Housing and carbon reduction:

Can mainstream ‘eco-housing’ deliver on its low carbon promises?

Jennifer Monahan

Thesis submitted for the degree of Doctor of Philosophy to the School of Environmental Sciences, University of East Anglia.

February 2013

Abstract

Energy policy is being driven by two predominant themes: climate change; and energy security. In response, the built environment needs to develop sustainable, decarbonised, low energy systems and approaches that are socially acceptable and economically beneficial. The UK mainstream house construction industry is being driven, through policy and regulation, towards achieving this end without evidence of how these new systems of provision are used by passively adopting households. This thesis considers the outcomes of this policy drive and questions the ability of the approaches taken to meet policy targets in the real world.

A case study, comprising 14 newly constructed low energy affordable homes in Norfolk, is used to evaluate the real world energy and carbon outcomes of the house building industries response to policy. The interdisciplinary study included: the embodied energy and carbon of construction; energy and consequential carbon from occupation; the influence of household attitudes and behaviour; and how passively adopting households adopt and adapt to new technologies. Four different energy technologies and design approaches were compared: conventional high efficiency gas boiler; active solar (thermal and photovoltaic); passive solar design and mechanical ventilation with heat recovery; and ground sourced heat pumps.

The study found there were significant savings compared with conventional housing. This was attributed to the improvements in built fabric and the technical aspects of the homes. Yet, there was a significant performance gap between design and actual. The occupants were found to be a critical factor in determining the energy and carbon emissions.

The findings pose significant questions on the capacity of policy to deliver the projected reductions in emissions of CO_2. Ultimately, it is how these new homes and technologies are used that will become increasingly important in the successful implementation of low carbon aspirations.

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Thesis Acronyms and Abbreviations

ADL1a 2010	Approved Document Part L1a
ASHP	Air Source Heat Pump
BedZED	Beddington Zero Emissions Development
BRE	Building Research Establishment
BREDEM	The Building Research Establishment Energy Model
BIS	Department for Business Innovation and Skills
BSRIA	Building Services Research and Information Association
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
CoP	Coefficient of Performance
CSH	Code for Sustainable Homes
CV	Calorific Value
DCLG	Department of Communities and Local Governemnt
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DER	Designed Energy Performance
EST	Energy Savings Trust
GHG	Greenhouse Gas
GPRS	Global Packet Radio Service
GSHP	Ground Source Heat Pump
GSM	Global System for Mobile Communications
ICE	Inventory of Carbon and Energy Database
ISO	International Standards Authority
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LED	Light Emitting Diode
LZC	Low and Zero Carbon
MEV	Mechanical Extract Ventilation

MMC	Modern Methods of Construction
MVHR	Mechanical Ventilation with Heat Recovery
NEP	New Ecological Paradigm
NHER	National Home Energy Rating
NPI	Normalised Performance indicator
OECD	Organisation for Economic Co-operation and Development
PAS	Publically Available Specification
POE	Post Occupancy Evaluation
PSD	Passive Solar Design
PSV	Passive Stack Ventilation
PV	Photovoltaics
RCEP	Royal Commision on Environmental Pollution
SAP	Standard Assessment Procedure
SHW	Solar Hot Water
TER	Target energy performance
UKLTCP	UK Low Carbon Transition Plan
VCF	Volume Correction Factor

Acknowledgements

The project from which this research arose was funded by Broadland District Council and the Carbon Connections Low Carbon Innovation Fund from January 2008 to March 2010 and was carried out in the Department of Environmental Sciences at the University of East Anglia, Norwich, UK. After a year's break I received funding from The School of Environmental Science which enabled me to complete this thesis, and for which I will be eternally grateful.

My most sincere thanks go to my supervisors Dr Jane Powell and Dr Gill Seyfang for their advice and encouragement on this journey. I am extremely grateful to Dr Powell without whose support and time this research would not have been possible. I would also like to thank the families at Lingwood, the team at Flagship Housing and Jo Franklin of John Youngs Homes Ltd. Without their participation and help this research would not have been possible.

I would like to say a special thank you to my family and friends for their understanding, support, and encouragement.

Most of all I would like to dedicate this to my Mum. She would have been very proud.

1. Introduction

1.1. Background to energy use and climate change

1.1.1. Climate change

"There is an overwhelming body of scientific evidence that the earth's climate is rapidly changing, predominantly as a result of increases in greenhouse gases caused by human activities" (Stern 2006).

Human activity, principally the emission of CO_2 from the combustion of fossil fuels, is augmenting the atmospheric concentration of greenhouse gases at an unprecedented rate. The net effect since the inception of the industrial revolution in 1750 has been one of warming (Solomon et al. 2007). The impacts on human society will be widespread and relate to destructive weather events, disruption of food production and human health (*ibid* 2007). A 2°C rise has become the accepted threshold beyond which climate change effects will be 'dangerous' (Copenhagen Accord, 2009). Society's principle response needs to be one of mitigation with urgent and radical moves towards decarbonisation (Anderson et al. 2008).

The global political response towards achieving long term reductions in emissions began with the United Nations Framework Convention on Climate Change in 1994 and the first legally binding protocol, The Kyoto Protocol, adopted in 1997 entering into force in 2005. Under the Kyoto Protocol the UK was committed to reducing its emissions by 12.5% by 2012.

The UK government acknowledged that the Kyoto Protocol was a first tentative step and more stringent cuts were required. The Energy White Papers published in 2003 (DTI 2003) and 2007 (DTI 2007) set out a policy to achieve a 60% cut in emissions by 2050, with a self-imposed reduction target of 20% to be achieved by 2010, exceeding that of its Kyoto commitment. These policy documents explicitly linked energy policy to environmental policy and made clear the UK governments' view that global leadership in decarbonisation would bring significant economic benefits in the long term. The Climate Change Act (Crown 2008), heralded as the "world's first long-term legally binding framework to tackle climate change", set a higher legally binding target of 80% reduction in carbon emissions by 2050 with an interim emission reduction of at least 34% by 2020 against a 1990 baseline (DECC 2008). The Act also provisioned for:

- A carbon budgeting system capping emissions over five-year periods, with three budgets set at a time. The first three Carbon budgets running from 2008-12, 2013-17 and 2018-22. Requiring reductions in emissions on 1990 levels of 22%, 28% and 34% respectively.

- A statutory requirement for the Government to report to Parliament on its policies and proposals to meet the budgets.

The 2009 UK Low Carbon Transition Plan (UKLCTP) (DECC 2009) set out the first three budgets, covering the period 2008 – 2022. Under the umbrella of a national decarbonisation strategy, the UKLCTP linked together the energy policy trilema with economic goals by "*cutting emissions, maintaining secure energy supplies, maximising economic opportunities and protecting the most vulnerable*" (DECC 2009 p5).

67% of the estimated emissions reductions were to be from the decarbonisation of power supply and from homes. The cross sector strategies focused on energy efficiency and the adoption of clean energy technologies. The underlying principle was one of maintaining a continuation of patterns of growth and trends in consumption and service as usual: Doing more of the same with less rather than doing different.

1.1.2. Energy and carbon in housing

1.1.2.1. Energy and carbon emissions from housing

Homes are responsible for a third of the UK's 491.7 Mt CO_2emissions[1] (Figure 1-1). As a dominant contributor the residential sector is a clear target for large cuts if the UK is to meet an 80% reduction in carbon emissions by 2050.

[1] In discussing greenhouse gas emissions, and carbon in particular, three different but related units of measure are used, carbon dioxide equivalent (CO_{2eq}), carbon dioxide (CO_2) and carbon (C). CO_{2eq} is a metric measure that enables the comparison of different green house gases based on the amount of warming (termed global warming potential, GWP) that a given amount of a specific greenhouse gas may cause using the functionally equivalent reference amount of carbon dioxide (CO_2). For example, CO_2, as the reference gas, has a GWP of 1 and methane has a GWP of 25. So, reducing 1 tonne of methane is the equivalent to 25tCO_2 or, to follow scientific convention, 25tCO_{2eq}. To further confuse the issue CO_2 is also referred to in terms of carbon (C), which is the fraction of carbon in CO_2 and is calculated by dividing CO_2 by 12/44. This thesis is concerned exclusively with carbon, CO_{2eq}, CO_2 and C are used where appropriate. Emissions are given in scale appropriate metric units, for the purposes of this thesis these are million tonnes (Mt), Tonnes (t) or kilograms (kg).

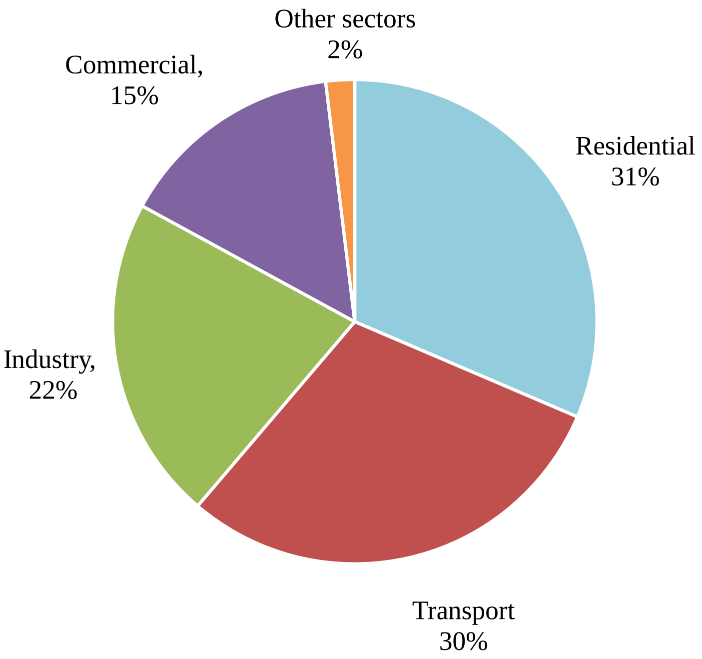

Figure 1-1 Showing CO_2 emissions in 2010 attributed by proportion to end use sector (including both direct emissions and indirect associated with the generation of power) (EEA 2011)

The energy profile of UK homes is dominated by space heating (62%) and hot water provision (18%), jointly responsible for 80% of all energy demand by end use (Figure 1-2). Of this 83% is derived from gas. Not all homes are connected to mains gas supply consequently oil and electricity are also significant. Appliances, lighting and cooking account for the remainder (DECC 2011a).

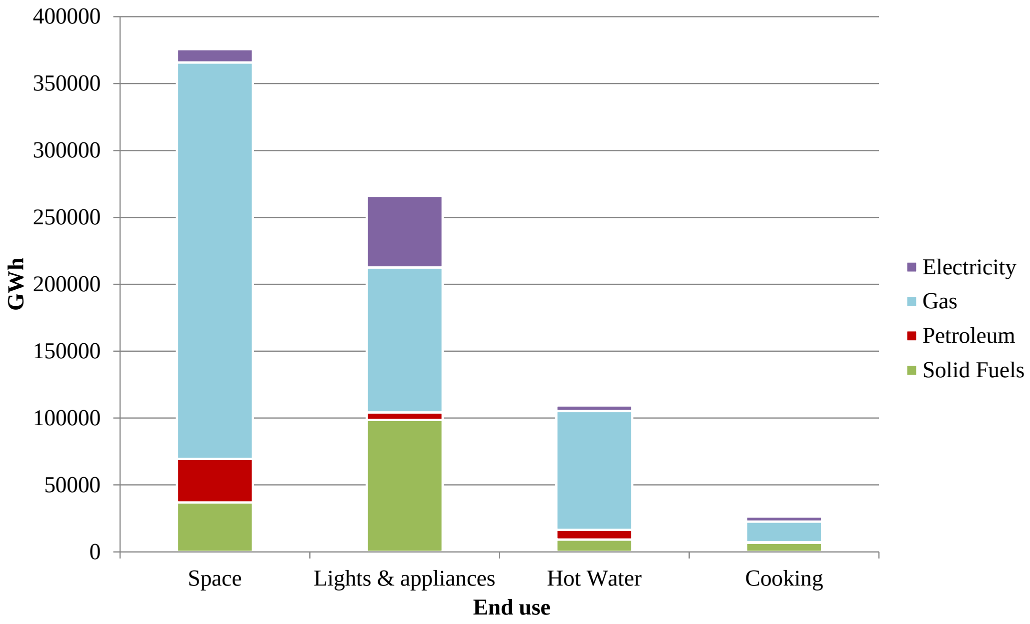

Figure 1-2 Domestic energy consumption by end use and fuel 2009 (DECC 2011a).

Since the 1970's overall energy consumption in households has risen by a third. This is attributable to a growth in demand for energy and demographic trends. In terms of changes in demand, appliance related consumption has tripled as the range, number and use of electrical appliances in the home has increased at a phenomenal rate, offsetting some of the efficiency gains from improvements in the thermal and heating system efficiency of homes over the same period (Palmer 2011).

The growth in energy demand is not just attributable to the proliferation of new technologies but is also due to demographic trends. The number of households in the UK is growing and is projected to increase by 29% by 2033 (DCLG 2011), fuelled by net migration, an increasing life expectancy and a trend towards lower density households. The number of single person households is projected to increase by 55% during the same period and is projected to be responsible for two-thirds of the projected growth (DCLG 2010a).

Despite this growth the number of new homes constructed has been on a downward trend since the 1960’s (Figure 1-3). This has placed pressure on the availability and affordability of housing. The Barker review of housing Supply (Barker 2004) and the subsequent Calcutt Review of Housebuilding Delivery (Calcutt 2007) indicated that housing delivery would have to increase dramatically to counter these socially unacceptable trends. The then government introduced a target to create 3 million new homes by 2020, a rate that would lead to the largest growth in housing stock since the post war period of the 1940's and 1950's. It is estimated that approximately one third of homes that will be in use by 2050 will have been constructed since 2006 (DECC 2011b).

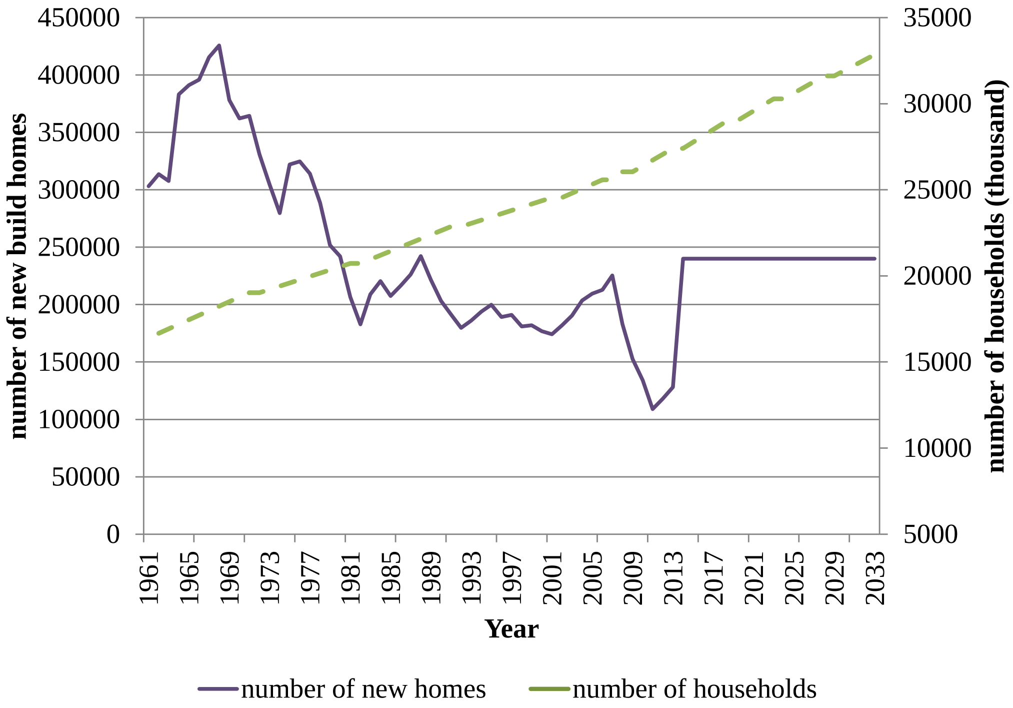

Figure 1-3 Number of new homes and number of households 1961 - 2033. 1961 – 2010 historic series and 2011 – 2033 projected (DCLG 2010a; DCLG 2011)

It is certain that these new homes will result in a net increase in national emissions. Reducing the energy demanded and consequential emissions resulting from the construction of new homes is of paramount importance if the net increase of emissions is to be minimised. This research is concerned with the carbon consequences of constructing new build homes.

1.1.2.2. UK house building industry and innovation

Since the 1990's almost all new housing constructed in the UK is constructed by private house building companies, self-build accounts for just 3% of all new homes per year, and, since the 1990's, all Social Housing is also constructed by this sector (Calcutt 2007). Although it is an incredibly diverse industry, ranging from large nationally operating businesses down to small businesses serving individual local markets, the majority of new homes are constructed by only a few companies. In 2006, 47% of new housing was delivered by just three companies (Calcutt 2007). The industry is also characterised as relatively uncompetitive as far as product and consumer are concerned (Barker 2004). Due to the constraints on land availability competition tends to focus on land acquisition rather than on product or the consumer (Barker 2003). Calcutt (2007) also points out

"Housebuilders are not in the business to serve the public interest, except incidentally. Their primary concern is to deliver profits for their investors." (p6).

Given this lack of competition, strong profit motive and a susceptibility to the volatility of the economy, it is unsurprising that the industry should be characterised as risk adverse and conservative (Barker 2003). Construction methods and materials have changed little since the 1940's. Innovation is slow with a pattern of tiny increments that could be described as more of a continuum than incremental innovation (Barlow 1999, Ball 1999). Left to their own devises there is no motive to change; it is an industry that could be described as having considerable resistance to change and innovation. Consequently government policy and regulation has been the principle driver of energy efficiency in new build homes.

1.1.3. Policy and regulation

There has been a significant amount of policy activity directed at reducing the energy and carbon associated with new housing in the UK (Figure 1-4). The UKLCTP cites two key policies for delivering carbon reduction from new build homes during the three budget periods: The Building Regulations and Zero Carbon Homes (DECC 2009).

The Building Regulations[2] are the principle mechanism for regulating the energy performance of buildings since the first minimum standards to limit heat loss were introduced 1966. Energy efficiency or conservation was not explicitly referenced until 1976. The Building Regulations themselves set out the minimum standards required in 14 key areas, or parts A to P (DCLG 2010b). In Part L the Conservation of Fuel and Power sets out the minimum standards required for a buildings energy demand (including: fabric, heating, cooling and ventilation systems and renewable energy generation). It has four parts: Parts L1a New Dwellings; L1b Existing Dwellings; L2a New Buildings Other than Dwellings; L2b Existing Buildings Other than Dwellings. Only Part L1a is relevant to new build housing and from this point forward reference to Part L or the Building regulations refers to Part L1a unless otherwise stated.

2The Building regulations as we know them today were provided for in the 1984 Buildings Act. The Buildings Act was a necessary primary legislation that enabled the regular reviews and changes to standards and technical specifications using the system of Approved Documents in England & Wales without the need for primary legislation to amend the regulations. More recently The Climate Change and Sustainable Energy Act, 2006, gave the legislative provision that enabled renewable energy technology to be brought within the Building Regulations.

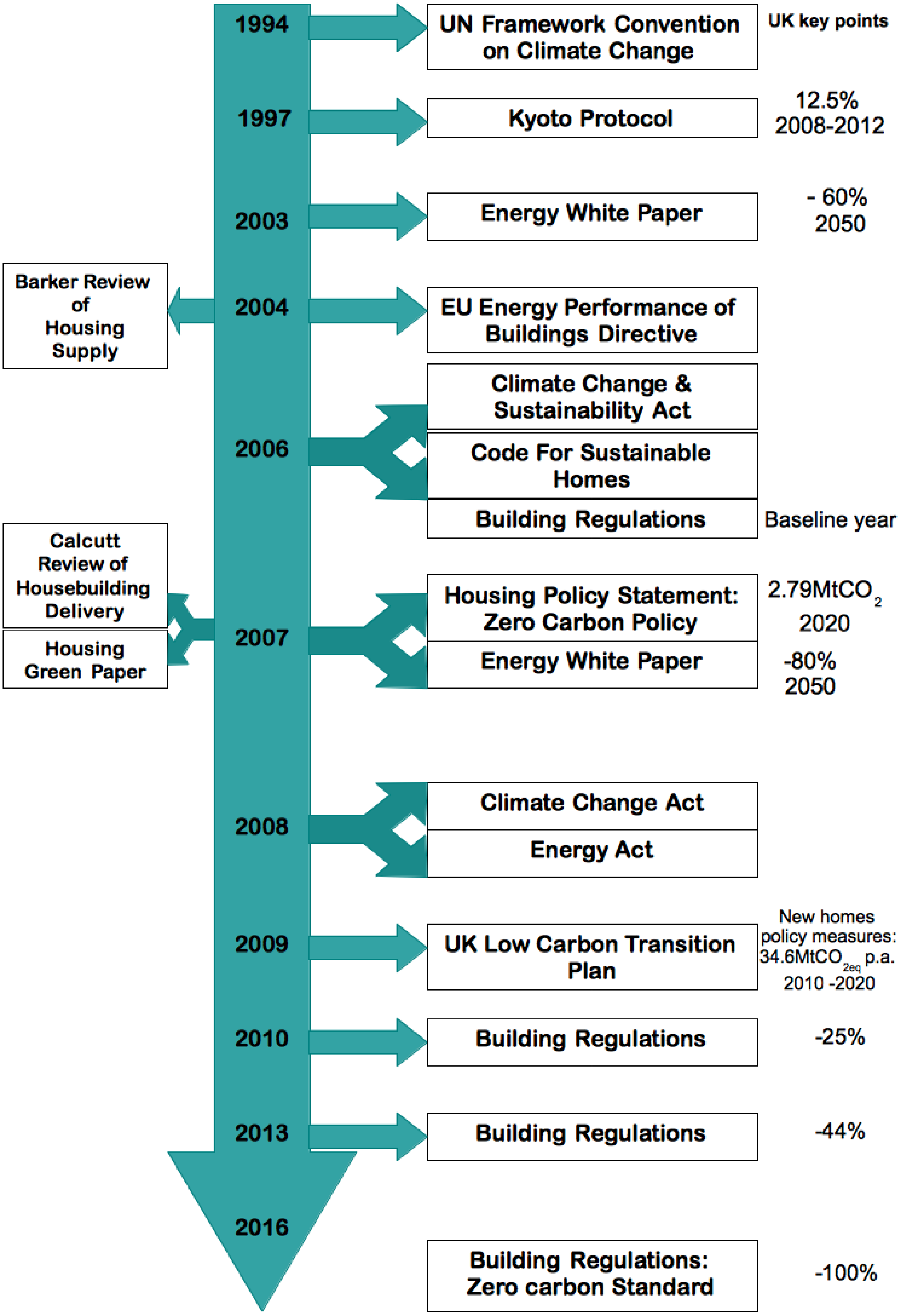

Figure 1-4: Carbon policy cascade showing development of policy and regulation of carbon in new build housing from 1994 to 2016

Since their introduction minimum energy standards have progressively tightened. The focus has shifted from energy conservation to energy efficiency to the current focus on carbon emissions. At the same time the regulatory approach has shifted from a prescriptive one of explicitly defining elemental standards based on U-values[3] to a performance based whole house approach (Hamza and Greenwood 2009). Major revisions in 2006 completed the shift replacing prescriptive compliance methods (i.e. the elemental, the Target and the Carbon Index methods) with a whole house carbon performance method. The method set maximum allowable CO_2 emissions for the whole building on the basis of annual CO_2 emissions and compared the Designed Energy Performance (DER) with a notional building of the same size and shape with specifications conforming to baseline Target Energy Performance (TER) equivalent to Part L 2002 standards.

Table 1-1: Minimum energy performance standards within CSH and how they relate to incremental changes in Building Regulations Part L

Date for Part L1a incremental change	Energy standard (percentage improvement over 2006 Building Regulations Part L1a
	10%
	18%
2010	25%
2013	44%
	100%
2016	Zero Carbon (100% regulated)

The Zero Carbon homes policy, announced in The Housing Policy Statement, Building a Greener Future, in July 2007 (DCLG 2007), declared that all new homes will be Zero Carbon by 2016. The policy was predicted to produce 2.2$MTCO_{2eq}$ saving by 2022 (DECC 2009). The pathway towards meeting the Zero Carbon policy will be met by incremental improvements to the building regulations in 2010, 2013 and 2016 based on an incremental percentage improvement upon the 2006 Building Regulations (Table 1-1). It was estimated that the incremental changes in Part L would deliver a carbon saving of 34.6$MTCO_{2eq}$ by 2020 (DECC 2009).

3 U-values are a measure of thermal transmittance expressed as units Watts per m^2 per degree of temperature difference (how much heat will pass through $1m^2$ of a structure when the air temperature on either side differs by 1^oC) and has the units W/m^2K.

1.1.3.1. A critical look at The Building Regulations and methods of compliance

The purpose of regulation is to establish rules that govern behaviour encouraging outcomes in a certain direction to meet policy goals (Breyer 1982). Stringent regulations can create a framework within which innovation can flourish by creating the pressure required to stimulate innovation leading to new technologies and improved standards. But, as a tool for innovation, performance based regulations also have the potential to stifle innovation by setting standards based on existing knowledge, practises and technologies (Gann et al. 1998, OECD 1997).

As a performance based standard Part L sets the final regulatory goal, leaving open the detail as to how this goal is to be met, enabling scope for trade-offs between the different elements that the goal is comprised of. However, if the knowledge and mechanisms for innovation are limited in scope it is possible for stringent performance based regulations to get unintended results (Gann et al. 1998). In the case of achieving zero carbon innovation in housing the construction sectors capability for compliance with an increasingly demanding Part L will depend upon the availability of new knowledge and skills, the development of innovative technology and design strategies and the development of appropriate mechanisms of delivery. Some commentators have suggested that the UK house building industry is completely unprepared for the challenges posed by these standards and has neither the technology, knowledge or structures required to deliver them (Lowe and Oreszczyn 2008). How house builders react and what solutions they actually adopt in a framework that effectively enables trade-offs between fabric and technology introduces uncertainty in the results that the zero carbon policy will achieve at each increment.

A further issue is that the entire process of articulating Part L and demonstrating compliance with it is a theoretical one. At no point is the actual energy and carbon emissions from a newly constructed home assessed. Yet, the goals envisaged for Part L and the zero carbon policy will only be realised if what is constructed performs as it is designed. This is particularly pertinent to the UK where the building regulations, though they set out minimum acceptable standards, are interpreted as “The Standard”, with the majority of house builders designing to meet and not exceed the regulatory minimum. As a consequence, there is very little margin between energy and carbon emissions in performance as designed and that achieved in reality in relation to conforming to minimum requirements. In reality a significant proportion of new homes fail to realise the anticipated savings through lack of compliance which has been blamed on poor understanding of low energy design and detailing, poor workmanship and lack of construction skills (HC 2005, RCEP 2007, Wingfield et al. 2008). Furthermore, the theoretical models and tools that are used to model energy demand have also been critisised as a source of discrepancy between performance and design (Wingfield et al. 2008).

SAP

The theoretical model used to assess DER and TER and therefore demonstrate compliance is the Standard Assessment Procedure (SAP) (BRE 2005). SAP is the Government's model for quantifying, assessing and comparing the theoretical energy, energy costs and carbon performance of homes. In addition to its role in Part L, SAP is also central to many other government policies, including modelling emissions of new build homes for carbon budgets (DCLG 2007) and provides *"accurate and reliable assessments of dwelling energy performance that are needed to underpin energy and environmental policy initiatives."*[4]

SAP was developed by the Building Research Establishment in 1992 and first published in 1995 based on an earlier model, the BRE's Domestic Energy Model[5] (Anderson et al. 1985). The model excludes appliance related energy and takes into account only the factors that contribute to the annual heating energy demand of a dwelling. Including:

- Thermal insulation of built fabric
- Thermal mass
- Ventilation characteristics of the building and the ventilation equipment
- Efficiency and control of heating systems
- Solar gains through glazed areas
- Fuels used to provide space and water heating, ventilation and lighting
- Internal heat gains through lighting, cooking and occupation
- Renewable energy technologies

4 DECC website http://www.decc.gov.uk/en/content/cms/emissions/sap/sap.aspx viewed 3/10/11

5 As a methodology it was constructed to be substantially more sophisticated than a simple heat loss model but not to a level of sophistication that would require complex simulation models and could be defined in a paper worksheet The paper worksheet is still published today; however assessment for energy rating purposes and for demonstrating compliance with the building regulations SAP assessments relies upon licensing arrangements via a competent persons using proprietary software (e.g. NHER, Elmhurst and BRE). Each software product is product is subtly different in terms of assumptions, pre-defined values and approved products. These outputs can influence the direction designers take.

SAP has been criticised for its outdated theoretical basis. The model was developed in the 1980's based on, and calibrated against, detailed monitored data from several hundred new homes. These homes were, by today's standards, poorly insulated with a relatively high heat loss. Heating patterns have also altered. Home heating in the 1970's typically consisted of single room heaters (e.g. solid fuel fire or electric or gas heater) and tended to follow a two zone pattern whereby the living area was heated to a higher temperature than the rest of the home. Today, homes are more thermally efficient, and have a very different heating pattern. Homes now typically have central heating systems that are more efficient, better controlled, and cheaper to run with the home heated to a higher more uniform temperature.

Further concerns have been raised with regards to SAPs conventions and its capacity to accurately model very low energy homes or passive solar design (Silver and Parand 1999; Reason and Clarke 2008). In super insulated and air tight homes incidental gains become increasingly important as a source of heat. At the same time lighting and appliances have become increasingly efficient resulting in lower incidental gains from these sources. However SAP in its handling of such incidental gains assumes inefficient practises overestimating the contribution to heating from these sources. SAP does not allow for detailed analysis of solar gains and the effects of thermal mass. In low energy homes and passive solar design these factors may result in significant underestimation of the amount of heating required.

A further criticism of SAP is that, in its assumptions, it favours technology over efficiency in designing homes to pass Building Regulations minimum standards (Reason and Clarke 2008). For example, the use of default values precludes accounting for efficiency measures such as low energy pumps, or light emitting diode (LED) lighting, super insulated pipe work. Whilst the assumptions made for the outputs of renewable energy technologies such as PV and solar hot water are, if not entirely unrealistic, optimistic (Reason and Clarke 2008). These underlying assumptions and focus on technology over efficiency could lead to the favouring of 'bolt on' technological solutions of limited lifespan rather than improved performance of the structure of the home itself which will be insitu for the lifetime of that home.

Incremental revisions since the SAP's introduction, most notably in 2005 and 2009, have been made to address some of the limitations of the methodology, to improve accuracy, accommodate changes in its assessment function from energy cost to carbon and the inclusion of renewable technologies. Further revisions are envisaged in 2013. But fundamentally SAP only models limited aspects of theoretical 'paper houses' using parameters based on assumptions about the real world. It is, therefore, unsurprising that

that the real world doesn't 'measure up' and there is a performance gap (Wingfield et al 2008). Yet SAP, to return to the quote from DECC (2007), is perceived as providing *"accurate and reliable assessments of dwelling energy performance*". This raises questions about the analytical basis in which policy has and continues to be made with regards to new build homes and their contribution towards meeting UK carbon targets. The implication of the evidence presented here suggests that the assumptions made by government with regards the level of energy and carbon savings made as a result of the incremental amendments of the Part L may be flawed.

As Part L moves increasingly towards zero carbon it is inevitable that it has become a driving force in innovating not just how homes are physically constructed but also the technologies that are used within them. How the house building industry responds to the incremental changes in Part L and which solutions they adopt will be critical to the long term outcome of the carbon performance of new homes. However these savings will only be realised if Part L is capable of producing outcomes in the real world that can meet policy objectives. Given the lack of innovation, poor environmental record, lack of engagement with sustainability and a lack of ability to meet even the minimum existing requirements, by a significant section of the house building industry (Ball 1999, Barlow 1999 Glass et al. 2008) an interesting question arises which this research will address:

Are the innovations currently being deployed by mainstream housing providers in response to regulatory changes capable of meeting policy goals?

1.1.4. Low energy and carbon building

Substantial energy and carbon savings can be achieved from new buildings using existing, mature technologies, and design strategies (Metz et al. 2007, Roaf et al 2007). The basis of achieving low carbon buildings is through a hierarchy of measures (Lysen 1996):

1. Reduce energy demand.
2. Displace fossil fuels with low and zero carbon (LZC) technologies.
3. Use energy as efficiently as possible.

1.1.4.1. Reducing energy demand

Firstly, demand is typically reduced by following a 'fabric first' approach, in which demand is reduced by minimising heat loss from a home through insulation, using thermally efficient windows and doors and minimising unwanted air infiltration by effectively sealing[6] the home (Table 1-2). Using these methods, the heat loss from a home can be minimised to a point where the energy demand for heating may become so low as to be negligible (Nicholls 2006; Roaf et al. 2007).

However, super-insulating and sealing a home increases the importance of ensuring adequate ventilation to maintain a healthy indoor environment. Health problems related to poor indoor air quality (for example, humidity, cooking smells and a build-up of pollutants emitted by building materials, fixtures, furniture and other contents in the home) have been associated with low energy buildings (Crump et al. 2009). As a consequence reliance upon ventilation from openings (i.e. windows) and air infiltration through the structure becomes inadequate and purpose provided ventilation is required as standard. Mechanical ventilation with heat recovery (MVHR) is increasingly being applied in new build homes in order to satisfy the goals of minimising energy demand without compromising indoor air quality (Crump et al. 2009; NHBC Foundation 2012).

This is the principle approach demonstrated by the PassivHaus Standard [7], developed by in Germany by engineer Wolfgang Feist. It uses rigorous design principles to achieve a maximum allowable primary energy demand of 120kWh/m^2/year and an air exchange rate not exceeding 0.6 air changes per hour @ 50Pa which eradicates the need for conventional heating systems. In climates such as the UK this typically involves:

- super insulation
- extremely high performance windows with insulated frames
- airtight building fabric
- 'thermal bridge free' construction
- a mechanical ventilation system with highly efficient heat recovery

The PassiveHaus Standard has become of significant interest in the UK as a solution to meeting the Zero Carbon target with an increasing number of homes being built to achieve the standard. Early examples to achieve certification include The Denby Dale PassivHaus, the first to achieve certification in the UK certified, completed in May 2010 (Figure 1-5) and Hastoe Housing’s Wimbish PassivHaus Project[8] in Essex occupied in 2011 and currently undergoing a post occupancy monitoring and evaluation (Figure 1-6).

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[6] Achieved by wrapping the house with a continuous impermeable air barrier and draught stripping all openings and gaps in the build fabric
[7] http://www.passivhaustrust.org.uk/ accessed 18/08/2011
[8] http://www.wimbishpassivhaus.com/index.html

Whilst commonly specified in non-domestic buildings and in homes across Northern Europe and Canada, mechanised ventilation systems are rarely applied and remain relatively untested in the UK mainstream housing. Yet, while we know a great deal of the technical efficacy of such systems operated in optimal contexts (Tommerup and Svendsen 2006) there is a dearth of evidence of the actual energy and carbon consequence of the adoption MVHR in UK homes. The widespread adoption of MVHR as an industry standard in response to regulatory drivers may be counterproductive and result in unanticipated negative results.

Figure 1-5:Denby Dale PassivHaus (image source: Yorkshire and Humber

Figure 1-6:Wimbish PassivHaus Project (Image source: PassivHaus Trust)

As a strategy approaches such as PassivHaus, which use the fabric first approach combined with mechanised ventilation, improves the energy performance of a house without necessitating significant changes to design or construction practise, and serves to isolate the building from its environment. This can lead to a ‘one-size fits all’ solution replicable in any given location. However, a buildings operational energy demand is related to both the site that a building occupies and the buildings built form (Brown and DeKay 2001; Harris and Borer 2005; Roaf et al. 2007). Designing a home to be unique to its context may offer opportunities to exploit rather than negate such contextual factors.

An alternative approach includes Passive Solar Design (PSD) principles that consider the site of the building as the context that influences both when and how much energy that building will need over the course of a year and suggests potential design strategies for heating, cooling, daylighting and ventilation that can best exploit the available solar energy resource in that environment removing or minimising the need for additional energy hungry mechanical systems (Roaf et al 2007) (Table 1-2). Using careful planning of architectural elements (including glazing, shading, thermal mass[9] and internal room layout) PSD optimises solar gain by converting available sunlight into usable heat or air movement without the need for mechanical systems (Crosbie 1998). Passive solar design can reduce the energy required to heat a home by up to 17% (Spanos et al. 2005). However, PSD strategies can only be effective in reducing energy demand when used in conjunction with, and not a substitute for, insulation and air tightness (Crosbie 1998). How much of this useful ‘free’ energy is utilised in practise will depend on a number of parameters, not least of which is how the sunspace and the ventilation system are operated together which is a function of both design and operation by the occupants.

Early examples of this approach in the UK include architects Robert and Brenda Vales’ Autonomous House in Nottingham constructed in 1993 (Vale and Vale 2000), The Honingham Earthsheltered Housing Scheme in Norfolk constructed in 2006 (Figure 1-7) and The Oxford Ecohouse constructed in 1994 (Roaf et al. 2007). The Autonomous House is an off grid low carbon home constructed to high thermal standards that uses solar technologies to provide energy requirements. The Honingham Earthsheltered Housing Scheme used PSD by orienting glazing to the south with exposed thermal mass internally with superinsulation and earth berming[10] to radically reduce heat loss and a passive ventilation system. The Oxford Solar House similarly applies PSD strategies using a solar sunspace in conjunction with thermal mass and superinsulation. However, the home also includes an automated system to operate the home to fully exploit the available solar resource without compromising thermal comfort and ventilation. The Oxford Solar house, which has been subject to many years of performance monitoring, requires 27kWh/m^2/year delivered energy without recourse to other mechanical systems (Roaf et al 2007).

[9] Thermal mass is the ability of a material to absorb heat. High density materials, such as concrete, clay, stone and water require a large amount of heat to change temperature and are therefore said to have a high thermal mass. In contrast lightweight materials such as timber are said to have low thermal mass. The use of mass materials acts to attenuate fluctuations in internal temperatures.
[10] Berming is where a building is partially buried under a mound or bank of earth, with the earth acting to provide mass and additional insulation.

Figure 1-7: The Honningham Earthsheltered housing project, Norfolk (image source: SearchArchitects)

Figure 1-8: The Oxford Solar House (image source:http://www.bbc.co.uk/oxford/content/image_galleries/solar.shtml?4)

1.1.4.2. Low and zero carbon technologies

The second hierarchy of measures to achieving a low carbon homes is to displace fossil fuel use by deploying low and zero carbon (LZC) technologies (Table 1-2). As demonstrated in the Vales Autonomous house and The Oxford Ecohouse. LZC technologies are defined as technologies that provide energy to a home with the net effect being the reduction of metered energy supply, lowering fossil fuel demand and carbon emissions. Zero carbon technologies are those derived from renewable sources and have net zero carbon emissions in operation, including wind, hydro, solar thermal, photovoltaics, biomass and biofuels. In the context of housing zero carbon technologies can provide heat (e.g. solar thermal, biomass and biofuels) or power (e.g. solar photovoltaics, wind turbines and hydro-electricity) (Table 1-2). Most are dependent upon the availability of the resource, which may be limited seasonally, are discontinuous in generation and their deployment constrained by factors including topography, landscape and social factors, such as planning policy or local acceptance. Consequently LZC technologies are typically deployed as supplementary systems to another principal system which will be mains gas, oil or electricity (e.g. solar thermal system supplementing an electric immersion or the main boiler system). Low carbon technologies are those that can result in reduced emissions by using fossil fuels more efficiently, including heap pumps and combined heat and power (CHP). Collectively low and zero carbon are defined in this thesis as LZC technologies.

The third hierarchy of measures use energy as efficiently as possible, including: commissioning, controls, metering and monitoring and user behaviour. These strategies can be effective in the efficient operation of systems, such as heating, hot water, ventilation and lighting controls, thus minimising the overall amount of energy required (Table 1-2).

Table 1-2: Summary of technical strategies for reducing energy and carbon emissions from new housing

Strategy	Carbon reduction step			Type of energy	
	Demand Reduction	Fossil fuel displacement	Technological Efficiency	Heat	Power
Fabric:					
Insulation	●			●	
Ventilation	●			●	
Airtightness	●			●	
Design:					
Passive solar design	●			●	
Thermal mass	●			●	
Technology: Renewable					
Photovoltaic		●		●	●
Solar Thermal		●			
Biomass		●		●	●
Biofuels		●			●
Wind		●			●
Hydro		●			●
Technology: fossil fuels					
Heat pump		●	●	●	
Micro-CHP		●	●		
Co-heating/ district heating		●	●	●	●
Post construction:					
Commissioning	●			●	●
Control	●		●	●	●
Meters & monitors	●			●	●

1.1.4.3. Embodied energy

The occupational energy and carbon emissions of a new home is important, but focusing exclusively on these aspects disregards the significant energy and carbon consequences involved in the initial construction of a home and the LZC technologies within them. The extraction, processing, manufacture, transportation, and use of a product requires energy and produces many environmental impacts, including emissions of CO_2. These impacts are regarded as the hidden, or embodied, burdens (termed embodied carbon and embodied energy). Embodied energy and carbon are not, in general practice, a consideration when a home is designed, specified and constructed. Yet, up to a third of the total emissions over the lifetime of a home will be attributable to its construction, more for low energy homes (Sartori and Hestnes 2007). Embodied carbon is of particular importance for low energy buildings because, although less energy is used during occupation, additional energy is often required for the manufacture of the increased levels of insulation, the heavier mass materials used and the additional technologies often deployed (Thormark 2002). The evaluation of energy and carbon performance of a home needs a holistic point view that considers not just the energy and carbon consequences of its occupation but also that involved in its production. This leads to the interesting research question which this research will address:

"What are the embodied energy and carbon consequences of constructing new low carbon homes compared with conventional construction?"

1.1.5. Mainstream low carbon buildings in the UK

There are now many exemplars demonstrating low carbon housing and LZC technologies in the UK. The majority of these, including the Denby Dale PassivHaus, The Vales Autonomous house, the Hockerton Housing project and The Oxford Solar House, were one off bespoke highly experimental projects created with the occupying household as the client, if not the architect, of the project themselves. Such households will have not only a high level of interest, and knowledge about their homes and the various features but will also have a vest interested in obtaining the best possible performance. Whilst their influence has been enormous in proving what is possible, their uniqueness can tell us nothing about how mainstream housing will innovate or how ordinary households will respond.

More recently a number of larger scale developments in the mainstream have been constructed. For example, the high profile BedZED housing project in Sutton constructed in 2002 and Elm Tree Mews Low Carbon Housing in York, constructed in 2008. Whilst these homes use significantly less energy than conventional contemporary homes neither of these projects performed in reality as predicted. For example, BedZED, a high profile pioneering carbon neutral development using passive solar design and a mix of onsite renewable energy generation, was predicted to have an averaged designed performance of approximately 75 kWh/m^2/year (Bioregional Development Group 1999) but achieved an average of 82 kWh/m^2/year with some homes exceeding 147 kWh/m^2/year (Hodge and

Haltrecht 2010). The Elm Tree Mews housing project, predicted to have a space heating energy demand of 34 kWh/m^2/year (based on a 107m^2 floor area), achieved 64 kWh/m^2/year in reality, a difference of 88% (Bell et al. 2010). This difference between predicted energy demand and that used in reality is widely reported in numerous studies (Bordass et al. 2001; Branco et al. 2004; Gill et al. 2010). This difference has been found to be dependant not only on physical factors intrinsic to the building itself (including accuracy of models used, quality of design and construction, the technical systems and local climate), but also, crucially, on how it is used (Branco et al. 2004; Wingfield et al. 2008; Juodis et al. 2009). As the energy demand for heating reduces because of improvements in the thermal envelope and technological improvements in the systems supplying heat and power, the significance of the user increases in importance (Papakostas and Sotiropoulos 1997; Haas et al. 1998).

Domestic energy consumption studies have frequently observed significant variation in energy consumption between different households (Gram-Hanssen et al. 2004), even between households occupying identical homes (Firth et al. 2008). Furthermore, when controlled for building differences and occupant characteristics, user behaviour is found to be a critical factor in the variation observed (Guerra Santin et al. 2009; Branco et al. 2004). This suggests that the performance gap is as much to do with the households themselves, how they use their homes as it is to do with modelling inaccuracies and technical failings (Wingfield et al. 2008). Whilst the effect of users on overall energy outcomes is widely recognised, how users behave and how this contributes is poorly understood.

The physical relationship between a building's thermal characteristics and local climate on heating demand is well studied, quantified and validated, as is the theoretical performance of new energy technologies. Yet we know very little about the how users interact with these new systems and how these interactions can explain the variance in energy and carbon outcomes from new low energy/carbon homes. If the actual energy savings achieved, due to the implementation of regulations, are lower than those predicted by engineering models there will be implications for policy targets.

New mainstream low carbon homes, which are almost exclusively affordable housing, are typically occupied not by well-informed households motivated to reduce their energy and carbon emissions but by passively adopting households. A passively adopting household is defined here as an individual or a household that does not actively choose to adopt low energy or environmentally aware behaviours or technologies but is guided towards such behaviour or desired outcomes through the provision of technology or design by an external actively adopting agent. How passively adopting households interact with these new technologies and design strategies will be massively important in shaping their effectiveness and the parity between their performance as designed and that of reality. The people who have to live in and make these homes and technologies their own may lead to outcomes that are unexpected, irrational, undesirable and counterproductive. This raises an interesting question with this research will address:

What is the influence of passively adopting households on the overall energy and carbon outcomes of mainstream new low carbon homes as they adopt and adapt to new LZC technologies?

