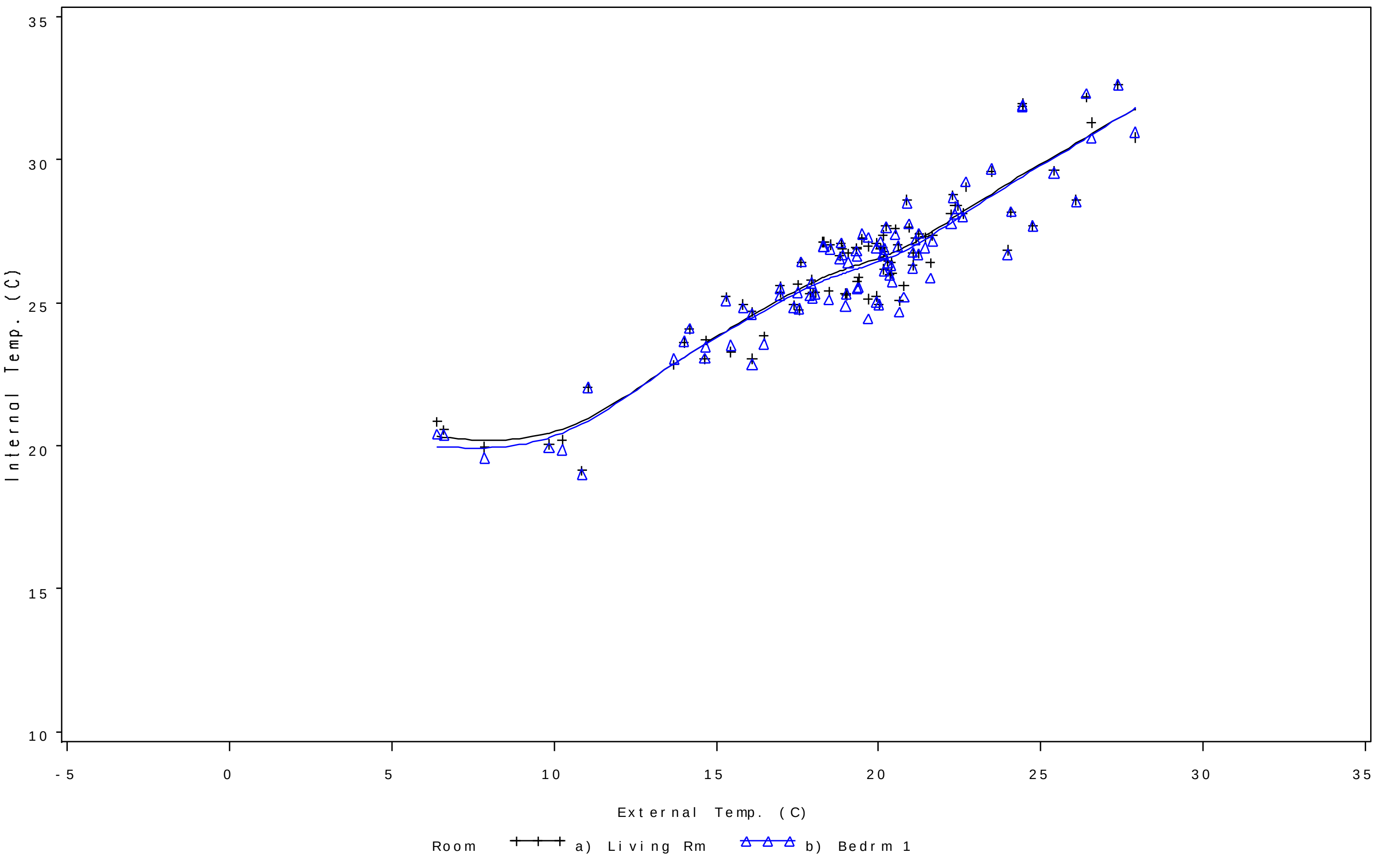
BedZED Phase 2: Dwelling G



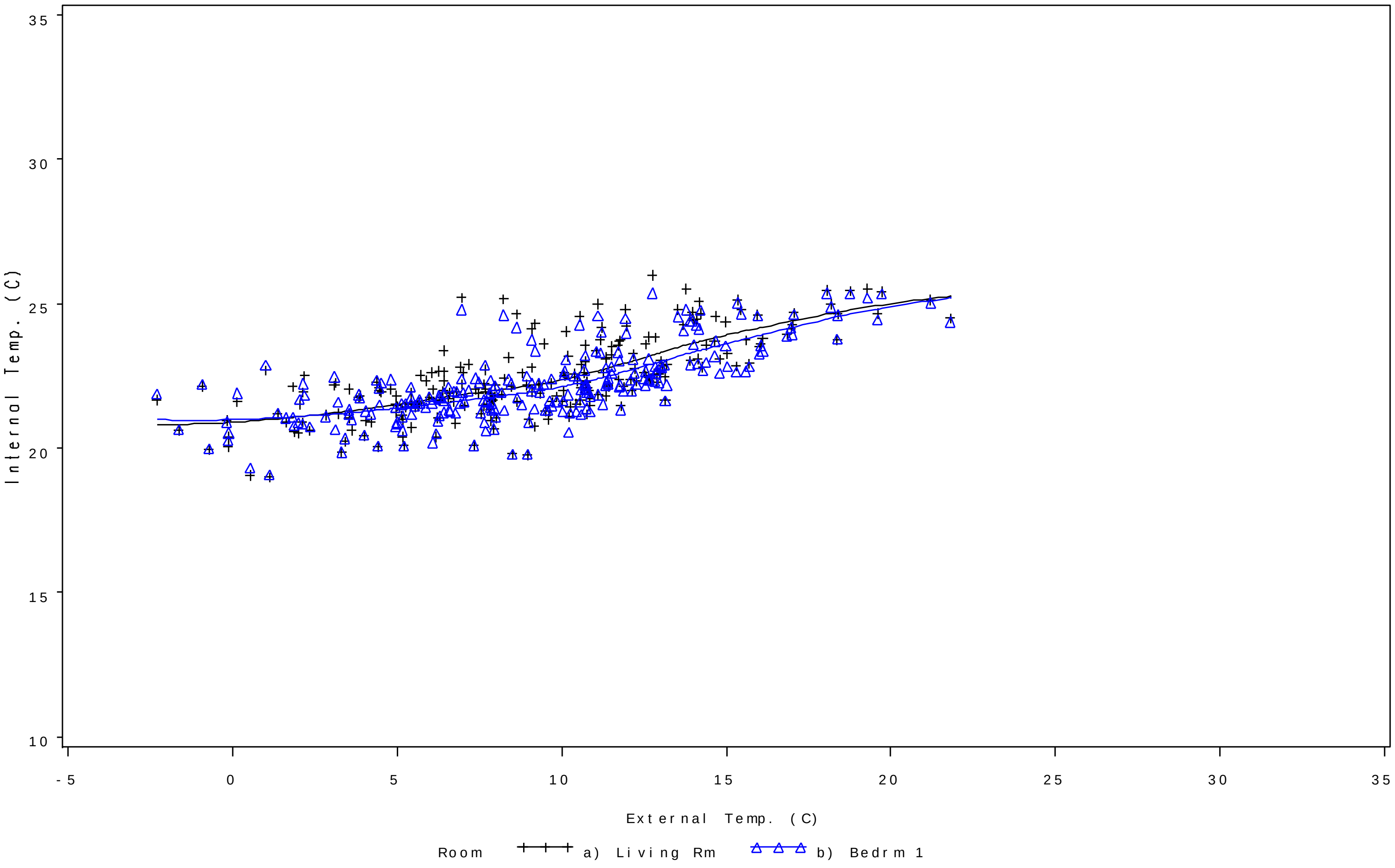
BedZED Phase 2: Dwelling H



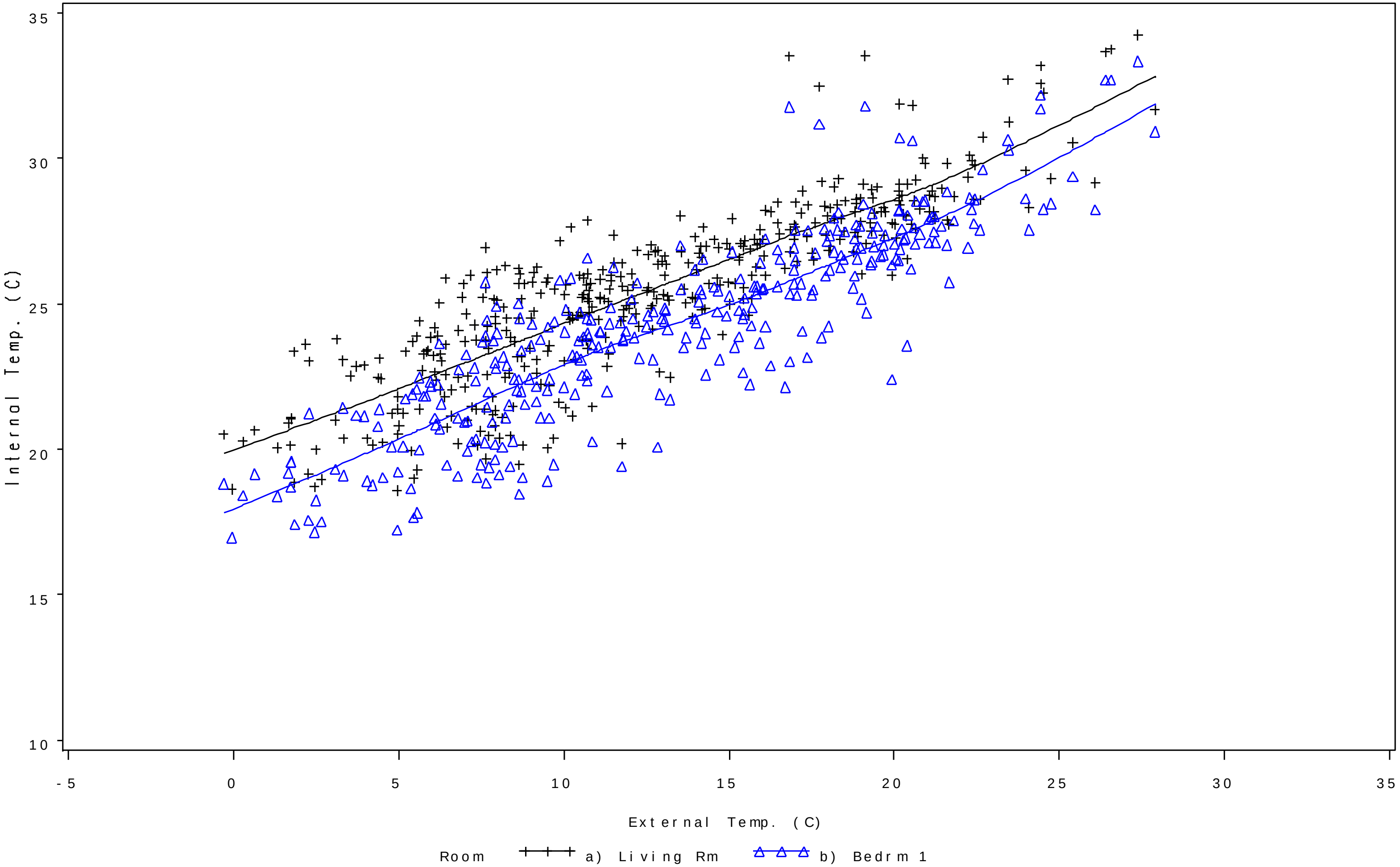
BedZED Phase 2: Dwelling J



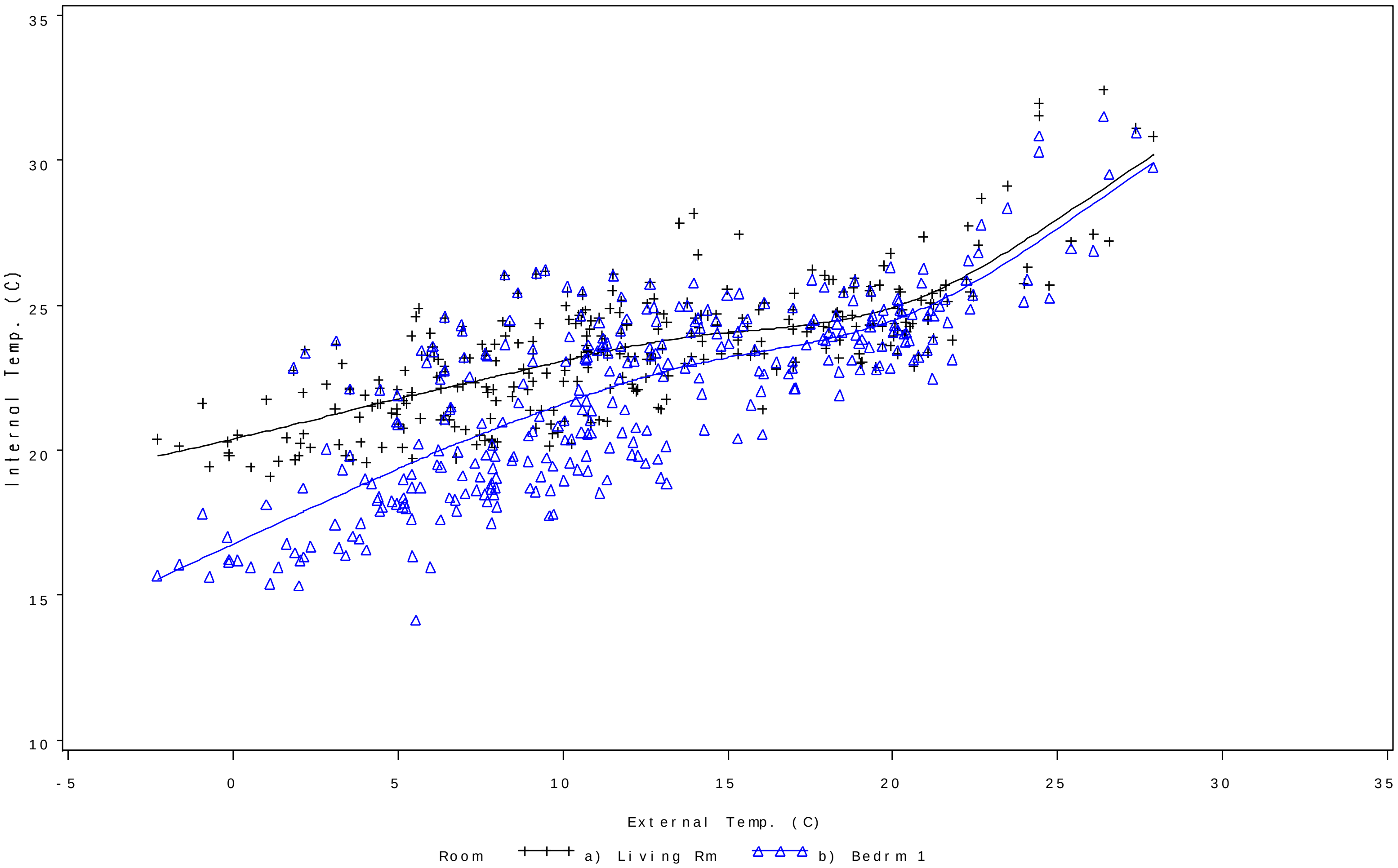
BedZED Phase 2: Dwelling K



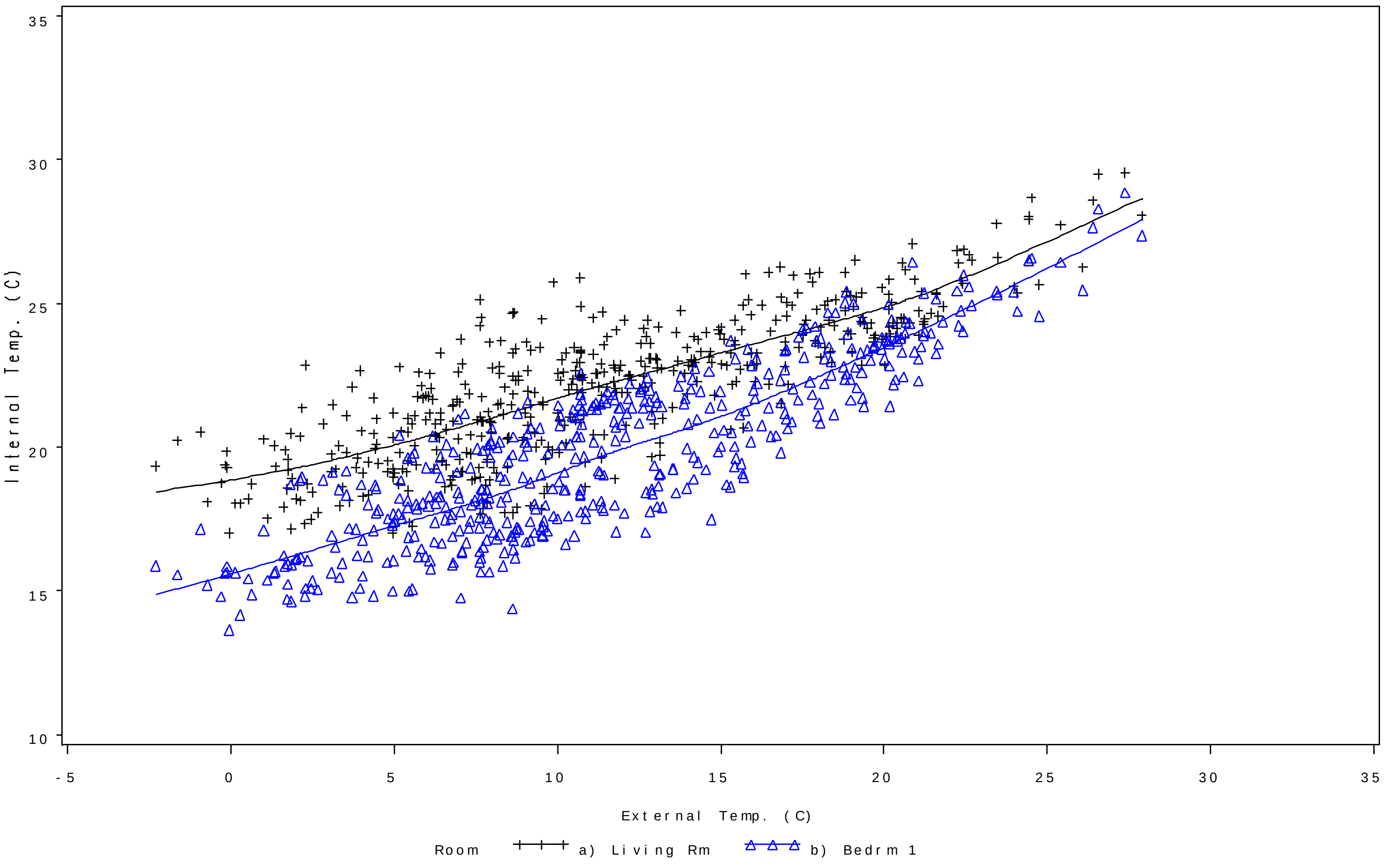
BedZED Phase 2: Dwelling L