1.1.6. An interdisciplinary approach

Reducing energy demand and carbon emissions from new housing is principally defined and understood as a technological problem in which built fabric and technology form the focus of efforts to solve the carbon reduction problem (Guy and Shove 2007). But clearly people are a factor. In addition to the technical there are non-technical, human social, cultural, institutional, and behavioural influences that are fundamental to shaping the overall energy performance of the home (Chappells and Shove 2003). Focussing almost exclusively on the technical aspects of structure and technology to deliver low carbon solutions divorces the house from its function as a home and an institutional amnesia regarding the reasons why the demand for energy arises in the first place. To site a seminal paper by Keating (1984) “Buildings don’t use energy: people do”. How people live in their homes, the technologies they have and how they use them play a fundamental role in shaping the overall energy demand and carbon emissions of that home.

Building energy and carbon performance is, therefore, determined by interactions between these three elements: building characteristics; technological installations; and the occupants of those buildings (Steemers and Yun 2009). For example, emissions arising from space heating are a function of the engineering and technical characteristics of the house itself (e.g. type, levels of thermal insulation and air permeability) and the heating technology employed (e.g. fuels used, efficiency of combustion/conversion, and the levels of control). They are also a function of the behaviour and lifestyle of the occupants themselves. Individual preferences, such as preferred temperature, how the occupants respond to meet their comfort needs (such as adjusting clothing or adjusting the thermostat), whether the whole house is heated to the desired temperature or just the rooms that are occupied and patterns of heating preference (intermittent or continuous) will have an enormous effect on a households overall heating related energy consumption. Energy demand and carbon emissions can therefore be described as complex expression of physical ‘things’ or technology, social institutions and individual characteristics. With this in mind the energy and carbon associated with the production and use of a new home can be described as a sociotechnical system (Hitchcock 1993, Janda 2009).

Consequently understanding the carbon implications of innovation in housing requires not just quantifying the energy and carbon costs of the material and technical but also the ways in which people interact with and shape the innovation. It is the viewpoint of this thesis that the three are intimately linked. Therefore, in order to evaluate the carbon consequences of new homes, and answer the three research questions posed above, four interrelated themes require consideration (Figure 1-9): lifecycle energy; energy performance; low carbon technology; and users.

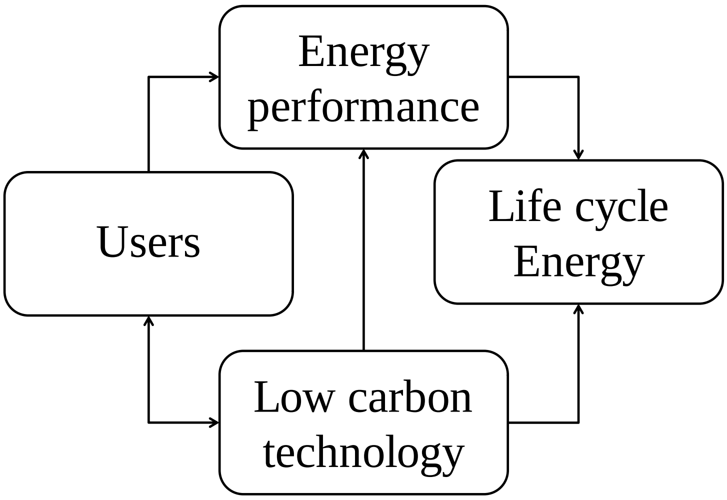

Figure 1-9: The four study areas and the interrelationships between them

As defined above the problem in question is a complex socio-technical problem that cannot be answered by one single discipline alone. How technologies are understood, appropriated and used, the qualitative, will have an influence on the quantitative. A single disciplinary approach will provide only a limited view of the topic (Steg 2008). An interdisciplinary approach enables a wider, more comprehensive view of the issues concerned. Yet conceptualisation of domestic energy and carbon remains largely within the disciplinary boundaries of engineering; economics; psychology; sociology or anthropology (Keirstead 2006). Each discipline fragmenting the system into discrete disciplinary appropriate sections and applying subject specific techniques, frameworks and philosophical biases to questions of disciplinary concern.

This is not to say that single discipline approaches have not been, or continue to be, valuable. It is not the purpose of this argument to dispute this. Rather, single disciplinary approaches have too narrow a perspective in addressing a complex problem like understanding energy demand and carbon emissions of innovations in housing. This limitation of disciplinarity in domestic energy and carbon studies is well recognised within the literature dating from the early 1980's with calls for the application of interdisciplinary and inclusive approaches (Yates and Aronson 1983; Lutzenhiser 1992; Hitchcock 1993; Wilk 2002). Hitchcock (1993) argues that *"energy consumption patterns are a complex technical and social phenomenon and thus to be fully understood must be viewed from both engineering and social science perspectives"*. For domestic energy consumption research to be able to advance addressing the problem of demand reduction and be of policy relevance, the 'norm' of dissecting complex problems into discrete disciplinary approaches needs to be challenged. Hitchcock (1993) proposed that, as a multifaceted problem, domestic energy consumption requires a broad socio-technical framework based on systems theory. In particular social science and engineering perspectives need to be more closely integrated suggesting that the divide could be bridged by the application of combinations of methods to the problem.

Understanding the carbon implications of innovation in housing requires an approach that crosses traditional disciplinary boundaries to gain holistic insights, rather than one which remains within disciplinary boundaries to produce a disconnected series of outcomes. Therefore, the research approach taken in this thesis is interdisciplinary. There is little consistency in defining the concept of interdisciplinarity (Bruce 2004). Therefore, interdisciplinarity is defined and applied here in this thesis as a research approach in which distinctive and appropriate theories and methods from a range of disciplinary perspectives is brought to together to provide a holistic or systemic outcome (Nissani 1997; Brewer 1999; Bruce et al. 2004).

1.2. This research

1.2.1. Summary of the research questions

This research addresses the carbon consequences of constructing low energy homes. Three aspects were identified earlier in this chapter: the carbon costs of construction; the contribution that new low carbon technologies make to carbon mitigation in the real world; and how these new technologies are used by passively adopting households. Three research questions were posed. The first question addresses the consequences of construction and asked:

What are the embodied energy and carbon consequences of constructing new low energy homes compared with conventional construction?

The second question considered the contribution that new low carbon technologies can make and asked:

Are the innovations currently being deployed by mainstream housing providers in response to regulatory changes capable of meeting policy carbon targets?

The third question considered the reality of how these technological innovations are actually used in the real world and asked:

What is the influence of passively adopting households on the overall energy and carbon outcomes of mainstream new low carbon homes as they adopt and adapt to new LZC technologies?

1.2.2. The aims and objectives of this research

The aim of this research is to answer the three research questions posed in order to evaluate the carbon consequences of constructing low energy homes and assess the effectiveness of the housebuilding industries response to regulatory drivers and its ability to meet policy targets.

To achieve this aim this research investigates the technical and social aspects that determine carbon emissions from mainstream low carbon housing. A development of 15 low carbon homes is used as a detailed case study. Whilst energy and social science research on energy and carbon in innovation in housing is not new, applying interdisciplinarity is relatively rare. Applying an interdisciplinary approach using both quantitative and qualitative methods to a case study enables a richness of detail not possible with single disciplinary methods or larger samples.

In order to meet the research aim four research objectives are identified. These are:

Objective 1: quantify the energy and carbon embodied in the construction and technologies of low carbon homes compared with conventional mainstream new build homes (Chapter 2) to fulfil research question 1.

Objective 2: quantify the energy and consequential energy and carbon emissions arising from the occupation of mainstream new low carbon homes (Chapter 3) to fulfil research question 2.

Objective 3: evaluate the effectiveness of different LZC technologies currently being deployed in new low carbon homes in reducing energy demand and carbon emissions (Chapter 3 and Chapter 4) to fulfil research question 2.

Objective 4: evaluate the influence of households on energy and carbon outcomes of new low carbon homes (Chapter 5 and Chapter 6) to fulfill research question 3.

These four objectives contribute to addressing the three research questions as discussed.

Research question 1 is addressed by determining the embodied energy and carbon consequences of construction and the specifying of new technologies in the cases study housing development using a lifecycle assessment framework from cradle to in-situ. This study determines how much energy and carbon may arise from the construction of new low carbon homes and contributes to the lifecycle energy theme identified in Figure 1-9. The study is described in Chapter 2.

Research question 2 is addressed by two studies. The first quantifies the energy and carbon emissions arising from one year of occupation of the case study development. The data are obtained by monitoring the metered energy consumption over the first year of occupation. This provides the input data required to determine annual energy demand from grid electricity and gas. In the absence of direct monitoring, the contribution of low carbon technologies to the annual total energy demand is modelled. This occupational energy will be used in conjunction with outputs from the embodied carbon study to determine the longer term lifecycle costs to compare different technologies and design strategies. This study is described in Chapter 3.

The second study focuses on a particular technology, MVHR. The study evaluates the effectiveness of the widespread adoption of technological innovations like MVHR in meeting regulatory goals. A review of current evidence and the evidence from the case study homes is used. This study is described in Chapter 4.

The third research question is concerned with an assessment of the influence of the households' lifestyle and behaviour on annual energy demand and carbon performance. This question addresses three of the themes identified in Figure 1-9, the user, energy performance and low carbon technology and the interconnections between them.

Two studies are used to address this research question. The first study addresses one aspect of the User theme, the influence of the user on energy performance, shown by a one way arrow between the User and Energy Performance themes in Figure 1-9. The study examines the differences in energy consumption between households, identifying explanatory factors. This study also draws on the work undertaken to address the annual monitored energy consumption and the technological assessment (related to research question 2). This study is described in Chapter 5.

The second study addresses the other aspect of the User theme, the interaction between user and technology as a two way influence, shown by the double ended arrow in figure 1, the users behaviour is both influenced, or constrained, by the technology but also able to influence the way in which the technology is used and its effectiveness. This study is described in Chapter 6.

1.3. The case study

With funding support from Carbon Connections[11], the author undertook a post occupancy evaluation and monitoring study of the development that included a carbon footprint of the construction and the energy performance of the home. This research arose from this monitoring and evaluation study.

1.3.1. Case study development

The case study development is a low energy affordable housing development constructed in 2008 in Lingwood, Norfolk in the UK. The development was designed and constructed by a consortium of partners, brought together by Flagship Housing Group Ltd. The development comprises 15 homes, seven 3 bedroom homes (71m^2 internal floor area) and eight 2 bedroom homes (83m^2 internal floor area). Eleven of the homes were for affordable rent and four for shared ownership. These homes were constructed on a rural exception site and were built to address local housing need.

The homes were designed to exceed contemporary energy best practise and include an experimental mix of new low carbon technology and design at market cost without additional grant funding. The homes, built with good levels of insulation and a visually distinctive untreated larch cladding were designed to meet an energy standard which equated to the Building Regulations ADL1a 2010 (Figure 1-10). They were awarded the Building Research Establishments (BRE) Ecohomes rating Excellent and achieved the UK governments Code for Sustainable homes Code level 3 (DCLG 2006).

[11] Carbon Connections is an investment body, set up by the Higher Education Funding Council for England (HEFCE) to seek out, encourage and invest in carbon-saving innovation either through technological advance or behavioural change.

Figure 1-10: Case study development

The development uses differing combinations of low and zero carbon technologies and design approaches. These include ground source heat pumps, solar thermal, solar photovoltaics and passive solar techniques. Design aspects, common to all the homes, included:

- High levels of insulation
- High levels of airtightness
- Ventilation via vents incorporated into window frames (passi-vent)
- Optimised solar orientation (south/north axis orientation)
- Energy efficient gas boilers (93% seasonal efficiency)
- LZC energy technologies: solar hot water, photovoltaic's, and ground source heat pumps
- Dedicated fixed low energy lighting
- Offsite manufactured timber frame
- Larch weather boarding
- All timber FSC certified

- Avoidance of UPVC, timber framed windows
- Reduced use of high embodied energy materials such as masonry and concrete
- Water efficient: Rainwater collection for grey water use (toilets and washing machines).Low water use toilets, baths and taps
- Communal recycling facilities
- Low density
- Affordable: affordable to both build and to run

The 15 homes comprised four blocks of terraced homes all constructed to the same specification using the same innovative offsite panellised construction system but each block had a different low and zero carbon (LZC) technology for providing heat or power (Figure 1-11).

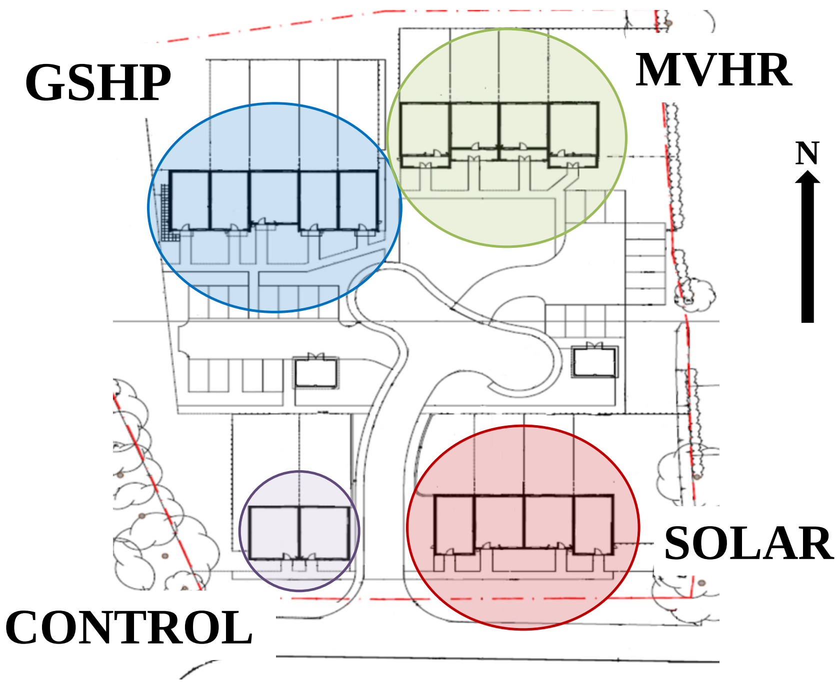

Figure 1-11: Case study site plan showing position of different LZC technology used

1.3.2. The construction

The Lingwood development was constructed using a novel offsite engineered structural panel timber frame construction with additional insulation materials to exceed current minimum building regulation standards. The modular timber frame panel system was produced offsite and supplied with factory installed insulation (Figure 1-12). An additional layer of insulation was installed during construction to enhance the thermal performance of the construction (Figure 1-13). Untreated Siberian larch weather boarding as the external facade was installed onsite. The substructure, foundations, first floor and roof are constructed using traditional construction approaches. The substructure consists of an over site poured concrete slab with steel reinforcement in shallow strip footings. Brick and cement block walling are used below the damp proof course. The suspended ground floor is formed from precast concrete and steel reinforced beams with an infill of concrete blocks.

Figure 1-12: Factory production of panel system (image source: Space4)

Figure 1-13: Panel system construction (image source: John Youngs Homes Ltd)

1.3.3. The four house types

There are four typologies of the basic house construction (Figure 1-14 and Table 1-3): Two homes acted as controls with conventional condensing gas fired instantaneous combi- boilers (CONTROL); 4 homes had the same boiler in conjunction with solar hot water systems and photovoltaics for power (SOLAR); a third block also had the same gas boiler but with a thermal sunspace to the south facing elevation and a mechanical ventilation system with heat recovery (MVHR); the fourth block were all electric with a ground sourced heat pump provided all heating and hot water needs.

Figure 1-14: Front elevation (image source: J. Monahan)

1.3.3.1. Control

The two control homes were both 3 bedroomed (83m^2) homes. The CONTROL homes represent the base case design model, as constructed, against which the other homes, enhanced with low carbon and renewable technologies, could be compared. Heating and hot water was provided from a high efficiency instantaneous condensing gas fired combination boiler, with a manufacturers declared seasonal energy efficiency of 91.3% (SEDBUK 2011). The heating system was controlled by an advanced seven day programmer and thermostat. Radiators were fitted to all rooms except the kitchen. All radiators were fitted with adjustable thermostatic valves. In the kitchen a warm air electric heater was installed in the under cabinet plinth.

Table 1-3 Characteristics of the fourteen homes (refer to text for definition of house types)

House ref.	No. people	Area/ m^2	Occupied hours/year	Gas boiler	Solar hot water/m^2	PV/ kWp	GSHP/ 3.75kW CoP 3.8	MVHR	Sunspace
GSHP1	3	71	8213				√		
GSHP2	2	71	6570				√		
GSHP3	3	83	4928				√		
GSHP4	2	71	8213				√		
MVHR1	4	83	8760	√				√	√
MVHR2	2	71	4928	√				√	√
MVHR3	4	71	6570	√				√	√
MVHR4	4	83	6570	√				√	√
CONTROL1	4	83	6570	√					
CONTROL2	4	83	6570	√					
SOLAR1	4	71	8213	√	4.04	1.6			
SOLAR2	3	83	6570	√	2.02	1.5			
SOLAR3	5	83	7300	√	4.04	1.5			
SOLAR4	3	71	6570	√	2.02	1.6			

1.3.3.2. Active solar (SOLAR)

The four SOLAR homes consisted of a block of two 2 bedroom (71m^2) and two 3 bedroom (83m^2) terraced homes (Figure 1-15). Their design, construction, and facilities were similar to CONTROL including an equivalent gas boiler but with the hot water being supplied from a thermal store rather than instantaneous. In addition the SOLAR homes were characterised by the addition of a roof mounted array of active solar technologies. These included a grid connected photovoltaic (PV) array to generate electricity and a solar thermal system for providing hot water (SHW).

Figure 1-15: SOLAR showing front elevation with PV and solar hot water collectors

PV

The PV system consists of a total of 38 polycrystalline modules installed on a south facing roof at an angle of approximately 45^{o} and covering 51m^2 of roof area, giving a total install capacity of 6.2kWp. The modules were split between the four homes giving each their own separate grid connected systems. Two of the homes had ten and two had nine PV modules (1.6kWp and 1.5kWp respectively) (Table 1-3)[12]. An inverter was installed next to the front door inside each home with an LCD display metering the electricity generated in kWh.

Solar hot water (SHW)

The solar hot water system supplemented the main hot water supplied from the gas boiler. Two homes had a single 2m^2 solar collector module and two homes had a double 4m^2 solar collector module (Table 1-3). A 210 litre thermal store, expansion vessels and associated controls were housed in a purpose built cupboard in the bathroom. The boiler contribution was controlled by a programmable seven day timer.

[12] The PV system installed provides electrical power during daylight hours to supplement the mains power being drawn from the national grid. The solar modules on the roof convert radiant energy from the sun into a direct electrical current (DC). The modules are connected in series to form a string (Solar Array). The string is then connected to the properties own inverter. The inverter converts the DC supply from the solar array into alternating current (AC) at 50Hz. This is the same frequency as the national grid supplied to homes. The output from the inverter must be synchronized with the main grid supply and the supplied inverter carries out this function. In addition the inverter has a built in LED indicator panel which meters the energy being generated.

1.3.4. Passive solar with mechanical ventilation with heat recovery (MVHR)

The terrace of four MVHR homes utilized the same heating system as CONTROL but differed in design (Figure 1-16). A double height sunspace with an internal brick wall aimed to utilise solar gain to moderate internal temperatures in conjunction with mechanical ventilation with heat recovery system (MVHR). The system used a balanced whole house extract with heat recovery system. The MVHR unit was housed in the loft with insulated ducts leading to the inflow and extraction vents. The extract vents were installed in the ceilings of the sunspace, kitchen and bathrooms, living room and bedrooms. Pre-warmed fresh air enters the home via inflow vents installed in the living room and bedrooms.

Figure 1-16: Lingwood MVHR homes showing south facing elevation (image source: J. Monahan)

Figure 1-17: Inside the MVHR sunspace showing internal thermal mass wall (image source: J. Monahan)

1.3.5. Ground source heat pumps (GSHP)

The terrace of four GSHP homes were all electric with space heating and hot water demand supplied by a ground source heat pump (GSHP) supplying heating through an underfloor heating loop in the ground floor and radiators to the upstairs. The heat pumps were housed externally in insulated purpose built housing with the controls and hot water tanks housed inside in the under stairs space and a purpose built cupboard in the upstairs bathroom respectively (Figure 1-18– Figure 1-21). It was estimated that the total floor area required for the heat pump components was 3.5m^2. This was estimated to be 4% of the total internal floor area. The heat delivery was controlled by a dial ‘thermostat’ positioned in the hallway and a summer/winter switch setting to operate the heating seasonally. The ground space limitations meant that conventional ground source heat exchangers buried in trenches at low depths could not be used. Vertical closed loop ground source heat exchangers were used, installed using a hydraulic rig. This approach minimised land required, construction time, ground works, disturbance, waste and materials.

Figure 1-18 Heat pump external housing and contents

Figure 1-19 Heat pump external housing and contents

Figure 1-20 Ground floor under stairs controls

Figure 1-21 Upstairs hot water

1.3.6. The monitoring and evaluation study

The data required for this interdisciplinary research was undertaken during the first year of occupation and included the following aspects:

- The materials and resources used during construction.
- The energy used during occupation and the resulting carbon emissions
- The energy produced by the different renewable energy technologies
- The contribution of the renewable energy produced to total annual energy budget and the resulting carbon savings

- The effects of occupants lifestyle and behaviour on annual carbon emissions
- An assessment of the occupant views of the technologies and how they used them.

An innovative smart metering system was going to gather data on energy consumption, appliance use, renewable energy production, and direct use of renewable energy in the home. Unfortunately, technical issues with the smart metering technology were unable to be resolved in the short data collection period. Manual meter readings and the results of modelling energy use and energy generation from the various technologies employed were used.

In addition to energy use data questionnaire surveys, two semi-structured interviews and informal conversions were used to gather quantitative and qualitative data pertaining to lifestyle, patterns of occupation and energy use as well as attitudes to energy and the environment (Appendix 1). All results described are anonamised to protect the privacy of the occupants.

1.4. Thesis structure

This thesis is divided into 7 chapters:

Chapter 1: Introduction

Chapter 2: Embodied energy study

Chapter 3: Comparative energy study

Chapter 4: A specific industry response to policy: increased deployment of mechanised ventilation with heat recovery in relation to building regulations part L1a and Part F

Chapter 5: The energy performance gap and household factors

Chapter 6: Adoption and adaption of new energy technologies by passively adopting households

Chapter 7: Overall discussion and conclusions

Chapters 2 to 6 are related to the four study themes as described in Figure 1-9 required to answer the three research questions. Each of these chapters were written as standalone research papers and were based on the case study housing development. Each includes a subject relevant literature review, methodology, results, analysis, discussion and conclusion specific to the topic and appropriate to the disciplinary approach taken. Chapters 2 and 3 are quantitative. Chapters 4 and 5 are mixed method, using both quantitative and qualitative methods. Chapter 6 uses a qualitative approach. The four study areas are inter-related, cross referencing between these chapters occurs throughout this thesis. Chapter 7 concludes the thesis by summarising the key findings from chapters 2 to 6, generalising the findings from the case study in the context of the research questions posed in section 1.2.1 and suggesting policy relevant recommendations.

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2. Embodied energy and carbon study

This chapter addresses research question 1 outlined in Chapter 1:

What are the embodied energy and carbon consequences of constructing new low energy homes compared with conventional construction?

The embodied energy and carbon consequence of the construction of an innovative low energy offsite modular timber framed construction (scenario 1) are compared with a model of an identical house constructed using two alternative scenarios: Scenario 2 as scenario 1 but with a conventional brick façade; and Scenario 3, a conventional masonry cavity construction.

A peer reviewed paper based on the research described in this chapter has been published and is included in Appendix 2 (Monahan and Powell 2011).

This chapter is organised as follows. Section 2.2 reviews the literature specific to the LCA method. Its application to studies of the environmental impact of constructing new housing with a focus on the UK is explored. The findings of these studies are summarised in terms of GJ per m^2 and, or, $kgCO_2$ per m^2 of floor area. The methodology is then described in 2.2. The results of the inventory analysis of the case study house (scenario 1) are given before of the two alternative scenarios (scenarios 2 and 3) in section 2.5. The results are discussed in section 02.6 before the implications for the UKs house building programme and its impacts on national carbon emissions are explored (section 2.7). Section 2.8 concludes this paper.

2.1. Introduction and background

The construction and occupation of buildings is a substantial contributor to global CO_2 emissions, with almost a quarter of total global CO_2 emissions attributable to energy use in buildings (B. Metz et al. 2007). A further 5% has been attributed to the manufacture of cement, a principal construction material (Worrelle et al. 2001). Reducing the energy demand and consequential carbon emissions attributed to buildings is clearly an important goal for government climate policy.

The energy and associated emissions of carbon (referred to in terms of CO_2) linked with the lifecycle of the built environment can be considered in three distinct, but inter-linked stages. These are construction, occupation, and end of life deconstruction. Reducing occupational energy has been a significant focus for UK mitigation policy at national level, particularly that relating to reducing the energy demand of housing. Although the energy used and consequential carbon emitted during the occupation of a building equates to the majority of that buildings lifetime carbon footprint, there are significant carbon consequences involved in the initial construction of a building.

The extraction, processing, manufacture, transportation, and use of a product utilises energy and produces many environmental impacts, including emissions of CO_2. These impacts are hidden, or embodied, resource or environmental burdens. Embodied energy and carbon are not, in general practice, a consideration when a building is designed, specified and constructed.

For housing constructed to conventional standards embodied energy forms a relatively low proportion of lifecycle energy, between 2 – 36% (Sartori and Hestnes 2007), there are exceptions to this, such as low energy buildings (Lippke et al. 2004). Embodied carbon is of particular importance for low energy buildings (Thormark 2002) because although less energy is used during occupation, additional energy is often required for the manufacture of the increased levels of insulation, the heavier mass materials used and the additional technologies often deployed. The embodied carbon of a low energy house is likely to contribute a greater proportion of its overall lifecycle carbon emissions during that buildings lifetime than would occur for a conventional house. The size of this substitution effect is unclear. The proportion of lifecycle energy attributed to the winning of primary materials, manufacture, transport and construction of a building has been found to be between 9 - 46% for a low energy house (Sartori 2007). The materials specified and the construction technologies used greatly influence the overall embodied energy and carbon emissions during the construction phase.

Another area of concern is the embodied energy associated with waste. In the UK the construction industry is responsible for over a third of all waste arisings (DEFRA 2009), although 51% of this is recycled or re-used, the majority as aggregate (VanGeem and Marceau 2008). On site construction typically has contingency and error related over ordering, amounting to approximately 10% of all materials brought to site, with 10 – 15% of the materials imported to a construction site being exported as waste (McGrath 2000). Reducing the embodied energy of construction waste needs to address the efficiency of both manufacture and use. One solution is the increased use of offsite manufacturing, or modern methods of construction (MMC), of housing components or whole houses. The factory production of construction elements can have much lower resource inputs and reduced waste outputs than compared with on-site construction (WRAP 2008a). A recent report estimated the waste reduction through substitution of traditional methods with prefabrication systems to be between 20 – 40%, the greater the prefabrication the greater the savings (WRAP 2008a).

With the UK governments' commitment to increasing the number of new homes and a substantial increase in the thermal renovation of the existing housing stock (DCLG 2007) there will be significant implications for the UK's national carbon budget. However the magnitude of this impact will be dependent upon how these houses are constructed.

2.2. A review of housing LCA literature

2.2.1. Carbon and energy in construction of housing

There is a small but growing body of literature on embodied energy and carbon in the construction of houses (these are summarised in Table 2-1). Many early studies are principally concerned with embodied energy, expressed as primary energy and not carbon.

Nässén et al (2007) summarised the results of 20 studies, predominantly Scandinavian, published prior to 2001. The studies were characterised as either cradle to construction or cradle to occupation. They found that the majority of studies used a process based (bottom up) life cycle assessment methodology rather than an input-output (top-down) life cycle methodology. The studies showed similar results with a range of 1.3 – 7.3 GJ/m^2 primary energy for residential buildings, an average of 3.1 GJ/m^2. I/O type studies consistently gave higher results in terms of primary energy than those using process based methodology. An average result 3.4 GJ/m^2 compared with 2.8 GJ/m^2 respectively. This is unsurprising as I/O type LCAs include a wider range of sectors, including service sectors.

Results concerning embodied carbon are scarcer still. In the same paper, Nässén et al. (2007) gave results of 264$kgCO_2/m^2$ detached and 360 $kgCO_2/m^2$ for a multi- occupancy dwelling. However, the studies all used different parameters, assumptions, factors, datasets and boundaries (Nässén et al. 2007). These methodological differences between individual studies raise questions on the comparability of the different study results. Studies differ by: country; house type (e.g. single dwelling or multiple occupancy); construction type; of data (primary or secondary such as a relevant substitute from another industry/country/process or modelled) (Sartori and Hestnes 2007).

Embodied energy values, and any estimates or embodied carbon values that are based on them, will also vary enormously between countries. In particular that related to electricity generation. There is enormous variation in the primary fuels used, the transformation processes used; the efficiency of the industrial and economic systems in place; and how these factors vary over time (Nässén et al. 2007, Sartori and Hestnes 2007). Comparative analysis between these studies is difficult without clear information on where and when the data used where collected. The differences between studies are too great for any real meaning or weight to be given to the results of any attempts at comparisons. Indeed both Nässén et al. (2007) and Sartori and Hestnes (2007) suggest that any direct comparisons or general conclusions would be inappropriate. The results from such lifecycle studies are indicative and should be interpreted with caution and careful attention to the methods used, the system boundaries applied, what has (or has not) been included before any interpretation can be made or conclusions drawn.

At the time of undertaking this study the literature specific to embodied carbon and energy of UK housing construction is sparse. Of the three papers found in the peer reviewed literature relevant to the UK the papers gave incomplete detail of the system under study and used older embodied energy data (Table 2-1).

Asif et al (2007) reported 3.25GJ/m^2, which is at the lower end of the range found in previous studies (Table 2-1). This may be due to the limited nature of the study. The authors confined the analysis to a narrow range of materials, failing to specify what cut off criteria were used or what and why materials were excluded. Furthermore the embodied energy data and carbon (reported in terms of GWP and in units of g/kg) was derived from relatively old secondary data and aggregated to a single value. No information was provided on waste or transportation. Hacker et al (2008) in a comparative study of four variations of the same house from lightweight (timber frame) to heavyweight (concrete) found a range of embodied carbon 492 – 569 $kgCO_2/m^2$ but did not provide findings as primary energy. Again boundaries are unclear, as are cut off criteria.

Table 2-1: Summary of embodied energy and carbon literature

Ref. source	Cited source	Study origin	No. cases	LCA scope	Main material	Primary energy GJ/m^2	Embodied carbon $kgCO_2/m^2$
Nässén et al. 2007	Adalberth 1997	SE	3	cradle to occupation	wood	2.9-3.7	
	Adalberth 2000	SE	2	cradle to occupation	concrete	3.2-3.5	
			1	cradle to occupation	wood	4.5	
			1	cradle to occupation	steel/ concrete	3.4	
	Thormark 2002	SE	1	cradle to construction	wood	6.2	
	Keoleian et al. 2000	US	2		wood	6.6-7.3	
	Buchanan and Honey 1994	NZ	4	cradle to construction	steel/ brick	4.7	
				cradle to construction	concrete	3.4	
				cradle to construction	wood	1.7	
				cradle to construction	wood/ brick	3.9	
Sartori and Hestnes 2007	Fay et al. 2000		1	cradle to occupation	wood/ brick	14.1	
	Mithraratne and Vale 2004		3	cradle to occupation	wood	4.4	
					concrete	4.8	
					super insulation	5	
	Winther and Hestnes 1999		5	cradle to construction + 50 years maintenance	wood + variant scenarios	1.5-3.1	
Monahan and Powell 2011	Hammond and Jones 2008	UK	14	cradle to construction	mixed	5.34	403
	Asif et al 2007	UK	1	cradle to construction	not known	3.25	x
	Hacker et al 2008	UK	4	cradle to occupation	mixed	x	492-569

The recently published inventory of carbon and energy (ICE) database (V1.6a) (Hammond and Jones 2008) addresses some of these consistency issues. The inventory, which is freely available in the public domain, contains data on embodied energy and carbon (as CO_2) for building materials from secondary sources. Using clear definitions the inventory aims to provide an open access resource for use in construction studies in the UK and provide some consistency across different studies published in the public domain. The inventory data defines: a cradle to gate boundary; UK preference in data sources, followed by EU or worldwide averages; the most recently available data; and British emissions factors applied to estimate fuel related carbon. Hammond and Jones (2008) applied the inventory to a number of UK housing construction case studies and reported an average of 5.3GJ/m^2 embodied energy and 403kgCO_2/m^2 embodied carbon. The average embodied energy is comparable with the findings of Nässén et al (2007).

The comparison of timber (or lightweight construction) versus concrete (or heavy weight construction) is fairly common in the literature (see for example: Buchanan and Honey 1994; Adalberth 2000; Mithraratne and Vale 2004; Hacker et al. 2008; and Winther and Hestnes 1999). Typically construction using higher embodied energy materials such as concrete, or brick based masonry construction and insulation materials is found to be of higher initial embodied energy than that of timber (Table 2-1). It has been argued that efforts to reduce occupational energy through the increased use of relatively energy intensive materials, such as insulation and high mass materials including concrete changes the relative proportions of total lifecycle energy (Winther and Hestnes 1999). Winther and Hestnes (1999) argue that there is a substitution effect which the reduction in occupational energy achieved is, to some degree if not completely, offset by the increase in embodied energy. Sartori and Hestnes (2007) in a review of literature that considered 60 cases found that low energy buildings the embodied energy was marginally higher proportion of total lifecycle energy, approximately 38% for conventional buildings (Treloar et al. 2000) and ranging between 9% (Feist 1996) and 46% (Thormark 2002) for low energy housing. This suggests that as occupational energy demand reduces, embodied energy in construction increases in importance.

Material substitution has been shown to reduce the initial embodied energy in buildings. Venkatarama Reddy and Jagadish (2003) compared the embodied energy of common and alternative building materials, such as concrete and burnt clay masonry in an Indian context. They found that the total embodied energy of load bearing masonry buildings can be reduced by 50% when low energy alternative materials are substituted, in the Indian case substitutes included unfired bricks. Other studies, for example Buchanan and

Honey (1994) in the New Zealand context, looked at the net carbon emissions from construction of buildings and concluded that significant reductions in CO_2 emissions would result from a shift from steel and concrete to greater use of timber. Although they note that such reductions in CO_2 would be compromised unless the timber is produced sustainably as a renewable resource.

In summary the studies found in the literature are often not comparative. They critically lack clear definitions and have inconsistent boundaries and are deficient in the level of detail required to make any comparisons. Despite this, there is a surprisingly consistent range of embodied energy and carbon results can be found within the literature.

Whilst a number of studies compare the relative merits of timber versus masonry/concrete construction in low occupational energy housing none of the studies cited have quantified and compared the carbon from construction of housing constructed using MMC methods with that from conventional construction in the UK. This forms the basis of the study detailed in this paper, in which the embodied carbon of a house constructed using MMC methods is compared with two alternative construction scenarios for the same house using a life cycle framework. The results are considered in the context of the UKs house building programme and its impacts on national emissions targets.

2.2.2. Life cycle assessment framework

The growing importance of environmental issues, such as climate change, has created a need to evaluate and compare the impacts of the products we use. A principle technique used to quantify and compare the environmental impacts of a product, process or service (from this point forward 'product' will be used as the general reference term) is Life Cycle Assessment (LCA). The majority of housing case studies found in the literature use a LCA method. LCA was first developed and applied during the late 1960's and early 1970's in separate methodological developments in the USA, UK, Germany and Sweden (Hunt et al. 1996; Baumann and Tillman 2004), principally in studies by companies seeking to reduce production costs, minimise waste and environmental impacts or compare production. Each study employed different methodologies making comparisons difficult and raising questions concerning robustness. During the 1990's a process of consensus building by the LCA community culminated in the standardisation of the LCA methodology in International standards, ISO 14040 to 14044 (ISO 2006) (Baumann and Tillman 2004). Life cycle assessment is still a relatively young discipline and is continually developing (Finnveden et al. 2009).

Recently, in response to demands for publicly available information on the carbon impacts of products and services, carbon footprinting has come to the fore and been widely promoted by non-governmental organisations, business and governmental institutions, for example Tesco's carbon labelling project (Tesco Ltd 2008, Weidema et al. 2008). A carbon footprint approach is a simplified accounting approach of quantifying and presenting data on emissions of carbon, with a single indicator, that of kg of CO_{2e}, which is more readily interpreted by non-expert audiences. Wiedema and Minx (2007) define carbon footprinting as:

"a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product." (p.4)

The Carbon Trust and DEFRA have developed a standardised methodology for assessing lifecycle GHG emissions, the Publically Available Specification (PAS) 2050 (PAS 2050 2008)[13]. The PAS 2050 (2008) specification is based on the existing the ISO 14040 and ISO 14044 standards, adopting a lifecycle approach but it clarifies, adapts and simplifies the specifications specifically to quantifying the carbon footprint of products across their supply chains *"from raw materials through all stages of production distribution, use and disposal/recycling"* (p.2). Clearly developed using life-cycle thinking, albeit in a slim line fashion, PAS 2050 (2008) aims to be practical to implement, and to support the comparability, compatibility and additivity of results. At the time of instigating the embodied carbon research presented in this chapter PAS 2050 had not been published therefore the ISO 14040/14044 specification was adopted as the framework for the embodied carbon and energy study.

The ISO 14040 defines LCA as the:

'Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.' p.2

As such LCA is both a model of, and a procedure for evaluating, the environmental impacts of a product (Baumann and Tillman 2004). As a model, life cycle assessment follows a product from its "cradle" of raw material extraction from natural resources through production, use and eventual "grave", its final disposal. In figure 2-1 natural resources use, as inputs in the system model, and pollutant emissions, as outputs in the system model, are quantified through the physical processes, the boxes, and flows of energy and matter, the arrows (Baumann and Tillman 2004).

As a procedural framework the ISO LCA consists of four main phases (ISO 2006)

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13 PAS 2008 is the reference used here as being contemporary with the research period. A revised edition has recently been published, PAS 2011.

(Figure 2-2):

1. Goal, scope and definition
2. Inventory analysis (LCI)
3. Impact assessment (LCIA)
4. Interpretation.

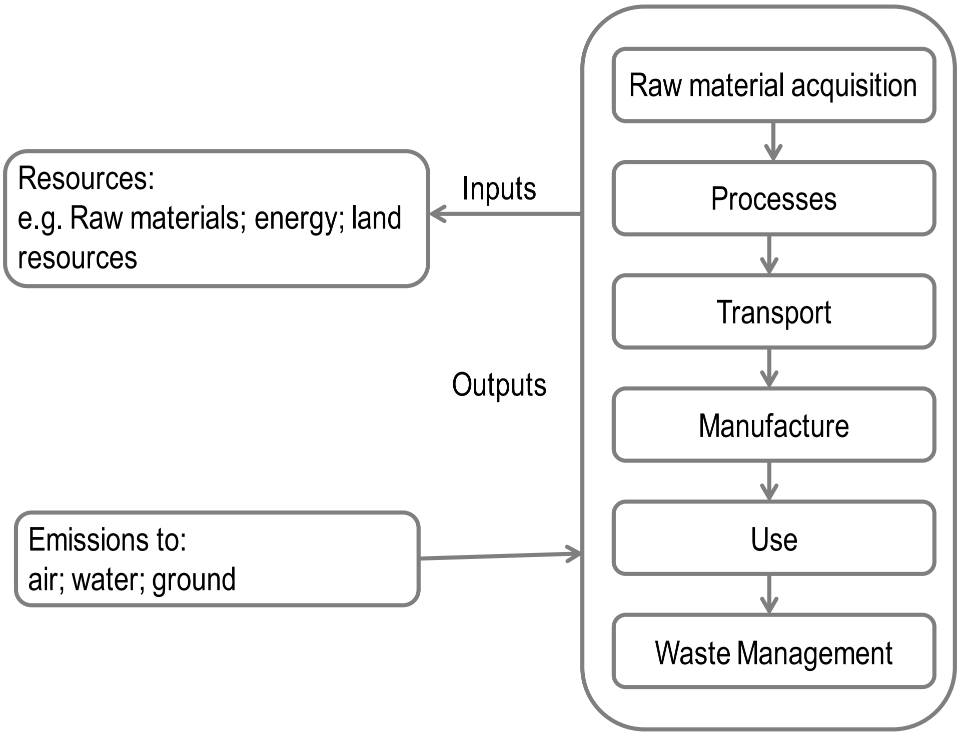

Figure 2-1: Life cycle model in which boxes indicate physical processes and arrows flows of energy and matter (Baumann and Tillman 2004)

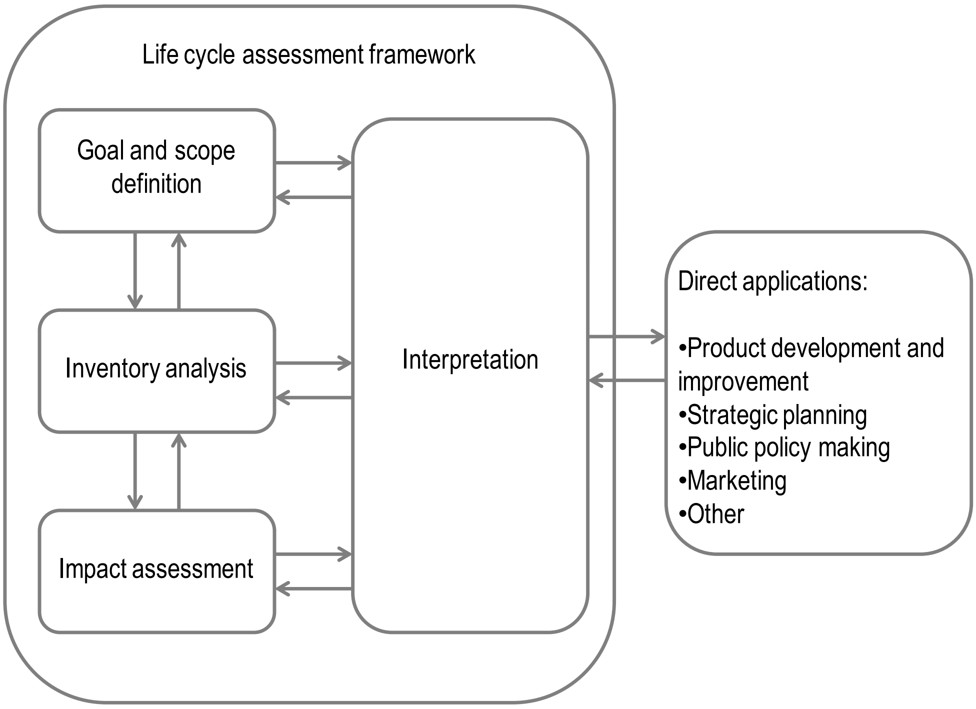

Figure 2-2: Four phases of an LCA (ISO 2006)

2.2.2.1. Goal, Scope and definitions

The initial goal and scope definition phase of an LCA specifies in detail the purpose of the study and research questions and defines the functional unit, system boundary, level of detail and how the environmental burdens will be allocated (Table 2-2) (ISO 2006). The aim of the goal and scope definition is to unambiguously state the choices made, the specifications employed and any assumptions made to facilitate the replicability, comparativeness and transparency in reporting results of the study. In reality not all the choices may be evident or even foreseeable at the outset of an LCA study and the process is an iterative one as indicated by the arrows in Figure 2-2. The goal is explicitly contextual and addresses questions of why it is being done, by whom and for what purpose. The scope is concerned with making choices concerning the methodology to be used in the LCA. These decisions will be influenced by the goal of the study and will relate to the subsequent modelling and phases of the study.

Table 2-2: Goal and scope components as defined by ISO (ISO 2006) p.11

Section	Definition
Goal	The intended application
	The reasons for carrying out the study
	The intended audience, i.e. to whom the results of the study are intended to be communicated
	Whether the results are intended to be used in comparative assertions intended to be disclosed to the public
Scope	The product system to be studied
	The functions of the product system or, in the case of comparative studies, the systems
	The functional unit
	The system boundary
	Allocation procedures
	The impact categories selected and methodology of impact assessment, and subsequent interpretation to be used
	Data requirements
	Assumptions
	Limitations
	Initial data quality requirements
	Type of critical review, if any
	Type and format of the report required for the study

The key definitions in the scope are the functional unit; system boundaries and allocation.

A functional unit is a quantified description of the performance of the product used as a common reference unit that will allow comparison on an equal basis and relates to the study goal. For example, in buildings and construction the functional unit could be at the level of the whole building or material/component (Kotaji et al. 2003). Whole buildings functional unit may be defined by a series of performance characteristics, chosen according to the study goals or on criteria such as m^2 internal space, m^3 volume, number of inhabitants. Building materials and components functional unit may be defined in terms of 1 tonne of mortar or per installed unit such as $1m^2$ wall with U-value X. In reality the situation may be more complex, alternative building elements may be likely to have secondary functions in addition to the main function. For example, in comparing alternative wall elements of equivalent load bearing and thermal properties may have different loads which require more or less concrete and steel in the foundations to achieve the required stability therefore comparing $1m^2$ of wall as the functional unit of study will be erroneous and such a study should be at the whole building level. The same alternative wall elements will also have one or more other functions in addition to that main function (e.g. load bearing) such as thermal or sound insulation that add value and effect overall performance. However, in some situations, when comparing elements with the same functional equivalence and primary and secondary functions it can be assumed that the comparative options will not affect the building performance and a comparative assertion can be made (Kotaji et al. 2003). For example, if window options are of the same size and thermal properties it may be assumed that window choice will not affect the wider structure of the building and comparative assertions can be made.