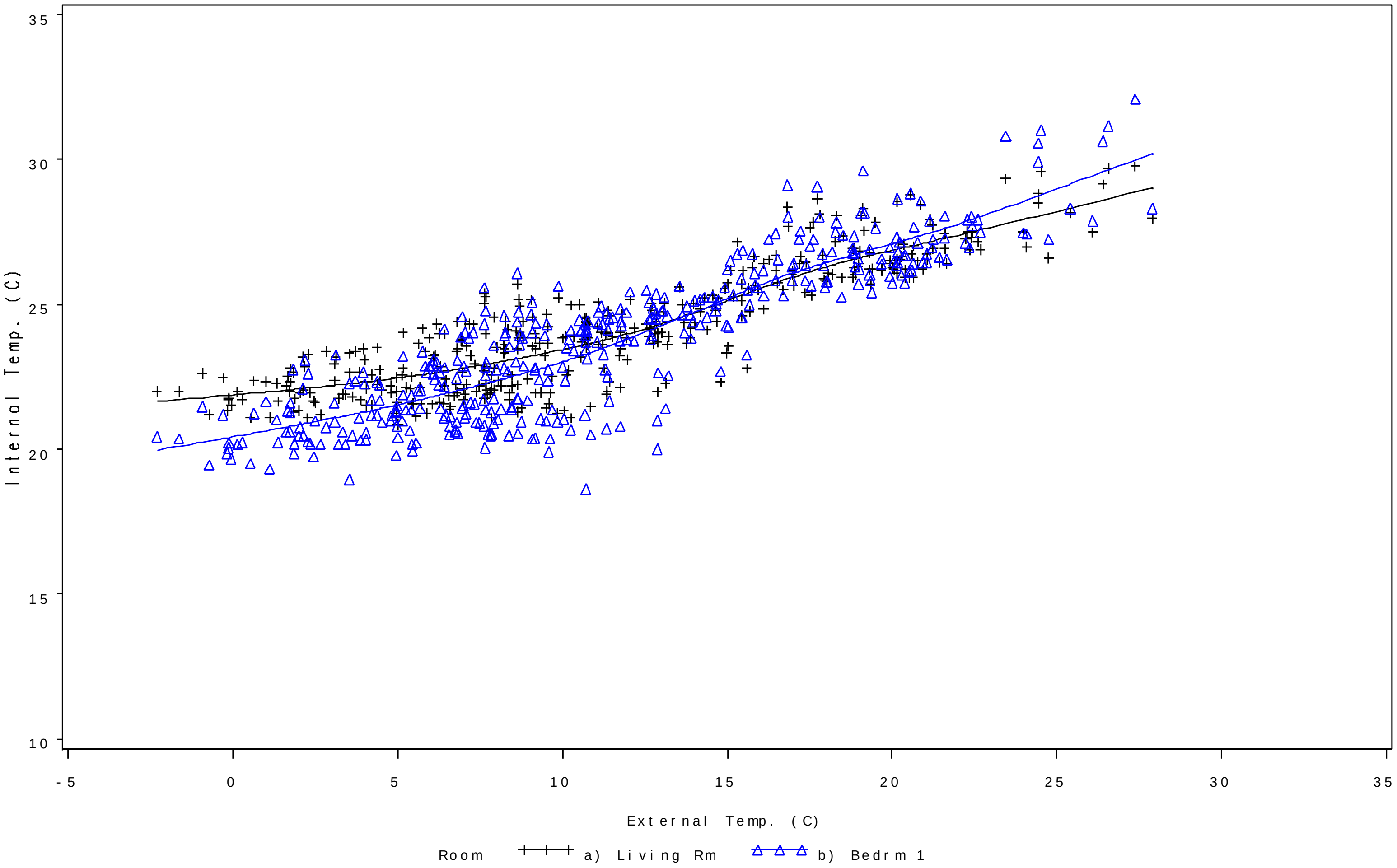
BedZED Phase 2: Dwelling M



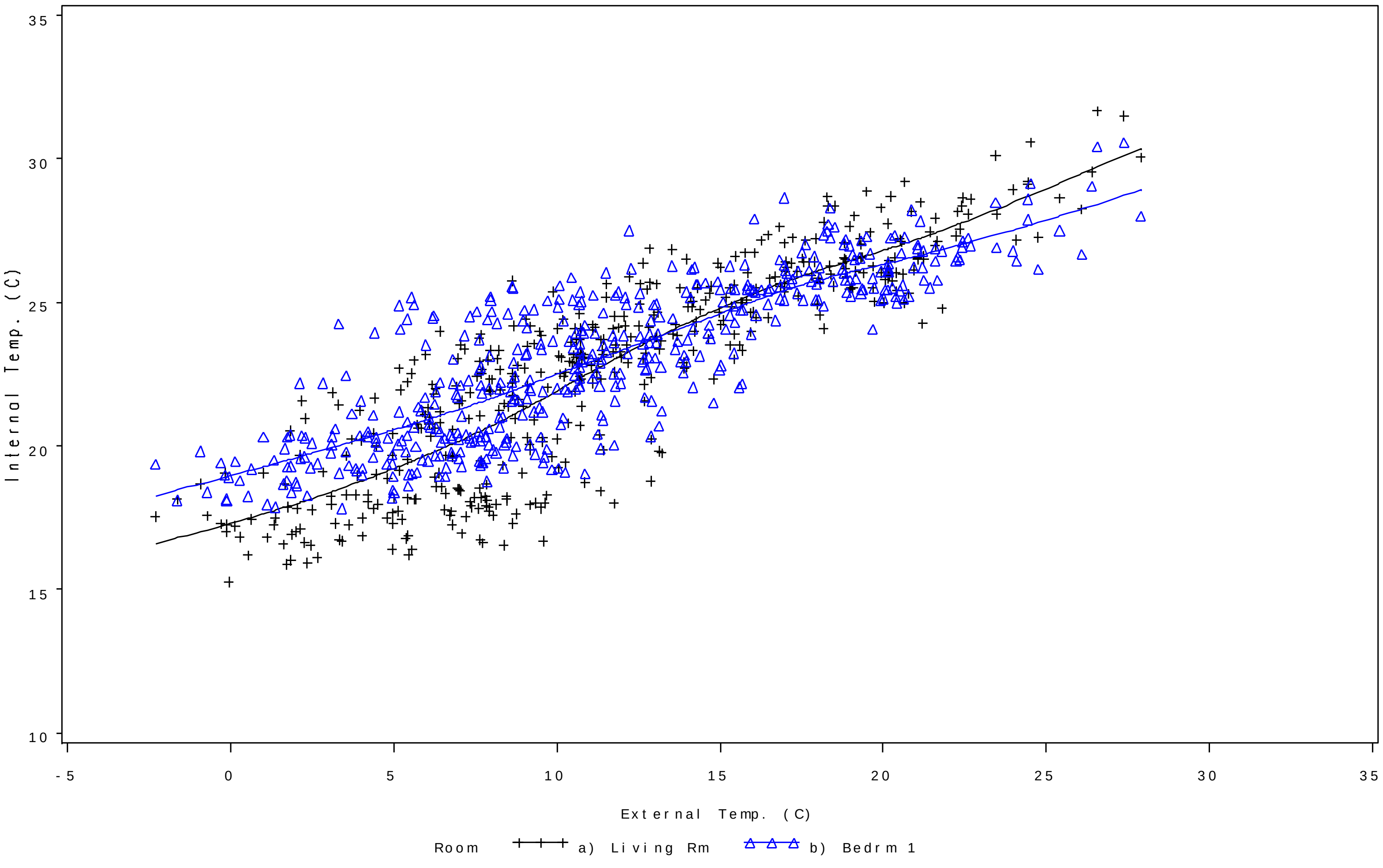
BedZED Phase 2: Dwelling N



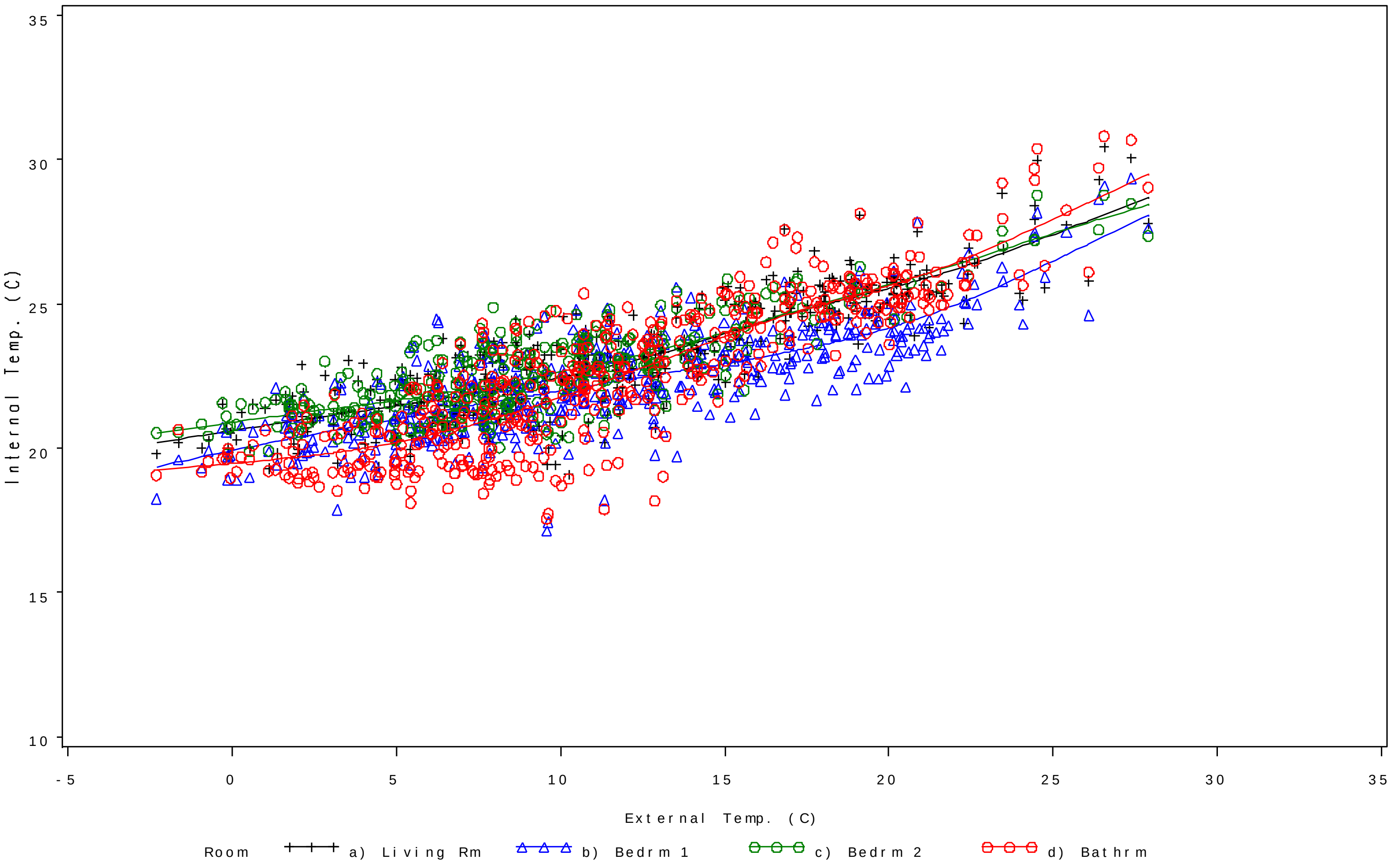
BedZED Phase 2: Dwelling P



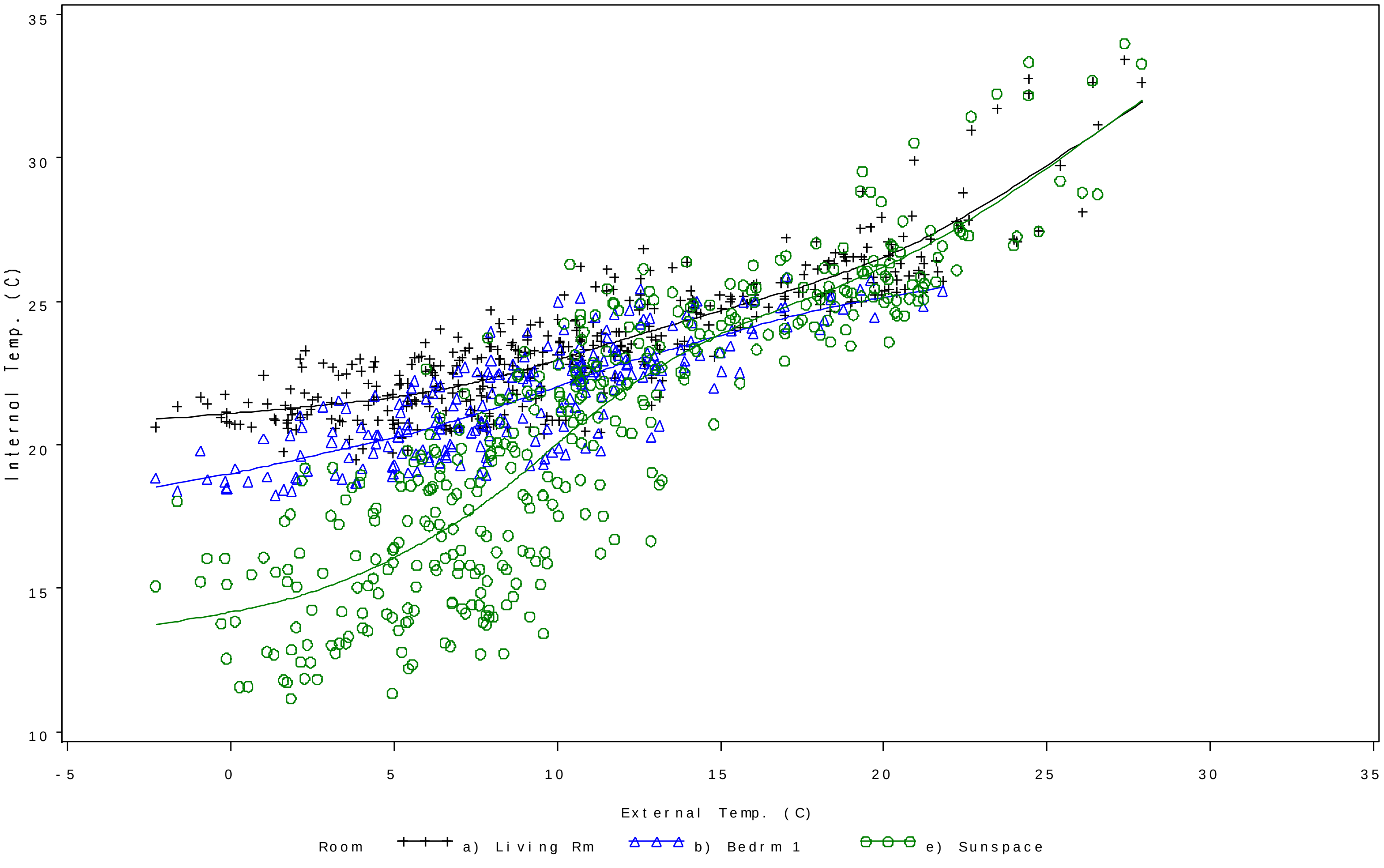
BedZED Phase 2: Dwelling Q



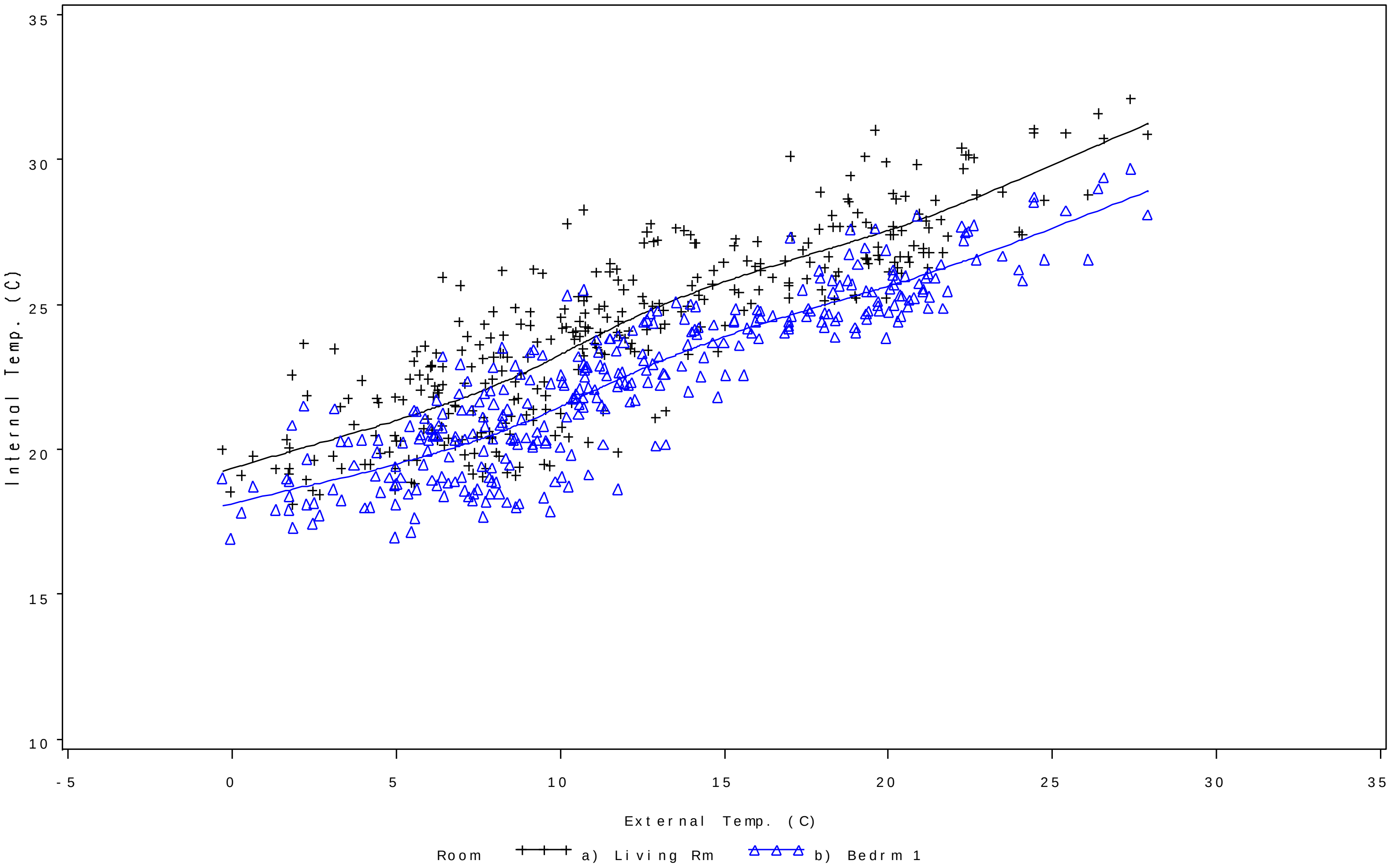
BedZED Phase 2: Dwelling R



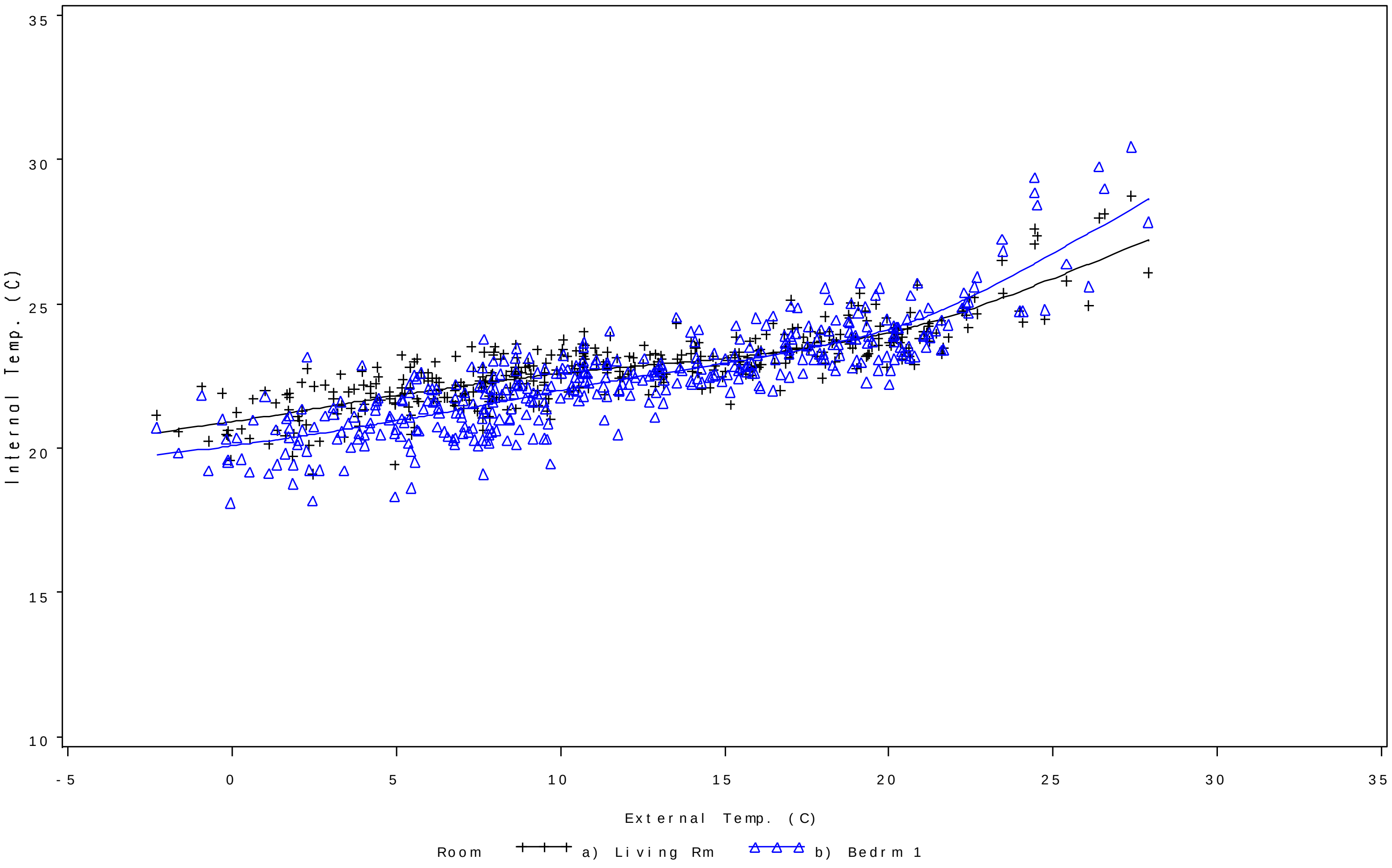
BedZED Phase 2: Dwelling S



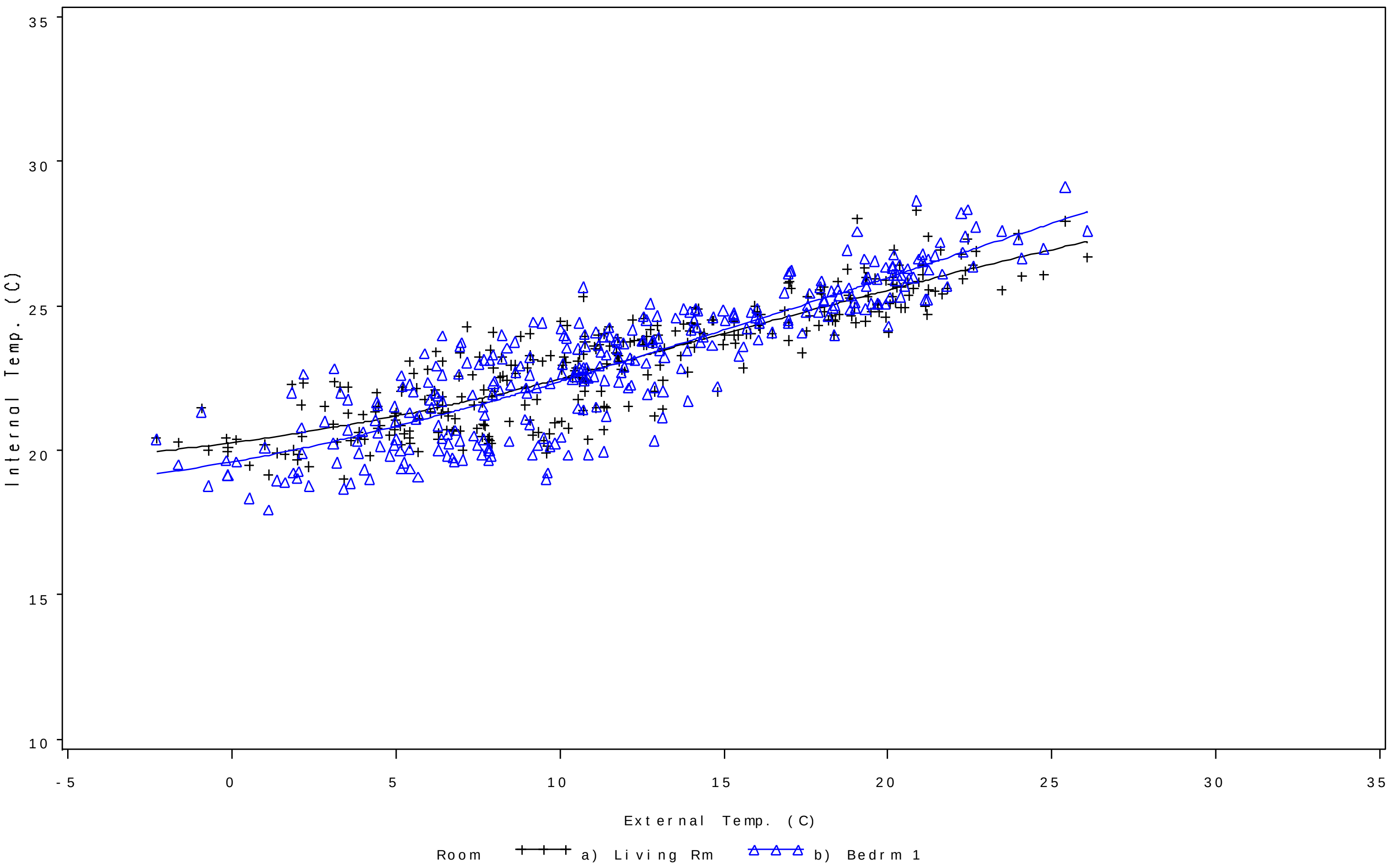
BedZED Phase 2: Dwelling T



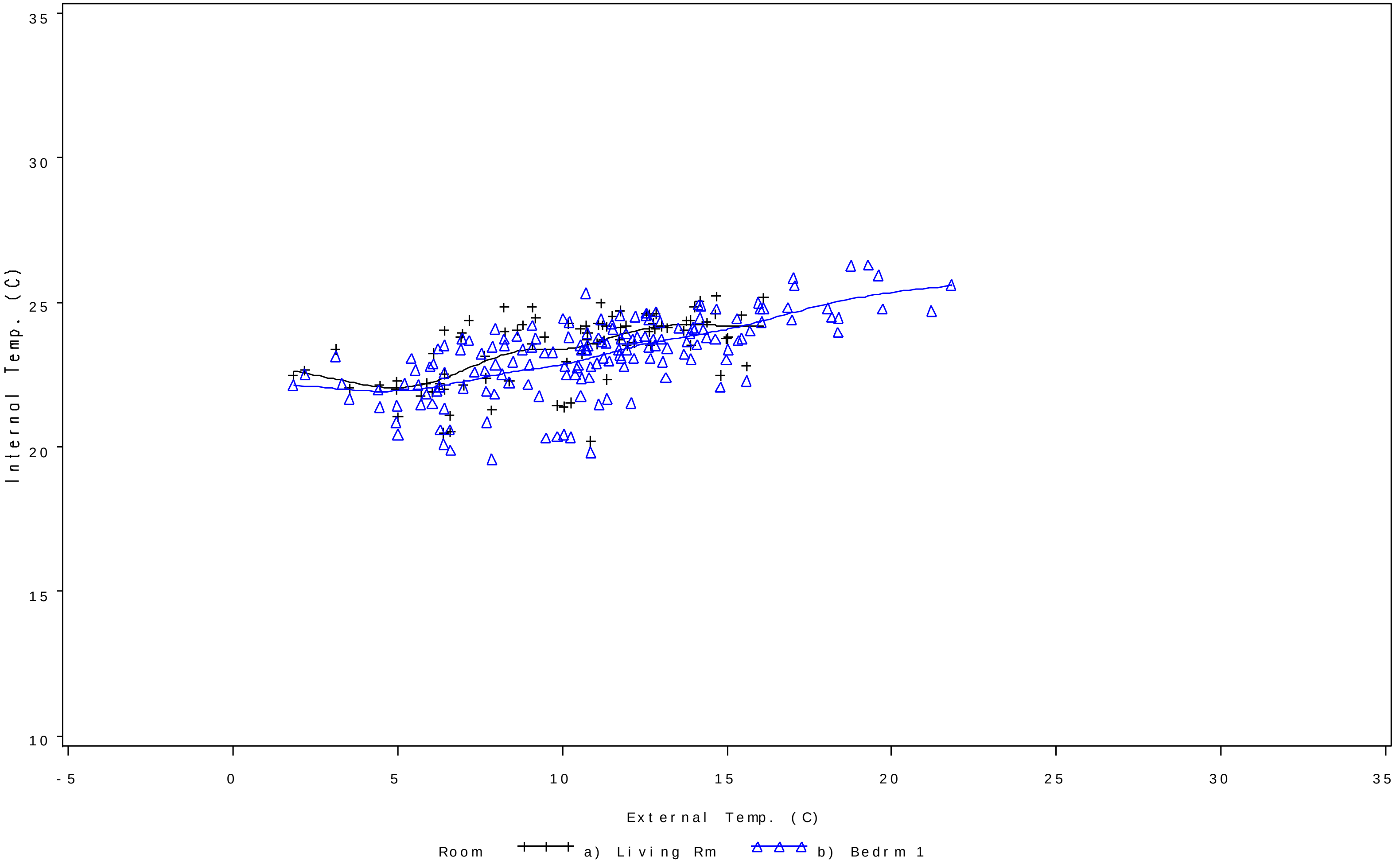
BedZED Phase 2: Dwelling V



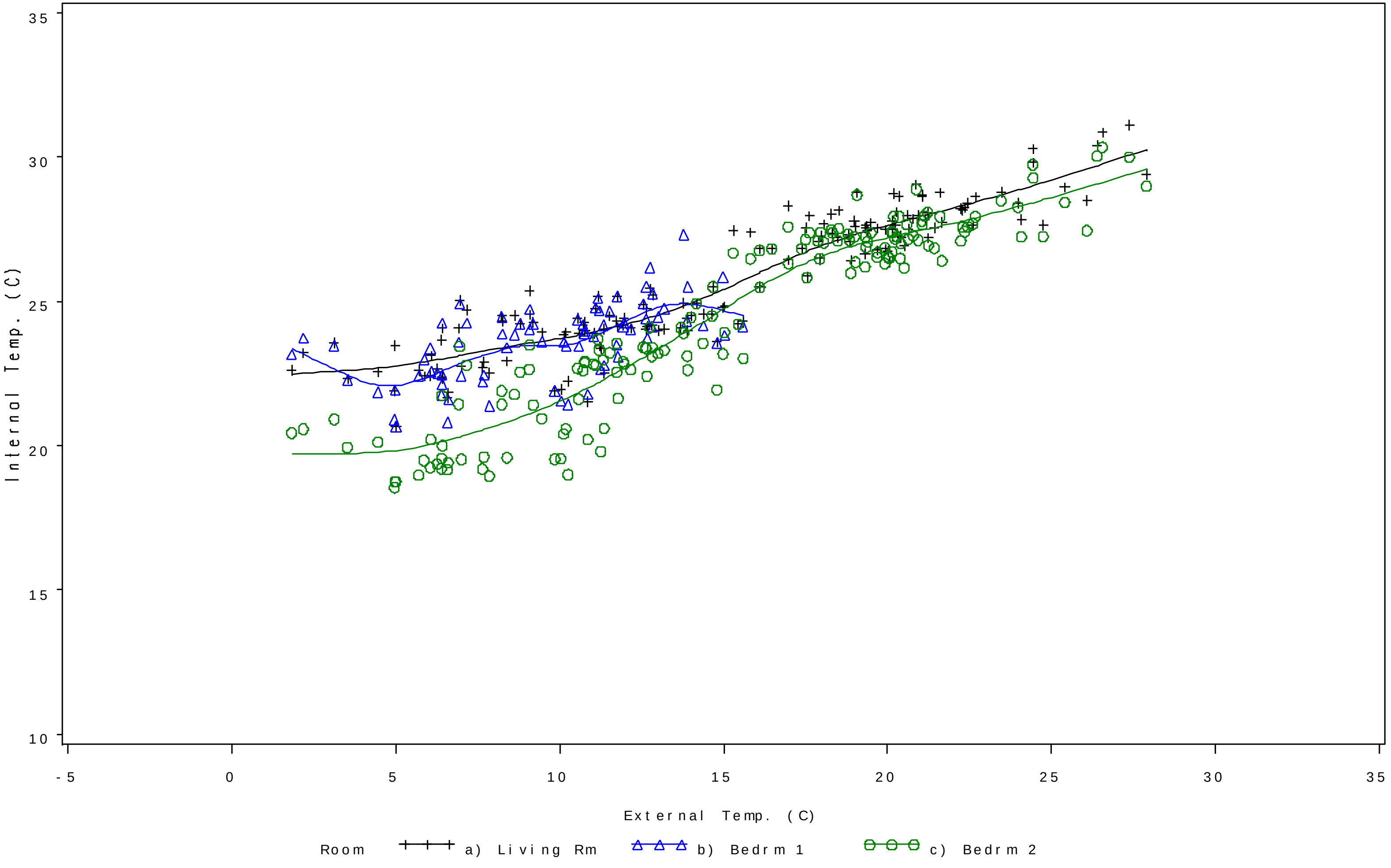
BedZED Phase 2: Dwelling W



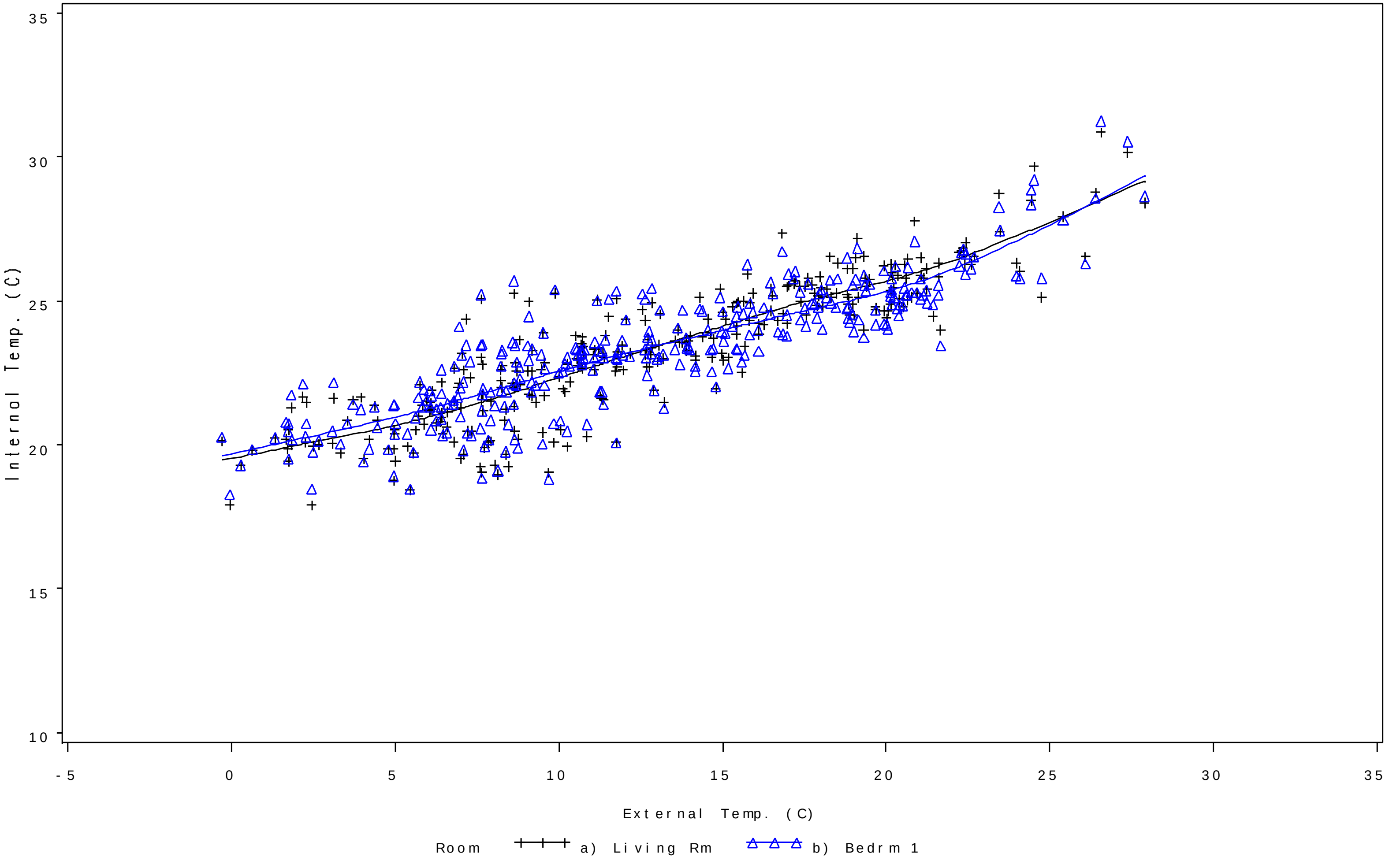