The system boundary is defined in ISO 14040 as a "set of criteria specifying which unit processes are part of a product system" (p4) and defines "the unit process to be included in the system" (p.12) (ISO 2006). The system boundary defines what it is that is to be accounted for and what is to be excluded in the LCA study. The processes included are in turn dependent upon the goal and scope definitions, the intended application and audience, assumptions made, data and cost constraints and the cut-off criteria (Baumann and Tillman 2004). ISO14040 does not specify where boundaries are to be drawn only that they must be clearly described. Boundary decisions are at the discretion of the practitioner and are, therefore are subjective and arbitrary (Finnveden et al. 2009).and obtained through experience (Frischknecht et al. 2007). This is a weakness of the LCA technique and ISO framework that makes comparisons between different studies difficult. Comparative analysis of different studies is dependent upon the system boundaries used by the different LCA studies and these are often inconsistent. This is why it is essential to clearly and explicitly define the system, including any excluded processes, materials, or services, all assumptions underlying the choices made and any cut-off criteria to be clearly defined. Sufficient information should be provided to allow another practitioner to duplicate the study and facilitate comparative analysis. Sinden (2009) notes that PAS 2050 (2008), in setting specific boundary requirements, has clarified this issue.

There are three main boundary types that define the extent and cut-off points of the Life cycle inventory (Guinee et al. 2002):

- Between the technical system and the environment
- Between significant and insignificant processes
- Between the technological system under study and other technological systems

The boundary between the technical system and the environment is, by convention, set at the point where raw materials are extracted at source and emissions and waste outputs are produced (Baumann and Tillman 2004; Finnveden et al. 2009). It follows that the cut-off points for the system are where these elementary flows enter or leave the system. ISO (2006) defines elementary flows as *"material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation"* (p 3). For example, crude oil is produced in the natural system and is therefore an input, or elementary flow, whilst diesel oil is a product in the technical system and is not. The outputs will be distinct as well. In many cases the boundary between technical system and the environment is self-evident. But in cases where the life cycle includes forestry or agriculture and emissions are to waste water systems and waste systems such as landfill it is less clear and the system boundary needs to be explicitly defined (Finnveden et al. 2009).

Defining the system boundary between significant and insignificant processes is problematic as it is generally not known in advance of the LCI phase, hence the iterative nature of LCA studies. Typically, LCA's account for the impacts arising from direct processes, such as extraction, transportation, manufacture and use, excluding second order impacts, such as infrastructure (e.g. the roads that good are transported on or the power stations that produce the energy used in manufacture) (Baumann and Tillman 2004). Second order impacts may be negligible and excluding them will not have any significant effect on the results (*ibid*). However the reverse may apply. For example, construction projects, such as the tunnels required the use of tunnelling equipment which may be specific to the excavation and construction of that tunnel project and have no other useful purpose after its function was fulfilled, being 'mined' into the ground adjacent to the tunnel after useful life. Its production would have a significant impact on the whole LCA of the construction of the tunnel and should be included. Conversely, plant machinery used on housing construction sites is often hired in and used on multiple construction sites over an extended period of time of that plants useful life. If the contribution of second order impacts from the use of such plant to overall life cycle of any one project is minimal, falling below the cut-off criteria, and it may be excluded from the study.

The boundary between the technological system under study and other technological systems refers to the fact that all technical systems are intimately embedded in a wider context of other background technical systems (Baumann and Tillman 2004). In reality no system is completely closed and it is impossible to clearly delineate a single products production and use processes from the background context. But boundaries need to be drawn somewhere to make a study manageable. For example, should the transportation of workers to and from the place of production be included? Where should the boundary be drawn between personal impacts and the production system impacts be drawn? In most cases such boundaries will be self-evident and relatively easy to clearly define. But in many cases this can be problematic particularly where processes are multi-functional, such as when a process is shared between more than one product system and it is not clear which product the impacts should be allocated to (*ibid*). Allocation is discussed below.

The start and end point of the life cycle need to be clearly defined. System boundaries are typically drawn from cradle to grave or cradle to gate. A cradle to grave is the full LCA from resource extraction, through use and final disposal at end of life. Cradle to gate is a partial LCA from resource extraction to the cut-off point at the end of production typically prior to transportation to the consumer. In the case of buildings, considered as an assemblage of products the gate boundary may be at the point of construction on site. In partial LCA cradle to gate studies the use and disposal of the product are outside the study boundary. A third definition, not widely used, is cradle to cradle (McDonough and Braungart 2002). In cradle to cradle assessment the end of life disposal for the product is into a recycling process which originates in new, identical, or different products.

The ISO standard defines 3 cut-off criteria that should be used: mass; energy; and environmental significance. Mass and energy cut-offs are set based on a contribution of more than a defined percentage of the product systems. Environmental significance cut-off criteria are based on the amount of the estimated quantity of individual data of the system that are specifically selected because of environmental relevance.

Allocation is a focus of much methodological discussion in LCA literature and is defined in ISO 14040 as *"partitioning the input or output flows of a process or a product system between the product system under study and one of more other product systems"* (ISO 2006) p.4. Allocation problems are encountered in three basic cases (Azapagica and Cliftb 1999; Baumann and Tillman 2004):

1. multiple output processes or systems(termed co-production). How much of the resources consumed or emissions emitted of the process are associated with the different fuels used
2. multi-input waste treatment processes (e.g. incineration or landfill)
3. open loop recycling processes or systems where a product is recycled, producing

a new product.

Allocation should be avoided by increasing the level of detail through either a) sub-dividing the unit process into two or more sub-processes or b) expanding the system to include the additional functions related to the co-products. If allocation cannot be avoided the inputs/outputs should be partitioned in a way that either reflects the underlying physical relationships (e.g. mass or energy) or that reflects some other relationship between them (e.g. economic value of the product(s), mass or energy).

Allocation for long lived products, such as buildings, is particularly problematic for end of life scenarios (Kotaji et al. 2003). For example, components and materials may be recycled, re-used, incinerated, or buried in landfill. For long-lived products, such as buildings, this will occur some distance into the future therefore current processes, technology and data are unlikely to be applicable (Curran et al. 2005). Construction waste management is in a dynamic transitional period as the UK continues to implement increasingly tighter regulation on waste in order to radically reduce landfill. How buildings constructed today are reprocessed at end of life is likely to be very different from those being reprocessed today (WRAP 2007, 2008b).

2.2.2.2. Life cycle inventory (LCI)

The second phase, the life cycle inventory (LCI) involves is the compilation of an inventory of the input/output data of the system under study. Baumann et al (2004) describe the procedure as three stages:

- Constructing a model of the system
- Collecting data
- Calculating the environmental loads

Data can be both quantitative and qualitative. Qualitative includes descriptions of technology, how and when emissions are measured and geographical locations of inputs/outputs (Baumann and Tillman 2004). For example, transport data will include routing and distances travelled as well as vehicle descriptions and fuel consumption. Data are collected from multiple sources including: databases, other studies; direct from manufacturer/supplier/customer; readymade inventories from academia/industry/government; or collected directly by the practitioner (*ibid)*.

Calculating the environmental loads is a process of normalisation, summing up and consolidating the data. Data in its raw state will often have different units and require conversion into a common unit. The process also needs to be documented.

Whilst inventory analysis is relatively straightforward it is however the most time consuming element of conducting an LCA and a significant source of error (Baumann and Tillman 2004). Firstly, there will always be gaps in data where no primary or suitable substitutable data are available. Data gaps are filled with estimates and assumptions derived from technical experts or modelled both of which will be dependent upon assumptions made. Secondly, the data will be normalized into consistent units involving conversions from the unit of data collection in to the normalized unit for calculation and human error is always going to happen.

2.2.2.3. Life cycle impact assessment (LCIA)

The third phase, the life cycle impact assessment (LCIA), aims to describe the potential impacts of the environmental loads quantified by the inventory analysis (Baumann and Tillman 2004). LCIA is not a compulsory element of a lifecycle assessment as defined by ISO 14040 and may be omitted. Depending upon the parameters of the study as specified in the goal and scope a partial LCA that summarises the LCI may be all that is necessary to fulfil these aims. In such partial LCA assessments the impact assessment is omitted and it is LCI that is summarised and used in the final interpretation phase. However, the inventory analysis can produce a large amount of information on emissions and resources which need to be summarised into environmentally relevant information, such as acidifications, eutrophication, global warming potential, ozone depletion, land use change, biodiversity. A further purpose, less often explicitly stated, is to aggregate the inventory data into fewer parameters, making it more manageable (Baumann and Tillman 2004).For example in embodied carbon studies the LCI collects data on energy consumption and this is then converted into carbon in units of $kgCO_{2eq}$ as the single indicator assessed.

Life cycle interpretation is the final phase in the LCA framework. The results of an LCIA or an LCI are summarised to form the basis for conclusions, recommendations and decision making as defined in the goal and scope (ISO 2006). Consequently, the outcomes from the interpretation are dependent on the assumptions, both explicitly stated and implicit, made in the initial phase.

2.3. Description of the case study

2.3.1. Model house

The analysis in this study is based on one of the Lingwood case study houses, a three bedroom semi-detached house of $83m^2$ internal floor area (Figure 2-3). Three scenarios are used: (1) the MMC case study as constructed with a larch facade; (2) as scenario one with a brick outer substituted for the larch as a facade material; and (3) a conventionally constructed house using masonry cavity construction (Table 2-3). Descriptions of scenarios one, two, and three are given in sections 2.3.2, 2.3.3 and 2.3.4 respectively.

Table 2-3: Design parameters of the three case study scenarios: (1) MMC timber frame with larch cladding; (2) MMC timber frame with brick cladding; (3) conventional masonry cavity wall

	Scenario (1) MMC timber frame larch facade	**Scenario (2)** MMC timber frame brick facade	**Scenario (3)** Conventional masonry cavity wall
number of floors	2	2	2
total internal floor area (m^2)	91	91	91
total footprint area (m^2)	45.3	46.6	46.8
total wall area (m^2)	113.5	115.0	115.3
wall width (mm)	273	319	327
opening area (m^2)	16	16	16
framework	timber	timber	masonry
u-value (W/m^2K):			
wall	0.18	0.18	0.18
floor	0.16	0.16	0.16
roof	0.14	0.14	0.14
windows	1.80	1.80	1.80

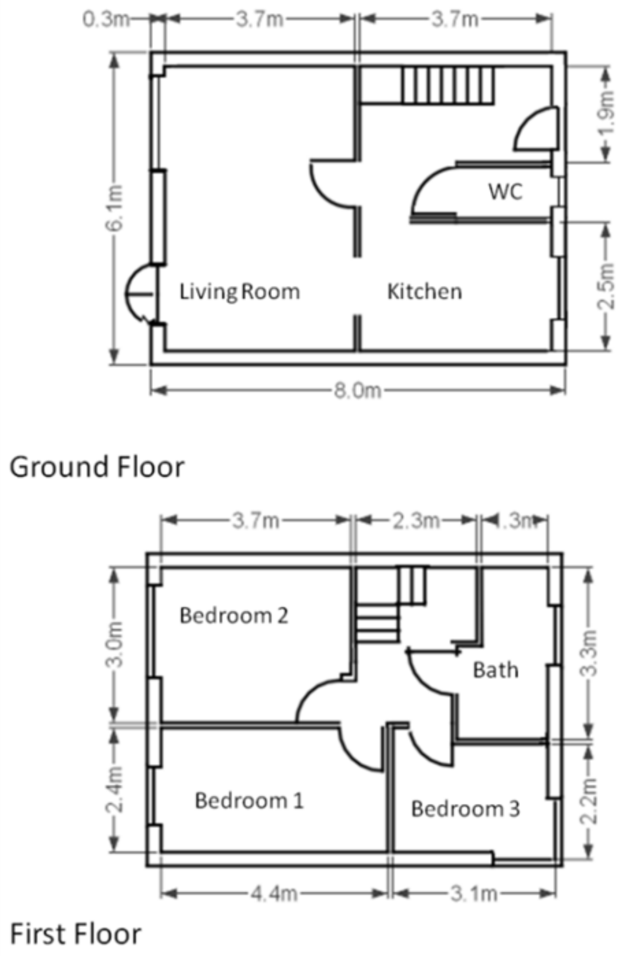

Figure 2-3: Plan dimensions of case study house

2.3.2. Scenario1: MMC timber frame larch cladding

The scenario1 house was constructed using a novel approach which combined offsite modular timber frame system with additional insulation materials to exceed current minimum building regulation standards and untreated Siberian larch weather boarding as the external facade installed onsite. The use of timber as a facade material is becoming more prevalent in commercial buildings as an aesthetic nod towards a buildings sustainable credentials but is still uncommon in mass produced housing in the UK at this time.

The pre-manufactured timber frame is a factory constructed modular system consisting of wall modules of a softwood timber frame with factory installed phenolic foam insulation to meet minimum building regulation standards, a cement particle board to form the inner outer surface and a waterproof polythene inner membrane (Figure 2-4). The modules are constructed to enable quick assembly on site and have the addition of design flexibility in the choice of material used as a facade. The first floor modules are constructed using engineered timber (I-beams and Glulam beams).

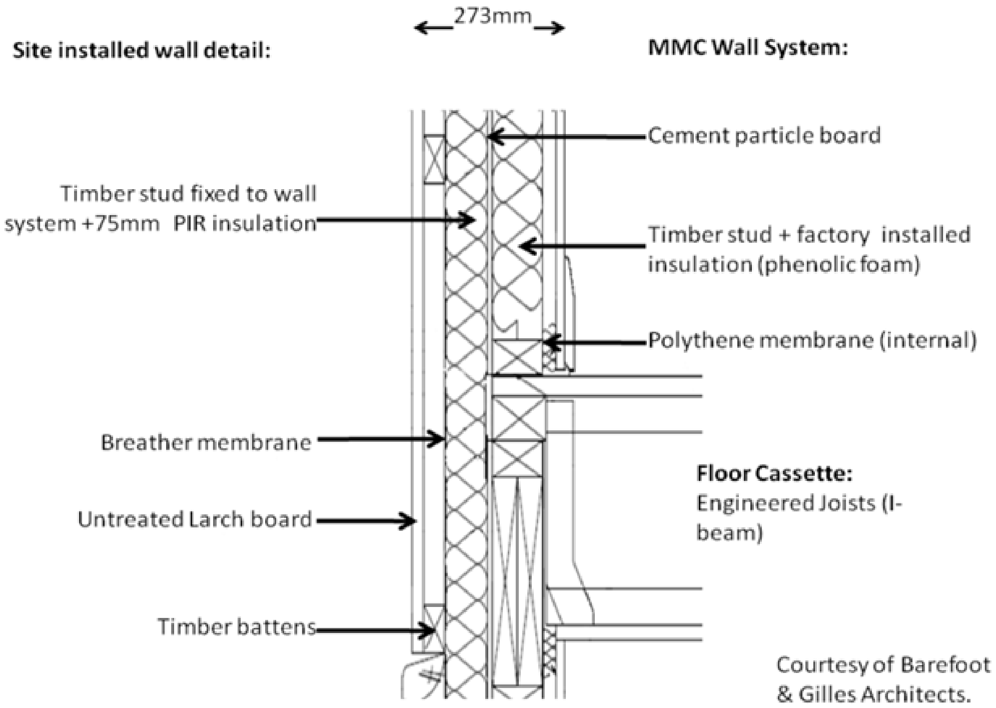

Figure 2-4: Sketch of MMC wall and floor components (source: Barefoot and Gilles Architects 2008)

The substructure, foundations, first floor, and roof are constructed using traditional construction approaches. The substructure consists of an over site poured concrete slab with steel reinforcement in shallow strip footings (Figure 2-5). Brick and cement block walling are used below the damp proof course. The suspended ground floor is formed from precast concrete and steel reinforced beams with an infill of concrete blocks.

Figure 2-5: Photograph showing oversite foundation slab and brick and block wall below damp proof membrane (image source: J. Monahan)

2.3.3. Scenario two: MMC timber frame brick cladding

In the scenario 2 house a brick facade replaces the larch facade and its associated components. The brick wall was assumed to be a single skin clay brick with a standard cement based mortar, fixed with stainless steel 'L-ties' to the MMC frame. The substitution required an increase in the wall width of the model house by 17% (Table 2-3). No other parameters were altered.

2.3.4. Scenario three: Conventional masonry cavity wall

In the Scenario3 house the timber frame and larch facade is replaced by a traditional masonry construction. This consists of a lightweight aerated concrete block internal wall, a cavity filled with a phenolic insulation and an outer brick facade. Steel wall ties were assumed to tie the inner and outer walls together.

Figure 2-6: Photograph showing a conventional brick and block wall construction with a full fill mineral wool batt insulated cavity (image source: S. Monahan)

The materials are substantially heavier than the timber frame in scenarios one and two and have a larger width. In this scenario the model was affected by an increased wall width and an increased substructure to accommodate the additional mass and wall width.

2.4. Methodology

2.4.1. Goal of this case study

The goal of the study is to investigate the carbon consequences of constructing new housing, comparing different approaches and identifying areas that could deliver reductions in embodied carbon. The ISO 14040/44 LCA framework is used as a tool to conduct a partial LCA, from cradle to site of the construction of a low energy house constructed using an offsite panellised modular timber frame system. Figure 2-7 shows the process flow chart and system boundaries of the LCA study. An inventory of the materials involved in the construction and the fossil fuel energy used during the construction was collated and then used to calculate the primary energy used. The primary energy data were then used to calculate the environmental impact indicator, embodied carbon, in units of kg CO_{2e}, the impact indicator.

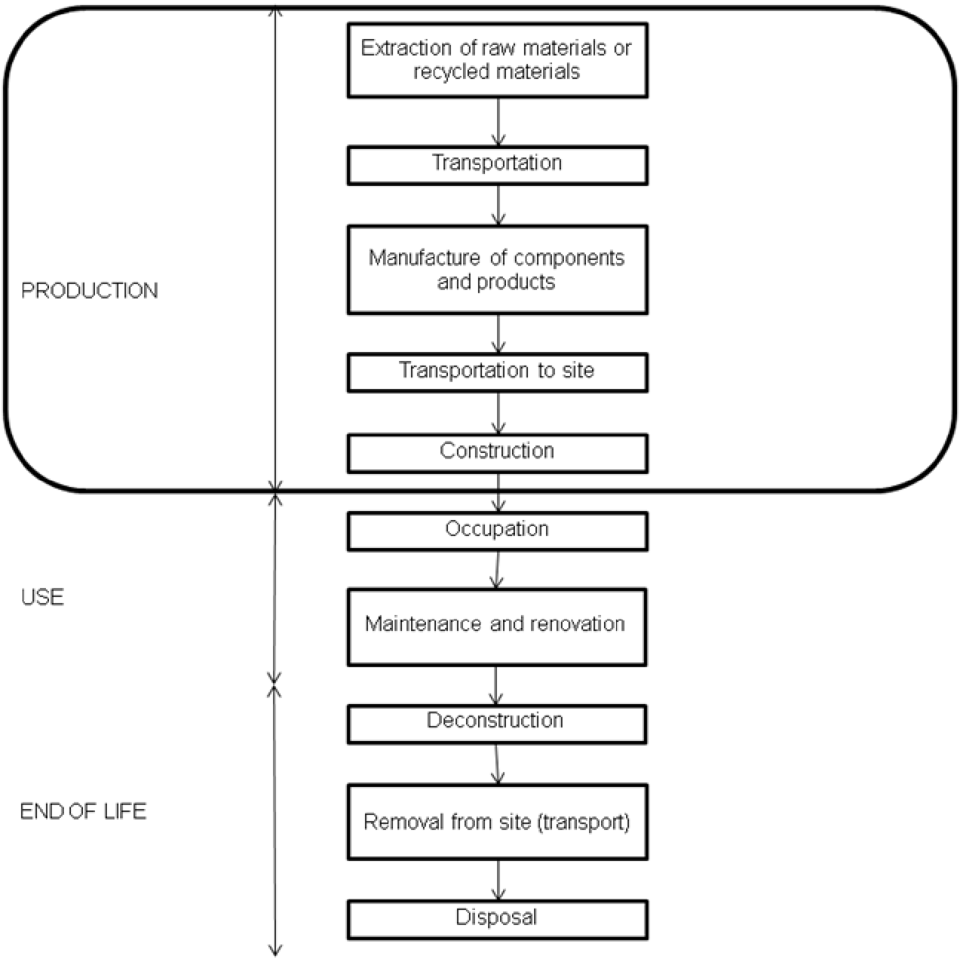

Figure 2-7: Lingwood embodied carbon case study process flow chart showing boundary at production stage

2.4.2. Case study boundaries

Figure 2-7 shows the case study boundaries of the embodied energy and carbon study to be from cradle to construction.

The study scope includes the cradle to site emissions from:

- materials and products used in construction
- final transport of the materials and products to site
- materials waste produced on site
- transportation of waste to disposal
- fossil fuel energy used on site during construction and in manufacture of MMC components

Second order impacts are outside the boundary of this study and are therefore excluded. Explicitly, the infrastructure required in production, such as roads, factories, warehouses and machinery, and the operational activities associated with administration and the workforce themselves (including their transport to site) were excluded.

The functional unit for this study is the external elements that constitute the envelope of a 3 bedroom, semi-detached house with a total foot print area of 45m^2 and a total internal volume of 220.5m^3. The envelope elements explicitly include floor substructure, external walls, and roof (including insulated ceiling).

For the purposes of the study internal elements, such as walls and doors, finishes, such as paints, plasterboard, skirting board etc., and fittings, such as bathrooms, lighting and kitchens etc., are excluded. The study assumed these would be equivalent for all construction types and, therefore, outside the scope of this study.

The windows were included. They were assumed to be identical for all three scenarios. They were included for completeness of the total embodied carbon for each scenario.

Allocation of the environmental impacts, where a process produces multiple or subsidiary products (for example timber production at a sawmill producing sawdust, woodchip and bark for use in wood fibre board manufacture or as fuels), are allocated by mass.

2.4.3. Inventory and data sources

The inventory of materials and inputs into the construction of the development were estimated from information provided by the quantity surveyors, architects, contractors, and companies providing goods and services along the supply chain for this property. The data were collected retrospectively, with varying degrees of quality as discussed below.

The dimensions of the house were obtained from the architects plans. Material quantities were obtained from quantity survey data, derived from measurements on plans and information provided by supply chain partners. In cases, such as shared party walls, the materials were allocated by proportional share of the total area.

Information regarding the offsite frame production process was obtained from the manufacturing company Space 4 Ltd, Birmingham. Data on production energy, materials, and waste materials (including their disposal) were provided as annual aggregated data. Allocation of annual energy and waste from the manufacturing process was by annual units of production. Some data on the manufacturing process was unavailable due to commercial confidentiality, in particular pertaining to the factory installed insulation. Data gaps were filled with secondary data from published literature where available or best guess estimates.

The datasets used for materials account for the movement of materials from place of extraction to factory gate. Transportation from factory gate to site is, generally, excluded. Data on transportation of materials from supplier (or storage site) to site were obtained from the contractors, John Youngs Homes Ltd (Table 2-4).

Table 2-4: Material suppliers and distances transported from supply site to construction site

Local Distribution	Distances/km
A&W Cushions Ltd NR2 4PW	36
Aspect Roofing Ltd NR16 2QW	104
Belmore Supplies Ltd NR3 2BS	44
C & H Concrete Products NR5 0TL	56
Carter Concrete NR26 8TP	108
Celotex, Ipswich, IP7 6BA	171
J Medler Ltd NR10 4DT	74
Keyline Ltd NR3 3TP	35
Space 4 (included in MMC data)	263

All the timber materials were imported. Data on supply chain was derived from the FSC certification chain of custody and provided by John Youngs Homes Ltd. It was found that the larch cladding was imported by boat from its region of production, the Irkutsk region of Siberia. The timber softwood was imported from Scandinavia. The structural engineered timber was produced and imported from the United States. Concrete based products and aggregates were all manufactured or extracted locally. Time constraints meant that it was not possible to gather data on other materials and all products used the routes taken between factory gate and supplier/storage site the transportation. The assumption was made that this was likely to be a relatively small contributor to the overall totals and could therefore be excluded. However, the inventory results for transportation is likely to be underestimated and interpretation of inventory results should be done so with caution.

No detailed records on waste were kept during the construction process, with the data on waste generated during on-site construction being limited to an aggregated volume. John

Youngs Homes reported 53 builders skips were used altogether. These were supplied by a local supplier (14km away). There was some onsite waste separation and recovery observed on site. Further information on waste management practices and material separation was obtained, from the site operators and waste management contractors. An average mass figure of 475 kg/m^3 for construction waste was used (Peng et al. 1997). Estimates of different waste streams and disposal routes were made based on benchmark data from The Smart Waste Scheme (BRE 2008) and from published literature (2007, WRAP 2008 a, b). It was assumed that timber, aggregates, minerals and metals were reused elsewhere and all other materials were sent to landfill. The quality of the data used is therefore not robust and any results are to be interpreted with caution.

Energy and fuels used onsite during construction are given in Table 2-5, including petrol, diesel, gas, and electricity, were derived from receipts and meter readings. As the data were collected post construction and derived from construction company records it was not possible to disaggregate the energy consumed to specific activities and, therefore, specific build components. Onsite energy is therefore presented as an aggregated figure for electricity and each fuel. This could be an area for future study.

Table 2-5: Onsite fuels used

Fuel (Unit)	**Quantity**
mains gas (kWh)	1107
UK grid electricity (kWh)	11106
diesel (l)	2070

Carbon emissions factors and embodied energy factors for materials, processes, and fuels were derived where possible from the UK or specific or relative to the country of production. A number of sources and databases were used including:

- published Government carbon emission factors (DEFRA 2008)
- The Inventory of Carbon and Energy (Hammond and Jones 2008)
- Econinvent database (Frischknecht and Rebitzer)
- U.S. Life-Cycle Inventory (USLCI) (NREL 2008)

The life cycle inventories for all three scenarios were modelled using MSExcel. Simapro V7.1 software was used in the analysis of the engineered timber components using the above inventory databases. Simapro (PRé Consultants**,** Amersfoort · The Netherlands) is a dedicated LCA software tool for undertaking LCA studies.

2.5. Results: Inventory analysis

2.5.1. Scenario 1: MMC timber frame larch cladding

2.5.1.1. Summary results

Scenario 1 required a total of 519GJ of primary energy to construct, which equated to an embodied primary energy of approximately 5.7GJ per m^2 of floor area (Table 2-6). The carbon embodied in the construction of the house amounts to 34.6 tonnes CO_2, approximately 405 kgCO_2 per m^2 of useable floor area (Table 2-6).

82% of the total embodied carbon is embodied in the materials incorporated in the building (exclusive of waste). The remainder were attributed to construction activities such as transporting materials from point of distribution to site, waste materials exported from the site and energy used onsite. Concrete and waste are the two predominant groups (Figure 2-8).

Table 2-6: Summarised inventory of materials, transport and fuels used in the construction of the case study house with associated embodied primary energy and embodied carbon (inclusive of MMC manufacture)

Category	Material	Quantity (kg)	Emissions ($kgCO_2$)	Primary energy (MJ)
Metals	aluminium	260	2140	40260
	steel	251	956	10722
Minerals	brick	2264	1175	18510
	cement (mortar/board)	2023	798	12997
	concrete	56651	9863	72142
	gypsum plaster products	1349	413	7207
Openings	windows	1277	1996	40584
	doors	142	246	4624
Plastics	HD polyethylene	56	90	4330
	LDPE	29	72	2558
	polyisocyanate insulation	187	561	13477
	polythene	146	285	13152
	PUR insulation	195	585	14058
Timber	composite board products	4330	3462	64116
	larch	1315	1421	15090
	engineered timber	222	152	2811
	softwood	6792	3056	50262
Fuel	mains gas (kWh)	1107	226	4128
	UK grid electricity delivered (kWh)	11106	948	12462
	diesel (l)	2070	363	5328
Waste		5350	4934	96728
Transport	factory gate to site	9365 tkm	883	13131
Total:			**34625**	**518677**

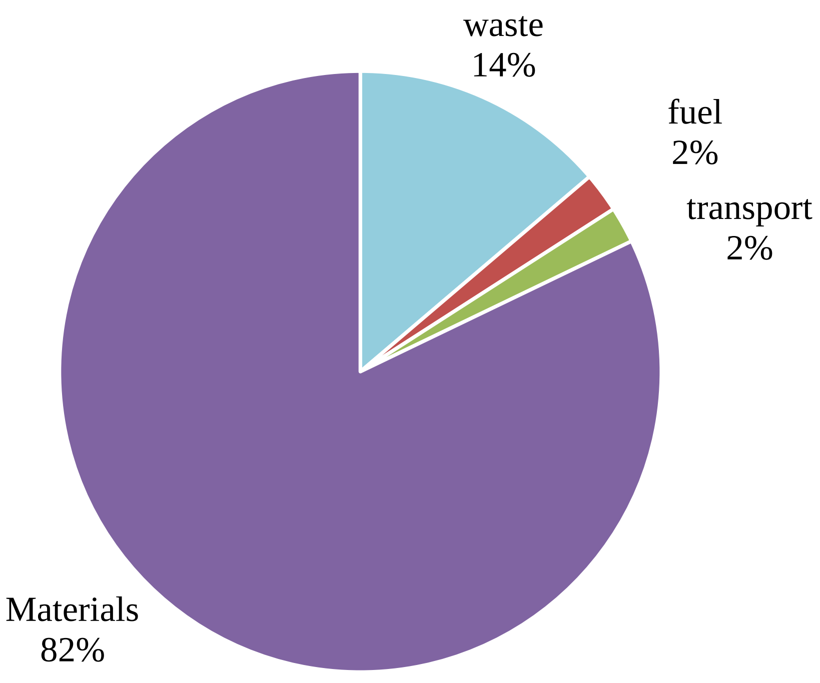

Figure 2-8: Summarised inventory results showing embodied carbon in construction, inclusive of offsite frame manufacture (kgCO_2)

2.5.1.2. Materials

In considering materials (Figure 2-9) minerals are the most significant material category, accounting for 45% of material related embodied carbon (excluding waste materials). The minerals category includes materials such as cement, gravels, sands, and concrete products. Concrete is the main contributor, with 36% of the embodied carbon associated with materials being derived from concrete (Figure 2-8 and Figure 2-9). Much of this is due to Portland cement, which has a high embodied energy of 0.83kgCO_2 per kg of product at the factory gate of the cement works in the UK (Hammond and Jones 2008).

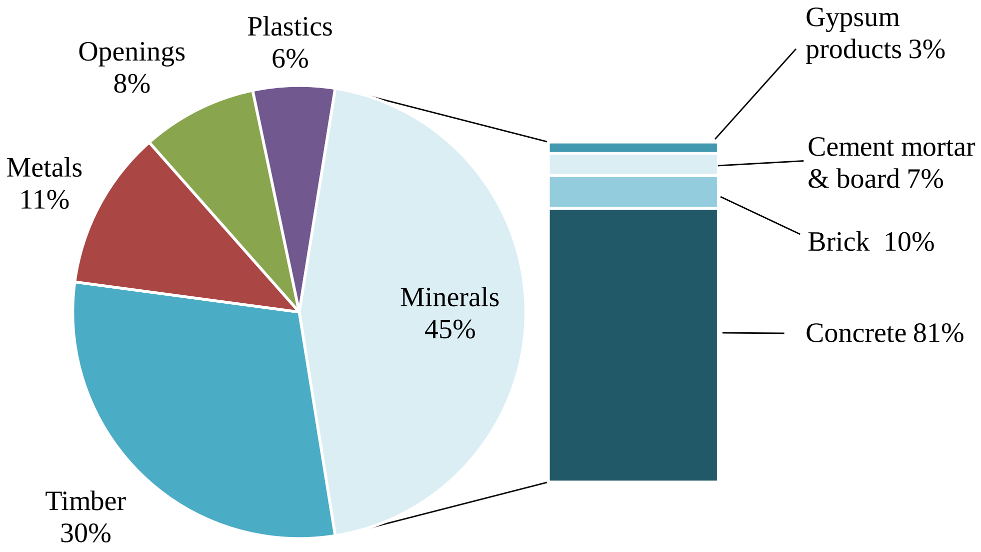

Figure 2-9: Proportion of embodied carbon in materials (excluding waste, transport, and energy in construction)

The majority of minerals were used in the construction of the substructure and foundations. These elements were responsible for 71% of the emissions associated with the use of minerals. The remainder of the minerals were incorporated in the ground floor (concrete block and beam, 16% of minerals emissions) and the roofing tiles (concrete tiles, 9% of minerals emissions).

As illustrated in Figure 2-10 half of the embodied carbon was attributable to the substructure, foundations, and ground floor. The principle material in these construction elements is minerals, specifically concrete. The MMC frame was responsible for 12% of the embodied carbon.

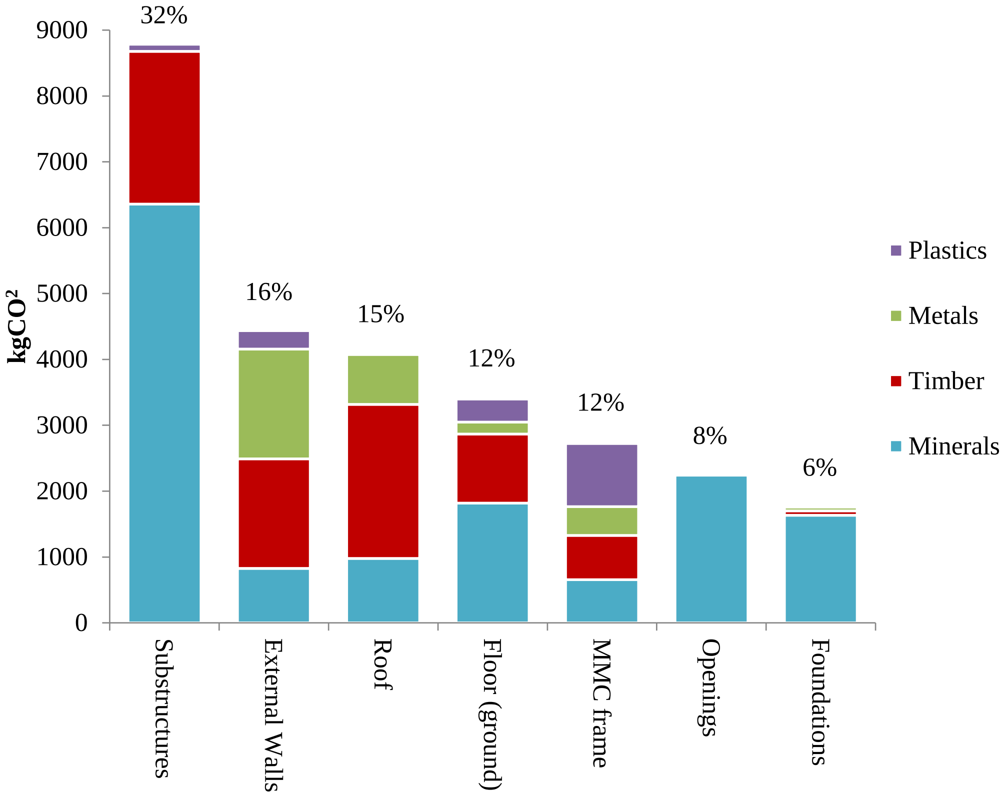

Figure 2-10: Proportions of material embodied carbon attributed to each structural component

Timber, a key material in the structure and external cladding, was responsible for 30% of the total emissions (inclusive of the timber used in the offsite frame and transport to UK distribution points). The majority of timber was found in the walls and roof. The larch cladding was responsible for 5% of all material emissions.

The remaining 25% of material related embodied carbon was attributable to metals, the openings (doors and windows) and plastics.

2.5.1.3. Transportation

Transportation from factories and distribution points to the site accounts for 9372 tkm, resulting in 2% of the total embodied carbon (Table 2-7). This is similar to other studies which also found transport to have a relatively low share of the total emissions of CO_2 (see Adalberth 1997).

Table 2-7: Summarised transportation inventory

Material	Material type	Distance to storage to site (km)	t/km	Emissions (kg/CO_2)	Primary energy (MJ)
Metals	aluminium	35	9	1	18
	steel	35	8	1	15
Minerals	brick	74	165	22	325
	brick	35	1	0	2
	cement	35	27	4	53
	concrete	108	667	88	1312
	concrete	35	160	21	314
	concrete	56	2326	307	4574
	concrete tiles	104	471	62	926
	plaster	43	59	8	115
MMC parts	mixed material	263	4241	206	3018
Openings		151	355	47	734
Plastics	polyisocyanurate (PIR)	35	5	1	11
	polypropylene	171	21	3	40
	polythene	35	0	0	1
Timber	chipboard	36	6	1	11
	larch	36	48	6	94
	OSB	36	104	14	205
	plywood	36	47	6	92
	plywood	104	2	0	5
	softwood	36	25	3	50
	softwood	104	517	68	1016
Waste	mixed material		101	13	199
Total			9365	883	13131

2.5.1.4. Waste

The construction waste consisted of two main waste streams, that occurring during onsite construction and that occurring during manufacturing of the frame. The inventory results for onsite production are given in Table 2-8 and those for the MMC components are given in Table 2-9.

Table 2-8: Summarised waste inventory results for onsite construction

Material	Material type	Weight (kg)	Embodied carbon (kg/CO_2)	Primary energy (MJ)
Metals	aluminium	260	366	6878
Metals	steel	221	67	921
Minerals	brick	821	427	6734
Minerals	concrete	657	85	624
Minerals	plaster/cement	821	0	1478
Packaging	miscellaneous		1550	30689
Plastics	HD polyethylene	56	73	3503
Plastics	LD EPS	29	58	2069
Plastics	polyisocyanurate (PIR)	187	493	11842
Plastics	polypropylene	3	11	313
Plastics	polythene	13	20	927
Timber	chipboard	33	17	315
Timber	larch	286	309	3282
Timber	OSB	623	504	9338
Timber	plywood	286	232	4293
Timber	softwood	1236	556	9144
Minerals	cement particle board sawdust	47	24	443
Plastics	lining external (m^2)	13	25	1191
Plastics	PUR insulation	33	100	2403
Timber	timber sawdust	40	18	340
Total			4766	92351

In total 17$m^3$of waste materials were reported in documented invoices to have been exported from the site during construction. This included excavated inert materials, waste and unused construction materials and other waste. In the absence of data on the composition of this waste a waste model was constructed in excel using published data to derive average proportions of waste by material in order to provide a best guess estimate. An estimated 4.9 tCO_2 resulted from this waste, equating to 109 $kgCO_2$ per m^2. Timber and packaging were the predominant contributors (33% and 31% respectively) (Figure 7). It was estimated that 65kg of waste (excluding inert site excavation materials exported from site) were produced for each m^2 of floor area.

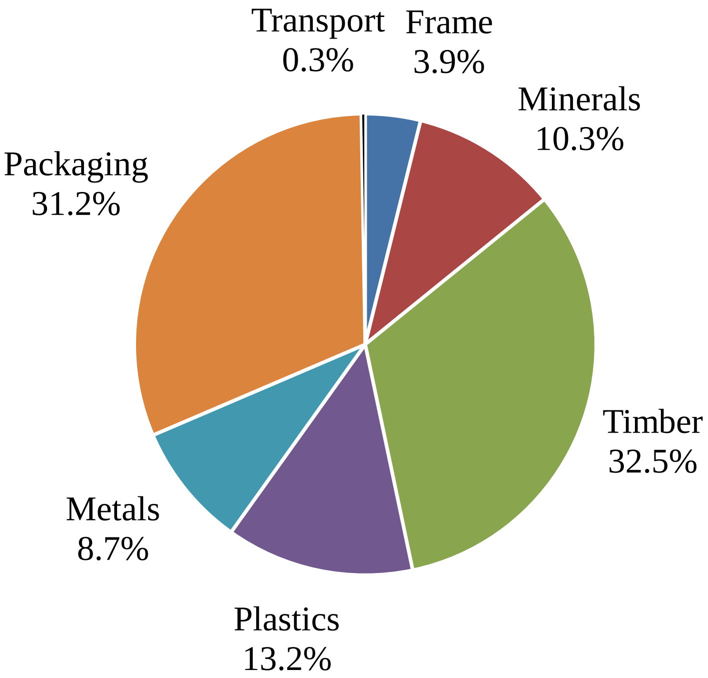

Figure 2-11: Proportions of different types of waste (by weight) occurring both onsite and offsite during the manufacture of the timber frame (off-site waste shown as frame category)

The manufacturing of the MMC components contributed an insignificant amount the total waste related embodied carbon (Table 2-9). The manufacturing waste data were incomplete, in particular relating to packaging, the majority of which was reported as being recycled. It was estimated that the reduction in embodied carbon attributed to resource efficiency was 0.3tCO_2 (WRAP 2008a, b). During the offsite manufacturing process, production waste was either returned to the manufacturing process or, being produced in quantities that are viable for export offsite, recycled into other alternative processes and products, resulting in just 2 kg of waste to landfill produced for each m^2 of internal floor area.

Table 2-9: Summarised waste materials from offsite manufacture of MMC structural components

Waste category	Material	Quantity (kg)	Embodied carbon ($kgCO_2$)	Primary energy (MJ)
Reused	timber	53	24	
Landfill	total landfill waste:	140	168	4377
Comprised of:	insulation	33	100	2403
	cement particle board sawdust	47	24	443
	timber sawdust	40	18	340
	plastic	13	25	11960
	transport (t/km) of waste	7	0.9	

2.5.2. Alternative scenarios

2.5.2.1. Scenario 2 MMC timber frame brick facade

The scenario 2 had an embodied carbon of 45.6tCO_2 and required 656GJ of primary energy. This equates to 535 kgCO_2 m^2 and 7.7GJ per m^2 primary energy per usable floor area.

For scenario two the material, transport and waste associated with the larch façade were deducted from the inventory. These were replaced by brick, mortar and steel wall ties. The additional wall width was accommodated in the model by the addition of concrete to the substructure. The inventory differences amounted to an increase of 132 GJ primary energy and 10.5tCO_2 (Table 2-10).

Table 2-10: Scenario two inventory changes

	Materials			Transport	
	m^2	**$kgCO_2$**	**MJ primary energy**	**$kgCO_2$**	**MJ primary energy**
Brick wall (single outer skin)	98	11194	156608		
Wall ties	6	36	301		
Concrete		2130	15689	123	241
Additional waste		112	1938	1	1
Displaced materials					
Larch and fixings	98	-2779	-40053	-10	-142
Total additional		10581	132546	221	1701

The walls (including brick facade and frame) in this scenario are responsible for 41% of the total embodied carbon, compared with 23% for scenario 1 (Figure 2-12).

Substituting the Larch façade with a Brick façade increased the embodied carbon of this element by a factor of four. The relatively small increase in substructure and foundations are accountable for 20% of the total difference in emissions. Unsurprisingly the majority of this difference is accounted for by the increase in minerals (i.e. brick, cement, concrete and sand). Typically, an increase in the total proportion of heavier materials in a construction project will also increase transport emissions, in this case by 25%. There was also a 14% increase in construction energy due to the increase in machinery required on site, including mixers for the mortar and lifting equipment for the bricks and blocks.

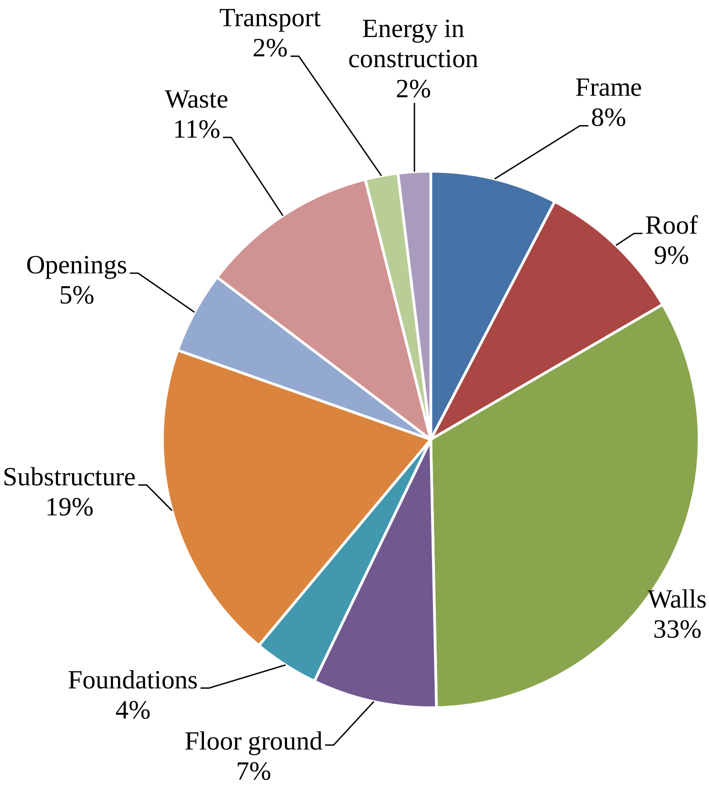

Figure 2-12: Scenario two total embodied carbon by proportion to construction component, including waste, energy and transportation

2.5.2.2. Scenario 3: Masonry results

Scenario 3 uses a traditional masonry construction consisting of a brick, insulated cavity and block wall to construct a house of equivalent dimensions and thermal performance as that of Scenario one. Scenario 3 was found to have a total embodied carbon of approximately 52tCO_2, and required 700 GJ (Table 2-11). This equates to 612kgCO_2 m^2 and 8.2GJ per m^2 primary energy per usable floor area.

Table 2-11: Summarised inventory of materials, transport and fuels used in scenario 3 with associated embodied primary energy and embodied carbon

By Material	**Embodied carbon/ $kgCO_2$**	**Primary energy/ MJ**
Minerals	34537	283204
Timber	5773	102120
Plastics	715	19718
Metals	1600	26835
Openings	2242	45208
Waste	5686	197497
Transport	1215	16296
Energy in construction	886	9037
Total	52599	699915

Scenario 3: Materials

Materials accounted for 86% of the total embodied carbon. 77% of which was attributed to minerals. In this scenario 67% of the total embodied carbon was accounted for by the walls, foundations and substructure, 43% and 24% respectively. Masonry construction requires an increased volume in load bearing foundations to accommodate the heavier masonry walls.

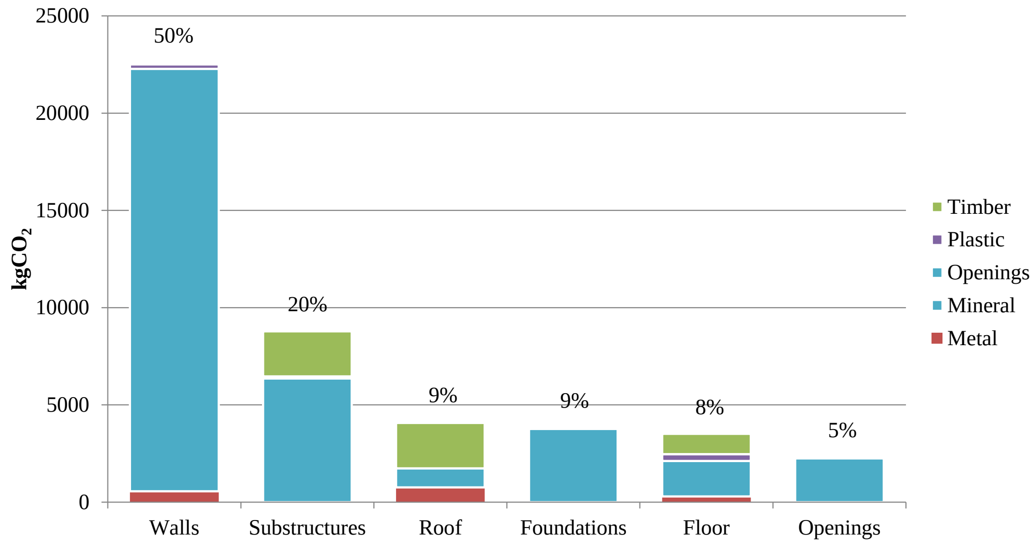

Figure 2-13 Proportions of material embodied carbon attributed to each structural component in Scenario 3

Scenario 3: Transport

Transportation, including that associated with waste accounts for 9201 tkm, resulting in 2% of the total embodied carbon (1.2tCO_2) (Table 2-12).

Table 2-12: Inventory results transport

Element	**Material type**	**km**	**t/km**	**Embodied carbon/ kgCO_2**	**Primary energy MJ**
Floor	steel galvanised	35	1	0.2	3
	steel/zinc coated	35	2	0.3	4
	cement	35	2	0.2	4
	concrete	108	227	30.0	446
	concrete	108	440	58.1	866
	polyisocyanurate (PIR)	171	16	2.2	32
	polyisocyanurate (PIR)	171	4	0.5	7
	plywood	36	47	6.2	92
Foundations	concrete	56	930	122.8	241
	brick	74	110	14.5	216
	cement	35	21	2.8	41
	concrete	35	130	17.1	255
	concrete	35	30	3.9	59
	concrete	56	66	8.8	131

	polythene	35	0	0.1	1
	softwood	36	5	0.7	11
Roof	aluminium	35	3	0.4	6
	steel	35	1	0.1	2
	concrete tiles	104	471	62.2	926
	chipboard	36	6	0.7	11
	plywood	104	2	0.3	5
	softwood	104	517	68.2	1016
Substructures	brick	35	1	0.2	2
	concrete	56	66	8.8	131
	concrete	56	2193	289.5	4313
	HD Polyethylene	35	0	0.1	1
	low density EPS	35	1	0.1	2
	polypropylene	171	1	0.1	1
	OSB	36	104	13.7	205
Walls	aluminium	35	2	0.2	3
	steel	35	1	0.2	3
	steel stainless	35	0	0.1	1
	brick	58	3673	484.8	7222
	polyisocyanurate (PIR)	35	2	0.3	5
	HD polyethylene/polypropylene	35	0	0.1	1
Waste	mixed material		122	16.1	32
Total		2132	9201	1214.5	16296

Scenario 3: Waste

The waste figures for this scenario were modelled using data from (DCLG 2007; BRE 2008; WRAP 2008 a, b). It was estimated that approximately $18m^3$ of waste would have been produced; approximately 104kg of waste (excluding inert site excavation materials exported from site) were produced for each m^2 of floor area. An estimated 5 tCO_2 resulted from this waste. Insulation and minerals, including plasterboard, cement materials, bricks and blocks were predominant accounting for 74% of the embodied carbon attributed to waste (Table 2-13).

Table 2-13: Scenario three inventory results waste

	Mass/ kg	Embodied carbon/ $kgCO_2$	Primary energy/ MJ
Insulation	762	2285	164776
Metals	17	30	739
Minerals	5285	1755	5454
Plastic	56	106	9440
Packaging	1107	803	11548
Timber	1417	652	5539
Total	8644	5632	197497

2.5.3. Comparative carbon analysis

2.5.3.1. Total embodied energy and carbon

Comparing the results of the three scenarios indicates that both scenario 2 and 3 both have significantly embodied energy and carbon than that of Scenario 1 (Table 2-14). Scenario two shows an increase of 26% embodied carbon and 31% embodied energy compared to the case study model house of scenario 1. Scenario 3 indicates increases of 51% embodied carbon and 35% embodied energy compared to Scenario 1.

Table 2-14: Total embodied energy and carbon comparison of the three scenarios

	Scenario one MMC	Scenario two: brick replaces larch	Scenario three: conventional masonry
Embodied carbon/tCO_2	35	46	53
Primary energy/GJ	519	656	699

In terms of materials the use of timber as a façade material in scenario one reduces embodied carbon by 29% compared with using a traditional brick façade (Figure 2-14). Comparing MMC (Scenarios 1 and 2) with traditional masonry construction (scenario 3) indicates that the increased use of masonry materials (constituted of fired bricks, aerated concrete blocks, cement mortars) has increased consequences in the embodied carbon in walls, foundations, waste, transport and onsite energy use (Figure 2-14).

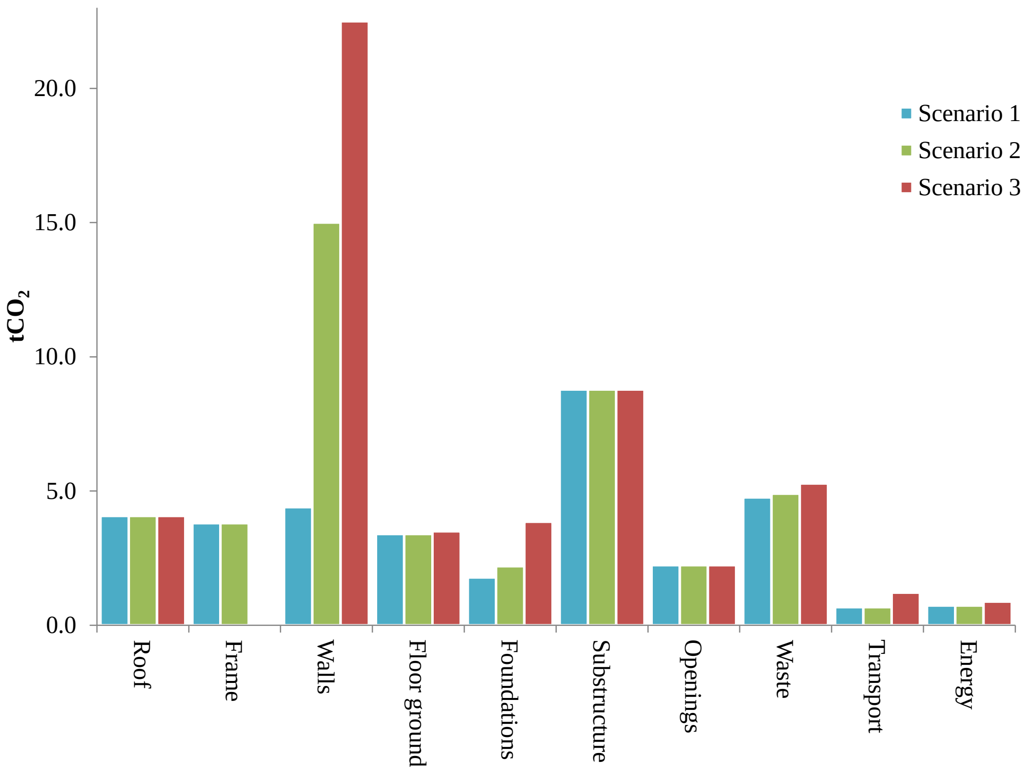

Figure 2-14: Comparison of inventory results summarised by component for the three scenarios

2.6. Discussion

This study found that a house constructed using a panellised timber frame MMC construction, produced a building with a 26% lower embodied energy and 34% reduction in embodied carbon than that of a traditional masonry construction for an equivalent house.

This is principally attributed to the use of materials, in this case softwood timber in the wall component, with relatively lower embodied carbon and lighter mass requiring less substructure than conventional. Atypical for the UK at the time, timber was not only used as the main structural material (in the MMC components) but also as an external facade material, rather than a more traditional brick facade. The displacement of brick with larch produced a carbon saving of 24%.

The use of a timber frame also produced a lighter weight structure when compared with a masonry cavity construction. The lighter structure required less sub structural support and, consequently, reduced foundation materials. This acted to reduce the use of high embodied carbon materials, such as concrete and steel reinforcing.

A further factor contributing to the lower embodied carbon of the case study home scenario 1 is the efficiency of factory volume production associated with MMC compared with scenario 3. Although this is a unfair comparison on these terms as traditional construction occurs onsite in a bespoke fashion, factory manufacture of masonry panels has been attempted, for example Hanson QuickBuild™ walling system (Hanson PLC 2008). Although outside of the boundaries of this study a comparison with MMC factory production and an onsite constructed timber frame would be a useful addition to the literature to examine more closely the production efficiency claims of such manufacturing techniques.

Despite the resource efficiencies found in the production of the MMC frame, onsite waste production in this case study was still a significant factor in the total embodied carbon, 14% of the total. However the manufacturing of the frame was a relatively small contributor to total waste related CO_2 produced, just 4% of waste related embodied carbon (Figure 2-11). This suggests further reductions in embodied carbon can be made by both increasing the amount of manufacturing that occurs off site and by reducing the amount of waste that occurs on site.

On small sites, such as those typical to rural sites, any 'waste' or surplus materials from unused contingency, over ordered materials or sizeable offcuts, are produced in relatively small quantities. Observation of site waste handling repeated over site visits towards the end of the construction process found waste separation tended to be poor. Anecdotal evidence from informal conversations and observation of site operations during the construction of the case study suggests significant barriers, such as time, lack of local infrastructure and health and safety legislation, exist to hinder the reuse of these materials locally or recycled back into the supply chain. The waste data collected, from both MMC and the on-site construction, was not of sufficient quality to make a robust quantification. Further research is needed to quantify the resource efficiency claims from MMC methods in comparison with that from onsite construction.

Despite the high proportion of timber throughout the structure half of the materials related embodied carbon was found to be associated with the construction of the substructure, foundations and ground floor (Figure 2-9). The relative importance of these substructural components reduces with the increase of carbon intensive materials in other components, for example in Scenario 3 the proportion attributed to these elements is lower at 35%. This suggests that these sub structural elements and the materials used would be a suitable target for reducing the embodied carbon still further in such MMC timber framed houses.

The substructural components were comprised of cementitious rich materials and bricks. Bricks, unless they are unfired, have a high embodied carbon factor. The cement in concrete and mortars can have a high energy input during manufacture and, consequently a relatively high embodied carbon, in addition to the release of CO_2 during the chemical changes that take place during manufacture. The amount of embodied carbon associated with cement production depends upon the primary materials and the energy source used in its production. The emissions associated with cement production can be reduced by the displacement of fossil fuels with both renewable energy and alternative fuels, such as waste tyres and substitute liquid fuels comprised of spent solvents (Environment Agency 2005). In the UK substitution is relatively lower than in Europe but increasing.

Reducing the environmental burdens from MMC timber frame construction further could be achieved in two ways. Firstly, reducing the use of cement in by substituting with lower embodied carbon alternatives. Materials include using ground granulated blast furnace slag, fly ash and other pozzolanic materials or lime based materials.

Secondly, using design strategies to reduce the volumes of cement required. These could include removing the oversite concrete ‘raft’, using isolated point foundations rather than strip foundations or using steel helical screw piles. Although a relatively high embodied energy product steel helical screw piles are both reusable and recyclable, which would be particularly beneficial if early design consideration was inclusive of end of life deconstruction. However, these strategies would be dependent upon the site ground conditions which may preclude such options.

Both these strategies would radically reduce the use of carbon intensive materials where no additional benefit to their use is possible in lightweight construction. There would also be other additional benefits such as reduced earthworks requiring less spoil and waste material for export off site, lower energy inputs and further benefits at end of life deconstruction. These strategies could be equally applied to traditional masonry construction where conditions allowed.

However, it is too simplistic to consider embodied carbon in production, the carbon and energy performance attributed to a material or component may have effects over the whole building life cycle performance, in particular during the occupational use phase. For example, the two key materials arising from the results presented here timber and cement, timber is perceived as an environmental ‘good’ and cements an environmental ‘bad’.

Timber, as in the larch façade in the case study, has uncertainties associated with it that will affect the durability and service life, such as resistance to decay and insect attack, weathering, dimensional changes related to moisture and structure, corrosion of metal fixings and fire. Timber cladding has been found to have a service life ranging from 17 years to 170 years or more (Davies 2008). Whilst it is difficult to estimate the durability of a natural product which will be highly dependent upon the qualities of the material itself, the environment in which it is installed and the maintenance regime in place it is likely that timber will have a limited lifespan before it requires either maintenance or replacement compared with masonry. This will have implications for embodied energy and carbon over the total lifecycle of the building if such facades require complete replacement at regular intervals. Extending the lifecycle through occupation to include maintenance would be a valuable addition to the research presented here.

Cement if considered using only the single factor of carbon emissions is a huge contributor to global GHG emissions and the concrete that contains it, is the main material used in the global construction industry. There is evidence to suggest that cement may not be an environmental unsound material. For example, cement has also been argued to have benefits including acting as a carbon sink and as a high thermal mass material (Damtoft et al. 2008). Cement based materials sequester CO_2 from the atmosphere during carbonation. The cement in concrete will bind approximately the same amount of CO_2 as was originally emitted during the calcinations process of the raw materials used. However this process, will only remove what was originally added and over considerable geological timescales. There is currently a dearth of literature that is both independent and peer reviewed that addresses this issue.

Secondly, and more relevant to this thesis, concrete materials have a high thermal mass. High thermal mass materials act as a thermal buffer, storing and emitting heat gained from the environment to which it is exposed. Thermal mass can assist in reducing occupational heating and cooling energy loads of up to 23% (VanGeem 2008) if used appropriately (Brown and DeKay 2001). However, in the case study, and typical of most timber frame construction, the majority of mass is isolated within the structure or beneath other material finishes and, consequently, insulated from and unavailable for the useful thermal storage that could offset the environmental burdens of its manufacture.

The full lifecycle, including occupation, maintenance, and end of life deconstruction and disposal needs to be considered. Consideration of embodied carbon needs to be integrated at the earliest design stage. If environmental burdens are to be minimised sensibly whilst maximising additional benefits there needs to be systemic intelligent thought in building design.

2.7. What are the implications for the UKs national carbon targets?

If it is assumed that the average area of a new home in the UK is 91m^2 (DCLG 2008) and that the targeted 3 million new homes will be new construction, rather than replacing existing stock, there will be an additional 273 million m^2 of new housing at a rate of 240,000 new homes per year. The carbon consequences will depend significantly upon how these homes are constructed. The range could be between 110 – 167 $MtCO_2$ depending on the proportions of all timber MMC to traditional masonry construction used. If it is assumed that the new homes are constructed in the same way as scenario 1 and have an embodied carbon of 405 $kgCO_2$ per m^2, the carbon consequences of the construction of 3 million new homes in terms of the UK's carbon emissions would be approximately 110 $MtCO_2$. However, this is unlikely to occur. Whilst the market share of timber frame new homes is approximately 22% (UKTFA 2009) the predominant preferred cladding material is brick and the majority of housing construction (including multi occupancy buildings such as flats) continues to be masonry. Therefore if only traditional build occurred the carbon consequences would be approximately 167 $MtCO_2$ (assuming an embodied carbon of 612 $kgCO_2$ per m^2 as estimated in scenario3).

To put this into context the UK currently emits 542.6 $MtCO_2$, of which 142.2 $MtCO_2$ (or 30%) is attributable to residential energy use (DEFRA 2009). On an annual basis the embodied carbon of construction of 240,000 homes could be between 6 – 10%of the annual housing emissions. A total of 3 million new homes could equal or exceed the annual emissions of the total housing stock.

The drive towards zero carbon by 2016 will negate a proportion of this increase through reduced energy demand in use, if they are replacing existing stock rather than adding to it. Whether this reduced demand will offset the increased embodied carbon required for construction will depend upon the materials used, the technologies used to supply services, the demands of the inhabitants and other social pressures and the end of life deconstruction.

In addressing carbon mitigation the UK's policy focus on energy efficiency and clean energy, to the exclusion of embodied carbon, may be missing an important point in terms of global carbon emissions. Much of the embodied carbon occurs elsewhere, materials are often produced and imported from elsewhere, and these emissions are unaccounted for. However, carbon emissions and the environmental damage of these emissions are no respecter of administrative borders.

2.8. Conclusions

The results indicate that the embodied carbon of a house constructed using offsite panellised timber frame (scenario 1) is approximately 35tCO_2. A comparison model of an equivalent home constructed using traditional masonry construction (scenario 3) was found to have an embodied carbon of 52tCO_2, 51% greater.

Despite timber being the predominant structural and cladding material, concrete is the most significant material by proportion in embodied carbon terms, responsible for 36% of materials related embodied carbon. Much of this is embodied in the substructure.

In considering the construction as a whole further embodied carbon savings can be made by:

- increased offsite manufacturing of components
- consideration of material specification and selection of sustainable materials or materials with reduced environmental impact (e.g. cement substitutes)
- design and placement of materials within the structure (such as mass materials accessible as thermal storage)
- On-site waste minimisation strategies

A systemic lifetime approach is also needed. Decision making based on a single issue, such as embodied carbon, can be misleading and counterproductive in the long run. The example given is of concrete; as a material it does have a large embodied energy and carbon burden, however it is a useful material and can also act to reduce the occupational energy demand if it is employed strategically within a structure.

And finally to answer the question posed, there will indeed be very significant carbon consequences to the UK's house building programme, despite its aspiration to 'zero' carbon status. The authors estimate between 110 – 167MtCO_2 depending on the proportions of all timber MMC to traditional masonry. A significant proportion of this will be outside of the national accounting framework and, consequently, concealed within imported materials and products. The overall impact will be dependent upon the types of construction employed and how integrated the sustainable construction agenda is embedded along the whole supply chain, from inception through design and on to construction, occupation and deconstruction.

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3. Energy and carbon performance: A comparative evaluation of the energy and carbon arising during the first year of occupation from a technical perspective.

This chapter addresses research question 2 outlined in Chapter 1:

Are the innovations currently being deployed by mainstream housing providers in response to regulatory changes capable of meeting policy carbon targets?

It is the first of two related studies and quantifies the energy demand, consequential emissions of carbon and annual running costs of innovation in new build homes. Its purpose is to assess whether innovation in construction and technologies in mainstream housing can deliver national carbon reduction goals. The results from Chapter 2 are used to quantify the lifecycle energy and carbon from construction to 20 years of occupation.

A peer reviewed paper based on the research described in this chapter has been published (see Appendix 2).

This chapter is organised as follows: Section two sets out the background and examines the factors that have contributed to the introduction of innovative design strategies and technologies in mainstream housing. The housing industries implementation responses and the factors that influence household energy demand are briefly discussed. The methodology is described in section 3. The results of the comparative analysis are given in section 4. The carbon embodied in construction and that emitted over a 20 year occupation period for each typology is then compared to evaluate the short term effects of technological lock in. The final section discusses the implications of these findings in terms of the policy outcomes.

3.1. Introduction

The UK government's Climate Change Bill pledges that the UK will make cuts in emissions of greenhouse gases of 80% by 2050 (Crown 2008). Currently, domestic energy consumption for space and water heating, cooking, lighting and appliances in the UK is responsible for approximately 30% of total energy consumption and 26% of total carbon dioxide emissions (DECC, 2009a). To meet the government's long term carbon targets household energy consumption will need to reduce by 29% based on 2008 levels by 2020 (DECC, 2009b). At the same time policy has sought to address sustainable development, fuel poverty and fuel security, all driving the desired outcome of a reduction in overall energy consumption. In response to this the built environment needs to develop more sustainable, less energy-intensive systems and approaches that are socially acceptable and economically advantageous (LWEC, 2008).

The UK government has identified the house building industry as a key sector for delivering carbon reduction and, consequently, the sector has been subject of numerous reports, initiatives and regulatory changes in recent years culminating in the aspiration to achieve a zero carbon standard by 2016 (DCLG, 2006). This aspiration, which will be delivered by a progressive and incremental tightening of energy standards in the building regulations, will instigate something of a revolution in the way new homes will be designed and constructed, and the ways in which energy, and the services that it provides, will be delivered. In conjunction with this there is a significant push for a new program of housing construction that could see an addition of 3 million new homes added to the total UK housing stock by 2020 (current economic climate not withstanding) (DCLG, 2007).

This new build programme will result in a net increase in the overall stock rather than just replacing inefficient old stock. Furthermore the initial house construction and manufacture of their low carbon technologies will also have significant energy and carbon emissions associated with their production and supply (known as embodied energy or carbon) (Monahan and Powell, 2011). New construction requires the mining, refining and manufacture of materials and products each with its own embodied energy and consequential carbon burden. For these reasons the construction of new homes will result in an overall increase in both energy demand and carbon emissions.

How the housing industry responds to the drive for zero carbon housing will be fundamental to the successful, or otherwise, achievement of decarbonisation of new build housing. Given the lack of innovation, poor environmental record, lack of engagement with sustainability and lack of ability to meet even the minimum existing requirements, by a significant section of the house building industry (Glass et al. 2008), there is considerable uncertainty in how the housing industry will respond.

Will the innovation and leadership shown by a small section, including private and social housing providers, transfer to the majority? Will the combination of an institutionalised risk adverse nature and the speed of change demanded, result in environmentally and socially costly mistakes, if there is no evidence base to support the decisions that are being made on the ground?

Which technologies and design strategies currently being deployed will effectively achieves the three policy aims of: low energy; low carbon; and affordability, for the benefit of society rather than for convenience of the house building industry?

This chapter begins to address these questions using a case study of 14 newly constructed homes that applied current best practise and available technologies, within currently acceptable build costs, without recourse to additional grant funding regimes to meet their environmental and social objectives. These homes use four different approaches to reduce energy and consequential emissions of carbon: ground sourced heat pumps; active solar (thermal and photovoltaic); mechanical ventilation and passive solar design; and conventional high efficiency gas boilers.

Two analyses were undertaken. The first investigates the findings of a year of monitored energy consumption and quantifies the resulting emissions of carbon dioxide. Patterns of consumption are shown and the relative performance of each of the four approaches is compared across three criteria: energy (kWh); environmental (CO_2 emissions); and cost (total annual fuel expenditure £). In the second analysis the carbon cost of construction (Chapter 2) and the low carbon energy technologies employed are factored into the analysis, along with the carbon emissions associated with occupational energy for a 20 year period. The analysis enables us to begin to understand the consequences, both intended and unintended, of the different approaches used and to address the questions posed above.

3.2. Background

Currently 58% of energy used by households is due to space heating, 24% to hot water and the remainder, 19% to cooking, lighting and appliance use (DECC, 2009c). In terms of CO_2, 57% of household CO_2 emissions were due to space heating, 25% to water heating and the remainder, 18%, to cooking, lighting and appliance use (DECC, 2009c). Household energy demand and the subsequent emissions of CO_2 are the expression of a complex and highly interdependent web of socio-technological networks ranging from government, to utilities to house builders to the individual consumer (Chappells and Shove 2003). For example space heating is a function of the technical characteristics pertaining to the house itself (notably type, levels of thermal insulation and air permeability) and the heating technology employed (efficiency of combustion, levels of control and the fuels used). It is also a function of the behaviour and lifestyle choices made by the occupants. Choices such as preferred indoor temperature, how the occupants respond to meet their comfort needs (such as adjusting clothing or the thermostat), whether the whole house is heated to the desired temperature or just the rooms that are inhabited the most and patterns of heating preference (intermittent or continuous) will have an enormous effect on a households overall energy consumption. By considering energy in this way a number of intervention points can be identified to produce reductions in emissions of carbon associated with domestic energy consumption:

- Reduce the need for energy inputs. For example, continuing the space heating illustration, increasing levels of insulation, reducing unwanted ventilation, and design strategies that optimise solar gain (termed passive solar).

- Decarbonise grid electricity fuel systems and change the way energy dependant services are provided at household level. Includes displacing fossil fuels with alternative, renewable energy sources and new low or zero carbon technologies (e.g. solar hot water, photovoltaics, wind, hydro and biomass).

- Increase efficiency of service provision. For example, A** rated gas and oil boilers or heat pumps.

- Influence consumer behaviour to induce change in the desired, low energy, direction. Strategies include providing information, such as product energy labelling and government funded social 'marketing' campaigns such as the UKs Act On CO_2 campaign (DECC 2009d).

There is a considerable literature that focuses on either the individual consumer, the influence of their behaviour and ways to change it in a pro-environmental direction (Wilson and Dowlatabadi, 2007, Jackson, 2005), or on the technical aspects of the house itself (Harvey, 2009). Yet there is a dearth of literature concerning a) how housebuilders are responding to policies to deliver lower carbon homes and b) how these new homes and technologies are subsequently used by households that can be thought of as 'passive adopters' of low energy lifestyles in the real world.

A passive adopter is defined here as an individual or a household that does not actively choose to adopt low energy or environmentally aware behaviours or technologies but is guided towards such behaviour or desired outcomes through the provision of technology or design by an external actively adopting agent. Consequently such individuals or households find themselves adopting pro environmental behaviours almost accidentally and without an underlying shift in attitude.

Current research indicates that house builders are adopting approaches related to the built fabric, principally increased levels of thermal insulation and reduced air permeability (Osmani and O'Reilly 2009). New low or zero carbon technologies are perceived as untested and concerns are being expressed regarding issues of cost, reliability, and installation capabilities. However, as carbon emission standards become increasingly stringent new low or zero carbon technologies are becoming unavoidable and increasingly being deployed.

3.3. LZC technologies: A brief review of performance

For the purposes of this paper the technologies that are available to house builders are those that are defined in the UK governments Building Regulations (DCLG 2010) and that fit within the definition in the Code for Sustainable Homes (DCLG 2008a):

"The installation of Low or Zero Carbon technologies which directly supply the dwelling with heat and/or electricity through a direct connection to the property or through a private wire arrangement." p. 45

These include:

- Solar Hot water (SHW)
- Photovoltaics (PV)
- Heat pumps: ground source and air source (GSHP and ASHP respectively)
- Biomass: log, woodchip or pellet fired boilers
- Wind turbines
- Hydro electricity
- CHP and district heating schemes

Other strategies are concerned with the design and orientation of the building and the thermal properties of the materials used. These passive solar techniques are design strategies that maximise free solar gain and include solariums, trombe walls, light tubes and shading (Brown and DeKay 2001, Roaf et al. 2003). They are often used in conjunction with passive and mechanical ventilation with heat recovery (MVHR) strategies to collect, store and distribute heat and, consequently, reducing the proportion of heating supplied by the conventional heating system. How much of this useful gratis energy is utilised in practise will depend on a number of parameters, not least of which is how the sunspace and the ventilation system are operated together which is a function of both design and operation. Furthermore MVHR systems are not passive systems and require power to run fans and associated equipment (termed parasitic energy demand). In theory a well designed MVHR system in a relatively air tight building will offset this parasitic energy demand through the energy savings derived from heat recovery. The air tightness of the building is critical to the efficiency of the heat recovery system. Ventilation heat losses can be typically 35-40 kWh/m^2/year in residential buildings and between 80-90% of this could be recovered by an MVHR system (Tommerup and Svendsen 2006). MVHR systems have been found to reduce the total energy for space heating by 20–50%, depending on climatic zone, building type and airtightness (EU 2001). However, MVHR systems are not passive systems and require power to run fans and associated equipment (termed parasitic energy demand). In theory a well designed MVHR system in a relatively air tight building will offset this parasitic energy demand through the energy savings derived from heat recovery. The air tightness of the building is critical to the efficiency of the heat recovery system. As with other LZC technologies, how much of this useful 'free' energy is utilised in practise will depend on a number of parameters, including design, climate and how it is used.

Solar hot water (SHW), photovoltaics (PV) and heat pumps have come to the fore as relatively mature technologies offering significant energy and carbon reductions within current construction practise and regulatory frameworks (Kierstead 2008).

3.3.1. Solar hot water (SHW)

The use of SHW systems can make significant carbon savings, depending upon the fuels displaced of between 230kg CO_2 year replacing gas and 510 kg CO_2 year replacing electric immersion and providing an average of 60% of a households hot water demand (EST 2011). SHW systems also require power for pumps and controls of approximately between 10 – 180 kWh per year (BRE 2009a; EST 2011). This is typically a small fraction of the total savings from SHW systems and is not thought to be a critical issue.

The contribution that solar hot water can make to a households overall hot water heating demand is hugely variable, with the solar proportion ranging from 9 – 98% (DTI 2001; EST 2001; BRE 2009a; EST 2011). The conditions of use have been shown to be a critical factor in determining system performance (BRE 2009a; EST 2011). This includes: volume of hot water demand (higher hot water demand enables greater solar contribution); timing of input from subsidiary heating systems ('topping' up at the end of day rather than beginning); and temperature (higher temperatures require significantly more 'top-up' from subsidiary system and increased heat loss from cylinder).

3.3.2. Photovoltaics (PV)

The annual yield of a PV array will be highly variable from year to year and is dependant upon climate factors. Studies on PV performance have found yeilds to be widely variable, for example studies on PV systems in Germany have found a range in system yields of 400 – 1030 kWh/(kWp/year), averaging at 885 kWh/(kWp/year) (Decker and Jahn 1997; Jahn and Nasse 2004).

PV systems vary widely in total installed generation capacity. PV systems are modular and the power rating of modules varies by manufacturer and model. In addition a PV system is not 100% efficient. There are losses associated with the inversion from DC to AC. An early study of 170 1-5kWp grid connected PV systems in Germany found that system losses fell within a range of 10 – 16% (Decker and Jahn 1997). Technical improvements have increased the conversion efficiency to 90% (Ayompe et al. 2011). The annual yield will also vary depending on climate (cloudiness and temperature) which also determines the conversion efficiency (amount of available sunlight converted to DC current) of the modules (Ayompe et al. 2011; So et al. 2007). Furthermore the conversion efficiency will also reduce over time. The causes for the reduction of conversion efficiency include photon degradation, severe discoloration, de-lamination, cracking of cover glass, splitting of back-sheets, wiring degradation and junction box failure (Dunlop and Halton 2006). The number of installed systems in the UK is still relatively low therefore the extent of these issues are not likely to become known until these systems have been in place for a number of years. However system yields can be accurately estimated (Bahaj and James 2007).

There are very few studies available to estimate the proportion of available PV generated electricity that is utilised directly in the home and that exported to grid. The studies that are available indicate a very wide range of between 20 – 73%[14] (Erge et al. 2001; Bahaj and James 2007). The proportion exported will be determined by occupation patterns and behaviour. Bahaj and James (2007), in a recent study of nine domestic PV systems in the UK, found that households that change the timing of activities such as washing and cooking (termed load shifting) to exploit the PV generated power used the most,

[14] A number of individual enthusiasts have published their own data as web blogs or discussed in web forums. The percentages cited range from 50% to 60% during the initial early stages of monitoring and rise to in excess of 70% after altering behaviour to accommodate solar generation.

concluding that PV can provide a significant contribution towards the annual electricity demand of a household but this would be limited if there was not a concomitant load shifting in consumption.

3.3.3. Heat pumps

Heat pumps, using the same process as found in a fridge or air conditioning unit, moves low grade heat from a source (e.g. air or ground), to a heat sink (i.e. heating and hot water). Air source heat pumps (ASHP) and ground source heat pumps (GSHP) are currently the most widely installed. The process requires power, for every unit of electricity required approximately 2 -4 units of useful heat will be produced. This ratio is the coefficient of performance (CoP) and is measured as the heating output (kW) divided by the total power consumed by the system including fans, pumps, and controls (also in kW). However, the CoP is dynamic, varying with the temperature difference between input and output. The heat source will vary over the heating season as it is depleted and the demands made upon it in terms of output will also vary. Therefore CoP is both a measure of the effectiveness of the heat pump system itself and a measure of the conditions in which it is used.

In a recent study of 83 installed ASHP and GSHP systems, the Energy Savings Trust found 87% of the systems monitored underperformed (EST 2010). GSHP were found to be lower than anticipated, CoP ranging between 1.3 -3.6. The report cited a number of contributory factors related to: design (including: sizing of pumps; ground loops; hot water cylinders; and heat emitter area), system installation (including: poor insulation, commissioning and incorrect temperature set up) and occupant behaviour. Despite the poor performance results the report concluded that heatpumps were found to reduce CO_2 emissions compared with other conventional heating technologies, including gas but were most effective if displacing conventional electric or oil fired heating systems.

3.4. Evaluating energy and carbon from new low carbon housing

Peer reviewed energy performance studies of new low carbon housing are relatively rare (Leaman et al. 2010). Recently, in response to the drive towards zero carbon and a need for evidence, the housebuilding industry has begun to invest in and collate this information[15]. Most studies are voluntary, carried out or commissioned by building owners or building designers (Stevenson 2009).

These buildings are typically unique, either experimental prototypes or small scale test beds. Drawing comparisons between different projects and buildings are difficult, not least because of the individual nature of each development, but also because there is no standard procedure or protocols for evaluating the energy use (Meir et al. 2009). Consequently, building evaluation studies use different approaches, resulting in inconsistency in methods, different parameters and how the results are presented (Stevenson 2009). More recently in recognition of this there have been efforts to consolidate the many methods available into a consistent methodology for the evaluation of domestic buildings (EST 2008; Leaman et al. 2010). As yet there is no consistent methodology.

3.4.1. Monitoring energy use

Energy and carbon performance is calculated from metered amounts of energy consumed and produced. Disaggregating total energy consumed to different end uses is more difficult unless sub metering and other monitoring equipment is installed to measure actual energy consumption to an appropriate resolution and the contribution made by the various technologies deployed to meet that specified end use.

Data collection methods used range from simple manual meter readings through to complex multiple sensor wireless remote GSM modem enabled centralised data loggers. The range and complexity of metering technology has increased rapidly in recent years. From relatively cheap simple clip on power meters that monitor electrical energy use to, at the other end of the scale interms of both cost, convenience, complexity and risk, wireless multi-sensors connected to centralised multifunction data loggers with GPRS/GSM[16] modem connection that enable a vast array of data to facilitate the calculation of actual energy demand and supply from numerous points. Equipment of this type is at the cutting edge of technology and not without substantial risks. Problems encountered have included: equipment faults; incompatible components; data communication losses between the sensors in the home and the data logger and between

[15] for example the Association for Environmentally Conscious Building AECB Low energy building data base A voluntary repository for information on new and retrofit low energy buildings which includes self reported energy data (http://www.retrofitforthefuture.org) and the zero carbon hub (www.zerocarbonhub.org).

[16] General packet radio service (GPRS) is a mobile data service supplied at a cost by volume of data using the Global System for Mobile Communications (GSM) cellular network.

the data logger and the researchers remote location; and managing the vast amount of data received (AECOM 2011). However, simpler methods are not without problems. Errors, both human in the manual reading recording or technical meter malfunction may occur and will not be apparent until the end of the study, if picked up at all (EST 2008). Metering may also change during the study period, for example a household may change tariff from a single rate to a dual rate or to pre-payment meter. These errors will not become apparent, if at all, until the end of the monitoring period jeopardising carefully designed research.

Whatever the means employed, the data needs to be consistent, reliable, replicable, and collected at a frequency that will give resolution sufficient to meet the requirements of the research goals (EST 2008). The frequency of data collection will be dictated by the subject of the study. For example, household energy demand has been shown to have a well defined weekly pattern of demand therefore weekly meter reading would be appropriate whereas appliances are more dynamic with each technology having household specific usage patterns and requires data collection at a much greater resolution (Wood and Newborough 2003). Within a weekly demand pattern the signature for individual appliance use or lighting use would be lost, therefore if the research design required to pickout these signals a higher frequency would be required, from hourly to minutes for individual circuits or appliances, generating a large volume of data. Whilst for technologies such as SHW, PV, or heat pumps the interval varies between seconds for PV and daily for SHW (EST 2008).

3.4.2. Energy benchmarks

In many cases gathering energy consumption data directly may not be practical. In such cases disaggregating raw energy data to different end uses is problematic. The use of benchmarks to provide a generalised percentage breakdown for different energy end uses has been used as a simple method (Beggs 2002). However, such an approach is not robust. Aggregated statistics on the energy efficiency and energy end uses of housing in the UK are readily available (DCLG 2008b; DECC 2009; Shorrock and Utley 2008). Benchmarks for energy consumption and end uses for housing based on physical and econometric models of the housing stock from these data are also available (Shorrock and Dunster 1997). However, the statistics, data and models are 1) aggregated for the whole UK housing stock 2) historical, providing information on the existing housing stock and 3) aim to provide information on the impact of policy over time on existing stock or for use in projections of changes to this existing stock. However, existing homes were constructed to much lower thermal standards than new homes. As standards have increased the proportional distribution of energy demand to space heating end use diminishes limiting the applicability of such benchmarks in the analysis of energy use patterns in new homes. There is an urgent need for benchmarks applicable for these new low energy homes.

3.4.3. SAP

SAP, based on The Building Research Establishment Energy Model (BREDEM) calculation procedure (Anderson et al. 1985), is the governments' methodology for calculating the energy demand and carbon emissions of a building (BRE 2009b). SAP calculates the useful energy required for heating systems using degree days and the homes heat loss, accounting for the complex interactions that occur between a home and the external environment. It is widely used and extensively validated (Dickson et al. 1996). Whilst there are criticisms of SAP, including outdated theoretical basis, inaccurate conventions and its capacity to model low energy homes (Silver and Parand 1999; Reason and Clarke 2008), SAP offers standardised occupancy, climate and exposure factors, which facilitate comparisons with other buildings, benchmarks and also enables normalised consumption to be directly compared with the SAP expectations as designed (EST 2008).

3.4.4. Normalising data

Many studies present data as raw total annual consumption, as kWh delivered energy, or kWh per m^2 (e.g. Gill et al. 2010). Such preliminary analysis of raw data establishes how much energy is being consumed, of what type of energy is being used, and enables the determination of carbon emissions (Beggs 2002). It does not enable comparative assertions to be made or benchmarking.

Furthermore, each home, even physically identical ones in the same location will not have identical energy consumption due to differences in households, exposure and micro climate and location (Juodis et al. 2009). This is further exacerbated with studies in different locations or longitudinal studies. In order to comparative data needs adjusting (or 'normalising') for parameters including weather and occupancy (Beggs 2002). The normalised performance indicator (NPI) method was developed to address these issues and expresses annual consumption in terms of a single indicator, kWh/m^2 or CO_2/m^2 (CIBSE 2004). Yet this is not the norm in published energy studies raising difficulties in comparing results. However, presenting data as a single normalised indicator can distort data, masking real patterns of consumption and underlying individual end uses (CIBSE 2004).

3.4.5. Small samples, variability and replicability

Differences in households and their behaviour creates significant variation in the amount of energy required to run a home, studies indicating up to 300% variation between different households occupying identical homes (Lutzenhiser 1993). Furthermore, the huge range of variation found between households has consequences for drawing conclusions from evaluation studies that are typically based on single dwellings or groups of homes less than 10 that often constitute the entire sample population. The low numbers studied are to a large extent dictated by the availability of test homes but also the practicality of studying homes and the people that live in them at the level of detail required. However, such small groups preclude the application of statistical analysis and any potential inferences arising from the results. In statistical terms the greater the sample the lower the uncertainty and vice versa holds true. Whilst a wealth of detailed information can be gained from studying such small groups it is gained with very high degrees of uncertainty. Generalisation for the population as a whole cannot be drawn and any findings remain suggestive but never conclusive.

3.5. Description of the case study homes

The case study is a low energy affordable housing development constructed in 2008 in Lingwood, Norfolk in the UK. The case comprised fifteen homes constructed using a timber frame system that achieved a Code for Sustainable Homes Level 3 (DCLG 2008a). Data from fourteen homes were used in this research, seven 3-bedroom homes and eight 2-bedroom homes. The case study is described in detail in Chapter one. The follow repeats a summary of this description for information.

3.5.1. Basic house type: Energy parameters

A calculation of whole house energy and carbon were undertaken for the basic case study hour constructions (CONTROL) of 83m^2 internal floor area and an equivalent house constructed using conventional masonry cavity construction (termed CONVENTIONAL throughout this chapter). The calculation was carried out using National home Energy Rating (NHER) Plan Assessor V4.2.28 software incorporating SAP 9.81 (BRE 2005). NHER plan assessor is one of several government authorised software for the production of SAP assessments. The SAP methodology estimates space heating, hot water, and lighting and does not consider any other energy end uses. The basic house construction thermal parameters and results of the SAP assessment are given in Table 3-1. CONVENTIONAL conformed to the minimum thermal and energy characteristics required to meet current UK regulation standards based on Part L1A 2006 (ODPM 2006).

Table 3-1: Thermal parameters of case study home (CONTROL) and masonry cavity to minimum regulations (CONVENTIONAL)

Parameter	CONTROL	CONVENTIONAL
U-value (W/m^2K):		
wall	0.18	0.28
floor	0.16	0.20
roof	0.14	0.14
windows	1.80	1.80
doors	2.40	2.40
Air permeability ($m^{3/}m^2hr$@50Pa)	7.00	10[a]
Heat loss parameter ($W/m^2/K$)	1.33	1.54
(kg $CO_{2/}m^2$/year)	22.30	23.73
Space + water heat demand (kWh/m^2/year)	50.00	

[a] assumed accredited construction details 'y' value (Y = 0.08) used

3.5.2. Four house types described

There are four typologies of the basic house construction, (Table 1-3): a control with instantaneous gas fired heating and hot water no additional renewable technology (CONTROL); as control with the addition of grid connected PV and solar hot water systems supplementing hot water and electricity (SOLAR); as control with a passive solar sunspace and mechanical ventilation and heat recovery (MVHR); all electric space heating and hot water provided by a 3.75 KW ground source heat pump with and under floor heating loop installed on the ground floor only with radiators upstairs (GSHP).

Other features included all fixed lighting was dedicated low energy lighting. In addition all appliances, including cooking, were the occupants own, purchased new upon occupation or bought with them from their previous homes.

Table 3-2 Characteristics of the fourteen homes (refer to text for definition of house types)

House ref.	No. Occu-pants	Area/ m^2	Occu-pancy hours/ year	Gas boiler	Solar hot water/ m^2	Photo-voltaic/ kWp	GSHP/ 3.75kW CoP 3.8	MVHR	Sunspace
GSHP1	3	71	8213				√		
GSHP2	2	71	6570				√		
GSHP3	3	83	4928				√		
GSHP4	2	71	8213				√		
MVHR1	4	83	8760	√				√	√
MVHR2	2	71	4928	√				√	√
MVHR3	4	71	6570	√				√	√
MVHR4	4	83	6570	√				√	√
CONTROL1	4	83	6570	√					
CONTROL2	4	83	6570	√					
SOLAR1	4	71	8213	√	4.04	1.6			
SOLAR2	3	83	6570	√	2.02	1.5			
SOLAR3	5	83	7300	√	4.04	1.5			
SOLAR4	3	71	6570	√	2.02	1.6			

3.6. Methodology

The study presented in this chapter included the following aspects of the monitoring and evaluation study:

- The energy used during occupation and the resulting carbon emissions
- The mains energy displaced by the different renewable energy technologies
- The contribution of renewable energy produced to total annual energy budget and the resulting carbon savings

- The embodied carbon of different approaches
- The effects of occupant lifestyle and behaviour on annual carbon emissions

3.6.1. Data

3.6.1.1. Occupancy

Data on occupancy patterns and energy use behaviour was gathered from questionnaires, interviews with householders and audits of appliances. These data were used to model energy use patterns and the contribution to total household energy from the various technologies employed.

Four of the homes were not occupied during the first six months of the monitoring period. These were: CONTROL 1; SOLAR1; MVHR 1; and MVHR2. Where a home was not occupied for a full year, back casting of data based on recorded consumption was undertaken to give a year's estimated consumption. SOLAR1 also switched to a prepayment meter shortly after occupation. It was not possible to gain further data on their consumption after that point. GHSP5 declined to participate in the study other than allowing meter readings.

3.6.1.2. Energy

Meter readings were taken from the electricity and gas consumer units, water meters and PV inverters, providing quantitative data on actual energy used (gas and grid electricity, total water consumption and annual PV production).

Energy data are presented in units of kWh at end use. Primary energy factors used were electricity 0.38 and gas 0.94 (DECC 2009).

Gas was metered in m^3. This was converted in to kWh by the following method:

$$(m^3 \text{ x VCF x CV}) / CF_{kWh}$$

Where:

volume conversion factor (VCF) is 1.02264 current to analysis period

calorific value (CV) 39.3808 current to analysis period

kWh conversion factor (CF_{kWh}) is 3.6

Energy costs were based on published average regional pence per kWh prices (BERR 2008) and were assumed to be £0.114 pence per kWh electricity and £0.003 pence per kWh for gas. For the analysis prices were held static to allow for comparability, however, in reality, some supplier switching activity occurred during the study and tariffs were changeable throughout the monitoring period. The use of a regional average, rather than actual, gave results that were both comparable and realistic. The average energy annual household expenditure in 2008 for the region was £900.

Normalised energy data

In order to undertake a comparison between the different homes and to enable comparison with results from other studies a normalized performance indicator, $kWh/m^2/year$ normalising for weather and occupancy. The method used as described in Beggs (2002).