BedZED Phase 2: Dwelling X



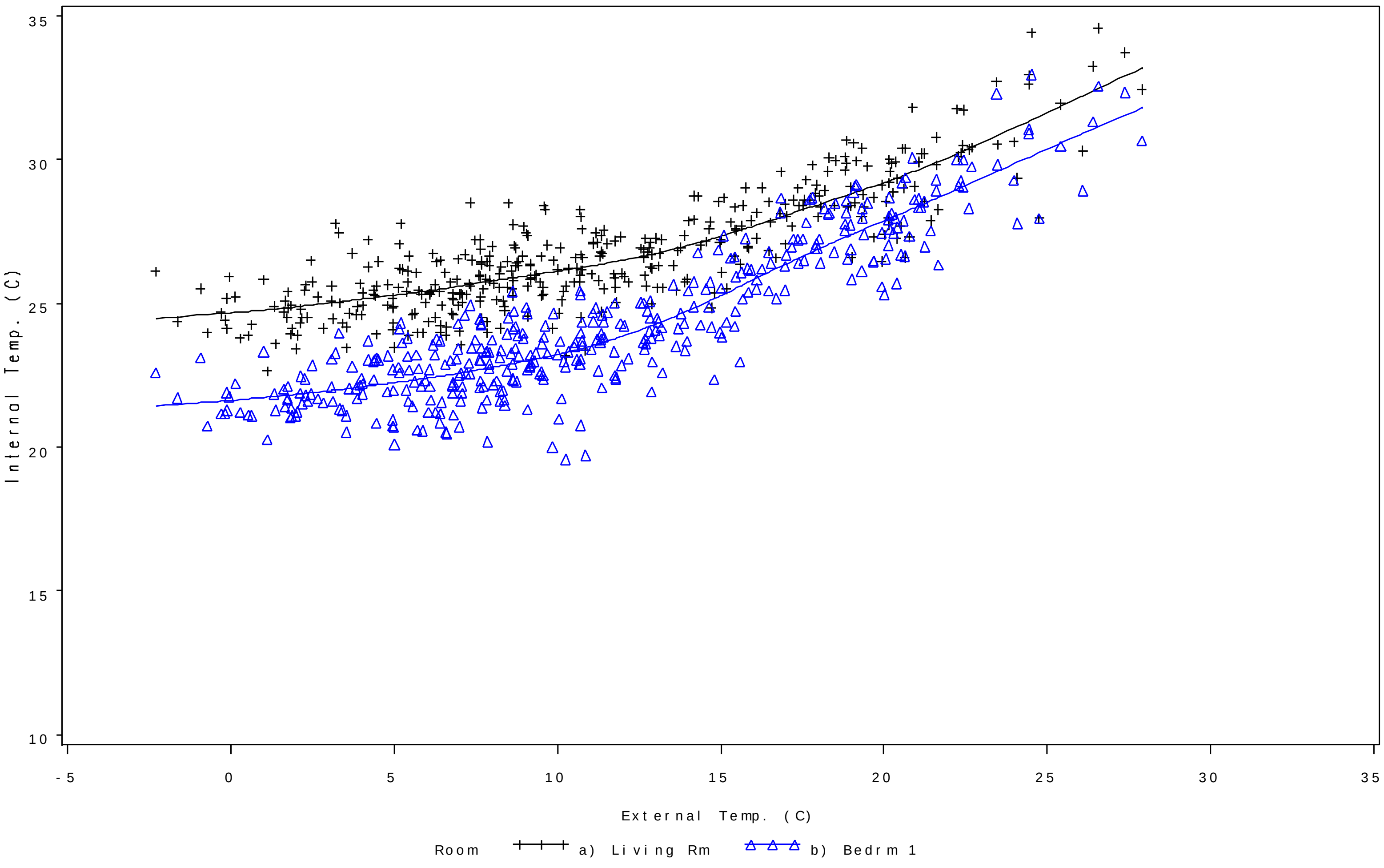
BedZED Phase 2: Dwelling Z

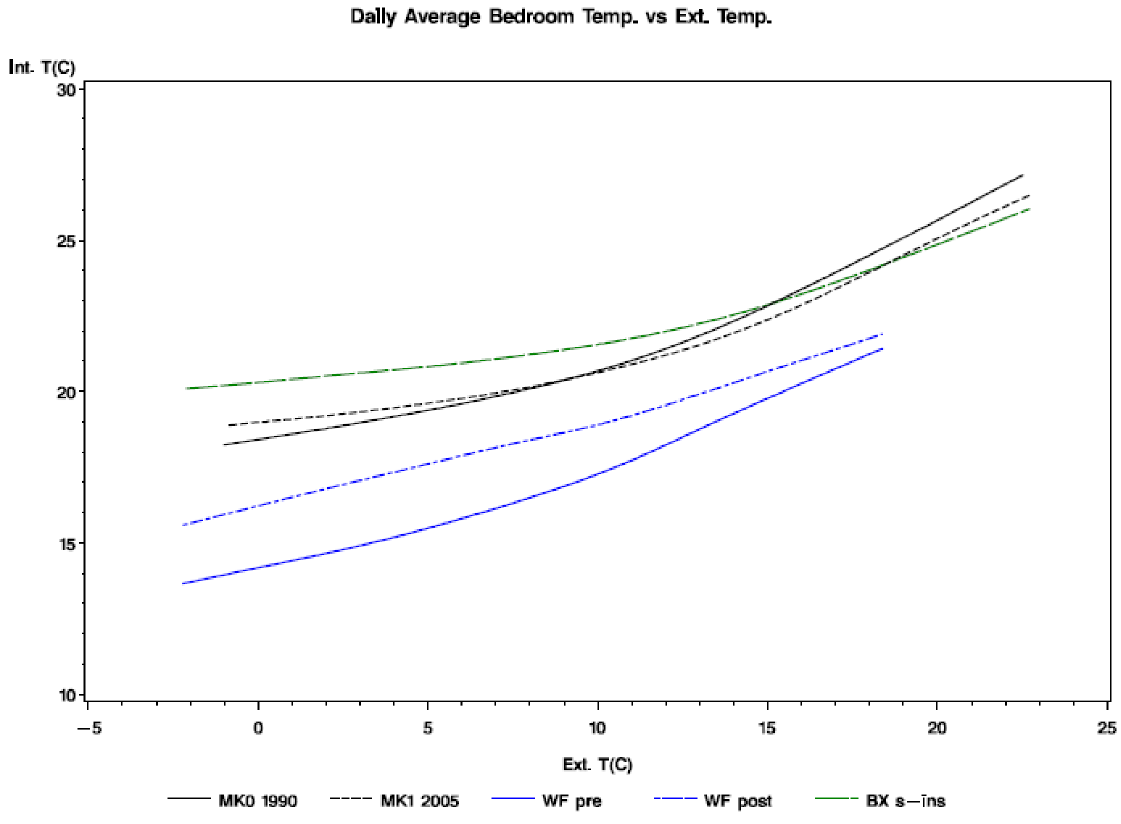


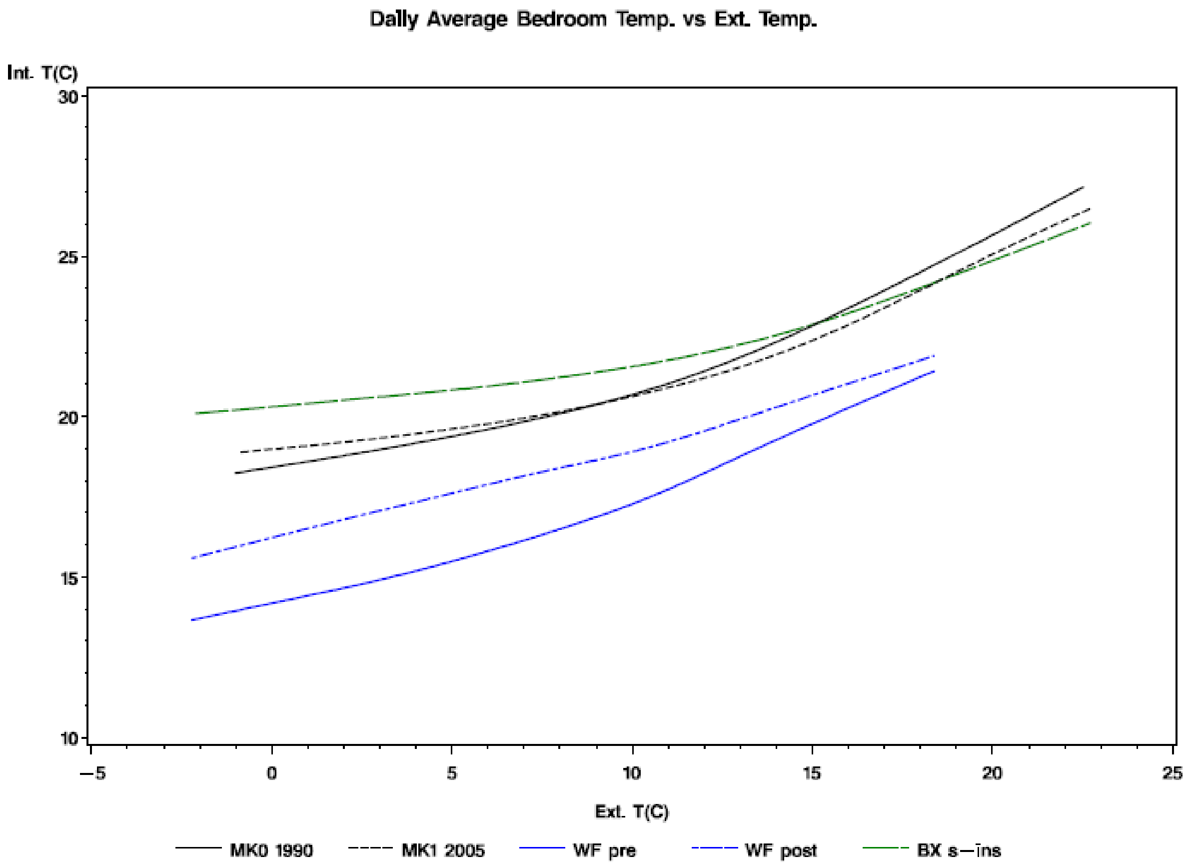
BedZED Phase 2: Dwelling AB



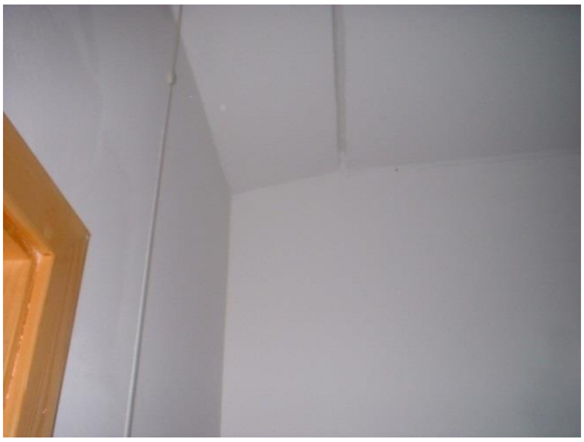
BedZED Phase 2: Dwelling AE

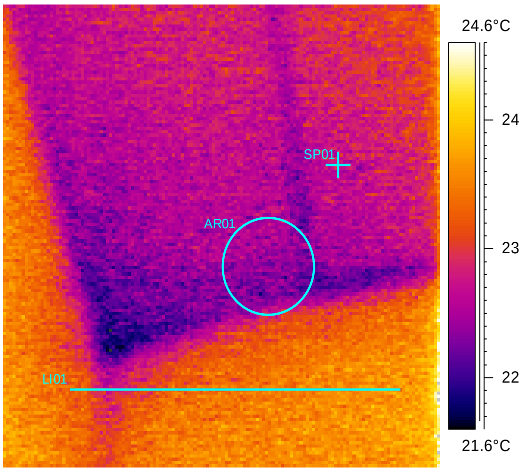


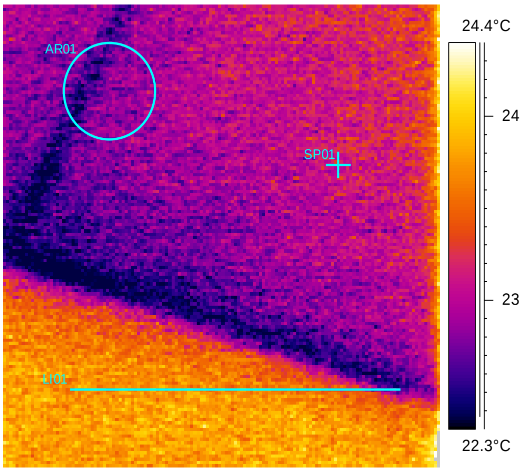