3.6.1.3. Carbon

In addition to those produced by the consumption of energy, carbon emissions are also produced during the manufacturing, installation and maintenance of the heating, hot water and other generating technologies used (referred to as embodied carbon). In this study each of the different house types uses a combination of different technologies to deliver heat or power. The embodied energy from each of these technologies is required to enable a comparison between each approach used over a 20 year projection post occupancy.

Published UK government carbon emissions factors for fuels used current to the time of analysis were used in calculations of carbon emissions (DEFRA 2008):

- Electricity 0.54kg CO_2/kWh
- Gas 0.206kgCO_2/kWh

It was also assumed that decarbonisation of the UKs electricity supply would follow the trajectory stated in the UKs transition plan (DECC 2009b), falling from 0.53kgCO_2KWh during the year of monitoring to 0.37 kg CO_2kWh at the end of the 20 year period.

A 20 year time period was selected because it was assumed no significant refurbishment or replacement of the homes and the technologies used in them would be required it. It also coincided with the available projected data for decarbonisation of the electricity supply.

Embodied carbon data for the heating systems and renewable technologies derived from published literature (Table 3-3). Embodied energy and carbon figures found in literature were modified, accounting for quantities of materials specific to the homes (i.e. copper piping, electrical cabling). Sources were provided by the installation engineers, manufacturers' manuals, and product information. Distances were calculated from Google Maps. Simapro V7.1 software was used in the analysis.

Embodied carbon data for the construction, sunspace, heating systems and energy technologies was derived from research described in Chapter 2 and published literature (Table 3-3).

Table 3-3: Embodied carbon values used in analysis (tCO_2)

	Gas boiler system[a]	**Solar hot water (inc. store)**[a]	**PV**[a]	**Heat pump**[a]	**Ventilation & heat recovery**[b]	**Sunspace**[c]	**Construction**[c]	**Total**
CONTROL	0.6						34.6	35.2
SOLAR	0.6	0.8	2.6				34.6	38.5
MVHR	0.6				0.1	10.9	34.6	46.1
GSHP				4.0			34.6	38.6
CONVENTIONAL	0.6						52.0	52.6

[a] (Frischknecht and Rebitzer 2005)

[b](Nyman and Simonson 2005)

[c] Chapter Two

3.6.2. Monitoring and limitations of this study

The results presented in this chapter are derived from both quantitative and qualitative data gathered during the first year of occupation, from January 21st 2008 to January 21st 2009.

It was planned to use an innovative smart metering system to gather real time data on energy consumption (heat and power), individual appliance use, renewable energy production and the direct use of the energy derived from the energy systems in the home. The contractor for this was sourced by the construction partnership with the specifications pertaining to the data required provided by the researcher. After lengthy initial delays in installation it became apparent that there were technical issues with the monitoring system and commercial issues with the company contracted. The contractor was dismissed from the project in September 2009, nine months in to the agreed year of monitoring, and too late in the monitoring period for sourcing an alternative. The initial delays and subsequent loss of the smart metering element had serious repercussions, compromising the original research plan and the quality of data that would be available. These issues were resolved by modifying the aspirations of the research. As it would no longer be possible to gather fine grained data on energy end use, the data available would be aggregate from meter readings that had been taken at irregular intervals. To resolve the apportionment of the aggregated energy consumption to end use and the proportions derived from grid supply and the energy technologies would be modelled rather than actual. This raises questions of robustness and reliability of the results presented in this chapter.

3.6.2.1. Solar PV

A Sunny Beam wireless monitor was supplied to each of the SOLAR homes, it was planned that these would be used to record data to derive the performance of the solar system and the contribution made to the households annual energy budget. Unfortunately these went missing prior to the occupants moving in and were not replaced. Readings of gross production were taken from the inverter during the monitoring period. The system efficiency, solar contribution to total household electricity consumption and directly used solar electricity were estimated in this study[17]. Qualitative data on patterns of occupation and appliance use was collected during the monitoring period and this was used to model the proportions of PV generated power directly consumed and that exported to grid.

In modelling the contribution of the solar PV generated electricity to total household load it was assumed that electricity consumption was constant during the year. Therefore metered electrical consumption during January, where daily solar production is at its lowest, would be representative of average daily electricity consumption. It was assumed that the increased use of electricity for lighting and other activities during the longer winter evenings would be offset by the small amount of solar produced during the same period. This daily average was extrapolated to give an estimated total annual electricity demand.

[17] The solar fraction is the amount of energy provided by the solar technology divided by the total energy required. It is dependent upon the systems overall efficiency, the interaction of the solar system with other technologies (e.g. boilers), overall energy demand and patterns of energy usage.

3.7. Results

The main results the each of the four the four different typologies is given. This is followed by a comparative analysis of the energy demand and related carbon consequences of the four different typologies. The final analysis compares the embodied and in use carbon over a twenty year period.

3.7.1. Results for each house type

3.7.1.1. CONTROL

The two homes showed similar annual consumption, 6% difference in total annual energy (Table 3-4).

Table 3-4: Control 1 and 2 annual energy consumption for gas and electricity and total (normalised) (kWh/m^2/year)

	Gas	Electricity	Energy (normalised)
CONTROL 1	86	51	98
CONTROL 2	89	56	91

3.7.1.2. SOLAR

SOLAR 1 did not provide data on PV production or quantitative data and was therefore not included in this analysis. The average total energy demand for the SOLAR homes was estimated to be 142kWh/m^2/year (Table 3-5) including grid and estimated generated energy from the solar systems. Of this 66% was for space heating and hot water demand provided by both mains gas and solar hot water. The four homes showed a wide variation in total annual energy consumption (Table 3-5). There was a 27% difference between the lowest and highest energy demand.

Table 3-5: SOLAR homes annual energy data by source per kWh/m^2/year

	Electricity		Heat			
	Grid	**PV**	**Gas**	**Solar hot water**	**Total energy**	**Energy normalised (inc. solar)**
SOLAR2	24	17	74	18	132	75
SOLAR3	60	17	64	28	169	65
SOLAR4	22	6	87	24	139	61

PV

In total the whole 6.2 kWp installed collectors produced an estimated 6224kWh of DC power during the monitoring period (Table 3-6). The annual yield of 903kWh/kWp for 2008 falls within the expected range based on published studies and the location and fall within the acceptable limits found in the literature (Decker and Jahn 2004; Ayompe et al 2011).

Table 3-6: Lingwood PV vital statistics

Total array area	51m^2
Total generated	6224 kWh
System losses	622kWh
Annual yield 2008	903kWh/kWp

Overall 54% of the total PV produced power was used directly. It is estimated that the proportion of solar PV directly used by the different households ranged from 23 - 41% (Table 3-7).

Table 3-7: Modelled PV results

	kWh				%	
	PV installed kWp	**Annual metered**	**Solar directly used (estimated)**	**Total estimated annual consumption (grid and solar)**	**Solar contribution to total annual electricity (estimate)**	**Solar generation used direct (estimate)**
SOLAR2	1.5	1681	1187	2868	41	89
SOLAR3	1.5	4236	1239	5475	23	93
SOLAR4	1.6	1532	434	1966	22	29

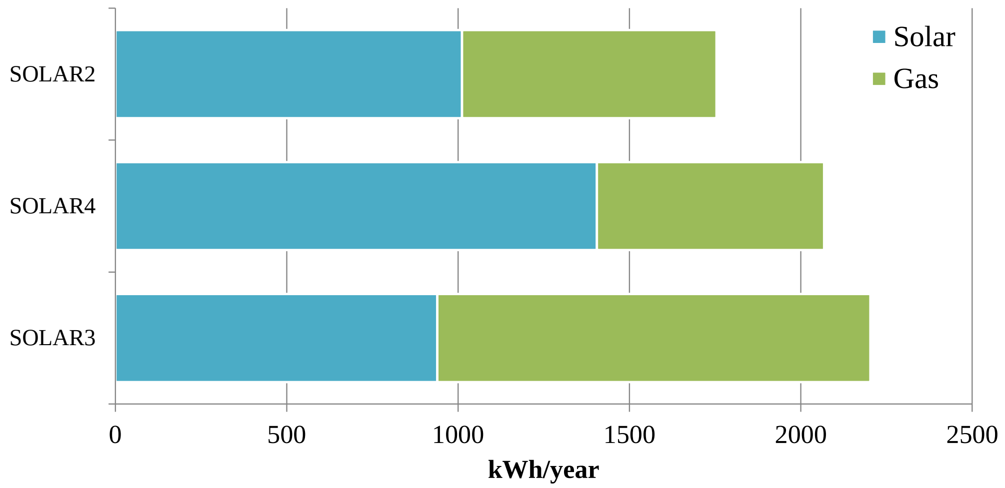

Figure 3-1: Estimated solar contribution to hot water demand

SHW

The solar hot water system was estimated to contribute between 45 - 70% of annual hot water demand for the three SOLAR households included in the analysis (Figure 3-1).

The overall contribution of the active solar systems to the estimated total annual energy consumption ranges between 17 – 27% (Table 3-5).

3.7.1.3. MVHR Results

The MVHR homes total energy consumption ranged from 104 - 150 kWh/m^2/year (Table 3-8).

Gas consumption ranged from 69 – 102 kWh/m^2/year. Of this between 56 – 71 % was estimated to be used for space heating. The remainder was attributed to hot water and a small proportion to cooking.

Table 3-8: MHVR annual energy consumption (kWh/m^2/year)

	Electricity	Gas	Energy normalised
MVHR1	49	101	67
MVHR2	36	69	101
MVHR3	42	102	97
MVHR4	33	91	83

Electricity consumption ranged from 33 – 49 kWh/m^2/year. It is estimated that electricity demand to power the MVHR system ranged 6-9% of total electricity demand for these homes.

In the absence of measured energy data, SAP 9.81 and the published manufacturers data were used to model the theoretical parasitic energy demand and energy savings from the recovered heat at the tested air permeability rate of 6.25 m^3/m^2@50Pa. An average net heating energy saving of 295kWh per year was calculated. Conversely, a net carbon increase of 28 kgCO_2 a year was found (Table 3-9). This is due to electricity having greater carbon emissions per unit than gas per kWh delivered.

Table 3-9: MVHR estimated energy and carbon balance

	kWh/year	kgCO_2 /year
Parasitic energy used (electric)	226	127
Energy saved (gas)	522	99
Net difference	295	28

3.7.1.4. GSHP results

The average total energy consumption for GSHP homes was 77/kWh/m^2/year. With the exception of GSHP1 all other energy uses showed a similarity (range 30 – 33 kWh/m^2/year). Space heating formed just over 55% of the annual energy budget (GSHP1, 2 and 4) (Table 3-10). The proportion was slightly higher for GSHP3 at 62%, the highest consumer using 38% more than the lowest consumer. All the systems were calculated to have lower CoP in use than the predicted performance.

Table 3-10: Energy data and CoP for GSHP homes

	All other energy (kWh/m^2/year)	Space heating (kWh/m^2/year)	CoP
GSHP1	39	47	2.07
GSHP2	30	38	2.43
GSHP3	31	50	1.75
GSHP4	33	40	2.22

3.7.2. Annual energy

Initial energy modelling, using the UK governments SAP methodology, compared a new build house that meets minimum construction regulation standards (CONVENTIONAL) and the basic house as constructed (CONTROL) showed a 7% saving in annual space heating energy demand and CO_2 emissions (Table 3-1). In reality all the homes used substantially more energy than that modelled for both the CONVENTIONAL and CONTROL. An average at 81 kWh/m^2/year for equivalent end uses compared with the modelled CONTROL of 50 kWh/m^2/year.

Average metered energy consumption of the fourteen homes was found to be 4132 kWh/year electricity and 6470 kWh/year gas, which is approximately 4% less electricity and 63% less gas consumption than the UK average household energy consumption.

The results suggest that, within the wide variations in energy consumption found and with the exception of GSHP3, the alternative typologies used less energy than CONTROL (Figure 3-2). Furthermore, within the wide variation no clustering of the different typologies is suggested by the normalised annual aggregated energy consumption (Figure 3-2).

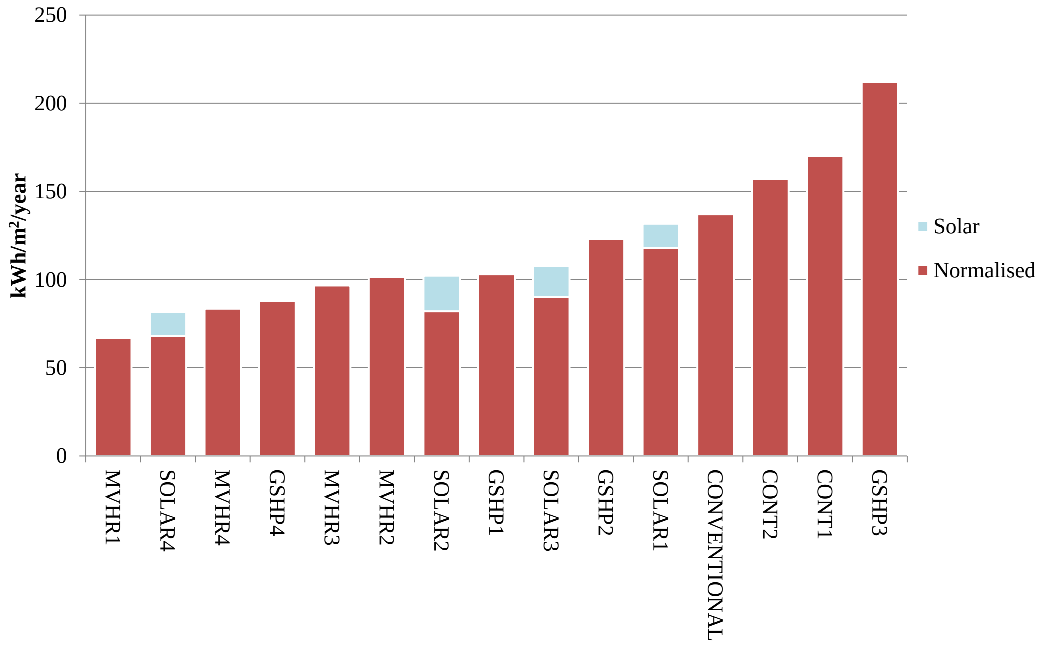

Figure 3-2: Annual energy (kWh/m^2/year) normalised for weather, occupation, and floor area with active solar contribution shown.

In considering the attribution of energy to end uses the proportion used for heating both space and hot water (66%) was found to be lower than the UK average of 82% (Figure 3-3). As a consequently the relative importance of other end uses (cooking, lighting and appliances)in such low energy homes increases, 34% of total energy compared to 17% for UK average (Figure 3-3). Of the four types the GSHP group had the lowest energy demand for heating related end uses whilst having relatively average energy demand for all other non-heating related end uses.

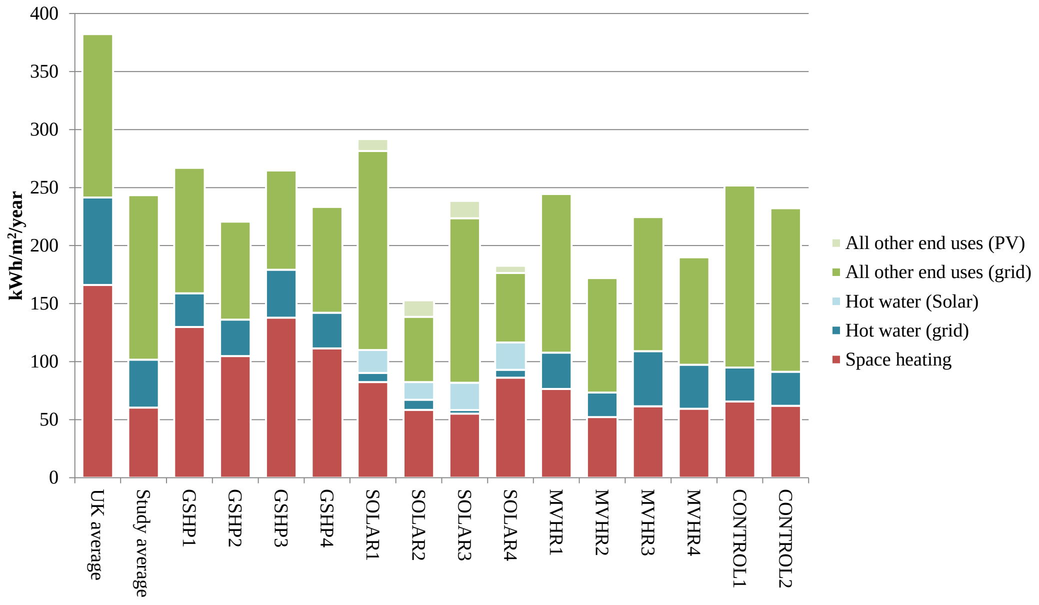

Figure 3-3 Energy attributed to end use for the fourteen case study homes. The UK average energy end use (DECC 2009) and the case study averages are also shown.

3.7.3. Annual carbon emissions

CO_2 emissions from the case study houses ranged from 24 – 51 $kgCO_2/m^2$/year, with an average of 42 $kgCO_2/m^2$/year, a 47% reduction when compared to average UK household emissions of 78 $kgCO_2/m^2$/year (DCLG 2008b; DEFRA 2009) (Figure 3-4). Taking the active solar technologies as an offset, displacing grid electricity and gas, the average offset was 0.8tCO_2/year. 60% of which was attributable to the PV displacing grid electricity and 40% attributable to the solar hot water displacing gas (Figure 3-4).

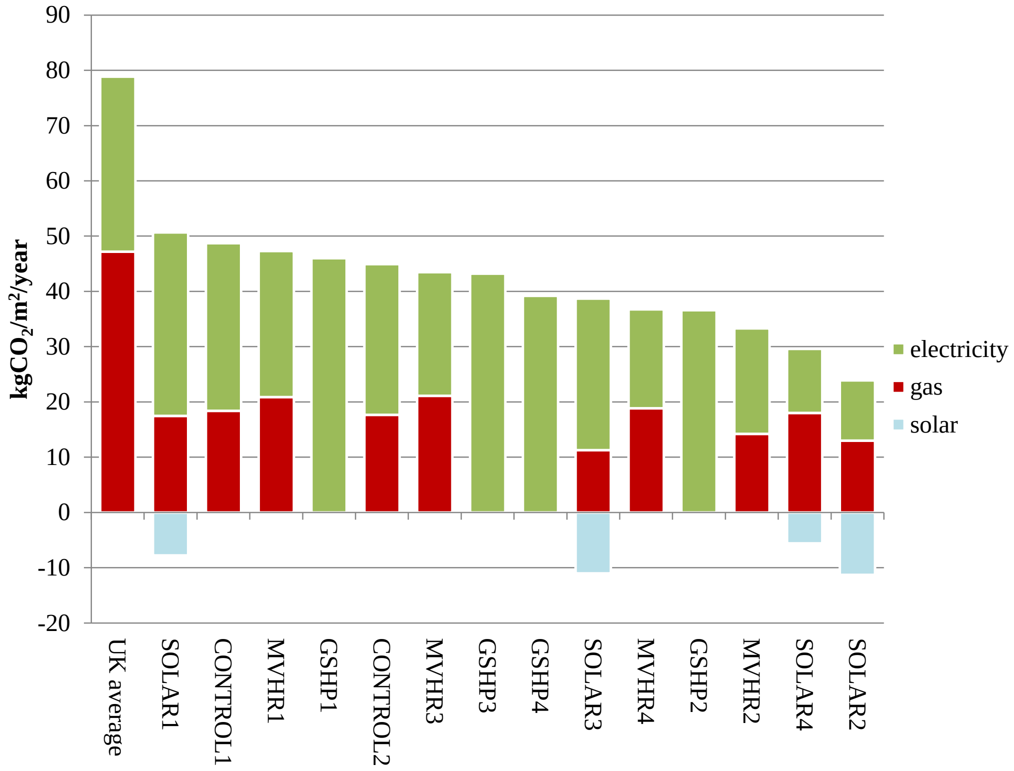

Figure 3-4 Annual emissions of CO_2 from the different energy sources consumed. Normalised by floor area and including the offset estimated from the active solar technologies ($kgCO_2/m^2/year$).

In the groups with gas heating systems (SOLAR, MVHR and CONTROL), 56% of emissions are associated with electricity consumption, compared with 40% for the UK average. Inferring that, for the majority of these low energy homes, (except for SOLAR2 and SOLAR4) it is end uses other than space heating that determine overall total CO_2 emissions. Modelling to attribute energy consumption by end use for this group of gas using homes supports this inference (Figure 3-5). Emissions associated with end uses other than space heating accounted for between 48 – 74% of total emissions, compared with 43% for the UK average. Furthermore, emissions from non-space heating end uses showed more variability across the fourteen homes than that associated with space heating.

For the all electric GSHP group approximately 50% of CO_2 emissions were attributed to space heating compared with the CONTROL homes (26%), this can be directly attributed to the higher emissions factor of grid supplied electricity than that of mains supplied gas (0.537 $kgCO_2/kWh$ and 0.206 $kgCO_2/kWh$ respectively).

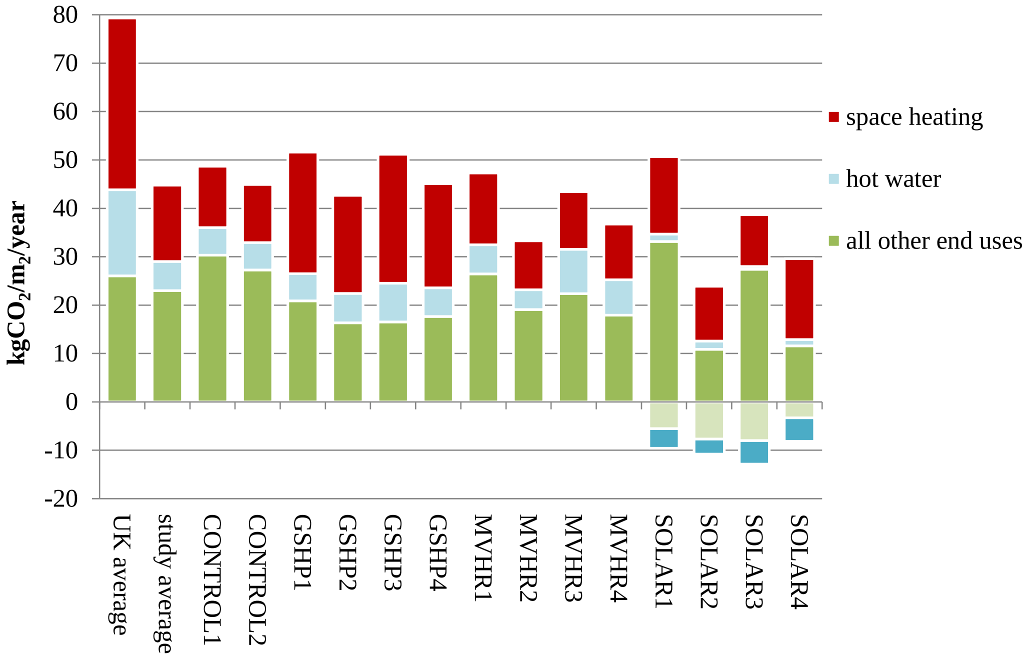

Figure 3-5 Annual emissions of carbon by house by end use. Normalised by floor area. Data includes active solar energy offset. UK average derived from (DECC 2009)

3.7.4. Annual running costs

The average annual running cost for the case study houses was approximately £583, of which £444 was for electricity and £135 for gas. This was estimated to be 35% lower than the regional average (Figure 3-6). There was a wide variation across the whole sample group and no discernible grouping apparent from this small group.

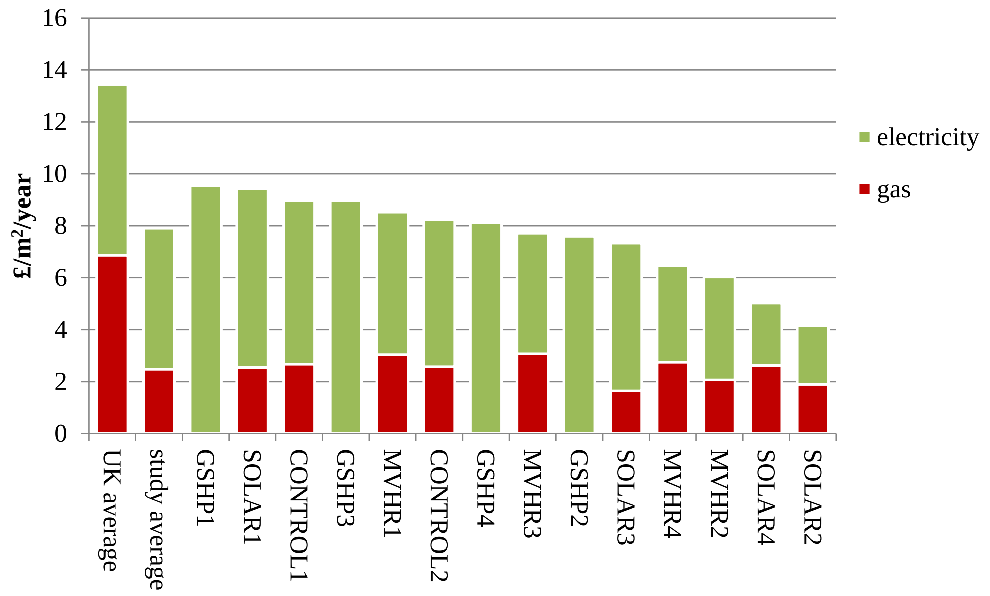

Figure 3-6 Annual running costs by house by fuel normalised by floor area.

3.7.5. Comparing energy, carbon and costs of the four typologies

It is useful at this point to summarise the results for energy (normalised), emissions (kgCO_2) and running costs (£) by aggregating for each typology. The summarised results show that all three alternatives to the CONTROL used less energy: GSHP 18%; SOLAR 25%; MVHR 14% (Figure 3-7). The combined results further support the finding that GSHP had the lowest end use energy consumption overall when compared with the other house typologies. All three 'low carbon' alternatives to CONTROL also had lower emissions: GSHP 11%; SOLAR 25%; MVHR 14%. Assuming that the energy cost tariffs were equivalent, the annual running costs compared with CONTROL were estimated to be lowest for SOLAR (25%) and 14% lower for MVHR. Interestingly, GSHP showed no difference in running costs when compared with the CONTROL.

The summarised results indicate the active solar technologies as demonstrated by the SOLAR group gave the optimum performance across all three evaluation criteria compared with the CONTROL, reducing energy, lowering emissions and reducing running costs considerably.

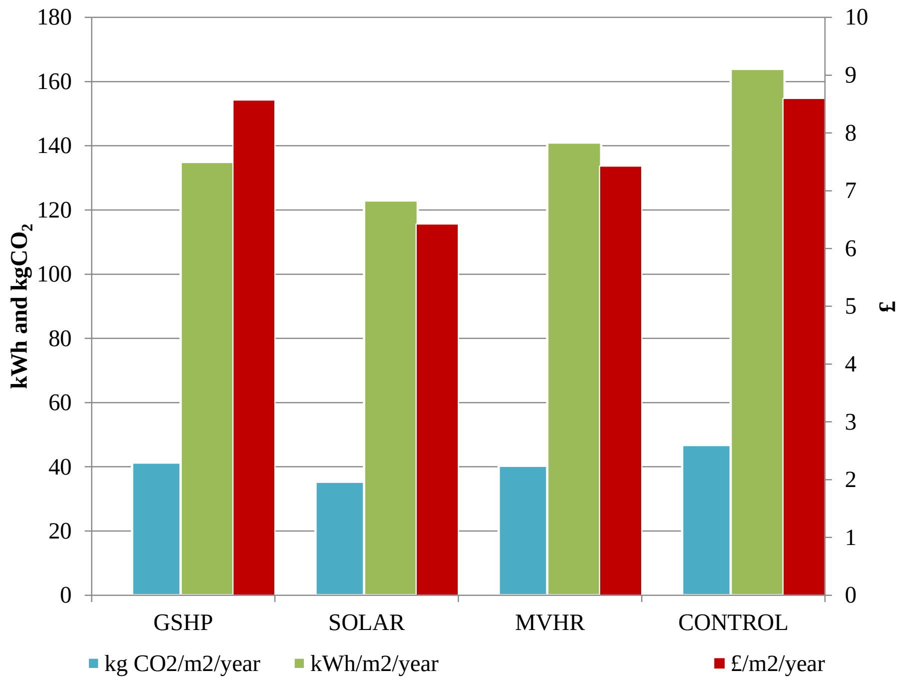

Figure 3-7: Summarised data for the four house typologies showing emissions of CO_2, and energy on the primary axis and running costs on the secondary axis.

3.7.6. Lifecycle carbon: comparing the four typologies over a 20 year period

To provide a holistic picture of the energy used and carbon emissions from the case study houses, the annual energy demand and associated CO_2 emissions for a 20 year period were combined with the initial energy and CO_2 emissions embodied in the production of each different house type and technology (Table 3-3 and Figure 3-8). This is particularly salient for homes reliant on electricity and, consequently, the decarbonisation of the UK electricity supply for delivery of carbon reductions.

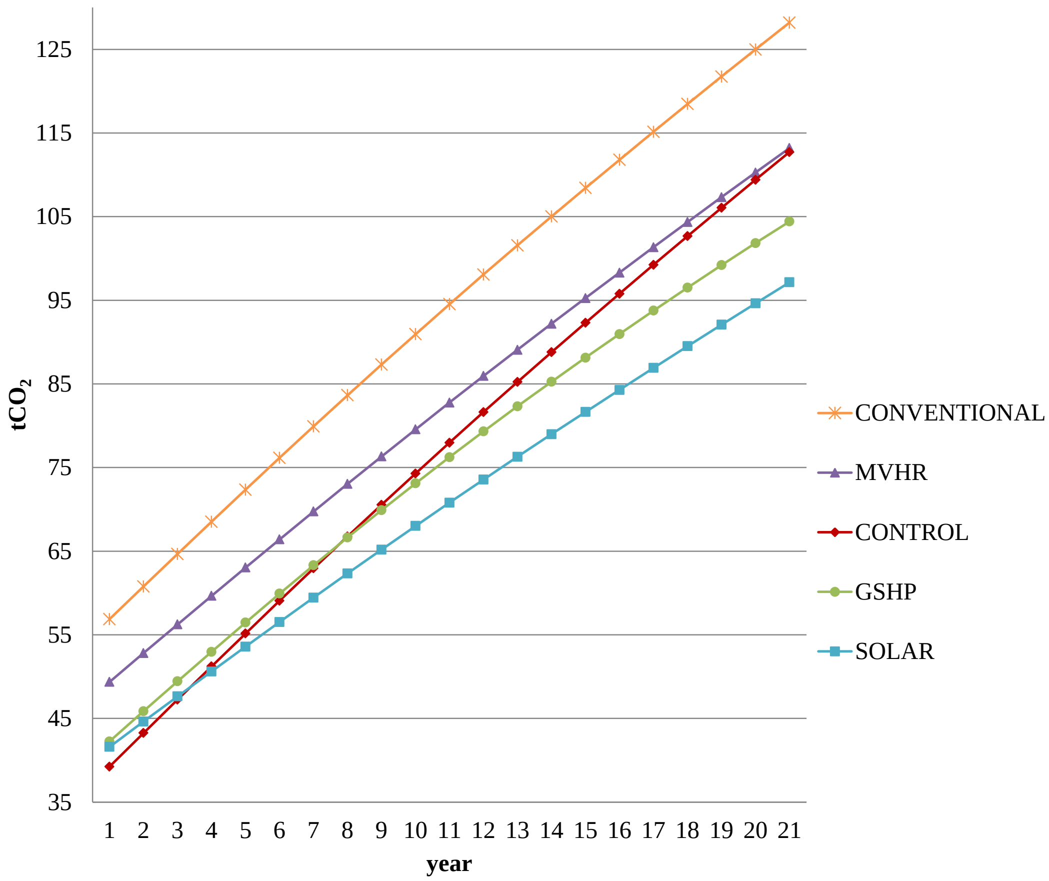

Figure 3-8: Embodied carbon and occupational carbon emissions from energy use over 20year time period.

Compared to the CONVENTIONAL model all the housing types have a lower initial embodied energy (Monahan and Powell 2011). Embodied carbon analysis presented in Chapter Two indicates this is directly related to the use of high embodied energy materials, including bricks and cement products found in conventional UK housing construction. However, high mass materials may also provide lifetime benefits of passive thermal storage, enabling daytime heat gains to be stored and emitted during the night, reducing the energy required for space heating or cooling. The effect of mass on occupational energy, in comparison with lightweight timber frame construction has been found to reduce space heating energy demand between 7-19% (Hacker et al 2008).

Nevertheless, taking into account the relative benefits of thermal mass found in the CONVENTIONAL model, all the case study housing types have consistently lower emissions during the 20 year occupation period compared to CONVENTIONAL. Of the four case study types CONTROL has the highest annual carbon emissions during the occupational period, consequently it continues on a higher carbon trajectory when compared with the three alternative low carbon scenarios. MVHR homes have the highest initial embodied carbon of all four house types (Figure 3-8) due to the substantial additional embodied carbon associated with the construction of the sunspace. The additional embodied costs are partly offset, to a small degree, by a net annual carbon saving from reduced energy demand when compared with CONTROL. However this annual reduction does not recoup the initial additional carbon costs until the end of the 20 year period.

In carbon terms SOLAR has the lowest annual carbon emissions during occupation over the 20 year period and, in consequence the lowest carbon trajectory, recouping the additional embodied carbon costs of the PV and solar thermal systems in three years post construction.

The GSHP homes recoup the additional carbon costs of the heat pump system during year 8 when compared with CONTROL. However, even with the projected decarbonisation of the UK electricity supply, GSHP have higher annual emissions than SOLAR. This suggests that further decarbonisation of the UK electricity supply and, or, installation of micro renewables (such as active solar technologies) to displace grid electricity, will be needed before the carbon payback time period and annual emissions can be as low as SOLAR.

3.8. Discussion

The results presented above show that the case study homes have a significantly reduced energy demand, carbon emissions and running costs when compared with current industry practise as modelled by CONVENTIONAL. The CONTROL houses achieved notable energy and carbon reductions through the application of best practise conventional technologies and construction processes. Of the three alternative typologies GSHP households had a high energy demand and, due to their reliance on electricity for all energy uses, were also disadvantaged by both a higher carbon factor and unit cost price of electricity compared with gas. The best overall performance across all three evaluation criteria were the SOLAR households reducing energy demand, lowering carbon emissions and running costs.

The reductions were largely attributable to the reduction in energy required for space and hot water heating demand. This is unsurprising as these homes were built to higher thermal efficiency standards than that found in the UK stock. The technical improvements in levels of insulation, reduced air permeability and more efficient heating technologies require less energy to provide the same utility (i.e. maintain an internal temperature of 21°C).

Therefore, the industry preference for enhancing the built envelope (Osmani and O'Reilly 2009) will produce significant energy savings. The inference is that UK policy is having some degree of success in reducing the energy and environmental burden associated with heating related services in new build homes regardless of which technology is used, be it a heat pump or an efficient gas boiler. However, the translation of this increased energy efficiency into reduced carbon emissions may not be fully realised if electric heating systems are used.

The use of all electric systems, specifically heat pumps, is projected to increase (DECC 2009) and recent market research supports this trend (BSRIA 2009). However, the research presented here suggests that the adoption of all electric heating systems as demonstrated here by heat pumps, may be counterproductive for both environmental and social policies.

Firstly, the performance of heat pumps in reality may not approach the levels claimed or anticipated. In the four systems presented here, none of the systems indicated a CoP approaching the 3.8 claimed by the manufacturers. The result could be due to modelling error, a fault in the system design or installation or household differences. Future monitoring work is required to provide data of sufficient quality to be able to make any robust claims for these particular systems and resolve this question.

Secondly, regardless of the efficacy of all electric heating systems, without decarbonisation of the electricity used carbon emissions will remain high. There is a need for significant decarbonisation of the UK electricity supply or a significant proportion of the electricity is supplied by localised low carbon micro generation such as PV. However, given current projections, it seems unlikely that the UKs electricity supply will substantially decarbonise in the next 20 years of house building and technological ‘lock in’ with heat pumps. Therefore, despite the energy savings demonstrated by technologies such as heat pumps, all electric homes will have higher carbon emissions.

Thirdly, all electric homes are more costly to run than those heated with mains gas because the unit price of electricity is higher and predicted to increase as investment in low carbon generation capacity increases. Even with advantageous pricing tariffs (e.g. economy 7), in high daytime occupancy households, such as these, it is likely that energy costs will not only remain high but also increase for all electric homes.

The widespread adoption of all electric heating systems will have major implications for the UKs GHG emissions. Whether this is a trend to be concerned about depends not only upon the ability of the UK's electricity supply to decarbonise but also to meet the growth in demand at a price that is acceptable to the consumer.

What is clear is that as the thermal envelope of low energy homes becomes more efficient, the energy used by these homes will increasingly be associated with end uses other than heating. Energy use behaviour will become an increasingly important factor in household carbon emissions. The case study showed almost no difference in consumption of energy associated with cooking, lighting, and appliance use than the average UK household. This was unsurprising for two reasons. Firstly, these households were passive adopters of low carbon homes, having no role in the design of or technologies deployed in their homes as an active expression of environmental beliefs, in much the same way as the majority of households in the UK. Secondly, as with most households in the UK, the occupants of this case study were in control of their own destinies when it came to the choice and provisioning of white and brown goods and how they used them. This suggests that the mere fact of living in a low energy 'eco' home does not necessarily prompt environmentally aware behaviour from the typical passively adopting household who finds themselves an 'accidental environmentalist'.

What is missing from this analysis, and analyses like this are questions about how households use new technologies and how these low energy 'eco' homes and the technologies within them can affect behaviour and expectations of service. It has also been suggested that low carbon technologies may promote more environmental behaviours. In the case of the SOLAR households the evidence is contradictory. SOLAR had the lowest total energy demand of those homes with gas. This could be an artefact of the modelling underestimating the contribution that the PV and solar hot water made. An alternative explanation could be that the presence of solar technologies, and by inference other micro-renewable technologies, could be influencing occupant energy use behaviour. A recent research report found the presence and use of solar technologies did indicate changes in behaviour especially in passively adopting households (Dobbyn and Thomas 2005). But this is not conclusive and other research has found contradictory results (Keirstead 2008).

The provision of information an often cited method for addressing this issue. Information in an accessible format may be a prerequisite to success, particularly as many of these technologies are not familiar to the average household in the UK. For example, the inclusion of PV contributed between 14 – 41% of the total electricity demand in the SOLAR households, proving their usefulness from an energy and carbon perspective. However with information on how to make the more of the generated power, plus the lack of a feed-in tariff or other financial incentives, much of the generated power was of no benefit to the households, due to the homes being a) unoccupied during the hours of production with generated power being exported directly to the grid; b) appliances being used at time of the day when solar production was at its lowest (e.g. washing machine and ovens used during the evening); c) over or under estimation of the ability of the power generated to meet the expected service (e.g. an expectation that the PV system could provide 'free' power to run washing machine, tumbler drier and cooker concurrently during daylight hours). However, just because information is provided does not mean that it will be read or followed. With the number of such mainstream homes and passive adopters increasing, this would be a valuable area of further research.

Whilst there were no technical difficulties experienced in the installation of the technologies there are a number of concerns regarding design, in particular concerning the relatively underutilized passive design strategies as demonstrated by MVHR. Passive design is a proven, well accepted means of designing a home that requires minimal or no space heating (Brown and DeKay 2001). However, as applied in this case study, the design and ventilation strategy were not fully integrated into the overall design of the home, their application was achieved more as a 'bolt on'. Firstly, there is a threshold of air permeability of the house envelope at which mechanical ventilation with heat recovery acts as a net energy user, with the parasitic energy demanded outweighing that saved and resulting in a net rise in carbon emissions. In the case study homes an air permeability of 7 m^3/m^2hr@50Pa was high. This resulted in the ventilation systems not performing as well as anticipated, the households complaining of cold draughts, leading them to disable the ventilation system and rendering the sunspace thermally redundant. Secondly, the designed mass to glazed collector area ratio was too low for the thermal mass to be a significant contributor. Additional mass was available in the concrete floor but this had been isolated by a carpeted floor covering. Thirdly, the relatively high initial embodied carbon of construction and ongoing high annual energy demand comparable to that of a home with no particularly specialist technology or investment (i.e. CONTROL) suggests its use in the mainstream is questionable if applied by inexperienced housing designers.

It is clear from this research there is no single 'magic bullet' low carbon solution. If zero carbon is the target for new build housing then perhaps policy needs to start considering household energy holistically and not just focussing on that pertaining to heating.

Housing designers will need to gain a greater understanding of how to exploit free energy, heat pumps will need additional supplementary technologies such as solar, and households will need to acquire a new energy literacy. Perhaps, in order to achieve the necessary future of zero carbon homes, we need to think more in terms of how energy is used over the course of a year and use a seasonally appropriate mix of technologies that work with the seasonally available resources. However government and industry may baulk at the costs and complexity of such a solution.

3.9. Conclusion

The built environment needs to develop more sustainable, less energy-intensive systems and approaches that are socially acceptable and economically advantageous. With this in mind this chapter posed the question: which technologies and design strategies currently being deployed in mainstream new build housing provide the best results to achieve the three aims of low energy, low carbon and affordability? Following on from this what, then, are the consequences of their deployment in terms of meeting these policy objectives?

All of the four case study approaches were successful, to varying degrees, in reducing the total energy consumed, consequential carbon emissions, and running costs during occupation. The use of solar technologies gave the most benefit across the three criteria and significantly reduced carbon emissions over a twenty year period. The use of sunspaces and heat recovery as applied in these homes did not give any substantial benefits compared to the control homes and did not recoup the initial embodied carbon investment until the end of the twenty year period.

Although heat pumps were found to have the best performance in terms of energy demand they were found to have comparatively high carbon emissions and running costs. This raises the question if the greater use of electricity for space heating is realised in the housing stock as a whole, how will this increase in demand will be met without raising emissions of carbon? If a large proportion of the projected 3 million new homes are constructed prior to the introduction of the zero carbon standard in 2016, and without either a substantial decarbonisation of the UKs already straining grid supply network or the creation of significant additional zero carbon capacity (from an increase in micro renewables such as PV or wind perhaps) might such a trend prove counterproductive for climate change policy?

What is clear from this study is that reductions in energy and consequential carbon emissions were derived principally from the increased thermal efficiency of the homes and consequent reduction in heating related energy demand. Furthermore, the results indicate that there was no discernible difference in non-heating energy consumption by the case study households than from any other household in the UK, despite these homes being heralded as a show case of affordable, mainstream, sustainable (low energy) living. Suggesting the occupants themselves made little if no contribution to the reductions found.

Currently there is a policy and regulatory focus on reducing heat related energy demand focusing on the fabric and technological aspects of efficiency. The results presented here suggest that in order to meet future carbon targets it will be necessary to move beyond this, requiring engagement from the occupants, and a change in behaviour and lifestyle and the tackling of other energy end uses.

If reducing emissions of carbon really is the target then the results and arguments presented suggest that the interpretation of policy on the ground may well be leading us further along the wrong path if infrastructural and social changes don't change concomitantly.

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4. Mechanical ventilation and heat recovery in low carbon homes: assessing the evidence

This chapter is the second of two that address research question 2 outlined in Chapter 1:

Are the innovations currently being deployed by mainstream housing providers in response to regulatory changes capable of meeting policy carbon targets?

As with chapter 3 its purpose is to assess whether innovation in construction and technologies in mainstream housing can deliver national carbon reduction goals. Chapter 4 focuses on a specific innovation, mechanical ventilation with heat recovery (MVHR), in new low carbon homes.

A paper based on the research described in this chapter has been submitted for publication and is currently undergoing peer review.

This paper considers the implications of the adoption of MVHR in new build homes in the UK. First, the policy and regulation background driving the adoption of MVHR as an industry design standard is discussed. Secondly, a review of the literature on the energy and carbon implications of MVHR systems is presented, including manufacture, energy in use and user evaluation. Thirdly, a case study of an evaluation of three new build homes with MVHR in Norfolk, UK is given. This paper then closes with a discussion of the implications for policy if MVHR becomes the industry standard in new build homes in the UK.

4.1. Introduction

Space heating, accounting for 62% of total household energy demand in the UK in 2010 (DECC 2011), has been a focus of research and regulatory attention. Following the mantra ‘build tight ventilate right’ housing designers have sought to reduce heatloss by increasing insulation standards and improving the airtightness of homes, reducing air infiltration rates to very low levels. Concerns of an increased risk of health problems related to inadequate ventilation have been raised (Crump et al. 2009). As airtightness levels increase in response to regulation, traditional ventilation strategies of purging air through opening windows, intermittent air flows from fans and a reliance on infiltration will be inadequate to maintain to maintain a healthy indoor environment. As a consequence specifying purpose provided ventilation has become standard practise. Mechanical ventilation with heat recovery (MVHR), in particular, is increasingly being applied in new build homes in order to satisfy the regulatory goals of minimising energy demand without compromising indoor air quality (Crump et al. 2009).

As a response to regulation, the adoption of MVHR as an industry standard is one that may be counterproductive and result in unanticipated negative results (Roaf et al 2009). While we know a great deal of the technical efficacy of such systems operated in optimal contexts there is a dearth of evidence of the energy and carbon consequence of the adoption MVHR in reality.

As regulation moves increasingly towards zero carbon it is inevitable that MVHR has become an innovation in the construction of new homes and the technologies that are used within them. How the housing industry, and the households who will have to live with the results, respond will be critical to meeting government carbon reduction goals. As industry responds to policy and regulation the outcomes are unknown. The response and resulting outcomes may be entirely unanticipated, the consequences unforeseen and the results contradictory to that planned.