Daily Average Bedroom Temp. vs Ext. Temp.
Int. T(C)
30
25
20
15
10
−5
0
5
10
15
20
25
Ext. T(C)
MK0 1990
MK1 2005
WF pre
WF post
BX s−ins

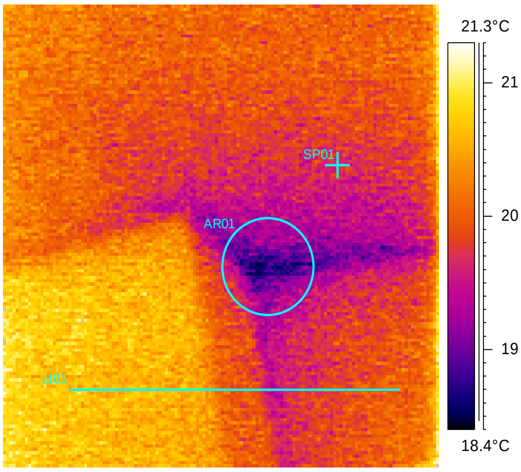

Daily Average Bedroom Temp. vs Ext. Temp.
Int. T(C)
30
25
20
15
10
−5
0
5
10
15
20
25
Ext. T(C)
MK0 1990
MK1 2005
WF pre
WF post
BX s−ins