4.2. UK housing policy and regulation background

In 2007 the then UK government introduced the Zero Carbon Homes Policy, clearly indicating the trend for increasingly stringent regulations and standards aimed at increasing the energy efficiency of homes would continue, culminating in 2016 with all new build homes built to a zero carbon standard (DCLG 2007). The instrument for delivering the zero carbon policy would be incremental improvements of the Building Regulations Approved Document Part L1a (the conservation of fuel and power) (ADL1A) on a baseline of the 2006 Building Regulations. The first of these incremental changes occurred in 2010 and are scheduled in 2013 and 2016 producing a 25%, 44% and 100% improvement on a 2006 baseline respectively. It was estimated that the incremental changes in Part L1a would deliver a carbon saving of 34.6MtCO_{2eq} by 2020 (DECC 2009).

The regulations are performance based, rather than prescriptive, comparing a notional emissions rate (TER) against that of the building as designed (DER) underpinned by minimum allowable standards for different elements (termed backstops). Compliance is achieved at the housing designers' discretion.

In 2006 amendments to ADL1a introduced a maximum allowable airtightness of $10m^3(hr/m^2)$ @50Pa and a requirement for airtightness testing (ODPM 2006). Housing providers adapted rapidly, achieving higher airtightness levels than predicted. As a result there has been a significant shift in the mean airtightness of dwellings from an average of 9.21 post 2002 (Grigg 2004) to 5.97 $m^3/(h\ m^2)$ at 50 Pa post 2006 (Pan 2010). According to the recent Part L and F consultation paper 30% of dwellings attain results lower than 5 $m^3/(h\ m^2)$ at 50 Pa (DCLG 2009) suggesting that, as PartL1a increases, dwellings will achieve very high levels of airtightness. Concern has been voiced that this trend may compromise indoor air quality and result in significant health concerns (DCLG 2009), (Crump et al. 2009). To counteract the potential health risks Approved document Part F (Means of ventilation) (ADF) (DCLG 2010) of the UK building regulations sets out changes to counteract the potential health risks of increasing airtightness.

The associated document (ADF) (DCLG 2010) defines ventilation as:

"The supply and removal of air (by natural and/or mechanical means) to and from a space or spaces in a building. It normally comprises a combination of purpose-proved ventilation and infiltration." p.8.

Whilst an aim of ADL1A is to minimise infiltration, the central aim of ADF is to ensure that purpose provided ventilation systems are capable of providing adequate ventilation to limit the accumulation of moisture and pollutants which would otherwise become a health risk[18].

ADF describes four systems (figure 4 -1): System 1: background ventilators and intermittent extract fans. System 2 Passive stack ventilation (PSV); System 3 Continuous mechanical extract (MEV); System 4: continuous supply and extract with heat recovery (MVHR).

18Adequate ventilation is specified as a default minimum whole dwelling ventilation rate of between 13 – 29 l/s depending upon number of bedrooms and occupants.

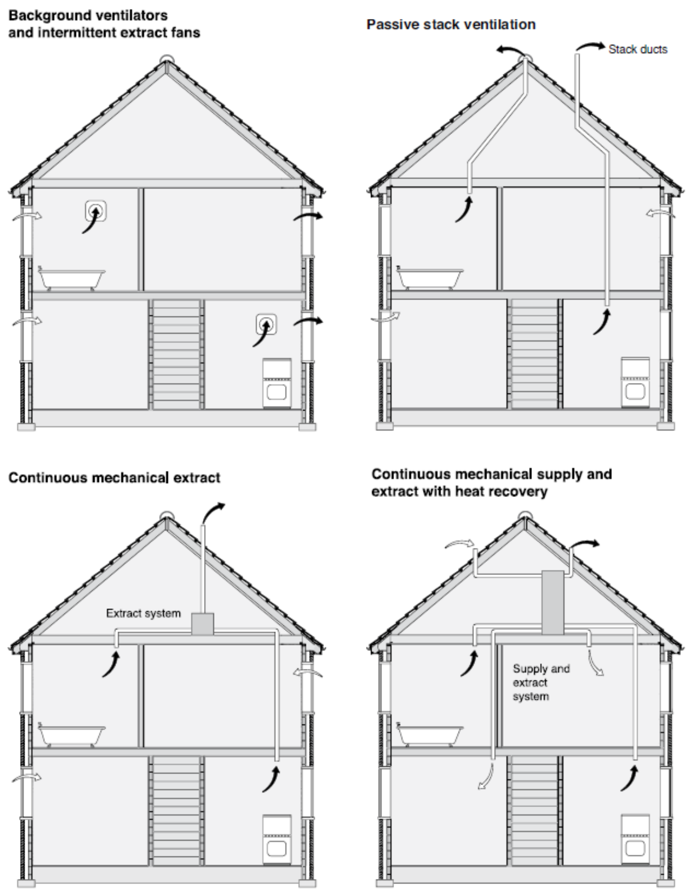

Figure 4-1: Four ventilation systems described in ADF2010 (DCLG 2010)

System 1involves: background ventilators and intermittent extract fans is the traditional and simplest strategy which relies on purpose made vents, including windows, airbricks and trickle vents, together with adventitious leakage of air to provide adequate ventilation. System 2: PSV exploits the buoyancy of warm and humid air found in rooms such as bathrooms and kitchens and the pressure differential caused by air moving over the roof to move moist stale air out and fresh air in through vents. Such systems are simple to operate, cheap to install and, if entirely passive, do not require energy to run. However, ventilation rates from these systems are highly variable, requiring careful design and installation to ensure adequate air movement. They can be difficult to control and, consequently, are difficult to predict (DETR 2002). System 3: MEV provides continuous extract ventilation which may be constant or variable and controlled manually or automatically in response to demand (e.g. humidity or CO_2).

System 4: Like MEV, MVHR is a continuous extract system that uses a system of inlet and outlet ducting in conjunction with a heat exchanger that pre-heats inlet air with heat extracted from outlet air. The HR recovers heat that would otherwise be lost as the stale warmed air is exhausted from the building. MVHR systems only require inlet and outlet ducts and no other ventilation openings to puncture the built fabric.

4.2.1. ADL1a and ADF as drivers for the adoption of MVHR systems

Recent changes to ADL1a and ADF are driving the adoption of MVHR as an industry standard and away from the use of natural ventilation systems (Roaf et al 2012).

Firstly, Part F guidelines favour the specification of continuous ventilation (systems 3 and 4). Changes to part F guidelines were introduced which differentiated between buildings with infiltration rates higher and lower than $5m^3(hr/m^2)$ @50Pa (DCLG 2010). For intermittent and passive stack design approaches guidance increased the background ventilation rates by 50%, increasing the difficulty of demonstrating compliance with ADL1a. For designs specifying continuous mechanical ventilation systems the guidance removes the requirement for background ventilation, allowing for less onerous infiltration rates greater than $5m^3(hr/m^2)$.

Secondly, the changes to ADL1a are creating conditions for the uptake of heat recovery. As airtightness and insulation standards reduce infiltration related heat loss the relative significance of ventilation heat loss increases (Liddament and Orme 1998). In order to comply with ADL1a strategies to compensate for ventilation heat losses will be required. Strategies include increasing insulation, incorporating renewable energy generation or by specifying heat recovery ventilation.

Thirdly, the UKs calculation methodology for assessing the energy performance of dwellings (The standard assessment procedure (SAP) (BRE 2009)), favours the specification of mechanical systems and heat recovery systems specifically (Vent-axia 2012). SAP accommodates different ventilation systems by different methods. Ventilation rates for intermittent systems, type 1 and 2, use prescriptive generic rates which are conservative. Mechanical extract systems, type 3 and 4, use SAP Appendix Q and specific product performance data which may be to a greater accuracy than generic ventilation rates. Furthermore, SAP assumes ventilation heat loss to be minimised when MVHR is specified. Both these factors act favourably on the resulting DER.

Finally, specifying mechanical systems may not only ease achieving compliance it also fits easily into current industry design and construction practise and is relatively easy to standardise across a design ‘book’(Vent-Axia 2012). Specification of another mechanical system doesn't require radical rethinking of designs, construction methods, and institutional arrangements that passive approaches imply.

The combined drivers of part L and part F, calculation and compliance procedures and relative simplicity of incorporating and standardising such systems in dwelling designs will increase the adoption of whole house MVHR systems as an industry standard.

4.3. Energy and carbon arising from the use of MVHR

4.3.1. Energy in manufacture: Embodied carbon

The inclusion of any new technology in the home has hidden energy and carbon burdens embodied during its manufacture, installation, and end of life disposal. The specifying of MVHR will, in the majority of cases, result in the addition of another technology rather than substituting for or removing the need for an existing one (the exception being those homes in which conventional heating systems have been eradicated). This will result in a net increase in embodied energy and carbon which should be to be taken into account. Carbon emissions are no respecter of geographical boundaries; emissions produced are still produced regardless of where the object in question is manufactured and when it is installed and operated, despite national policy and accounting boundaries.

The embodied energy and carbon from the production and maintenance of a MVHR unit is estimated to be relatively low, approximately 2000MJ and 97kg CO_2 per unit over a 50 year lifetime not including end of life disposal (Nyman and Simonson 2005). However, if MVHR becomes the industry norm for the majority of new build homes and an increasingly significant number of energy retrofitted homes this relatively small amount will increase in significance. Potentially offsetting any real energy or carbon gains from use.

4.3.2. Net energy balance

MVHR systems are not passive systems and require power to run fans and associated equipment (termed parasitic energy demand). As a consequence there is a trade of between the mechanical ventilation (MV) and the heat recovery (HR) parts of the system. MVHR has a positive effect on reducing ventilation heat loss but a negative effect on power consumption (Laverge and Janssens 2012).

4.3.2.1. Heat recovery

Heat recovery systems have been shown to significantly improve the energy efficiency of buildings (Zmeureanu and Yu Wu 2007). Ventilation heat losses can be typically 35-40kWh/m^2/year in residential buildings and between 80-90% of this could be recovered (Tommerup and Svendsen 2006). A study on the simulated performance of MVHR systems in Finnish apartment buildings found that MV without HR uses 67% more energy in cold climates than when HR is used (Jokisalo et al. 2003). The inclusion of HR has been estimated to result in a 20% reduction in final energy consumption in homes in cold climates (Fehrm et al. 2002).

Studies have demonstrated this pattern in different countries. In an early study, Hekmat et al. (1986) compared different residential ventilation systems in different US climatic conditions found that the inclusion of HR reduced the total heating energy demand by 9–21%. More recently a number of studies in Europe have been published. Maier et al (2009) compared the effect of ventilation systems in 22 low low-energy homes in Germany. The study found ventilation systems with a function of heat recovery have between 10 – 30% lower heating energy consumption than ventilation systems without. This range is narrower than that found in an earlier European project that found that MVHR systems reduced the total energy for space heating by 20–50%, depending on climatic zone, building type and airtightness (EU 2001).

4.3.2.2. Mechanical ventilation parasitic energy demand

The overall net energy balance will only be a net energy saving if ventilation heat loss savings achieved by the HR are larger than the power required by the MV system. If this is not achieved the system as a whole will be an energy consumer (Roulet et al. 2001).

The Specific Fan Power (SFP) of the fans used in MV systems refers to the power consumption, in Watts, of the fan (plus any other electrical system components) divided by the air flow through the system, in Watts per litre per second (W/l/s) (BRE 2009). ADL1a introduced minimum acceptable SFP's, ≤ 1.5 W/(l/s) in the case of MVHR systems (Table 4-1) (DCLG 2011). However, SFP is not constant but changes with both air flow rate and pressure changes. Furthermore, SFP consumption of an MV system can also depend upon how well designed the system is (Liddament and Orme 1998).

Table 4-1: Recommended minimum standards for mechanical ventilation with heat recovery systems ((DCLG 2011) Adapted from Table 32 p 98)

		Efficiency
Fan power (SFP)	Type 1: Intermittent extract	0.5W/(l/s)
	Type 3: Continuous extract	0.7W/(l/s)
	Type 3:Continuous supply ventilation systems	0.5W/(l/s)
	Type 4: Continuous supply and extract with heat recovery	1.5 W/(l/s)
Heat recovery efficiency:		≥70%

4.3.3. Primary energy and carbon

The net energy and carbon balance is also strongly dependent upon the primary energy and carbon intensity of the fuels used to provide power to the MV and the space heating offset by the HR.

4.3.3.1. Primary energy

The majority of studies typically report analysis and findings in terms of delivered energy and not primary energy (Dodoo et al. 2011). Primary energy, in this context, is defined as the total energy needed in order to generate the final energy service. It contrasts with delivered energy as it includes inputs and losses of all processes along the supply chain, including extraction, processing, distribution, and conversion to heat or power. Each stage resulting in losses and, consequently, differing factors. For electricity this is further complicated by fuel mixes differing between countries and regions. For example in the UK grid electricity has a primary energy factor of 2.92, whilst gas used in domestic heating has a primary energy factor of 1.02 per unit of fuel delivered (BRE 2009). Furthermore, each of these fuels will be used in different technologies with differing efficiencies to provide the final service.

This has implications for the net energy balance of MVHR systems in different contexts. Firstly, different systems will have different fan power primary energy inputs depending on country of use and source of power (i.e. national or regional grid or local generation from onsite such as CHP or renewable energy). This raises questions of the comparability and transferability of studies to different contexts. Secondly, different heating systems and the fuels used will give very different results for net primary energy, even if all other parameters are held equal. This suggests that the heat loss energy related savings will be larger for energy intensive systems such as electrical rather than gas.

Of the few comparative studies that consider the primary energy implications of different heating systems on the overall efficacy of MVHR in dwellings with different heating systems, the largest primary energy savings were consistently associated with electrical resistance heating systems (Nyman and Simonson 2005; Dodoo et al. 2011; Laverge and Janssens 2012). Dodoo et al (2011) analysed the impact of heat recovery on the operational energy demand of residential buildings comparing electric resistance heating, bedrock heat pumps and district combined heat and power (CHP) in Sweden. MVHR was found to be least effective in homes connected to district systems. Reducing the final energy for space heating and ventilation by 55% and 22% for energy efficient and conventional buildings, respectively, for electric resistance heating systems and 37 – 22% respectively for heat pumps. Critically the study found the lowest net primary energy savings in systems installed in homes heated by CHP and no savings in homes connected to conventional district heating systems. Whilst homes in the UK are conventionally heating using disconnected systems, typically condensing gas boilers, there is an increasing promotion of district heating systems (DECC 2009). This raises questions on the assumptions upon which the efficacy in reducing heat demand via MVHR is based in the UK context as housing evolves in response to the low carbon agenda.

4.3.3.2. Carbon

The net CO_{2e} balance of MVHR also varies according to context, in the same way as primary energy, with the carbon intensity of the fuels used in the provision of power and heat in the home effect the overall carbon balance. There is a dearth of peer reviewed studies that report the net CO_{2e} balance of MVHR systems in the real world. Based on monitored energy consumption, Monahan and Powell (2011a) reported a 14% carbon reduction in homes using a MVHR system when compared with three alternative carbon reduction strategies deployed in a UK case study of 14 homes. Singh and Eames (2012) modelled the carbon implications of retrofitting a range of interventions in typical existing UK dwellings heated by gas central heating systems, including: reducing infiltration by 70%; the use of MVHR and grid electricity; and renewable generated electricity. The MVHR system reduced energy and consequently CO_2 emissions by 12%. Critically, this increased carbon savings to 21% when the power used was derived from renewable energy sources.

4.3.4. The performance gap between theoretical and reality

The actual energy performance of technologies, such as MVHR systems, in reality do not often match that calculated by design. This performance gap is related to both technical and behavioural issues (Bordass et al. 2001).

4.3.4.1. Technical

Infiltration and airtightness

The primary energy savings of MVHR systems have been found to be greater in low energy homes compared to conventional buildings due to higher air tightness of low energy homes (Dodoo et al. 2011). Unintentional airflows can considerably reduce the efficiency of performance of the system. MVHR systems critically depend on balanced supply and extract flows. If the building envelope is absolutely airtight then the two flows are automatically equal. However all buildings have infiltration to some degree and so differential flows may occur (Manz et al. 2001). There will be a level of airtightness above which the MVHR system will become a net energy consumer. Modelling has shown this to be 0.5 ac/h @ 50Pa (Lowe and Johnstone 1997).

Studies of retrofitting MVHR in typical leaky UK homes support this, indicating that without significant reduction of infiltration and ventilation there are no energy benefits or health benefits from such systems (Lowe and Johnstone 1997). A study of end use energy in a typical building in the US for different climatic conditions, found MVHR increased net energy use as the parasitic energy generally outweighed the energy saved from heat recovery in typical homes (Sherman and Walker 2007).

Design, installation, and commissioning

Design, installation, and commissioning may also significantly affect the performance of MVHR systems. Design problems include poor positioning of inflow and outflow vents and the specification of incompatible alternative ventilation strategies including passive vents, MEVs and cooker hood extraction units (Laverge and Janssens 2012). Installation problems include: missing insulation of ductwork and units; ductwork installed incorrectly, supply and extract vents positioned incorrectly (Lowe and Johnstone 1997). The Building Services Research and Information Association (BSRIA), a principle provider of testing in the UK, found that 95% of homes tested failed to meet building regulations requirements. Reasons found included ductwork incorrectly fitted (82.5% of cases) missing or blocked with insulation and fans undersized or insufficient in number

(Gilbert 2012). Commissioning problems included: fans operating at incorrect speeds; unbalanced flows which lead to a ‘two-fold’ increase of electrical consumption (Lowe and Johnstone 1997; Laverge and Janssens 2012).

4.3.4.2. Behavioural

However well designed and optimised a home and its MVHR system is, the operating conditions will be the critical determinant of the overall energy balance of an MVHR system post commissioning (EU 2001). In reality MVHR systems in the domestic environment do not operate in isolation as the sole means of ventilation. They operate within the context of natural or demand control ventilation: principally openable windows. The balancing and control of these two systems, and the resulting energy outcomes, are attributable to how they are used by the households themselves (Stevenson and Rijal 2008). Post Occupation Evaluation (POE) studies consistently report that residents do not balance these mechanical and natural ventilation systems. The reasons theorised in the literature for this disparity include misuse of technology; poor use of controls; and a lack of occupant understanding.

Misuse of technology: Balancing purpose provided MVHR and window opening

The frequency of window opening by occupants has been found to be significantly high in low energy homes (Macintosh and Steemers 2005; Stevenson and Rijal 2008). A POE of an experimental zero carbon home found the occupants opened windows more often than they did in their own homes in response to comfort dissatisfaction relating to overheating (Stevenson and Rijal, 2008). Conversely, Lowe et al (1997) found the opposite behaviour in retrofitted homes. Residents reduced the frequency of window opening post installation of the MVHR due to improved air quality. Previously the windows were opened in response to comfort dissatisfaction relating to humidity, smells and ‘stuffiness’.

Occupants may have a preference for natural or demand control ventilation systems by convention (Laverge et al. 2011). Maier et al (2009) in a case study of 22 homes in Germany found that occupants responded to comfort dissatisfaction (including high levels of CO_2 and relative humidity) by opening windows rather than by a modification of the air flow rate of the MVHR system. They theorised that, in the absence of a relationship between the length of ventilation time and indoor climate parameters, opening windows for ventilation may be permanently related to habits which would be very difficult to overcome.

Use of controls

How, and if, users make use of the controls of technologies may also have an influence on the energy and carbon outcomes of such technologies. Studies of MVHR systems in passively adopting households suggest that there may be a low level of user interaction with the controls available to them (Lowe and Johnstone 1997; Macintosh and Steemers 2005). Lowe et al (1997) reported occupants, whom had previously actively disabled mechanical extract ventilation systems and blocked up air vents, had not altered the control settings of the MVHR system, despite complaints about noise and 'draughts' which could be alleviated by reducing fan speed. This lack of interaction has also been identified in new purpose built homes. Macintosh et al (2005), in a study of the Iroko Coin Street Development in London UK, found that nearly half (47%) of the residents of the development had made no adjustments to their MVHR system controls throughout the year.

Positioning of controls in inconvenient locations has been suggested as a contributing factor to inhibiting use (Macintosh and Steemers 2005). The design of controls may also be a key contributing factor impacting on behaviour (Stevenson and Rijal 2008). The design of the controls themselves may also be flawed. Many flow rate controls are designed to be intuitive, consisting of dials or digital screens showing 3 settings (1, 2 and 3 or boost) with no indication of how these numbers relate to the rate of air flow. The user has to interpret the meaning. However, if the user does not understand the system then this may constitute a lack of clarity of function and contribute to user uncertainty (Stevenson and Rijal 2008).

Occupant understanding

A lack of understanding of the purpose and functioning of an MVHR system may be a key contributor to poor management of the systems (Macintosh and Steemers 2005). Ezratty et al (2008) noted occupants, when reporting on ventilation system, were often inconsistent and contradictory in their reports, suggesting both a lack of understanding of the systems installed and an awareness of their function. This finding is common across studies, which consistently cite low levels of occupant awareness and understanding of MVHR systems (Lowe and Johnstone 1997; Leech et al. 2004; Macintosh and Steemers 2005; Stevenson and Rijal 2008).

If intuitive controls with little or no visual correlation with or feedback on effect create problems with understanding or misunderstanding of system use then this is a design failing. Therefore the disjunction between predicted and actual performance is due to the design failing rather than a lack of control by the user.

The effectiveness and use of technologies such as MVHR is principally understood and analysed from a technical perspective. The evidence base in the literature is dominated by technical studies focussing on the operational efficiency of technology and much of that based on models. People are reduced to quantitative data relating to how often and for how long a window has been opened, or whether a dial has been turned, or not, in response to certain predefined environmental stimuli and its effect on the operational efficiency of the system. Yet users clearly have a critical role in shaping the final energy and carbon outcome. A lack of, or incorrect, interaction with the system components, such as controls and windows, on the part of the user can lead to inefficient or inappropriate use that is perceived as a misuse of the system. This misuse is ascribed to ignorance of the user. Yet there is little knowledge about how passively adopting households actually understand or frame these new technologies as they adopt and adapt them to suit into their preferences.

4.4. Case study

4.4.1. Case study description

The case study consists of three homes in a new development of 15 homes in Norfolk, UK. The homes were constructed in 2008 to meet an energy standard which equated to the Building Regulations ADL1a 2010. The homes, constructed as a test bed for different low carbon technologies, were part of a yearlong evaluation study. The overall comparative energy and carbon evaluation of the 15 homes included embodied carbon (Monahan and Powell 2011b) and energy in occupation (Monahan and Powell 2011a).

The three homes used a balanced whole house mechanical ventilation extract with heat recover in conjunction with a solarium to the south facing front elevation. The system had a SFP of 1W.l.s and a manufacturer’s declared heat exchange efficiency of 89%. The MVHR unit was housed in the loft with insulated ducts leading to the inflow and extraction vents. Inflow vents were located in the ceilings living room and bedrooms, while extract vents were located in the kitchen, bathrooms and sunspace. The occupier had control over the air flow by an air flow controller (positioned by the bathroom door) (Figure 4-3) which had three factory set speed settings:

2. Night (100m^3/h)
3. Day (150m^3/h)

4. Boost (225m^3/h)

The evaluation study was quantitative and qualitative. During the yearlong study the following data were collected:

1. Metered energy use for gas and electric consumption based on manual meter readings.
2. Two semi-structured interviews with each household, the first within the first month of occupation, the second at six months, of between 30 minutes to one hour in duration.
3. Informal observation of behaviour and field notes from site visits during the yearlong monitoring and evaluation study.

Two analyses were undertaken based on monitored energy data and SAP 9.81 to model the energy balance of MVHR in these homes. Firstly, an assessment of the airtightness of the homes as constructed and the potential effect on effectiveness of the MVHR system was examined. An energy and carbon model, using SAP9.81, SAP Appendix Q and the MVHR manufacturers' product data, compared the energy and carbon emissions demand for heating if the home was 1) naturally ventilated and 2) ventilated using the MVHR as specified at different air permeability rates (q50)[19] (Figure 4-2).

The second analysis considered the energy and carbon balance of the system in use. Monitored energy use, SAP 9.81 and system manufacturers data were used to model the theoretical parasitic energy demand and energy savings from the recovered heat at the tested air permeability rate of 6.25 m^3/m^2@50Pa (Table 4-2). It was assumed that parasitic energy demand was met by grid electricity and the heat recovery energy saved was displacing gas[20].

The third qualitative analysis was based on the semi-structured interviews with the householders. The analysis includes the users' experience of the system including: general user experience; user control; user understanding; and maintenance and ownership.

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19 Air permeability, known as Q50, has units of cubic metres per hour per square meter of envelope area (m^{3}hrm^2.) It is the volume of air that passes through the enclosing fabric in one hour at Pascall 50. It is used as an indicator of the rate of natural ventilation through a building, the lower the number the more air tight a building is said to be.

20 It was assumed that the boiler SEDBUK 91% and the total amount of gas saved was adjusted for this.

4.5. Results

4.5.1. Net energy and carbon

4.5.1.1. Airtightness and effectiveness

The comparison of natural ventilation and MVHR indicate that there is no net carbon benefit until q50 falls below 6m^3/m^2/hr@50Pa (Figure 4-2).

The homes were designed to achieved an air permeability rate of 7.00m^3/m^2/hr@50Pa One of the homes were pressure tested prior to occupation and achieved an air permeability, q50 of 6.25 m^3/m^2@50Pa. This is just on the cusp of being of net carbon positive compared with natural ventilation (Figure 4-2), assuming the equipment is utilised as anticipated during the design stage.

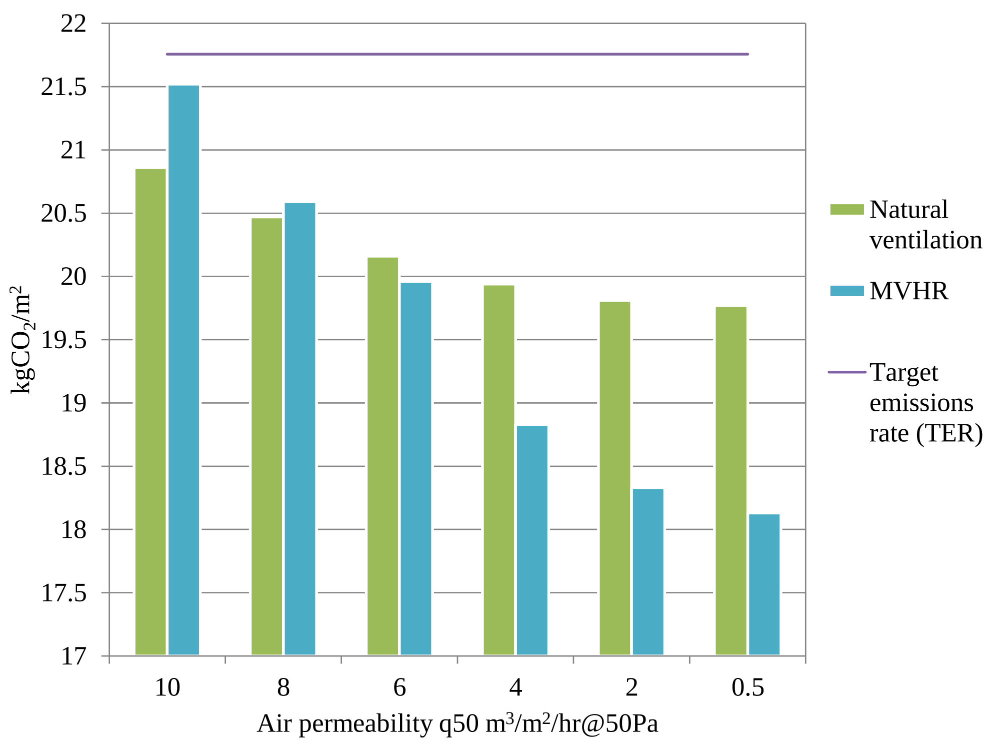

Figure 4-2: Modelled carbon emissions for natural ventilation compared with MVHR for different air permeability rates

4.5.1.2. Energy and carbon balance

The results of the energy and carbon balance illustrate the difference between end use energy and primary energy (Table 4-2). End use energy suggests there was a net energy saving of 295kWh a year. However, in primary energy terms there was a near balance in energy, showing a very small net increase in energy. There was a net carbon increase of 28 $kgCO_2$ a year (Table 4-2). This is due to electricity having greater carbon intensity per unit than gas.

Table 4-2 MVHR estimated energy and carbon balance

	End use energy kWh/year	Primary energy kWh/year	$kgCO_2$ /year
Parasitic energy used (electric)	226	632.8	127
Energy saved (gas)	522	634.8	99
Net difference	295	-2	28

4.5.2. The user experience

All the householders interviewed expressed reticence about the MVHR systems, including doubts about its energy saving claims and experience of discomfort from ‘cold draughts’.

The main living area and bedrooms were of small size (18m^2 and 11.5 – 8.6 m^2 respectively), offering limited choice for positioning of furniture such as chairs, sofas and beds. Consequently many of these items had been positioned under the vents which resulted in the families sitting directly under the vents and experiencing discomfort.

4.5.2.1. Use of controls

The MVHR system had three points of control available to the occupiers. Two on/off switches, one located below the loft hatch in the upper floor and the other in the kitchen and an air flow controller. Neither on/off switch was marked or indicated as related to the MVHR system. The air flow controller had a 3 speed dial showing settings 1, 2, 3 and a small red light indicator for filter maintenance (Figure 4-3). Each household was provided with an information pack on hand over. The information pack contained manufacturer’s installation and commissioning documents. There was no information on the purpose, function, or use of the MVHR system purpose provided for the user.

Figure 4-3: Image of air flow controller (source: J.Monahan)

One household used the on/off switch located below the loft hatch upstairs to switch the system off within days of moving in. Expressing a dislike of the MVHR as it felt 'draughty' and made the home feel cold. At times when the home felt stuffy or the bathroom damp they preferred to open windows to ventilate. The system remained decommissioned for the remainder of the monitoring period. The second household operated the system via the on/off switch in the kitchen to create 'cool draughts' when required. In particular turning the "fan off at night because we freeze". This household reported that, after an initial period of experimentation, the dial was never used and remained at its highest setting. The third household had moved the control setting to its lowest and it had remained on constant throughout the monitoring period.

4.5.2.2. Learning in the absence of information

In the absence of information each household was left to build their own understanding and knowledge. The absence of information initially caused confusion:

> *"we don't' really understand it. But it hasn't been a problem on the other hand….It's just as it is we haven't done anything and to be honest we wouldn't particularly know what to do with it." (MVHR7m)*

This was followed by a process of experimentation and the use of different strategies. One household switched the system of by the switch below the loft hatch. Two of the three households implemented a process of trial and error until a satisfactory result was achieved. For example:

> *" After we initially moved in and you know like you do is tamper with things….I turned it up and it got more draughty and then I turned it down and I thought oh that helped and then I turned it back down to one and it's been there ever since" (MVHR7f)*

And:

> *"I sort of muddled through it…It was very much I don't know what this does; I found a switch do you know what I mean. Then we find another switch thinking there's another switch we haven't found. I remember at one point thinking what is all this doing? What's it for?" (MVHR8)*

This household learnt that the system could be controlled by the switch in the kitchen and this became the mechanism for management of the system.

One individual took a more considered approach, taking time to analyse the system and understand it based on his own observations and those of his neighbours, often taking the lead role in discussing the operation with the other households, gathering information on how they used it, correcting them if he thought their understanding was incorrect and adding to his own knowledge and passing that knowledge on in an iterative way.

> *"<He> has understood it but I don't I mean you was out there the other day talking to the new guy <MVHR9> that's just moved in yeah and I don't get it even when he was out there explaining it still don't understand it even when I listen to it. But and he's like yeah I need more information." (MVHR8f)*

The third household, taking residence three months after the first two households, received instruction on the operating of the system from their neighbours. This information was applied to turn off the system.

4.5.2.3. Understanding

The way in which a technology is thought about may affect the way in which it is used. MVHR8 provided a vivid example of this. Although MVHR8*m* spent time working out the system their understanding, which made perfect sense to them, expressed itself in ways that contradicted the purpose of the system. This household were observed using the ventilation system in warmer periods as air conditioning, altering the ventilation setting to maximum (3) to provide cooling draughts. At the same time cross ventilation had been made by opening up the front door and the back patio doors. This resulted in an elevated power demand over the summer period and no energy benefit during the winter.

For this household the "draughts" created by the system were associated with air conditioning that had been experienced on holiday and this framed how they understood and used the system. During the summer this was a positive special benefit:

> *"It's like aircon like you're on holiday because you can feel the breeze coming through and its keeps the rooms … without having to open the windows or things like that or you turn it off if you don't want the breeze to come through" (MVHR8f)*

At other times, the 'cold draughts' the system was controlled by the on/off switch in the kitchen and the air flow dial was never used. She had difficulty in connecting it with heating. So it remained, for her, as an air conditioning system.

4.5.2.4. Maintenance

The MVHR systems have a filter that requires regular maintenance, a relatively simple procedure of checking, cleaning, or replacing filters. The air flow speed control LED indicator is programmed to prompt filter maintenance every three months.

In this case the filter is housed in the heat recovery unit which is housed in the loft. The loft door has a sticker on it informing the tenants that the loft is out of bounds. The housing design team had decided that the unit was not to be tampered with by the tenants. However, there was no information informing the tenants of this process, nor had the housing landlord put protocols put in place. Whilst it was made very clear who was not to take on this maintenance role, it had been neglected to describe who would.

In the absence of any other information, quite naturally as the light was red, a colour typically indicating danger or fault, perceived the light as a fault which required action. This action could be reporting, ignoring, or dealing with themselves. One household elected to ignore the light. Another household reported the 'fault' and in the absence of any help left the system running as it was remarking that *"it's one of those things that doesn't affect use as it doesn't really do anything"*.

Both households raised the issue of liability, as one pointed out:

> *"How does that leave us because he <MVHR7m> was trying to fix something that was their (the landlord) responsibility or ... what if I broke it then what? Because I don't' know what it is and without looking at it he doesn't even know if he can do it or not." (MVHR7f)*

No maintenance was reported to have occurred to any of the three participating households in the year of monitoring.

4.6. Discussion

4.6.1. Airtightness and construction

Currently, 70% of new homes achieve an air pressure test result of greater than $5m^3/m^2/hr@50Pa$ (DCLG 2009). It is likely that the majority of new homes will be designed to an airtightness level of 5 $m^3/m^2/hr@50Pa$ or less until post 2013 amendments of the building regulations. Furthermore, airtightness testing is not mandatory on all new homes only a proportion. A significant number will not reach their designed airtightness due to construction flaws which will neither be identified or corrected post construction. Consequently it is likely that a significant number of new homes will not be constructed sufficiently air tight for MVHR systems to operate as a net energy saving/carbon saving.

4.6.2. Balancing purpose provided and windows

Out of the three households participating in the study, one house permanently switched of their system preferring to open windows when they felt the home to be stuffy or humid, for example after cooking of showering. This suggests, for some individuals and households, the mechanisation of ventilation will not be acceptable. This will be problematic for two reasons. Firstly, if window opening is an entrenched behavioural response to discomfort relating to air quality then this will affect the efficiency of MVHR systems which are designed for continuous operation in buildings with low natural ventilation levels. Secondly, if households elect to permanently switch off their systems preferring to use natural ventilation then there is an increased risk of inadequate ventilation and the associated health risks in airtight homes.

4.6.3. Use

Of the three households only one household participating in the study operated the system as envisaged, continuously operating at its lowest air flow. Another household permanently disabled the system. The third used their system occasionally to provide cooling at times of overheating, strongly identifying the system as air conditioning. Whilst any conclusions can only be tenuous at best with such a small number of cases the results suggest that a significant proportion of households will either not use the ventilation system at all or will use it in a manner contrary to that of its imagined purpose. Further investigation with a larger sample group is urgently needed.

If the mechanisation of fresh air becomes institutionalised as a standard domestic technology and is identified by a significant number of households as a means of cooling rather than associated with indoor air quality and heat, as suggested in the results of this study, then this could lead to an increased acceptance of air conditioning in the home. Such a trend would be contrary to the intended outcomes of policy, leading to a load shift from heating to cooling and representing no energy reduction overall.

Furthermore, this trend may be exacerbated as overheating increasingly becomes an issue as the global average temperatures increase (Bone et al. 2010). If so, there are doubts that MVHR systems will be able to achieve the required level of purging for effective cooling during these conditions. This 'failure' will be exacerbated by the operating conditions. Some households will never use their systems, some will not use the controls available to them, while others will want the technology to cool them. If overheating is not to become a significant health risk during summer time and air conditioning is to be avoided as a technological response then passive measures will be necessary (Bone et al. 2010).

4.6.3.1. Maintenance

Regular maintenance of MVHR systems is required to maintain the efficacy of the system to provide adequate ventilation and good indoor air quality. In addition, poorly maintained systems may contribute to increasing health risks. The results of the case study suggest that this may be problematic for reasons of responsibility but also relating to reliance on households themselves to do this. Responsibility for this duty will vary depending upon the ownership arrangements of the home and equipment in it, such as MVHR. In socially rented housing such as the case study presented here, it may lie with the Housing Association. Contractual arrangements will be required to ensure systems are maintained and this will have related costs for the lifetime of these systems.

It is likely that, for the majority of cases, new build homes will be privately owned. The householders themselves will be responsible for the task of checking, cleaning and changing the filters regularly. Will these passively adopting household take on the responsibility for this additional housekeeping practise? None of the three households participating in the study reported any maintenance occurring during the year. Currently UK manufacturers of MVHR systems report no market for replacement filters, with some reporting no filter sales (Crump et al. 2009). This strongly suggests that maintenance is currently non-existent and may become a critical issue as uptake of these systems increases.

4.6.4. Alternatives to mechanised ventilation systems: Natural ventilation and passive design approaches

There are increased energy and carbon burdens in specifying MVHR systems. Each system will have an embodied energy associated with its manufacture, installation, maintenance, and end of life disposal. Whether this net energy and carbon balance is negative at end of life is dependent upon the overall amount of energy and carbon saved during its operational life.

An alternative approach argues for designing out all unnecessary technology, prescribing the use of passive systems where appropriate (Nicol and Roaf 2007). However, passive/natural ventilation systems are incompatible with heat recovery and therefore will have a higher ventilation related heat loss and an increased space heating energy demand. On the other hand with no mechanical elements used passive systems will have lower power consumption (Simonson 2005). The resulting net energy and carbon balance may be as complex as that found in mechanised systems. Yet passive systems may offer an alternative solution in some cases, particularly if households are shown to be rejecting mechanised systems.

Passive/natural ventilation measures are not without risk. Occupants may not open windows due to noise pollution or safety fears (Macintosh and Steemers 2005). In addition, measures, such as air bricks, trickle vents and flues may be inappropriately sealed as occupants seek to increase comfort by removing sources of 'draughts' (Lowe and Johnstone 1997).

Furthermore, passive ventilation also requires a holistic approach in which the building is considered within its environmental context (Brown and DeKay 2001). Moreover, in passive systems ventilation rates are highly variable, require careful design and installation to ensure adequate air movement, are difficult to control and, consequently, difficult to predict (DETR 2002). This is problematic for volume house builders when the product is mass produced from limited one size fits all design books and when designing to meet increasingly stringent codes, regulations and standards. Regardless of the relative merits of passive systems, there may be a lock in to MVHR as a technological fix because it is easy to add on to existing models of how homes are built and supplied within existing institutional and regulatory practises.

4.7. Conclusion

MVHR may, in reality, not be an optimum solution. As a response to a complex problem it is a technological mechanised solution. The alternative solution is non-mechanised passive means. However, MVHR offers a simple 'plug and play' technology that fits into current construction practise. It does not necessitate the need to radically rethink modelling, design or construction methods.

Yet the evidence presented here indicates that MVHR systems in new build homes are not meeting their intended aims of providing adequate ventilation in an energy and carbon efficient manner. Firstly, they are being applied in homes that are not sufficiently airtight to enable optimum energy performance and may, in reality, result in a net increase in energy and carbon. However, as airtightness standards increase in response to changes to the building regulations this may become increasingly less likely.

Secondly, and critically, there is a strong likelihood that users will not adopt this technology in replacement of habitual window opening to provide ventilation. The result may be inadequately ventilated homes. As the potential efficacy of these systems increases due to rising airtightness standards, there may be an attendant increase in poor indoor environments and related health problems in new build homes. However, as this technology begins to become increasingly common households may adapt and change practise.

Furthermore, MVHR system may not be used as intended, if indeed they are used at all. The mechanisation of ventilation may institutionalise the notion that ventilation is provided by automated mechanical means as a default position. There is a suggestion that users are framing this technology, not as relating to heating but, conversely, as cooling. This, in conjunction with overheating issues frequently experienced in super insulated air tight homes and a predicted increase in average temperature, may be a tipping point towards the widespread adoption of air conditioning in homes. This represents an unwanted, unplanned for and contradictory outcome of policy supposedly aiming at reducing energy demand and emissions.

4.8. References

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5. An examination of the energy performance gap

This chapter addresses research question 3 outlined in Chapter 1:

What is the influence of passively adopting households on the overall energy and carbon outcomes of mainstream new low carbon homes as they adopt and adapt to new LZC technologies?

This chapter describes the first of two related studies that focus on the influence of the households on the performance of new LZC technologies in mainstream new build housing. The second related study is described in Chapter 6. This chapter is concerned with how the occupants of the case study homes influence their annual energy demand. Firstly, by examining the variability in energy demand between the different households in new low carbon homes, and secondly, it identifies explanatory factors for this variability.

This chapter is organised as follows: firstly, a literature review on the energy variation between households and in particular the determinants that have been found to be critical to that variance is presented. The literature considers the scale of variance observed, the physical characteristics, household characteristics and behavioural variables found to have significance in determining household energy use in previous studies. Secondly, the results of the case study of 14 new build homes in Norfolk, UK, presented in earlier chapters, are explored in more detail to reveal contributory factors behind the variance observed. The analysis and discussion considers the socio-economic descriptive of the case study households and the variance found in energy consumption (both heat and power). Quantitative and qualitative data are given and the results of correlating these data with energy consumption and explanatory variables identified. Finally, this paper closes by drawing conclusions from this study and recommendations for policy and future research.

5.1. Introduction

The UK's Building Regulations, AD Part L1a, aims to reduce energy demand in new build homes in relation to space heating, cooling, ventilation, lighting, and hot water (DCLG 2010). The implementation of incremental tightening of standards, scheduled for 2010, 2013 and 2016, is predicted to result in significant improvements in the energy efficiency of new build homes. However, the success of these regulatory changes depends not only on how the regulations are implemented but also upon how these homes are used in the real world.

Regulations have been shown to be successful in reducing energy demand and carbon emissions arising from buildings (Beerepoot and Beerepoot 2007; Leth-Petersen and Togeby 2001). However, the overall energy and carbon reductions may be lower in practise than predicted (Branco et al. 2004; Hill et al. 2011; Monahan and Powell 2011). Firstly, the measurement of actual energy performance is neither standard practise nor mandated by regulations. Consequently, motivation to demonstrate the achievement of performance targets once the home is constructed is non-existent. Secondly, the quality of design and construction are not reflected in heat loss calculation norms nor are they considered at design stage (Juodis et al. 2009). Yet, it has been widely reported that there is typically a significant difference found between the predicted designed performance of a building and how it performs in reality (Bordass et al. 2001; Branco et al. 2004; Wingfield et al. 2008; Gill et al. 2010).

This difference depends not only on physical factors intrinsic to the building itself (including quality of design and construction, the technical systems and local climate), but also on how it is used (Branco et al. 2004; Wingfield et al. 2008; Juodis et al. 2009). Building energy performance is, therefore, determined by interactions between these three elements: building and climate characteristics; technological installations; and the occupants of those buildings (Steemers and Yun 2009). As the energy demand for heating reduces because of improvements in the thermal envelope and technological improvements in the systems supplying heat and power, the significance of the user increases in importance (Papakostas and Sotiropoulos 1997; Haas et al. 1998).

Significant variation in heat and power consumption has frequently been observed between different households (Gram-Hanssen et al. 2004), and between households occupying identical homes (Firth et al. 2008). Studies have identified that this variability is attributable not only to physical aspects, such as differences in built structures and technologies, but also to the occupant (Sonderegger 1978). Furthermore, when controlled for building differences and occupant characteristics, user behaviour is found to be a critical factor in the variation observed (Guerra Santin et al. 2009; Branco et al. 2004). 3Whilst the effect of users on overall energy outcomes is widely recognised how users behave and how this contributes is poorly understood.

The physical relationship between a building’s thermal characteristics and local climate on heating demand is well studied, quantified, and validated, as is the theoretical performance of new energy technologies. Yet we know very little about the how users interact with these new systems and how these interactions can explain the variance in energy and carbon outcomes from new low energy/carbon homes. If the actual energy savings achieved, due to the implementation of regulations, are lower than those predicted by engineering models there will be implications for policy targets. Identifying the potential explanatory factors for this observed performance gap and variability between homes highlights the need for a reality check in the ability of regulations to deliver policy targets.

This study aims to gain an insight into the effect of occupants on energy consumption in new low carbon homes. It investigates the variation in energy consumption observed and reported in Chapter 3, revealing the explanatory factors behind this variability. To do this it has three objectives:

1. To describe and compare the case study households with the national population
2. To quantify the variability in energy demand between the different households
3. To identify explanatory factors for the difference found between household energy consumption

Whilst both heat and power are considered, heating energy is the focus of this study. Because low carbon innovations, driven by regulations, are predominantly related to space heating (e.g. the thermal envelope and LZC technologies as described in Chapter 1).

5.2. A literature review of the variance in household energy consumption

Early evidence of variation between the energy use of different households was first identified by Socolow (1978) in the widely cited Twin Rivers Programme, a study of the impact of users on space heating demand. This multidisciplinary study of nominally identical homes found a factor difference of 3 between the minimum and maximum energy users of gas for space heating during winter. Subsequent studies have consistently found similar large variations between lowest and highest consumers for both heat and power related consumption internationally (Table 5-1).