Appendix 8 : BedZED Air-tightness and Infra-Red Thermography Test Results





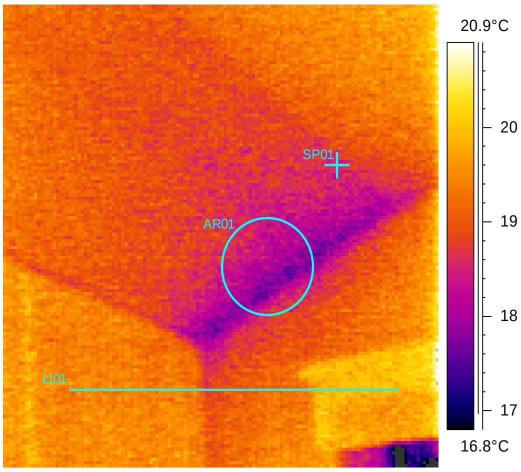




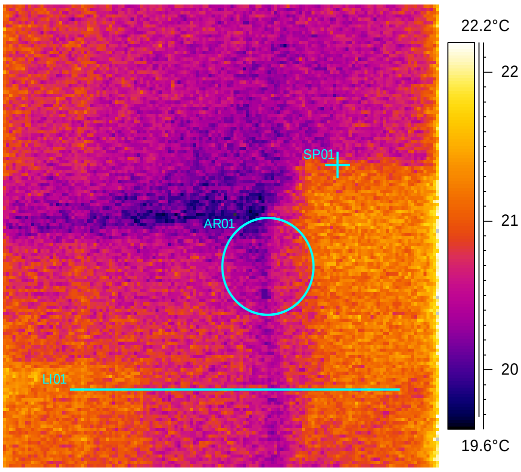
Cold spots at junction of wall and ceiling possibly due to incorrect edge detailing above the bathroom ceiling.

The higher wall surface temperature is due to the party wall facing the next door heated space.