There is typically a greater variability in power consumption than heat consumption. For example, in a recent study of a 26 identical low energy house development, heated from a central biomass heating network and with identical individual mechanical ventilation systems with heat recovery (MVHR) systems, Gill et al. (2010) found total energy consumption, (normalised by kwh/m^2 floor area), varied by a factor of difference[21] between lowest and highest consumers of 2.8, with power (3.7) having greater variance than heat (3.1) (Table 5-1).

In the literature significant variance is often found in power consumption not just between households but also between studies (Table 5-1). Lutzenhiser and Bender (2008), reporting on the power consumption of a heterogeneous group of 1627 homes across Northern California, found the variation to be extreme, reporting a factor difference of 40 between minimum and maximum users. Conversely, Morley and Hazas (2011), in a study of three different blocks of student accommodation found a factor of difference ranging from 1.7 – 3.4, while Firth, et al. (2008), in a study of 72 UK homes from 5 different sites, found power consumption varied by a factor of 9.5.

Heat related energy consumption was found to demonstrate less, but still significant variability (factor of difference ranging from 1.2 – 6) (Table 5-1). There is however far more consistency across studies, when compared with power related energy, with a factor of difference between lowest and highest consumption typically approximately 3 (Sonderegger 1978; Guerra Santin et al. 2009; Gill et al. 2010; Gram-Hanssen 2010). Both Firth et al. (2008) and Gill et al. (2010) highlight Sonderegger's (1978) earlier finding: variance was significant even between dwellings from the same site with similar built form.

[21] Factor of difference is the ratio of difference found between the lowest and the highest energy consumer in the sample group of interest. It was calculated by: $(kWh_{max}-kWh_{min})/kWh_{max}$ where kWh_{max} is the highest energy consumer and where kWh_{min} is the lowest energy consumer in the sample group of interest.

Table 5-1: Summary of literature on variance in domestic energy consumption (by heat and power) for dwellings that are heterogeneous or homogenous in character. Variation shown as factor of difference found between minimum and maximum energy consumers (adapted from Morley and Hazas 2011).

	Country	Energy	Factor of difference	Dwelling difference
Sonderegger (1978)	US	Heat	3	Homogenous
Guerra Santin et al. (2009)	Netherlands	heat	≈ 3	Heterogeneous
Juodis et al. (2009)	Lithuania	Heat	6	Heterogeneous
Juodis et al. (2009)	Lithuania	heat	1.2	Homogenous
Gram-Hanssen (2010)	Denmark	Heat	3.7	Homogenous
Gill et al. (2010)	UK	Heat	3.1	Homogenous
Gill et al. (2010)	UK	Power	3.7	Homogenous
Lutzenhiser and Bender (2008)	US	Power	40	Heterogeneous
Firth et al. (2008)	UK	Power	9.5	Heterogeneous
Gram-Hanssen et al (2004)	Denmark	Power	3	Heterogeneous
Morley and Hazas (2011)	UK	Power	1.7 - 3.4	3 homogenous groups

The research presented in Table 5-1 suggests that variance between households is lower, but still significant, when the buildings studied are similar (Morley and Hazas 2011). This suggests that the source of difference between different households cannot be entirely explained by physical difference in the building themselves.

5.2.1. Proportions of variance attributed to physical characteristics and occupant behaviour

In reality it is not possible for any two buildings to be perfectly identical. Homes are built or assembled by hand. There will be some micro-scale differences, such as defects in fabric construction or other undetected flaws in the built fabric or in the equipment or appliances installed. Building characteristics, therefore may still be a factor, though lesser, in determining the difference in variance between similar homes.

Sonderegger (1978) controlled for building characteristic by comparing the same house containing different households (movers) with houses where there were no changes in households (stayers). They found that 54% of the variance observed was attributed to building characteristics. Critically, 71% of unexplained variance was due to some intrinsic aspects of the households themselves, defined as ‘occupant behaviour’. However, the study failed to define ‘occupant behaviour’. Whether factors such as household size, patterns of occupation, cognitive factors of the individuals, use of systems of the building itself were of influence where not examined.

Sonderreger's (1978) findings were echoed by Guerra Santin et al. (2009). In this later study of space heating energy from a heterogeneous sample of 15,000 Dutch homes, 42% of variance in heat related energy consumption was found to be attributable to building characteristics. However, only 5% of variance was found to be attributable to the households themselves. Here the authors drew a distinction between household characteristics and behaviour. Noting that 1) the methodology, regression analysis, did not handle data on behaviour well and 2) the effect of occupant behaviour may be larger than expected, recommended that research on behaviour was needed.

Dwelling size and shape has also been shown to determine both space heating demand (Sardianou 2008, Sonderegger 1978) and power demand (Guerra Santin et al. 2009). The influence of size can be controlled to some extent by normalising the data and using a comparable metric. Studies have typically used kWh m^2 rather than kWh, (see Gill et al. (2010) and Firth et al. (2008) for example). In such cases the factor of difference between lowest and highest energy users is reduced. For example, Gill et al. (2010) found a factor of difference of approximately 5.3 for heat in kWh but this reduced to a factor of difference of approximately 3.1 for heating when normalising for size differences to kWh/m^2 terms. In studies that normalise the sample for physical characteristics, including size and construction type, the variance found can be related to characteristics intrinsic to households themselves and what they do rather than any factors intrinsic to the home itself. Studies of homes that are as physically similar as possible, and with physical characteristics controlled for, demonstrate a lower degree of variability, suggesting that this reduces the influence that any physical differences may have on the overall energy outcome and increases the importance of occupant behaviour in the variance observed.

5.2.2. Occupant behaviour

There is a vast literature concerned with 'occupant behaviour' in the context of energy consumption but much of it fails to define what 'occupant behaviour' is (Poortinga et al. 2004). In this research occupant behaviour is defined in broad terms as the interaction between many variables including household characteristics, cognitive factors, and the use of equipment, systems, and controls. Clearly, occupant behaviour in an energy consumption context is complex.

5.2.2.1. Household characteristics

The determinants of household energy consumption, both heat and power, have been studied extensively and found to be strongly related to occupancy patterns (Papakostas and Sotiropoulos 1997; Haas et al. 1998; Leth-Petersen and Togeby 2001; Branco et al. 2004; Lindén et al. 2006). Occupancy patterns are influenced by household characteristics including personal circumstances and socio-economic characteristics including age, household size, employment status, and income. The effect of these household characteristics, have all been studied extensively and found to be significant determinants of energy consumption.

Age of householders has been found to be an important influence on energy consumption particularly related to life stage. Older households typically tend to consume more energy for space heating than younger ones because they are at home for longer periods of the day and typically heat their homes to a higher temperatures (Schuler et al. 2000; Liao and Chang 2002; Lenzen et al. 2006; Lindén et al. 2006).

Size of household has also been found to correlate with energy consumption across international studies (Schuler et al. 2000; Firth et al. 2008; Pachauri 2004). Larger households, whilst consuming more energy in total, tend to use less energy per capita than smaller ones (Lenzen et al. 2006). A recently published report examining power consumption in UK households, found that single person households use as much, and in some cases more, power than typical families on certain appliances and practises, such as cooking and laundry (EST 2012).

Income has also been found to be a significant parameter linked to energy consumption (Colton 2002) with higher income groups using more energy in the home (Biesiot and Noorman 1999, Gatersleben et al. 2002, Guerra Santin et al. 2009, Poortinga et al. 2004). This has been found to be particularly salient to power related consumption, where high income households tend to have a greater number of appliances (Benders et al. 2006; Genjo et al. 2005; Vassileva et al. 2012).

Income and household size are consistently the principle socio-economic variables on which energy consumption depends, whereas education, gender and ethnicity may have very little influence (Gram-Hanssen et al. 2004). Yet energy consumption still varies considerable between households of comparable socio-economic characteristics suggesting that socio-economic characteristics do not entirely explain occupant related variance in energy consumption (Schuler et al. 2000).

5.2.2.2. Cognitive variables: Values, attitude and motivation

Differences in household energy consumption may also be due to differences in consumption related behaviour. There is a vast literature using many different theories and models to explain consumer behaviour (see Jackson 2005 and Wilson and Dowlatabadi 2007 for extensive reviews). Values, attitudes, and motivation have been widely cited as factors in consumer behaviour (Gatersleben et al. 2002; Poortinga et al. 2004; Lindén al. 2006; Vringer et al. 2007).

Vringer et al (2007) examined the effect of values and motivation to act in relation to climate change on energy consumption in households in Netherlands accounting for socio-economic characteristics. They concluded there was no relationship between total household energy consumption, values, or motivation. The study did however, find a small difference in energy consumption between groups with different levels of motivation, with the least motivated consuming more energy.

An earlier study examining the same value, attitudes and pro-environmental behaviour, (Poortinga et al. 2004), used the New Environmental Paradigm Scale (NEP) (Dunlap et al. 2000; Dunlap 2008) as a measure of general environmental concern to elicit pro-environmental attitudes and values. This was related to home energy as a proxy for environmental behaviour, finding that attitudes were significantly related to values and environmental concern, but could explain only a small proportion of the variance found in home energy use. Rejecting attitudes and values as an explanatory factor they concluded that household energy consumption was more strongly related to socio-economic variables, such as household size and income, which influenced individual abilities to behave in certain ways, and behaviour was strongly determined by contextual factors.

Many studies have similar findings suggesting the relationship between cognitive variables such as attitudes, motivation, and values and energy consumption may not be critical determinants in variance between different households (Gatersleben et al. 2002; Poortinga et al. 2004; Stokes et al. 1994; Vringer et al. 2007).

However, energy use behaviour is complex and the result of the interplay of many interconnected factors. For example Gatersleben et al. (2002) found that households with high pro-environmental attitudes often have higher energy consumption because they typically have higher incomes (related to their socio-economic status) which gave them access to larger homes and more appliances. But the case was not as clear cut as implied because levels of consumption were also related to educational level, with higher levels of education being associated with lower levels of energy consumption (Gatersleben et al. 2002).

Contextual factors and attitudes can be interrelated resulting in difficulties in assessing the contribution each makes to the resulting energy consumption. Picking apart these different variables and ascribing a value to their contribution may be impossible and may, in the end not be fruitful in understanding variance.

5.2.2.3. Behaviour: comfort control and understanding

What households actually do in their homes, how they relate to the different systems and controls available to them, rather than what motivates them, has been found to be a significant source of variance (Combe et al. 2010; Shipworth et al. 2009; Stevenson and Rijal 2010; Tommerup et al. 2007; Wingfield et al. 2008). This is particularly pertinent to space heating. How households ventilate and heat their homes, the levels of comfort they adopt and the degree of understanding of the technologies and associated controls and how they are used, have been shown to be critical.

Comfort

Occupant perception of comfort (relating to temperature and air movement) is often cited as a key factor in determining the energy consumed to meet t occupants' comfort needs. Internal temperature, in particular has been found to be a critical factor in determining energy consumption (Lindén et al. 2006). Obviously higher temperatures require more energy to achieve and maintain. Furthermore, the settings of a thermostat (related to internal temperature) and the timing/length of time of the heating period also determine how much energy is used (Shipworth et al. 2009). Tommerup et al. (2007), using calculations based on single family homes in Denmark, found energy consumption increased by 10% per 1^{o}C rise in temperature. Shipworth et al. (2009) found a 1^{o}C rise in temperature produced a 1.55% increase in CO_2 and a 1% increase in duration resulted in a 0.5% increase in CO_2. Furthermore, this study also found that use of controls by a household did not necessarily relate to either a reduction in average temperature or shortening of duration of heating system use nor guarantee reduced energy demand.

Control and user understanding

The design of controls may be a key contributing factor impacting on behaviour (Stevenson and Rijal 2008). Combe et al. (2010) found that 66% of occupants of a low carbon housing development could not programme their controls as desired, resulting in systems being used ineffectively. Conversely, in an earlier study, Pett and Guertler (2004) found 68% of occupants did know how to use their controls. However, the remainder were found to not understand them and either left them to someone else to change or just left them as they were found. The study also concluded that combinations of heating and ventilation controls, often consisting of a bewildering array of switches, buttons and options, can often confuse occupants

This point may become increasingly salient as new low carbon buildings, and the systems in them, become increasingly novel and complex. Stevenson and Rijal (2008), evaluating the Stewart Milne Sigma Home (the first to achieve the UK's Code for Sustainable Homes level 6 zero carbon standard), suggested that occupant understanding of how their appliances and systems work is often overestimated. Despite careful instruction during a lengthy induction prior to occupation the occupants did not understand the heating, venitilation and lighting systems. Furthermore they failed to understand how the different systems interacted (heating and venitaliton and windows) using the systems in a counterproductive way. The occupants also found problems in interacting with the control interfaces finding them 'puzzling' and too complex.

5.2.3. Variance, behaviour and interdisciplinary methods

The literature on variance in energy consumption of households living in identically-designed homes provides unequivocal evidence that households have a unique influence on energy demand in the home (Morley and Hazas 2011). Yet, much of the literature is quantitative in nature, seeking to identify and quantify the effects of these explanatory factors in order to draw generalisations applicable to broader populations. The literature has shown that individual household energy demand is the outcome of a complex array of different factors, including physical, technical, socio-economic, cognitive and behavioural, the interplay of which will be unique to each house/household. Consequently, many authors conclude that understanding variation and the unique differences of individual households calls for quantitative energy use data to be combined with the richness of detail that qualitative understanding can provide (Crosbie 2006; Firth et al. 2008; Owens and Driffill 2008).

As new build homes become increasingly energy efficient the role of the user will increase in importance. At the same time novel systems requiring new understandings are being introduced that increase the complexity of these homes. The evidence base in the literature suggests that, where other factors are held equal, it is the how the user interacts with their homes and the systems in them that is the critical factor in determining the overall energy performance of a home. Yet we know very little about the how users interact with these new systems and how these interactions can explain the variance in energy and carbon outcomes from new low energy/carbon homes. Understanding how households interact with these new homes and systems is becoming increasingly important if these new homes are to meet their low carbon expectations.

5.3. A description of the case study

A detailed description of the case study is given in Chapter 1, a summarised description follows for reference.

The 15 homes were constructed in 2008 to meet an energy standard which equated to the Building Regulations ADL1a 2010, and were constructed as a test bed for different low carbon technologies. The 15 homes comprise of four blocks of terraced homes all constructed to the same specification and using the same innovative offsite panellised construction system but each block had a different low and zero carbon (LZC) technology for providing heat or power (Figure 5-1). Two homes acted as controls with conventional condensing gas fired instantaneous combi- boilers (CONTROL); four homes had the same boiler but used in conjunction with solar hot water systems and photovoltaics for power (SOLAR); a third block of four homes also had the same gas boiler but with a thermal sunspace to the south facing elevation and a mechanical ventilation system with heat recovery (MVHR); the fourth block of four homes were all electric with a ground sourced heat pump providing all heating and hot water needs. Eleven of the homes were rented and four were shared ownership[22]. The households supplied all their own appliances, furnishing and final finishes, including flooring.

[22] Shared ownership is where the occupier owns a proportion of the home with the remainder owned by the landlord.

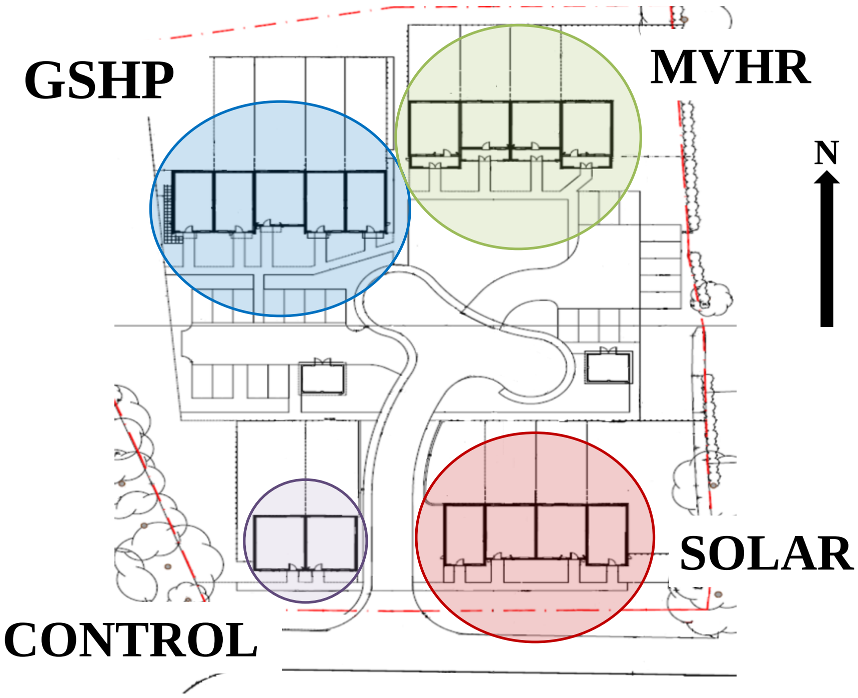


Figure 5-1: Case study site (Lingwood, UK) plan showing site layout and allocation of technologies to properties

5.4. Methods and data

This evaluation study used a mixed methods approach, combining quantitative and qualitative methods during the yearlong study. The data collected included:

1. Manual metering readings for gas and electric consumption.
2. Manual reading of solar PV inverters
3. Appliance audit: type, numbers, energy rating. Included white goods, computing, home entertainment (TVs, gaming, DVD players, Hi-fi equipment), home computing and peripherals. Excluded phones, ipods, kitchen and DIY tools.
4. A questionnaire survey (see Appendix 2) was used to gather data on socio-economic characteristics (household size, age, occupancy, income) and reference pro-environmental indicator behaviours (recycling rates; home composting; whether appliances were on standby or switched off at sockets).
5. New Environmental Paradigm scale questionnaire was used (see Appendix 2) as a proxy for environmental attitude (Dunlap et al. 2000).

6. Two semi-structured interviews, the first within the first month of occupation, the second at six months and each lasting between 30 minutes to one hour.
7. Informal observation of behaviour and field notes from site visits during the year.

The meter readings, survey, interviews and appliance audit were undertaken by the researcher. Three of the shared ownership households elected not to participate in the study.

5.4.1. Pro-environmental attitude and activity

Dunlap et al.'s (2000) New Ecological Paradigm (NEP) scale was used as a measure of pro-environmental beliefs. The NEP scale has become the most extensively used measure of environmental concern and has been used globally in hundreds of studies since it was first published as the New Environmental Scale in 1978 and revised in 1990 as the New Ecological Paradigm (Dunlap 2008). The later revised scale was used in this study. The NEP Scale, which is predominantly used as a measure of environmental beliefs, quantifies the extent to which an individual endorses (from low to high) an ecological world view. It has also been used by researchers as a measure of environmental concern, environmental values and environmental attitudes. The scale is a standard likert type response set of 15 individual statements grouped into three major themes found in the environmental literature: existence of ecological limits to growth, importance of maintaining the balance of nature, and rejection of the anthropocentric notion that nature exists primarily for human use. In this study the paper based scale set were self-completed by the household after the first interview and returned by post.

The study used the 15 point New Environmental Paradigm scale as a self-reported survey provided to each adult (aged 16 years and over) resident in the homes. Not all households participated. In total seventeen responses were returned, representing 11 of the 15 households.

The statements are worded so that agreement with the 8 odd numbered statements and disagreement with the 7 even-numbered statements indicates a pro-ecological view. Consequently an agree response to the 7 even numbered statements are environmentally negative. These negative statements had the polarity of their responses reversed for the analysis (Table 5-2).

Table 5-2: Scoring for responses to 15 statements in NEP scale survey.

Response	Scoring	
	8 odd numbered statements	7 even numbered statements (polarity reversed):
Strongly agree	5	1
Agree	4	2
Neither agree nor disagree	3	3
Disagree	2	4
Strongly disagree	1	5
Don't know	3	3

The responses to each of the 15 statements were input in to a spreadsheet. The NEP score was then calculated by calculating the mean score for each respondent and the overall sample group. The scores were added together to give a total rating score of between 5 (minimum possible) and 75 (maximum possible) for each respondent. The higher the score the stronger the pro-environmental attitude. A minimum score (15) would indicate a very weak pro-environmental attitude and a maximum score (75) would indicate a very strong pro-environmental attitude. Neutral would be indicated by the median score (45). The scores were grouped into ordinal categories rating pro-environmental attitude (Table 5-3).

Table 5-3: NEP scale categories and score range

Category	Score range
Strongly un-environmental	5 - 15
Fairly un-environmental	16-25
Mildly un-environmental	26-35
Neutral	36-45
Mildly pro-environmental	46-55
Fairly pro-environmental	56-65
Strongly pro-environment	66-75

Given such a small sample group more robust in depth statistical analysis is not viable. Therefore the NEP results were treated in this study as a single construct indicating overall pro-environmental attitudes of the households.

Reference pro-environmental behaviours included recycling; home composting; standby behaviour. Recycling rates were categorised as high, average, or low base on number of materials and regularity recycled. Home composting was categorised as a yes or no response. Standby behaviour was categorised as switched off at the socket or left on standby response.

5.4.2. Semi-structured interviews

Semi-structured interviews were used to complement the quantitative survey instruments and elicit the householders' opinions and experiences, providing a much richer understanding of the households behaviour in their homes. The interviews used open ended questions that targeted four areas:

1. General: design; problems; previous homes; community spirit; occupancy patterns
2. Information and knowledge: information provided; how it was used; support
3. Resource use:
    a. heat and ventilation preferences and practises
    b. appliance use: patterns and standby behaviour
4. Technology: use of controls and management systems; understanding of individual systems and interactions between systems

The interviews allowed the householders to talk about their homes and their specific technologies within a structured framework of the four areas. In cases where the household consisted of two adults the interviews were with both where possible. In cases where this was not possible the interviews were with the individual who spent most time running the home. The interviews were approximately 30 minutes to one hour in length. The interviews were analysed and coded into themes by hand using coloured marker pens.

5.4.3. Energy use data

National, regional and local gas and electricity energy data came from DECC (2012). CO_2 factors used factors contemporary to 2008 from DEFRA (2008).

Four types of analysis were undertaken:

1. A comparison of the metered energy consumption with average regional and national domestic energy consumption

2. Socio-economic data was used to describe the case study households

3. The metered and modelled energy consumption data were used to investigate the amount of variance between the 14 households and explore the relationship between energy consumption and socio economic variables

4. Examines the differences found in energy consumption between the households and explores different factors that contribute to those energy outcomes

5.5. Results and discussion

5.5.1. Comparing metered energy demand with regional and national consumption

All the case study homes demonstrated significantly lower (52%) energy consumption than both national (United Kingdom) and local (Broadland District Council), homes (Figure 5-2). The majority of difference was attributed to the lower gas demand, which was 63% lower than the national average. Electricity demand was found to be 4% lower than national average. It should be noted however that this analysis used only metered energy and excluded energy derived from onsite renewables, (i.e. solar PV and thermal). Including the solar contribution shifts these findings. Gas demand (as a proxy for heat including heat derived from solar hot water) was found to be 60% lower than the national average. Electricity demand (including electricity derived from PV) was found to be 1% higher than the national average.

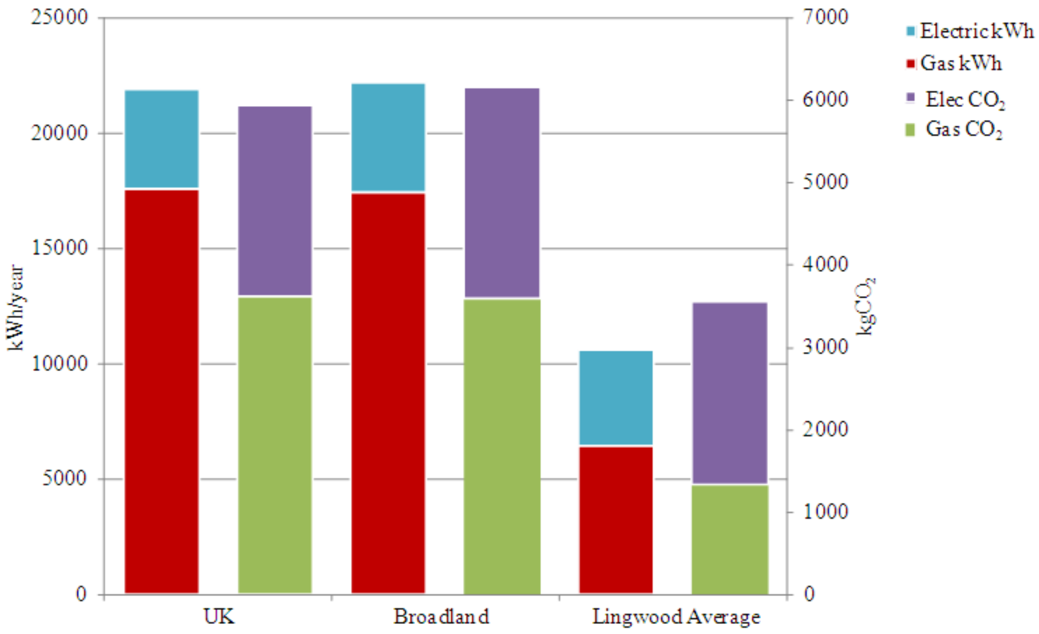


Figure 5-2: Annual gas and electricity consumption per household (kWh/year) and carbon emissions (kgCO_2) comparing average for United Kingdom, Broadland District Council and Lingwood case study, excluding contribution of other fuels and renewables (source for national and local authority consumption statistics: DECC 2012)

When factoring in the contribution from the PV system, these households did not demonstrate any discernible difference in power consumption compared to the average UK household. Technology, specifically PV, rather than behaviour may be the critical factor in lowering power demand in these households.

Much of difference in gas demand can be attributed to heating, and therefore, related to improvements in the thermal structure of the home and the technologies providing heating. Nevertheless, space heating related energy consumption exceeded that anticipated by the design (see Chapter 3). If the assumption that these homes are constructed the same holds, much of this is likely to be attributed to the occupants. However, the literature indicates that this is unlikely to be the case. There will be physical differences both known (including orientation; position in terrace and size) and unknown (including construction flaws) (Morley and Hazas 2011). Whilst known physical differences are easily modelled and quantified, the unknown differences are often hidden and only revealed by extensive testing (Lowe and Johnstone, 1997).

5.5.2. Socio-economic description of case study households

5.5.2.1. Number of occupants, age and gender

All of the 14 households were families with 43% being single parent households. This is significantly higher than the UK average, where only 7% of all households are single parent (DCLG 2011). It is also higher than the total social rented sector where 16% are single parent households (DCLG 2011). In the case study, 90% of the single parent households had a female head of household, with 59% of the adults being female (Table 5-5).

Household size averaged 3.5 persons per household and ranged from two to a maximum of 5 (Table 4). 38% were four person and 29% were three person households. The mean household size for the UK was 2.4 in 2009 (DCLG 2011).

The adults were predominantly under 40 years of age (n19). 79% were aged between 25 and 44. This is higher than the UK average of 35% of all households reporting this age range (DCLG 2011).

5.5.2.2. Income and employment

All the households that reported their income (n10) had combined household incomes lower than £30k (Table 4). 50% reported a total annual household income of between £10 -£20k. This is a lower income compared with the UK, where 60% of households earn less than £30k per annum and 25% earn between £10 -£20k (ONS 2012).

43% of adults were in full-time employment, 33% were part-time and 24% were not employed (of these 2 were on long term sickness and 2 were receiving community support assistance to enable independent living). The group has lower employment rates compared with UK average (where 51% are in full-time work, 8% are in part-time work and 41% are not employed) and higher employment rates than that typically found in the socially rented sector (where 23% are in full time employment, 10% are in part-time employment and 67% are not employed) (DCLG 2011).

5.5.2.3. Hours of occupation

When asked how many hours a day on average the house was unoccupied 36% reported less than 3 hours a day, 64% between 4 – 8 hours a day (n11). Only 1 household reported being unoccupied for between 9-12 hours. Unfortunately no statistics were available to compare this group with the national average.

5.5.2.4. Summary

In summary, the case study group are relatively homogenous in comparison with the wider UK population. They are characterised as relatively young families, a high proportion of single parent families with a female head of house, of low income, with high densities of occupation and a high rate of hours of occupancy (Table 5-5).

These variables are used to explore the variance found in energy consumption between these homes.

5.5.3. Environmental attitude and behaviour

5.5.3.1. NEP results

The NEP score was used as a proxy indicator for environmental beliefs, the higher the score the greater the concern for the environment. The total aggregated NEP scores ranged from 46 to 70, with an average total score of 56. The NEP scores for each individual were summarised into categories (Table 5-4). The majority of households, 67% (n10) were categorised as holding a pro-environmental attitude to some degree (Figure 5-3).

Table 5-4: NEP score categories

NEP score	Category	Indicator score
<45	mildly unenvironmental	1
45 - 50	neutral	2
51 - 55	mildly environmental	3
56 - 60	fairly environmental	4
61 - 65	very environmental	5
66 - 70	strongly environmental	6

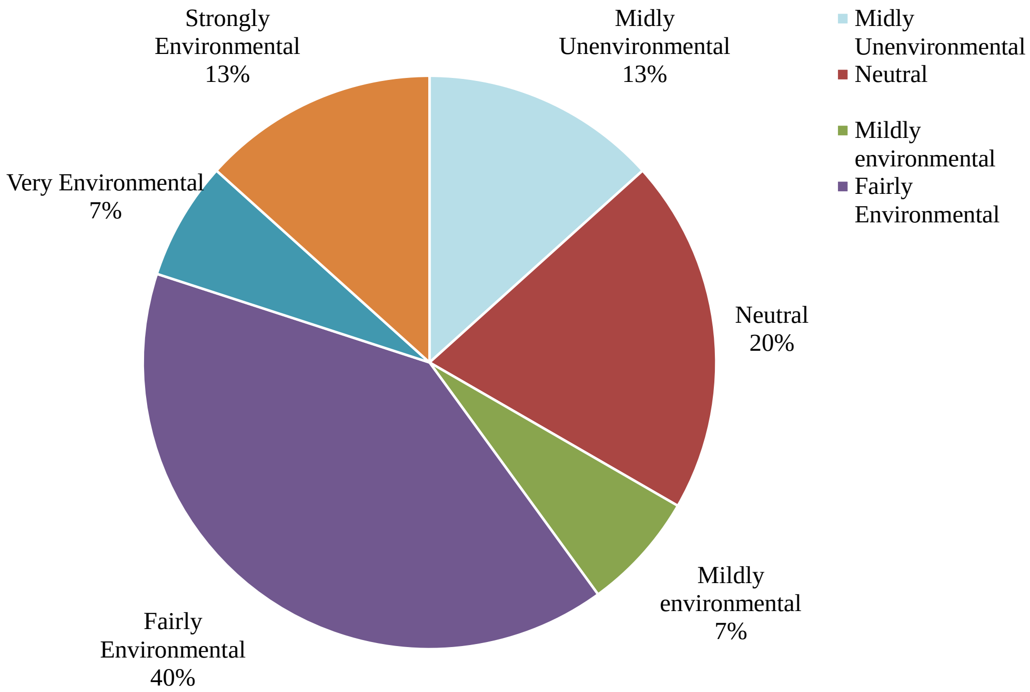


Figure 5-3: NEP score responses summarised into categories (total number of cases, 15)

Strength of environmental beliefs did not correlate with pro-environmental action in these households. Using the NEP score as a proxy for strength of pro-environmental beliefs were found to be have weak correlation with activities used as indicators of pro-environmental action, including home composting (r=0.42), recycling rates (r=0.49), standby behaviour (r= 0.40) and energy consumption (r=0.20) with similar results when disaggregated into heat and power. In common with Poortinga et al. (2004), strength of environmental beliefs is not a sufficiently strong explanatory factor for energy use in these households.

5.5.4. Variation in heat and power

In common with the findings of other studies, (including Firth et al. (2008), Gill et al (2010) and Gram-Hanssen (2010)) each of the 14 households had a different energy demand (Figure 5-4). Energy consumption (normalised) between these households varied by a factor of difference of 2.16 (Figure 5-5).

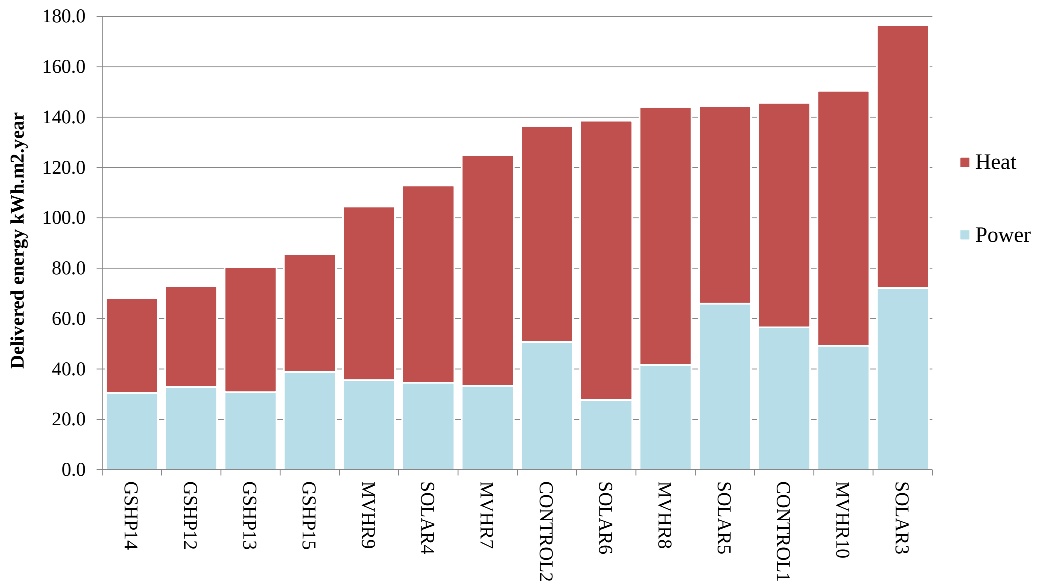


Figure 5-4: Energy consumption by heat and power (kWh/m^2/year) for case study homes includes energy from all sources.

Disaggregating this data further into heat and power related energy use shows that differences are not consistent for each energy use and this varied between each household. Heat related energy consumption showed greater variability than power related consumption, a factor of difference of 1.94 and 1.60 respectively. These findings are different to that found in the literature (Table 5-1). Firstly, these households had less variability, but still significant, than that found in the literature. Secondly, previous studies show power to have a greater variability compared with heat. The converse results may be a consequence of factors relating to methods including small case study size and homogeneity of socio-economic factors. Yet, Gill et al (2010), in a comparable study found power to have greater variability than heat. The authors assumed buildings and technologies were a constant, despite the homes in this study consisting of 2 and 3 bedroomed homes and apartments. This suggests that either, there are greater differences between the homes physical and technical systems that need to be identified and corrected or, alternatively, if the assumptions made hold and physical and socio-economic characteristics are equal or similar then these differences may relate to other unidentified factors.

In the solar households this was reversed, with less variability in solar hot water consumption than solar PV consumption (Figure 5-5). However, this analysis is only based on 3 cases and modelled results rather than measured consumption so must be treated with caution. This would benefit from further research.

The lower variability of solar hot water consumption may be a function of the relative homogeneity of both the dwellings and the socio-economic characteristics of the households themselves. If this is the case, this supports the assertion that, the physical and socio-economic characteristics of these households is not a large contributor to the variability observed; rather the variation shown predominantly relates to differences in the conditions of use.

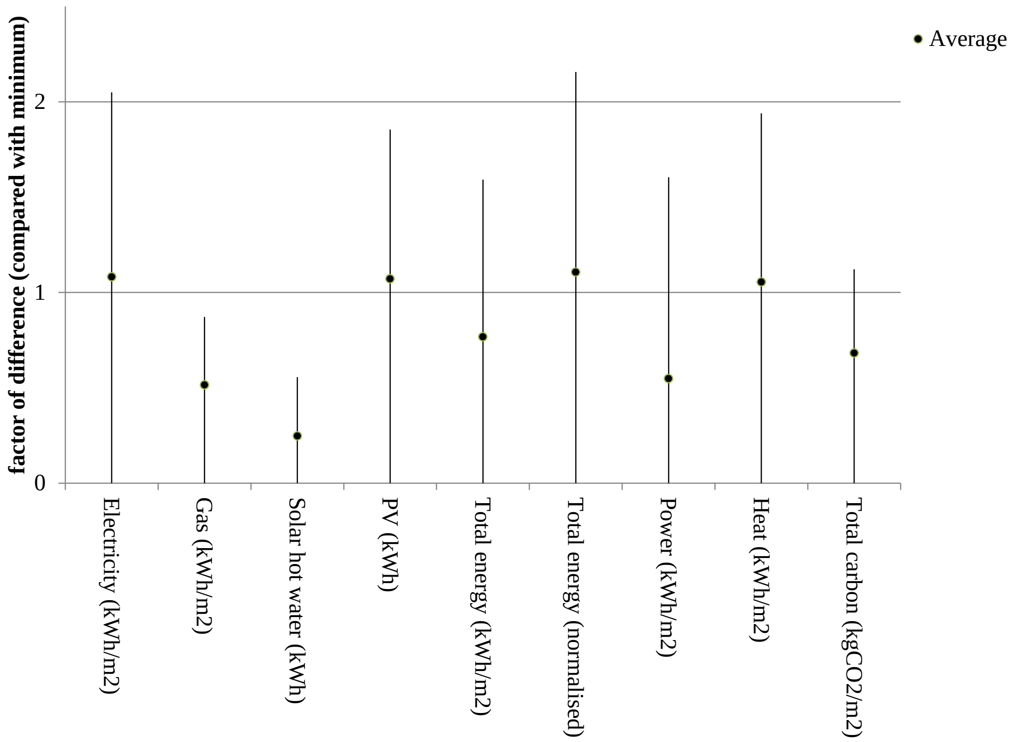


Figure 5-5: factor of difference between minimum and maximum energy demand and mean value by energy source and end use for case study homes (n14). Also showing normalised for occupancy and carbon emissions.

Investigating further into the relationship between heat and power consumption, only a very weak relationship between heat and power consumption (correlation coefficient r=0.41, $R^2 = 0.17$) was found in these households (Figure 5-6). This is also true of the GSHP households (correlation coefficient r=0.32), despite the apparent clustering of these four homes (Figure 5-4 and Figure 5-6). This suggests that there may not be a relationship between heat related energy consumption and power related consumption in these households. High heat related energy consumption is not necessarily related to, or indicative of, high power consumption or vice versa in these homes.

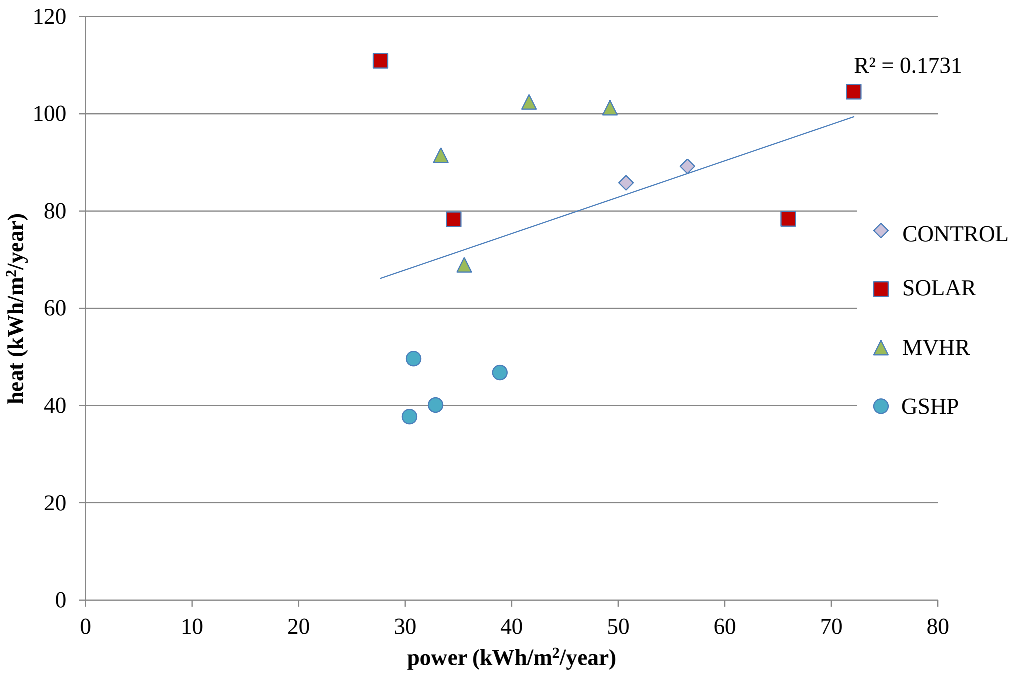


Figure 5-6: A plot of heat related energy consumption and power related energy consumption of case study homes

5.5.5. Exploring variation

Variation in heat and power is explored in more detail in the following section.

5.5.5.1. Power

The different technologies deployed in the case study development were predominantly related to heating, with the exception of PV which is exclusively related to provision of power. The households provided their own appliances and consumer electronics. Therefore, it was assumed that there should be no influence of the technologies upon power related consumption which is more likely to be related to levels of appliance ownership, technological efficiency, patterns of usage and user behaviour (EST 2012).

The numbers of appliances owned by the case study households ranged from 4 - 13 (Table 5-7). In these households no correlation was found between power consumption and number of appliances (r=0.17). Whilst it is an intuitive assumption that high rates of ownership of appliances should indicate high rates of electrical power demand the results suggest that, for these households at least, this may not be the case. Nor was any correlation found between electricity consumption and the energy rating of white goods (r=-0.055) or standby behaviour (r=0.26). The correlation between electricity consumption and socio-economic variables, including hours of occupation (r = 0.39, R2=0.16) and income (r=-0.01, R2=0.0021) were also found to be weak. This may be an artefact of the relatively similar occupational and economic profiles of these households rather than true reflection. A larger study would be needed to address this. The number of electrical appliances analysed in this study was limited and would need to include a greater range of items, including mobile phones, ipads etc. Even within the short space of time since undertaking the data collection the number and range of these devices has increased. Furthermore, a larger more representative sample group would be required to test this relationship further.

A discernible correlation between power consumption and size of household (r=0.69, R^2=0.48) was found (Figure 5-7). Suggesting that in these households, household size is a critical explanatory variable in power consumption. In these households the larger the household the more power consumed (Table 5). This finding accords with findings from other studies (Schuler et al. 2000, Firth et al. 2008 and Pachauri 2004).

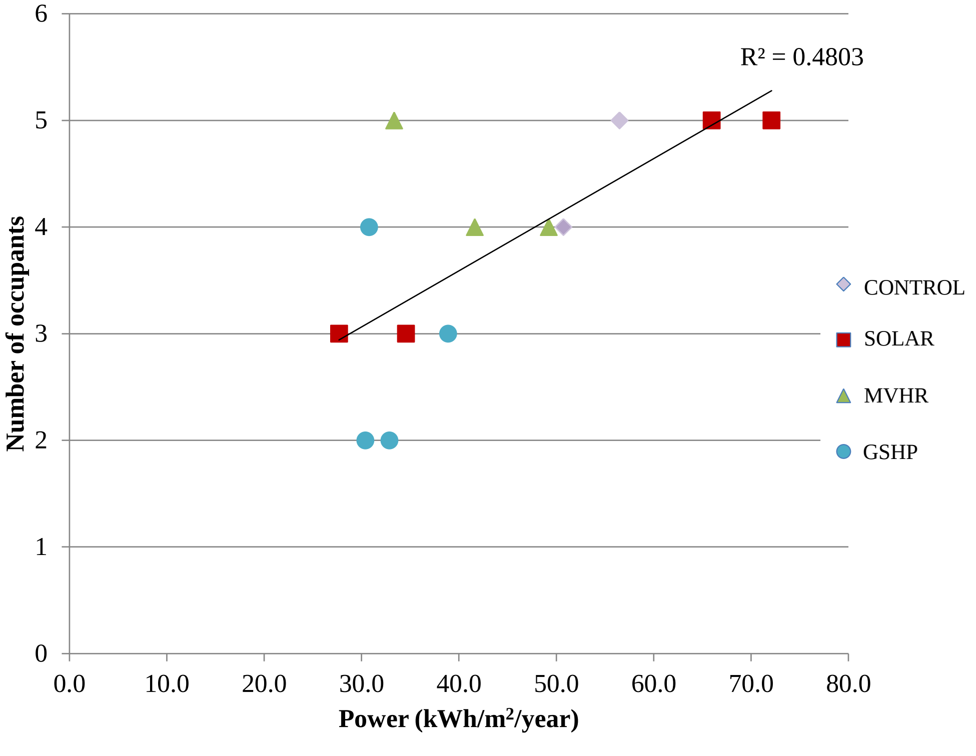


Figure 5-7: Plot of power consumption and number of occupants

5.5.5.2. Heat (space and water)

Whilst these homes required significantly less energy for heating end uses than an equivalent home constructed to minimum regulatory standards, all the case study homes used more energy for space heating and hot water than predicted (see Chapter 3).

Initial analysis considered the relationship between heat related energy consumption and socio-economic variables (including household size, hours of occupation and income) and physical variables (including house area, exposure).

A strong correlation was found between heating energy consumption and household size (r=0.61, R2 =0.37). This suggests that, as found by Schuler et al.(2000), Firth et al. (2008) and Pachauri (2004), and in common with power consumption, household size may be a critical explanatory variable related to heating energy consumption. However the relationship between household size and heating energy was not as robust as that found for power consumption.