Infra-red Thermography Test : Bathroom Ceiling

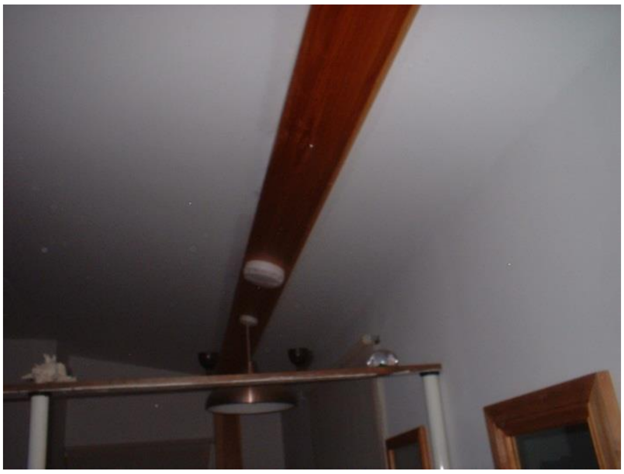


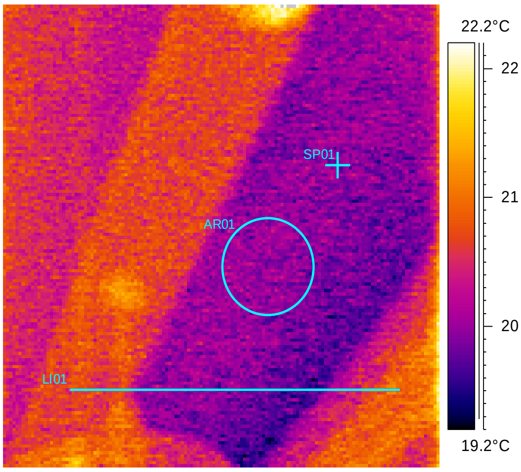
Cold area visible along the end of east wall and the concrete ceiling joint, possibly caused by missing insulation or cold air ingress between the roof flashing and the edge of the roof concrete slab



Cold area visible at junction of roof and walls, possibly caused by incorrect edge detailing at the junction of the walls and roof.

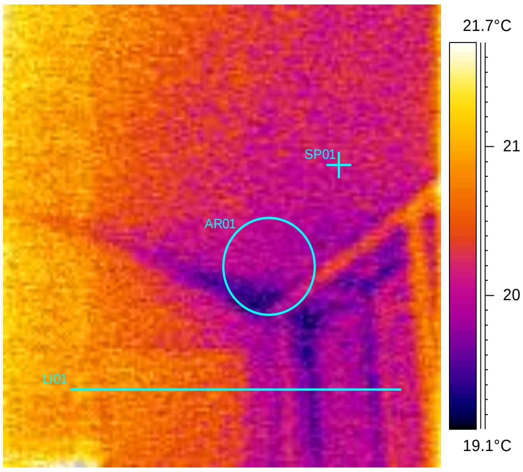
Infra-red Thermography Test : Living Room Ceiling





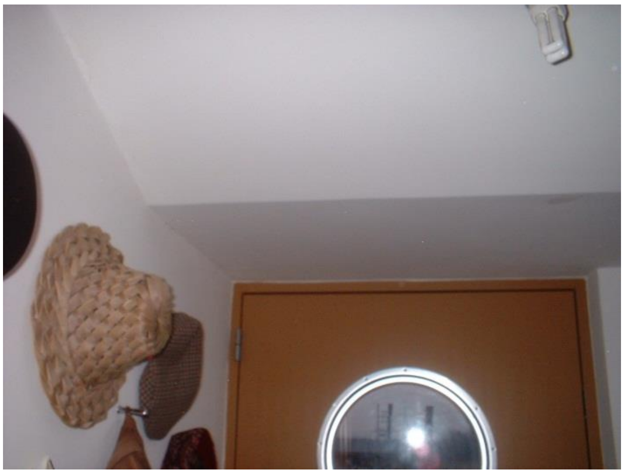
Thermographic test suggests an area of missing roof insulation

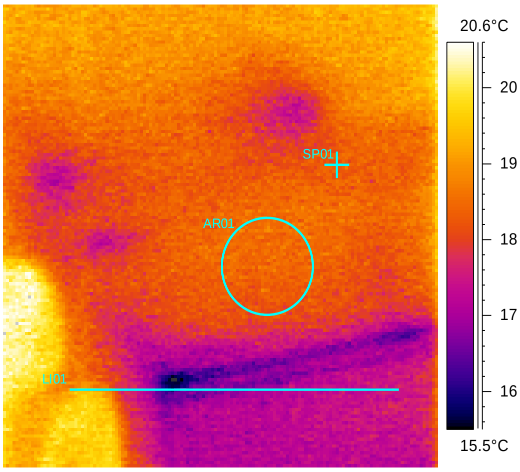
Infra-red Thermography Test : Bedroom Ceiling

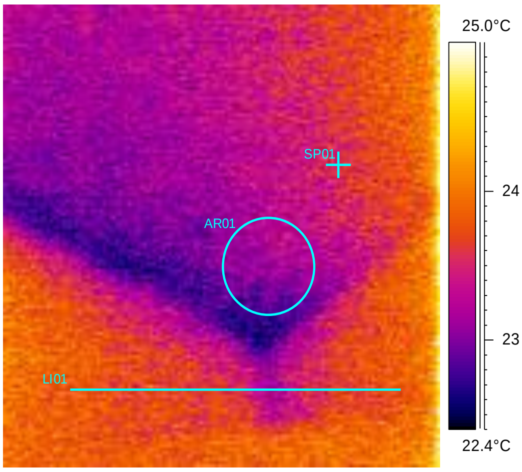


Cold spot at junction of wall and ceiling suggests possible incorrect edge detailing. Decrease in surface temperature of the ceiling towards the colder sunspace.

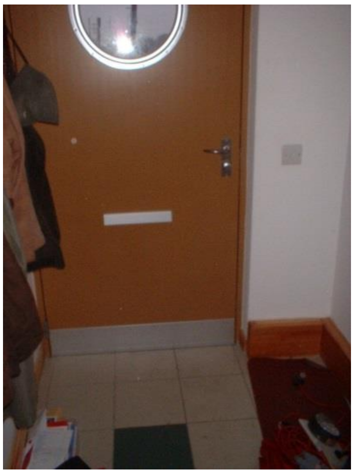
Infra-red Thermography Test : Kitchen ceiling

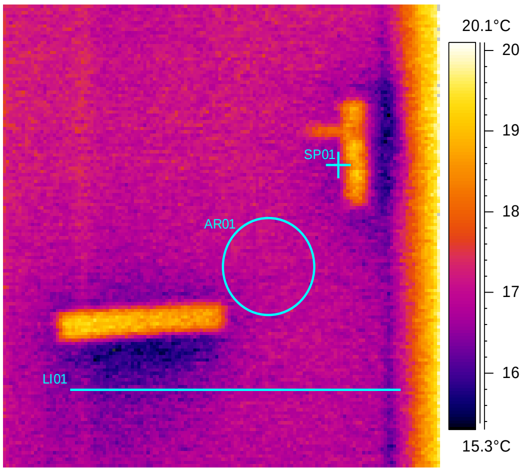






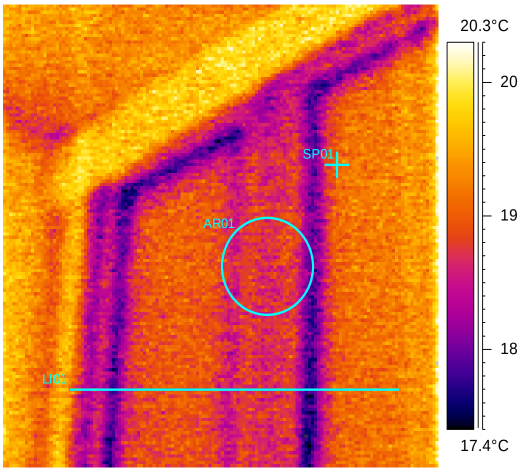
No missing roof insulation. Cold spots along the ceiling possibly caused by cold air ingress between the roof insulation and the concrete slab

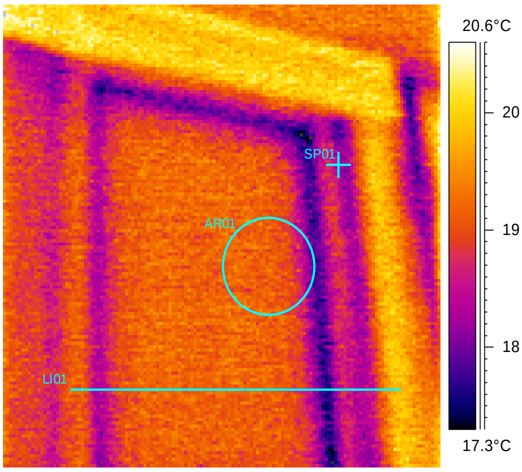




Air ingress through the letter box

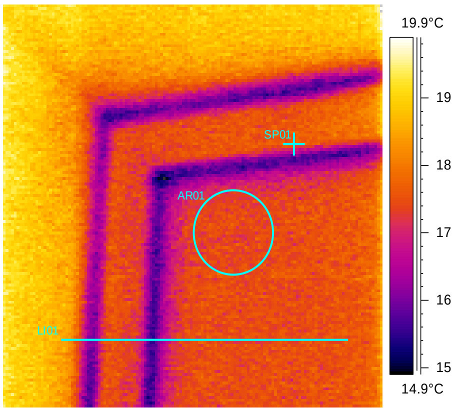
Infra-red Thermography Test : North facing entrance hall

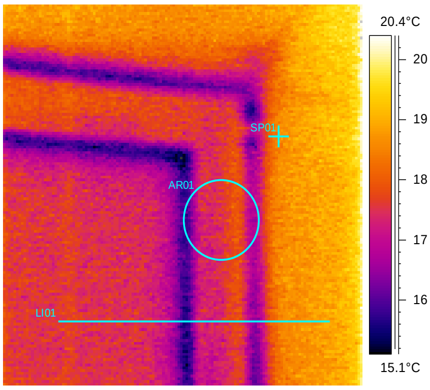


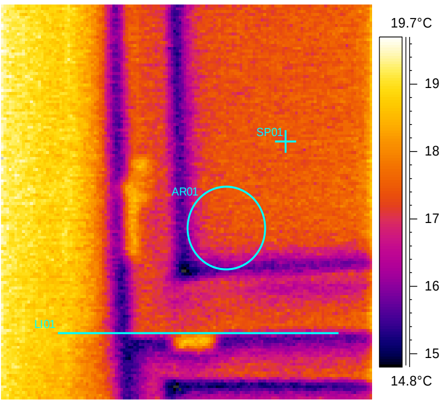


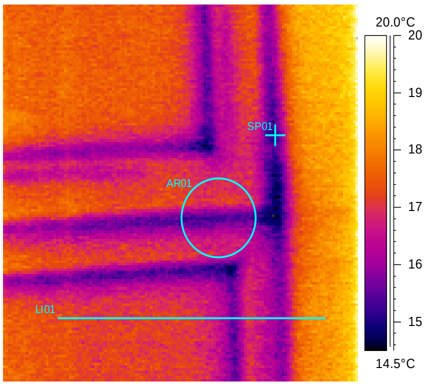
Double-glazed, argon-filled windows with low-emissivity glass.   No air ingress between the frames while the house was depressurised.

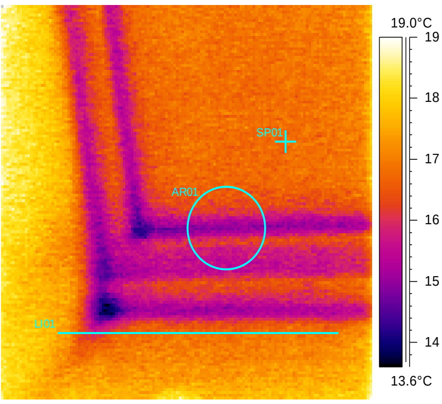
Infra-red Thermography Test : Sunspace through the kitchen windows

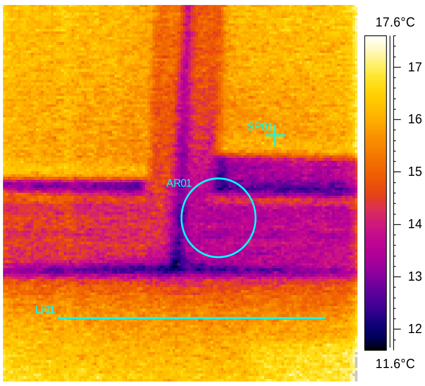






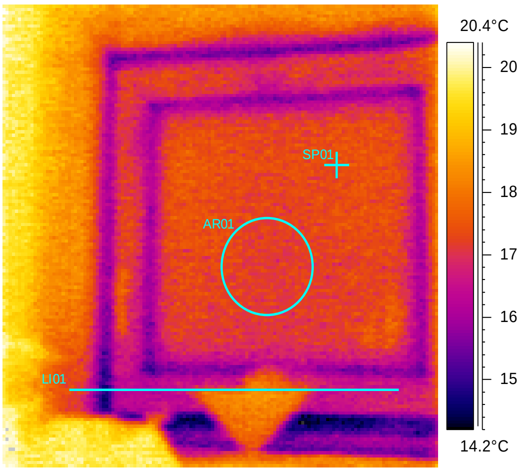






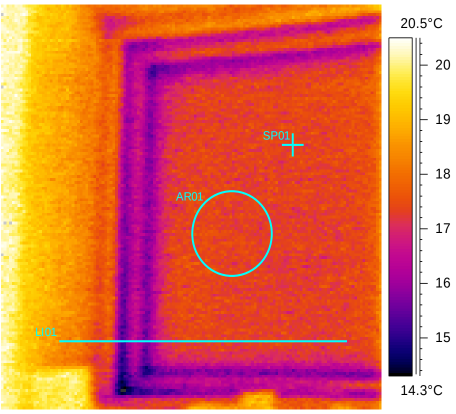
No air ingress between the frames while the house was depressurised

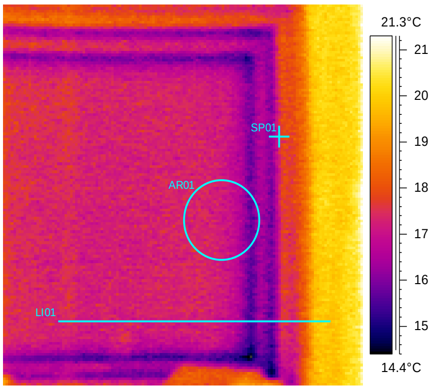
Infra-red Thermography Test: Glazed doors leading into Sunspace



Triple glazed argon-filled window with low emissivity glass. No air ingress between the frames while the house was depressurised.

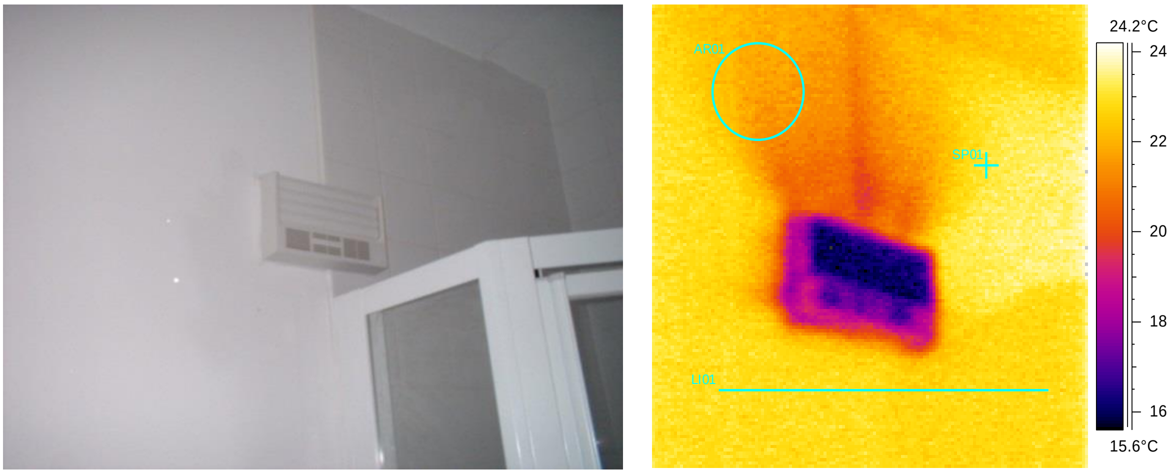
Infra-red Thermography Test : East facing window





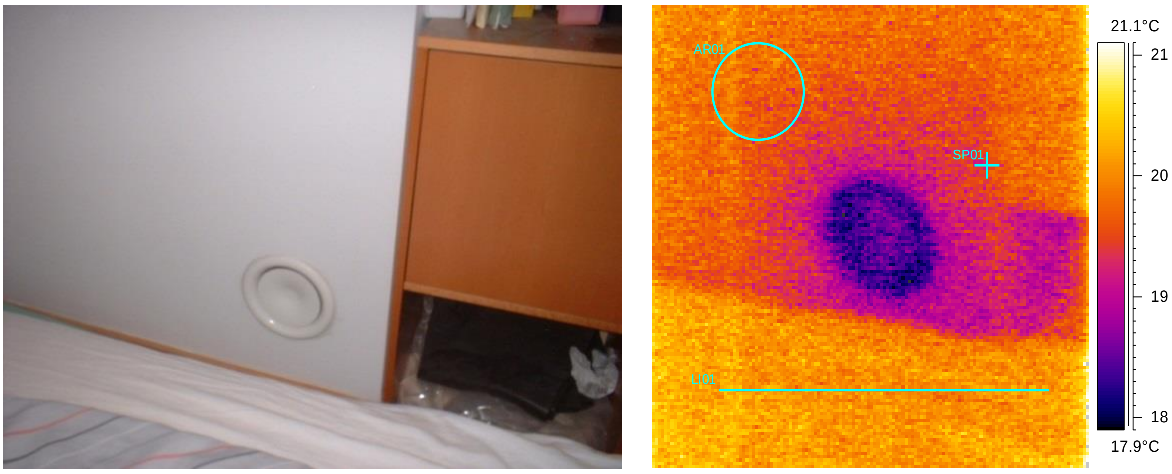
Triple-glazed, argon-filled window with low emissivity glass. No air ingress between the frames while the house was depressurised.

Infra-red Thermography Test : North facing window



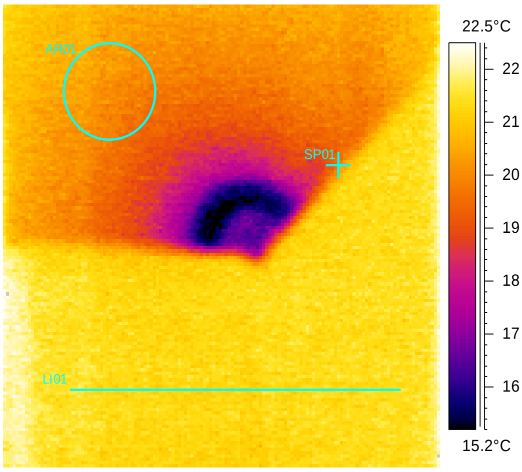
Bathroom wall opening to the passive stack vent. Cold air ingress during depressurisation indicates the bathroom passive vent is open and functioning.

Infra-red Thermography Test : Bathroom passive stack ventilation



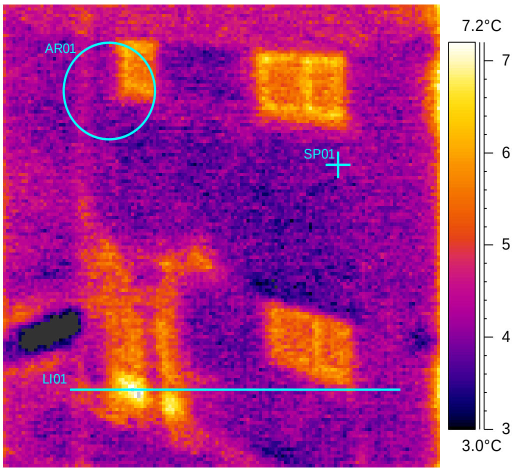
Bedroom wall opening to the passive stack vent. Cold air ingress during depressurisation indicates the passive vent in the bedroom is open and functioning.

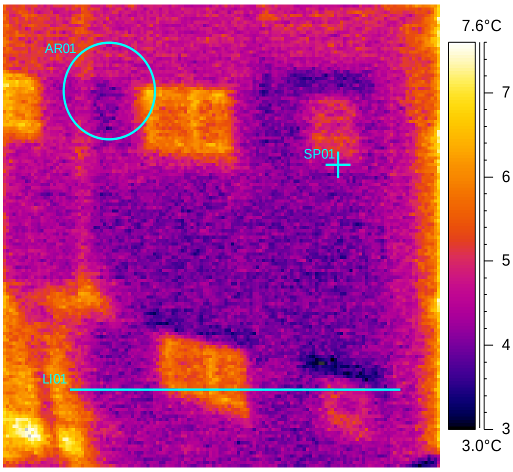
Infra-red Thermography Test : Bedroom passive stack ventilation



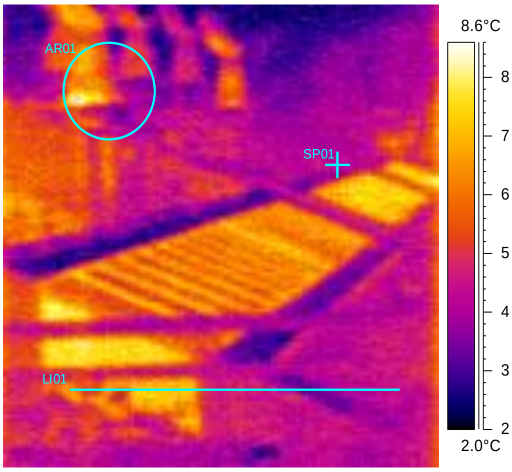
Kitchen passive stack vent opening above the cupboards. Cold air ingress during depressurisation indicates the passive vent in the kitchen is open and functioning.

Infra-red Thermography Test : Kitchen passive stack ventilation



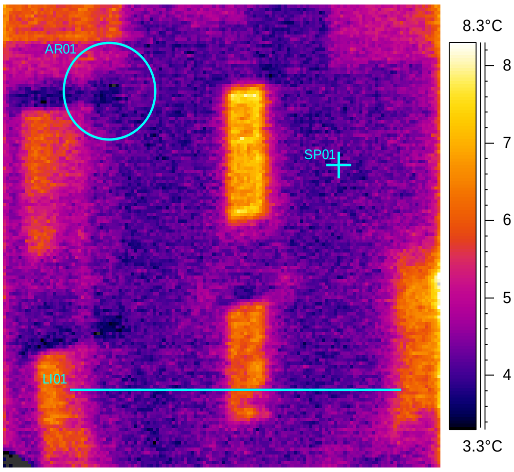


No missing cavity wall insulation. The main source of fabric heat loss is through the windows and the door. Higher heat loss through the main living space windows indicate higher indoor temperature compared to the sunspace.



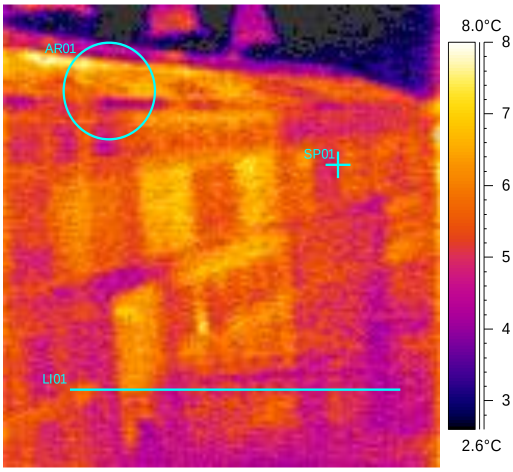
Rooftop windows for daylight are the main source of heat loss through the roof.

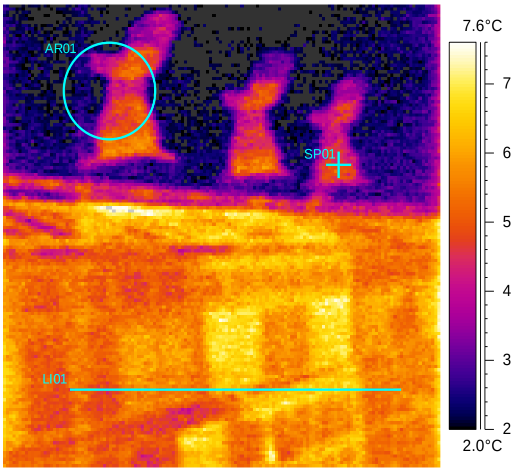
External Infra-red Thermography Test: West Elevation



No missing cavity wall insulation.

External Infra-red Thermography Test : East Elevation





Greater heat loss in the middle flat indicates extra source of space heating or windows open to the sunspace.

External Infra-red Thermography Test : South Elevation