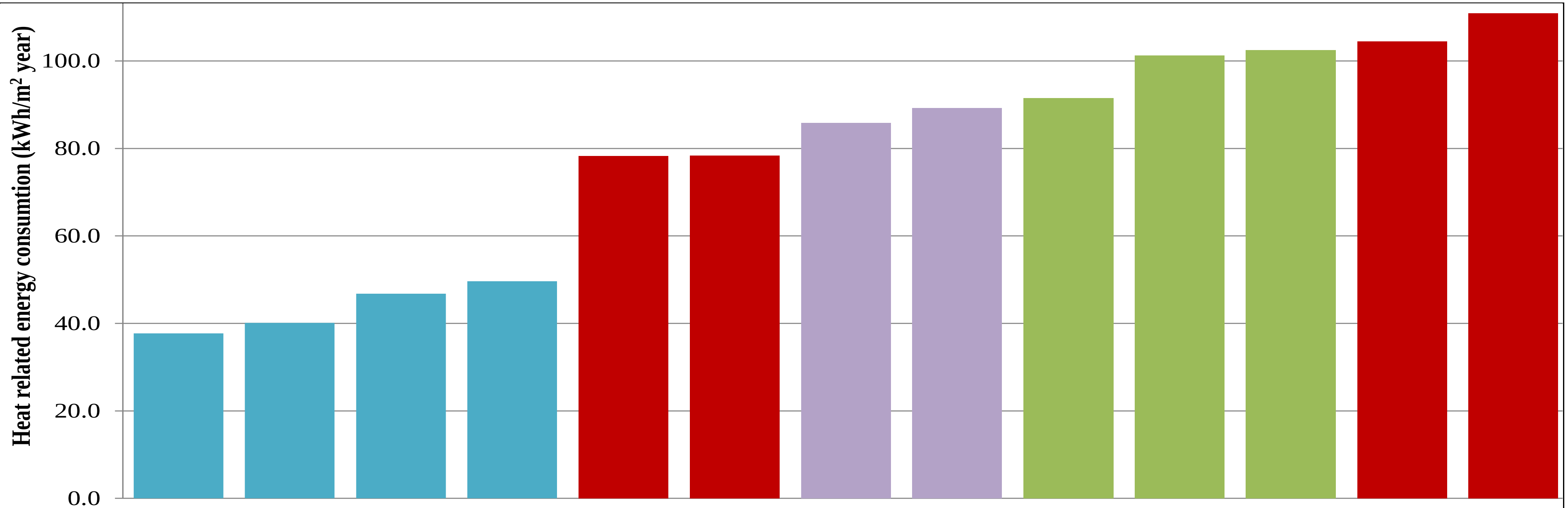
No correlation was found between heating energy and hours of occupation (r=0.08, R2=0.01) and income (r=0.29, R2=0.09) suggesting that, in the case study households, these variables are not critical determinants of the differences found in heat related energy demand. This differs from the findings of both Colton (2002) and Biesiot and Noorman (1999) where income was found to be significant explanatory parameter linked to energy use. The finding of this case study may be a reflection of the relative homogeneity of incomes and the small number of the households studied rather than a finding that undermines the findings of other studies. However, if it is assumed that this finding is correct then there are other underlying factors which need to be taken into consideration.

In considering the physical variables no correlation was found between floor area and heating related energy consumption (r=0.16, R2=0.03). Variance in heating related energy use may also be in some part explained by the degree of exposure of the homes, with ‘position in terrace’ weakly correlating with heat consumption (r=51, R2=0.26) but this correlation was not strong enough to be the dominant factor. However, given the relatively homogenous nature of the sample group this may be misleading and not be the case in a larger more diverse sample.

Table 5-5: Socio-economic results

Case number	CONT1	CONT2	SOLAR3	SOLAR4	SOLAR5	SOLAR6	MHVR7	MVHR8	MVHR10	GSHP12	GSHP13	GSHP14	GSHP15
Adults >20	2	2	2	1	2	1	2	2	2	1	1	1	1
Children <12	3	2	3		3	2	3	2	1	1	2	1	2
Teenagers 13-19				2					1				
Hours occupied	24	16-20	24	16-20	16-20	16-20	24	16-20	24	24	12-15	20-21	24
Income	£20 - 30k	£10 - 20k	< £10	< £10k	£10-20k	£10-20 k	£20-30k	£20 -30k		£10 -20k	£10-£20k	< £10	£10 -20k

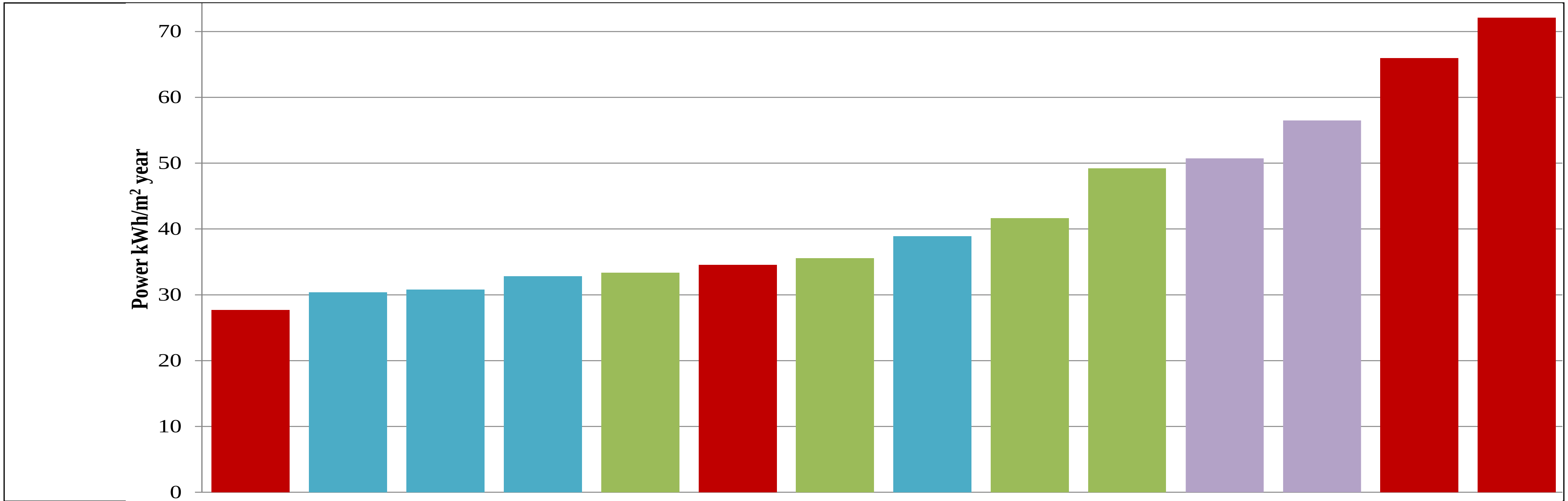
Table 5-6: Quantitative and qualitative data pertaining to heat related energy consumption includes contribution from all energy sources on site



Case number	**GSHP 14**	**GSHP 12**	**GSHP 15**	**GSHP 13**	**SOLAR4**	**SOLAR5**	**CONT 2**	**CONT 1**	**MVHR7**	**MVHR10**	**MVHR 8**	**SOLAR3**	**SOLAR 6**
Technology type	ground sourced heat pump	ground sourced heat pump	ground sourced heat pump	ground sourced heat pump	PV solar hot water	PV solar hot water	gas boiler	gas boiler	sunspace + MVHR	sunspace + MVHR	sunspace + MVHR	PV + solar hot water	PV solar + hot water
Floor area	71	71	71	83	83	83	83	83	83	83	71	71	71
Position in terrace	mid	mid	end	mid	mid	mid	end	end	end	end	mid	end	end

Household													
Number.occupants	2	2	3	3	3	5	4	5	5	4	4	5	3
Hours occupancy	20-21	24	24	12-15	16 -20	16 -20	16 -20	24	24	24	16 -20	24	16 -20
Temperature preference (self reference)	warm	cool	cool	warm	average	cool	warm	warm	warm	hot	cool	hot	warm
System use:													
Information read	no	yes	no	yes	no	skim read	yes		skim read		skim read	can't read	yes
System controls altered	yes	yes	yes	yes	yes	yes	yes		yes	yes	yes	no	yes
Altered by whom	neighbour	occupant	neighbour	occupant	freind	occupant	occupant		expert	occupant	occupant		occupant
TRV's adjusted	N/A	N/A	N/A	N/A	yes	no	yes		yes		yes	no	yes
Hot water controls adjusted	no	yes	yes	no	yes	yes	yes		yes		yes	no	yes
Heating controls adjusted	yes	yes	yes	yes	yes	yes	yes		yes		yes	no	yes

Table 5-7: Quantitative and qualitative data pertaining to power related energy consumption includes contribution from all grid and PV electricity sources on site



Case number	SOLAR6	GSHP 14	GSHP 13	GSHP 12	MVHR7	SOLAR4	GSHP 15	MVHR8	MVHR10	CONT 2	CONT 1	SOLAR5	SOLAR3
Household:													
No. occupants	3	2	3	2	5	3	3	4	4	4	5	5	5
Occupancy hours	16 -20	20-21	12-15	24	24	16 -20	24	16 -20	24	16 -20	24	16 -20	24

Appliances:													
White Washer	A	not known	A	A	A	not known	not known	not known	not known	B	A	A	B
Dryer	yes	yes	no	no	no	yes	yes	no	yes	yes	yes	yes	
Refrigeration	not known	not known	A	not known	not known	not known	not known	combi not known	not known	B	A	Fridge A Freezer B	not known
Dishwasher	no	no	no	no	no	no	no	no	yes	no	no	no	no
Cooking fuel	gas	electric	electric	electric	gas	gas	electric	gas	gas	gas	dual	gas	electric
Microwave	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
Brown (no.)	3	7	13	7	9	11	9	10		11	13	6	4
Behaviour:													
Appliances on standby	off	yes	yes	off	off	yes	off	yes	yes	yes	yes	off	yes
Recycling rates	high	average	average	average	average	average	high	average		average	high	high	low
Home composting	no	no	no	no	yes	no	no	no		no	yes	yes	no
NEP	56	46	61	50	57.5	49	59	56		44	52	68.5	

5.5.6. Exploring differences in households

Despite the similarities between these households it has been shown there is a considerable variation in energy consumption, even within the smaller groups sharing the same technology. These differences cannot be explained fully by the physical, technical, cognitive or socio-economic differences between households. Household energy demand is complex, attributable to physical, technical and human characteristics. The variance observed is an expression of this complexity. The next section explores descriptive qualitative data derived from semi-structured interviews to put the quantitative findings into context and examine in closer detail other underlying factors that may contribute to the differences found.

5.5.6.1. Differences in heat and power

In this case study and in common with other studies (including Schuler et al. 2000, Firth et al. 2008, and Pachauri 2004) the majority of the larger households consumed more energy than smaller households. But, this pattern is not a consistent rule. For example MVHR7 was a large five person household yet had a lower annual energy demand than other smaller households (Figure 5-4). Nor does this pattern appear to apply equally to heat and power consumption in the same households (Table 5-6 and Table 5-7). For example, SOLAR5, a 5 person SOLAR household with a relatively high energy demand (Table 5-6), had a low heat demand but, conversely, one the highest power demands of the case study (Table 5-6 and Table 5-7). Whereas SOLAR 6, a 3 person household, had the lowest power related energy consumption (Table 5-7) and the highest heat related consumption (Table 5-6). The following explores these interesting examples further.

SOLAR5 were an enthusiastically pro-environmental household, not just scoring the highest NEP but also demonstrating a high level of pro-environmental behaviour, such as recycling, composting and showing keen pride in the vegetable garden they had created and talking at length about their make do and mend philosophy. They were enthusiastic about and highly engaged with their solar and boiler systems, including timing tasks to coincide with the ‘free’ energy from the PV system. Whilst they hadn’t altered the programming or thermostat settings for the boiler, they had elected to turn the boiler off and relied on the SHW for all their hot water needs. They avoided using the heating system until it became too uncomfortably cold as which point the heating was used for 3 hours in the evening. At other times they preferred the home cool and adopted other strategies to maintain comfort if needed:

"The kids and I will stick more clothes on if they need to but I'll just go and have a hot bath later to warm up if I get too cold" (SOLAR5)

In the light of this evidence their power demand appeared anomalous. However, as their interviews revealed, with three small children and a husband needing a clean freshly pressed uniform for work every day, this household did a lot of laundry. At least one laundry load required drying and ironing daily. Rather than line dry, a second hand compact tumble drying was used to dry four to six loads a week. But, as they explained the reasoning behind their choices:

"things just weren't getting dry as quick, I couldn't get the stuff dry in the in the airing cupboard…the kid's just need a lot more space and the heater stopped working in the bathroom….my airer snapped in the garden."(SOLAR5)

For this household their high energy consumption was not related to the physical, nor how they used their LZC technology but their practises relating to laundry that were the important explanatory factor for their high energy consumption.

SOLAR6, their SOLAR neighbour, was also enthusiastically engaged with her technologies. The head of house had been given a talk on how to operate her systems and had read the information pack. She had been proactive in setting up the systems, altering the controls, programmers and thermostats on the heating systems when she had moved in (Table 5-6 and Table 5-7). Furthermore, in order to utilise the solar PV to its maximum benefit she had purchased timers to go on plugs to enable the 'free' power to be used even when she was out, such as slow cooker and washing machine. Yet, on talking about her systems and energy consumption it transpired that the solar hot water system was not being used in combination with the boiler to best advantage:

"I was sort of looking at the monitor … and I was sort of keeping an eye on the temperature of it and it wasn't…you did need to boost it with the gas…I just boost it whenever I needed it". (SOLAR6)

The boiler was not only on a timer to heat the hot water, it was also often used manually to keep the temperature in the hot water tank up, effectively reducing the solar contribution, resulting in higher gas demand than her neighbour. Despite having a good understanding of how to operate the controls and confidence in managing the systems, this household demonstrated a poor understanding of how the different systems interacted. However, the hot water demand was not sufficient to explain the high heat energy consumption. Preferring a warmer home than their neighbour, this household struggled to maintain a comfortable temperature in the main living area. It later transpired that there was a fault with the patio doors which created a significant heat loss and cold draughts in the main living area. In assuming all homes in a single development are identical and differences attributable to the physical elements (such as construction and technology installation) will be minimal and can therefore be assumed irrelevant studies on variance, such as Firth (2008) and Gill et al (2010), may be flawed.

For this household, their energy consumption was related to high heat related consumption. This in turn was attributed to the physical failings in the dwelling and how they used their technologies rather than household practises and behaviour. Unfortunately the monitoring study was not longitudinal and was not able to follow the household after the physical flaw had been rectified.

5.5.6.2. Engagement and understanding

Each household was provided with an information pack in a large Arch lever file that included both generic information pertaining to their tenancy and specific information on operating the technologies found in their homes. Only 36% of the households interviewed had read the tenants pack and the information specific to their heating system management and controls. A common complaint was that, although the pack was very large and contained a lot of information it contained little or no useable information on a) how their systems worked and b) how to programme and operate their systems effectively. On examination the information was predominantly technical installation and commissioning manuals. Despite the lack of usable information the majority of households (91%) had altered their heating and hot water system controls and settings (Table 6). In the absence of usable information, adequate instruction and knowledge a trial and error approach was adopted to meet households’ expectations. This led to diversity in system set ups and operational conditions which contributed to the variability found between households.

Some households had similar energy demand but the qualitative data reveals that there are significant differences in how they used their particular systems to meet their needs. This was most evident in the homes that needed the balancing of multiple systems, particularly the MVHR homes, than in the GHSP homes where control was limited to opening windows, a thermostat and a winter/summer/holiday setting.

For, example, the MVHR households, MVHR8 and MVHR10, had similar heat consumption but very different thermal comfort expectations and approaches to achieving that comfort. Their homes required balancing the boilers, MVHR systems and openings (including windows and doors). MVHR10 preferred their home hot, having the highest recorded internal temperature 24°C, and were at home 24 hours a day (Table 5). Expressing a dislike of draughts the windows were opened infrequently and the ventilation system was not accepted for this reason. In contrast MVHR8 preferred their home ‘fresh’, often opening windows and doors for ‘fresh air’. They also liked the ventilation system, using the system to create ‘cool draughts’ on demand via an on/off switch located in the kitchen rather than controlling the rate of air flow by the control located upstairs. MVHR10 were latecomers to the development, moving in six months after their neighbours. After being instructed on the various controls and ways of operating the system discovered by their more experienced neighbour (MVHR8), MVHR10 turned off the MVHR system within days of moving in. It remained off for the duration of the monitoring. Both households had altered their boiler settings and thermostats. MVHR10 had a higher temperature and longer heating periods but much lower ventilation rate than MVHR8. Conversely MVHR8’s predilection for ventilation accounted for a higher rate of heat loss, increasing heating energy demand. By looking in such close detail the differences between these households is revealed.

Engagement and understanding of the new energy technologies including heat pumps, SHW and MVHR, may also be a critical factor in efficient performance of these low carbon homes. For example SOLAR3 provide an extreme illustration. This household had the highest energy consumption for both heat and power of all the households studied despite having the lowest income and a relatively low number of appliances (Table5 and Table 6). This household was receiving support to enable them to live independently. Their boiler and SHW system had not been adjusted post occupancy by themselves, or by the professional care workers that visited them in their home or the housing association. Nor did they have any understanding of, or interest in, the technologies, their function and purpose or the benefits they could bring. Furthermore, neither adult could read, and, as the information provided was in a written format, it was inaccessible to them even if they had been interested. Despite a low income this household preferred their home hot and they preferred to wear light clothing. During the monitoring period their meter was changed to a pre-payment meter. For this household, human factors relating to competency may have been the critical factor in determining their energy use.

What this analysis reveals is that, within this small case study, the characteristics contributing to the differences in energy consumption observed are complex. Furthermore, underlying each households energy demand is a blend of these characteristics unique to that individual household: there is no such thing as a standard household. These characteristics are lost in aggregated analysis or analyses that seek to explain variance by quantitative variables as found in the literature. In addition to the factors identified in the literature (including technical; socio-economic) other factors found in this study included: lack of understanding; deficit of knowledge; and behavioural idiosyncrasies particular to each household. This finding validates the conclusions of authors including Morley and Hazas (2011), Crosbie (2006) and Owns and Driffill (2008), who assert that understanding variability in energy use between households requires a mixed methods approach, combining both the quantitative and qualitative.

5.5.7. Limitations of this study

There are a number of points to note with regards to this study that affect the robustness of the results and wider relevance of findings. Firstly, the case study involved a small number of households and therefore does not allow for statistical analysis. However this allowed the use of in-depth qualitative interviews required to gain the finer detail needed and ensured that these data were manageable. Secondly, the homes and the households occupying them were homogeneous in character and did not reflect the diversity found in new build housing in the UK or internationally. This homogeneity however was advantageous in that it reduced the influence of variables including employment, occupation and income. Thirdly, related to data quality, the energy data pertaining to the different systems are based on modelled consumption rather than monitored data and subject to criticism on accuracy and claims made upon the use of such data. However, the primary data were based on actual metered data and the modelled results cross referenced with this to ensure overall accuracy.

5.6. Conclusions

This study had three objectives. Firstly, to describe and compare the case study households with the national population. These households were found to be relatively homogenous in comparison with wider the UK population. They were characterised as relatively young families, with a higher proportion of single parent families with a female head of house, lower income than average, with higher densities of occupation and a higher rate of hours of occupancy than the UK average.

Secondly, to quantify the variability in energy demand between the different households. These households are superficially very similar, occupying identical homes and sharing similar socio-economic characteristics yet energy consumption across all the homes was still found to vary by a factor of difference of 2.6. Furthermore, heat related energy consumption showed greater variability between households than power related consumption. These findings differ to previous studies where variability was found to be greater and power consumption was more variable than heat between households (Table 5-1)

Thirdly, to identify explanatory factors for the difference found between household energy consumption. Variance in energy consumption between households is a well-documented phenomenon. The difference in energy consumption between households has been thought to relate to differences in physical characteristics; technical characteristics and household characteristics including: occupancy patterns, age; household size; income; values, attitudes and motivation; and behaviour. This study examined the relationship between these characteristics and the energy used in a small case study, furthering earlier studies by using in depth interviews to explore the underlying contributory factors that explain this variation in household energy consumption in new build low energy housing.

The key findings are summarised as:

- Household size was found to correlate with both heat and power consumption. This relationship was strongest for power consumption, the larger the household the more power consumed.

- In these households socio-economic factors (including age, income and occupancy) and environmental beliefs did not correlate with energy consumption and could not fully explain the variance found in both heat and power consumption.

- The relationship between appliance ownership and power consumption was found to be weak suggesting that rates of ownership did not necessarily relate to levels of power consumption. The small study group size and homogeneous characteristics suggest that this needs further research to clarify this result.

- Heat related energy consumption and power related consumption were not related to each other in these households. High heat related energy consumption is not necessarily related to, or indicative of, high power consumption or vice versa in these households.
- Information provided was found to inadequate both in content and format. Additional support, such as face to face tuition in the home, will be needed for some households particularly those with additional needs.

These findings show there is a high degree of variation in energy consumption between homes that share similar physical characteristics, technologies and household characteristics. This variance cannot be explained by singular variables attributed to differences in physical, technological or socio-economic characteristics alone. Critically, variance in energy consumption was found to be attributed to a complex mix of physical, technical, social and behavioural reasons. By using both quantitative and qualitative methods this study reveals that variance in energy consumption between households is a complex interaction between multiple sources of differences unique to each individual households.

Whilst the findings are specific to this case study they highlight the complexity of energy use in the home. Whilst policy and regulation are clearly reducing the energy demand required by housing for heat related end uses there is, and will continue to be, a disparity between what is aspired and what is achieved. This study has shown a critical contributor to this disparity to be the occupants themselves and how they elect to live in and use these new homes and new technologies. As regulation moves housing towards ever lower heat related consumption the importance of the user increases. If each household’s energy consumption is as singular as implied, what are the implications for policy? The evidence presented here suggests that the occupant contribution to the performance gap may prove difficult to close.

A number of recommendations can be made to close this performance gap. Firstly, how buildings are assessed and commissioned post completion has to change. Measurement of actual energy performance needs to become standard practise. The performance gap relating to physical and technical performance needs to be minimised prior to occupation. This can be achieved by a commissioning process in which the home is considered a whole system which includes: physical fabric; technology; and the occupants themselves as a unique unit and not a generic entity. This would require systems to be commissioned and programmed with the participation of the household. Secondly, the way information is provided to households needs to improve. Not only improving the quality and relevance of the information provided but also a broader range of formats. Reliance on written documents excludes many households. Other media, such as DVD or online support and face to face tuition in the home would greatly improve this situation and should become standard practise at handover for all new homes. Finally, the models used in design and performance calculations need to account for households in a more realistic manner. As this study highlights there is a dearth of knowledge of how occupants actually use their homes and new technologies and the impact upon energy consumption in reality remains poorly understood. More research is needed to develop this knowledge and enable it to be incorporated into future modelling, improving the accuracy with which energy consumption in the home can be predicted, minimising the performance gap and increasing the likelihood of more realistic policy targets for energy and carbon emissions from new build homes.

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6. The adoption and adaptation of new low carbon technologies in the home

This is the second of two chapters that address research question 3 outlined in Chapter 1:

What is the influence of passively adopting households on the overall energy and carbon outcomes of mainstream new low carbon homes as they adopt and adapt to new LZC technologies?

The preceding chapter 5 was concerned with the differences between households and the effects on energy demand. This chapter considers how users are interacting with new low and zero carbon technologies in new homes. The study described evaluates the ways in which users gain knowledge on understanding and using their energy systems providing power, heating, cooling and ventilation and associated controls and how users adapt to new technologies.

This chapter is organised as follows: section two explores the current understanding of the post installation effects of low and zero carbon (LZC) technologies in home. Section three presents the methodology used; the findings are given and discussed in section four; the final section draws conclusions of these findings and the implications for policy outcomes.

6.1. Introduction

Homes use 30% of the total energy used in the UK and are responsible for 26% of the UKs total carbon emissions (DECC 2009). If the UK government is to meet the Climate Change Acts 80% reduction in carbon emissions by 2050, the contribution from buildings will be crucial (Crown 2008). Homes have become a particular focus of policy attention. The UK government, through a series of rapid and incremental improvements in the building regulations, aims to make all new homes zero carbon by 2016. This has instituted innovation in how homes are constructed and the adoption of new low and zero carbon (LZC) technology.

However homes and the LZC technologies within them rarely, if ever, perform as anticipated (Wingfield et al. 2008). Households may not understand how to operate, or be sufficiently motivated, to use systems effectively (Stevenson and Rijal 2008). Users may reject new and unfamiliar technology, particularly if such technology has been imposed upon them (Chappells and Shove 2000). Furthermore, users do not always behave in ways that are expected, seeming to wilfully ‘misuse’ their homes and technologies to detrimental effect on energy performance (Lomas et al. 2009).

The process of adoption of new technologies may not be one-way; users may also be influenced by the technology. LZC technologies may be more than a technical means of reducing carbon emissions they may also have positive effects on people’s energy use behaviour. Households may adapt their daily routines to maximise the benefits of LZC technologies (Keirstead 2007). Furthermore, by making energy visible, LZC technologies may also influence households in an indirect cognitive manner, raising awareness of energy use, stimulating a shift in attitude and a positive change in energy behaviour (Bergman and Eyre 2011, Hargreaves et al. 2010).

Yet, little is known about how users are adopting and adapting to new LZC technologies (Lomas et al. 2009). This is particularly pertinent as LZC technologies become more widely adopted in mainstream households, where households do not actively choose a home with LZC technologies. Such households can be considered passive adopters of these new technologies[23]. How are such passively adopting households appropriating (Mackay 1992) and domesticating (Lie and Sorensen 1996) these new technologies? And, at the same time, what changes are happening in households as they accommodate these new technologies? Understanding how users are adopting and adapting to new LZC technologies is essential to closing the gap between design and actual performance and closing the gap between policy targets and outcomes in the real world. Research is urgently needed to find out how users actually respond to the technological innovation happening in new build homes. This paper and the study described is a contribution to this knowledge.

6.2. Post installation effects of LZC technologies in the home

There is a small but growing body of literature concerned with the effects of LZC technology in the home, much of it is concerned with information based interventions, particularly smart and visible metering (Darby 2010, Hargreaves et al. 2010). There is a notable absence of literature that explicitly considers how households are adopting and adapting to new energy related technologies, including photovoltaics (PV), solar hot water (SHW), ground sourced heat pumps (GSHP) and mechanical ventilation with heat recovery systems (MVHR).

[23] A passively adopting household is defined here as an individual or a household that does not actively choose to adopt low energy or environmentally aware behaviours or technologies but is guided towards such behaviour or desired outcomes through the provision of technology or design by an external actively adopting agent.

The literature, which is predominantly economic in nature, is concerned with consumer and market related events prior to bringing technology into the home. This includes consumer purchasing decision behaviour (Kaplan 1999), market related barriers (Faiers and Neame 2006, Haas et al. 1999) and policy related assessments (DECC 2011).

The literature concerned with post installation effects of new energy technologies in new housing is almost exclusively assessments of technical performance (for example PV (Ayompe et al.2011, Decker and Jahn 1997, Jahn and Nasse 2004), solar hot water (Hill et al. 2011), heat pumps (EST 2010) and community heating schemes (Gill et al.2010, Pilkington et al.2011). The majority of these studies find that the technologies studied rarely achieved predicted energy performance. Conditions of use were cited as the predominant explanatory factor.

The presence of LZC technology may not reduce overall energy demand and may increase overall energy consumption in some households (termed rebound effect [24] (Sorrell and Dimitropoulos 2008). Erge et al. (2001), evaluating the German '100,000-Roofs-Solar-Programme', found total annual electricity consumption of households with a PV system was no different from that of households without a PV system. However, other studies contradict this conclusion. Haas et al. (1999), in a study of German households, found that the purchase of a PV system led to changes in consumption, both positive and negative depending on initial energy demand. The study found consumers with a high initial demand reduced their overall electricity demand. Conversely, for consumers with a low initial energy demand, a rebound effect was found and this group increased their electricity consumption. The authors concluding that for PV to be a tool for overall demand reduction it was an "energy conservation tool for the rich". A rebound effect is most strongly related to low income households, for example, a study of 9 low income households in the UK found an increase in total annual energy consumption in 8 of the 9 households of between 3 – 34% (Bahaj and James 2007).

However, this rebound effect may also have a cognitive component. Users of LZC technologies may be conscious of this rebound effect percieving themselves to be less concerned with the amount of resource they were using and may be well aware that they were using more (Caird et al. 2008).

Alternatively, the presence of LZC technology may have cognitive effects that encourage energy efficient related behaviours (Keirstead 2007, Hondo and Baba 2010). Keirstead

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[24] The rebound effect (also referred to as the take-back effect) refers to the behavioural response to the introduction of new technologies that increase the efficiency of resource use. These responses tend to result in a paradoxical increase in resource consumption that negates some, or all of the efficiency gains (See Sorrell, S. and J. Dimitropoulos 2008).

(2007), in a study that specifically addresses behavioural responses to PV, suggests that LZC technologies might bring a ‘double dividend’, not only resulting in low carbon energy generation but also encouraging households to reduce their overall power consumption and to load shift demand to times of peak low carbon electricity generation. Keirstead (2007) proposes this may be due to the cognitive linking of power generation and consumption derived from using power generated from technology in the home. Other studies have also found some degree of load shifting, with 43 – 47% of households with PV and SHW changing their patterns of consumption to accomodate the generation profile of LZC technology (Keirstead 2007; Caird et al. 2008).

Hondo and Baba (2010), in a study of the changes in behaviour as households appropriate LZC technology, suggested the installation of micro-generation had a galvanising effect encouraging households to increase energy efficiency related behaviours, describing the effect ‘‘a sense of mottainai strengthened.” Although mottainai is a broad concept, it can be interpreted here as a sense of regret concerning wasteful use of objects or resources. Suggesting that as households start to obtain some degree of energy autonomy this may have caused feelings that such power should not be squandered or used wastefully. They suggest this change in behaviour could be attributed to the following mechanisms:

1. Technologies provide a visible connection between production and consumption (changed sense of *mottainai)*
2. Technology raises awareness/consciousness and thus promotes pro-environmental behaviour
3. Technology increases communication among family members regarding environmental behaviour and consequently promotes environmental behaviour.

Visibility may be a factor in a technologies capacity to shift users to lower resource use. However, the studies in which this was observed were specifically concerned with solar technologies. Whether or not the same effects would be found in households with less visible LZC technologies is as yet unknown.

Information, specifically its presentation and clarity may also be a factor in effecting a change in behaviour in households post adoption of LZC technology (Dobbyn and Thomas 2005, Bahaj and James 2007). Positive changes in energy consumption are more likely where the presence, purpose, and use of the LZC technology had been clearly and simply explained and the user had received clear instructions on what they could do to maximise the technologies effectiveness (Dobbyn and Thomas 2005). However, Bahaj and James (2007), in a study on the provision of feedback on energy production and consumption in low income households with PV, found information on consumption did result in a reduction in power consumption, but, rather like the errant dieter, within twelve months not only had consumption increased back up to levels prior to receiving feedback but, in some cases, also exceeded it.

These studies are exclusively concerned with information as produced and imposed by experts to be consumed by non-expert households. There may also be other, informal, routes by which households gain and transmit information and knowledge (Darby 2006). This informal transmission of knowledge is important as it can reflect underlying everyday reasoning (Kempton and Montgomery 1982). In this research this informal knowledge will be referred to as folk knowledge and is defined as the intuitive understandings accrued through everyday experience. Folk knowledge contrasts with expert knowledge which is grounded in institutional understandings derived from learnt knowledge and skills obtained from training and education. Exploration of informal folk knowledge remains virtually unreported in the literature and is a significant deficit to understanding how users and new technologies interact.

LZC Technologies rarely perform as well as they were predicted and human behaviour, or 'misuse' of technologies, (Lomas et al 2009) is a predominant cause of this performance gap (Stevenson et al 2010). Yet, design may also be a significant contributor to how users appropriate new technologies (Rohracher 2003).

The designers and experts involved in the production of new homes and the LZC technology within them, by necessity, have to make assumptions about how and who will be using these homes and technologies (Ornetzeder and Rohracher 2006). In anticipating how users will interact with the products they are producing they implicitly or explicitly, build in prescriptions for use. Decisions will be made about capabilities and how different tasks and responsibilities will be distributed between the user and the various technological components. Many of these assumptions and decisions will already be prescribed, embedded in diverse regulations, design guidance, mandatory or voluntary codes and institutions. In this way experts attempt to configure users, constraining their actions in relation to the artefacts with which they interact. However, homes and the technologies within them appear to lead a double life. There is the one which conforms to that imagined by the designer and another more complex and messy reality that contradicts that imagined, producing unexpected or disappointing results (Mackay 1992). Users may use technologies in ways that are not foreseen, they may redefine a technologies purpose, customise it or invest idiosyncratic symbolic meanings in it or even reject it (Mackay 1992, Jelsma 2003).

A contrasting approach in the field of sociology of technology, perceives technology as much shaped by its users as its users are influenced by it. The conceptualisation of things (devices, machines, appliances) as carrying *scripts*, or structural features that encourage certain user actions while constraining others was developed by Akrich (1992) and Latour (1992). Using the metaphor of a play or movie, the concept holds that technologies possess scripts that prescribe the actions of actors (or users). For example, a car can encourage the driver to wear a seat belt by sounding an alarm or demanding that a belt is worn by refusing to start if the belt is not used. The process is illustrated in Figure 6-1. Such scripts are the product of *inscriptions* by designers. Designers anticipate how users will use the artefact that they are designing, implicitly or explicitly, building into the hardware/software prescriptions for use as imagined. Latour (1992) describes this process as delegation of specific responsibilities or values to the artefact and the user. The user translates, or decodes the scripts by a process of *description*.

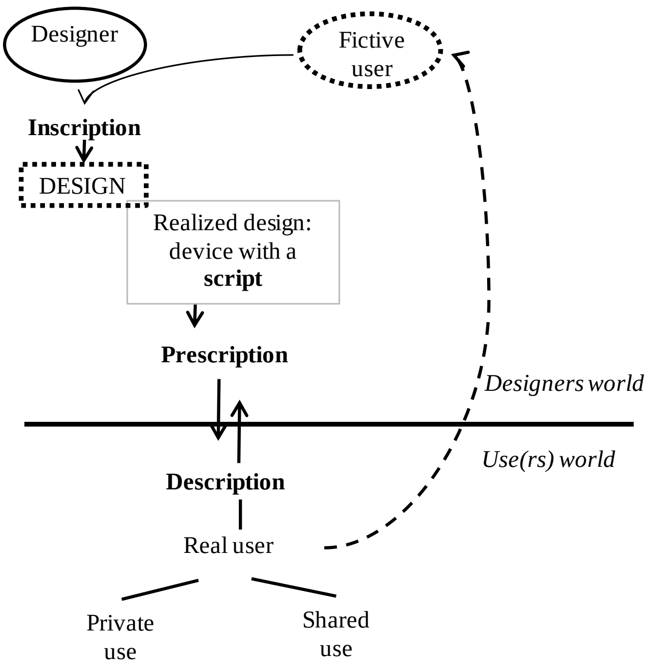


Figure 6-1: Semiotic notions connecting design and use process (adapted from (Jelsma 2003)

It follows that, by inscribing an object with prescriptive scripts, a designer can effectively close down or open up the ways in which a user is able to interact with that technology and effectively drives behaviour in a certain direction (Jelsma 2003). However, a script cannot constrain the user completely. As the designer inscribes the hardware/software of an artefact they will have a fictional user in mind. But this fictional user may be incomplete or wrong, leading to disjunction between the script, as written by the expert, and the way users read it. In this way users may not conform to the fictional user imagined by the designer. The user, in reality, may do things that deviate from the model and behave in ways that are unforeseen or unaccounted for.

In addition to its application as an analytical tool useful for comparing designers conceptions and users actual behaviour and interpreting what is happening, the concept of scripting offers an alternative lens through which to view the interactions between users and LZC technologies in new homes. Conventionally the technical point of view perceives the user as a subversive antagonist who, either through ignorance or wilful misbehaviour, misuses their home and the technologies within them to detrimental effect on performance (Mackay 1992, Guy 2006, Lomas et al. 2009), a point of view that is incongruous with the silent subservient role given to the user as an expert inscribes their roles in the technologies they impose or the knowledge they impart. But, through the lens of scripting, the conflicts, understandings and knowledge arising as users interact with new LZC technologies can be viewed, not as misuse, but as a disjunction between the designer and the user. Highlighting these disjunctions may have a benefit in improving performance and usability of new technologies. This raises interesting questions on the ways in which technologies and knowledge are produced and imposed by experts and how technologies and knowledge is used (or consumed) by households.

The literature concerned with understanding the post-installation effects of new LZC technologies in passively adopting households is primarily technical in nature and concerned with quantifying changes, theorising the potential cognitive effects of specific technologies and information on energy performance or identifying causal factors contributing to performance deficits. Very few studies consider the effects of LZC technology on domestic energy consumption as it is appropriated by passively adopting households. The literature does not describe how passively adopting household are 1) adapting to new technologies and also 2) how users are in turn adapting these new technologies. The study described in this chapter is a first to fill this research gap by exploring qualitatively how passively adopting housholds are both adapting and adopting new LZC technologies within the constraints imposed upon them.

6.3. Methodology

The study described in this chapter uses qualitative empirical data collected during the year long case study described in Chapter 1. This included:

1. Two semi-structured interviews, the first within the first month of occupation, the second at six months and each lasting between 30 minutes to one hour.
2. Informal observation of behaviour and field notes from site visits during the year.

Semi-structured interviews employ a relatively open framework which allows for focused conversation between researcher and subject. Unlike more focused frameworks (e.g. questionnaires) where detailed questions are pre-planned, semi-structured interviews are structured around more general questions or topics which are identified prior to the interviews. The detailed questions arise as the conversation flows during the interview, allowing both the interviewer and the interviewee the flexibility to probe or discuss further specific issues, thus providing not just answers but the underlying reasons for those answers. As a tool its major benefit is it encourages two-way communication and a rapport to be built up between individuals which helps to build trust and may encourage interviewees to more easily discuss sensitive issues.

The semi-structured interviews were conducted face to face with each of the households in their homes. In cases where the household consisted of two adults the interviews were with both where possible, in these instances quotes are attributed by the use of *f* for female and *m* for male. In cases where it was not possible to interview both adults the interviews were conducted with the individual who spent most time running the home.

The participants were asked to comment on three themes:

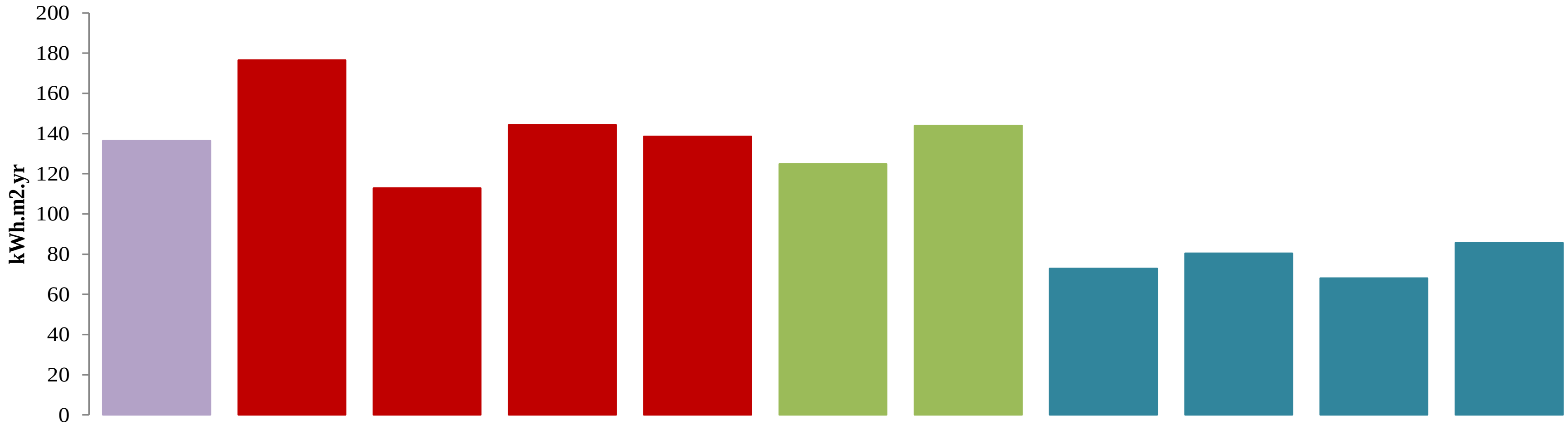
- Information and knowledge: what information was provided to tenants about the low energy aspects of their homes and instructions on how to use their particular technologies; whether and how they used that information; other support employed.
- The ways in which they had altered their technologies as they adopted them into their lives
- The ways in which they accommodated their technologies and adapted to them.

The interviews allowed the householders to talk about their homes and their specific technologies within a structured framework of the three areas of interest. The interviews were transcribed verbatim and the transcriptions coded into themes common across the households within the interview framework (Miles and Huberman 1994). This qualitative material was supplemented by informal field notes and observations taken during site visits to take meter readings and interviews. During these visits opportunities for observation and casual conversation with the residents often arose and the use of a field note book allowed for this empirical data to be collected and used to support the data collected during the interviews.

Not all the case study households choose to participate in this element of the research, semi-structured interviews were conducted with 11 tenanted households. No shared ownership households elected to participate in this element of the study. Other data collected included quantitative data on energy use and socio-demographics of the case study households. These are described in Chapters 3 and 5 of this research and a summary is provided in Table 6-1. It should also be noted that these household are not randomly selected. The households were selected by the housing association based on evidenced housing need and no other selection criteria.

The findings of this analysis are described in the following section.

Table 6-1: Summary of interviewee data including total energy use in kWh/m^2/year and socio-demographic data



Case number	**CONT2**	**SOLAR3**	**SOLAR4**	**SOLAR5**	**SOLAR6**	**MHVR 7**	**MVHR 8**	**GSHP 12**	**GSHP 13**	**GSHP 14**	**GSHP15**
Technology:		PV +SHW	PV + SHW	PV + SHW	PV + SHW	Sunspace + MVHR	Sunspace + MVHR	GSHP	GSHP	GSHP	GSHP
Household:											
No.Occupants	4	5	3	5	3	5	4	2	3	2	3
No adults interviewed (>20)	1	2	1	1	1	2	2	1	1	1	1
Gender	F	F + M	F	F	F	F + M	F + M	F	F	F	F

Income	£10 - 20k	< £10	< £10k	£10-20k	£10-20 k	£20-30k	£20 -30k	£10 -20k	£10-£20k	< £10	£10 -20k
Information pack read	yes	can't read	no	skim read	yes	skim read	skim read	yes	yes	no	no
System use:											
System controls altered	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
Altered by whom	occupant	N/A	freind	occupant	occupant	expert	occupant	occupant	occupant	neighbour	neighbour
TRV's adjusted	yes	no	yes	no	yes	yes	yes	N/A	N/A	N/A	N/A
Hot water controls adjusted	yes	no	yes	yes	yes	yes	yes	yes	no	no	yes
Heating controls adjusted	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes

CONT control; PV photovoltaics; SHW solar hot water; MVHR mechanical ventilation with heat recovery; GSHP ground sourced heat pump; TRV's thermostatic radiator valves.

6.4. Results

The results that follow are organised into four sections. The first three concentrate on the three themes that form the framework of the interviews. These are: information and knowledge; the ways in which households had altered the technologies as they adopted them; and the ways households had accommodated the technologies as they adapted to them. The final section describes experts' scripts and how these passively adopting households subvert them.

6.4.1. Information and knowledge

6.4.1.1. Formal information provision

"Erm ooh them big books?" (SOLAR4)

Figure 6-2 image of tenant information pack

Each household was provided with an information pack in a large arch lever file that included both generic information pertaining to their tenancy and specific information on operating their homes (Figure 6-2). On inspection the information on the different systems typically consisted of manufacturers' technical documentation, installation and commissioning manuals and manufacturers operating manuals.

An underlying assumption, as discussed in Chapter 5, on the part of the designers responsible for producing the information pack was all the households were both literate and competent with interpreting written material. This assumption was incorrect. One household in the development was illiterate, with poor cognitive skills and was unable to read the information. Another householder had a low level of literacy, finding the material difficult to read and interpret. Both these households were excluded from benefitting from this material. It has been estimated that 25% of the UKs adult population has difficulties with reading and mathematics (BIS 2011) implying that reliance on one method for instructing householders how to use novel systems may be problematic. This suggests that in inscribing how information on the operation and maintenance of homes and systems was to be provided, the experts assumptions on the competencies of the fictional user is incomplete. Designers of such support materials need to adjust their model of the fictive user to include a wider range of competencies. The outcome of this may be to inscribe the function of education to a wider range of media and methods of delivery, such as film or verbal face to face.

Three different approaches were taken by the tenants towards the information pack:

1. Read cover to cover thoroughly
2. Skimmed through and dip in when needed: *"Yeah every now and again I just have little you know sift through." (SOLAR6)*
3. Didn't read it at all "*it's more there for reference really."(CONTROL2)*

A common complaint was that, although the pack was very large and contained a lot of information it contained little or no useable information on a) how their systems worked and b) how to programme and operate their systems effectively. On examination by the researcher the information was predominantly technical installation manuals aimed at expert installers. Consequently, even if they had read the pack thoroughly, the households were unable to work with the information as it was too technical in nature, contained the wrong information (i.e. expert guidance on installation and commissioning and not guidance on use aimed at non expert users) or was missing any information relevant to their technology.

Where operating instructions aimed at the non-technical user were provided they were commonly found to be *"very minimal and doesn't actually tell you how to work it." (GSHP15)*

> *"It didn't explain anything which you needed explaining. And it just basically showed you these pictures and said like right this umbrella symbol on the digital thing in there (indicates towards the cupboard under the stairs) indicates that you're going away on holiday but there's nothing in there to say like how it would set for that or anything in detail" (GSHP13)*

Additional support from the developer or the housing association was also limited or non-existent. The housing association staff had no experience or knowledge of the technologies nor were they given any training. As a consequence the households were very much left to find their own way of doing and understanding and reliance upon informal knowledge.

6.4.1.2. Informal Information and folk knowledge

In the absence of reliable and usable 'expert' knowledge the households were left to develop their own strategies. These households self-organised and worked things out for themselves in a number of ways. They talked to each other, transmitting knowledge ('folk' knowledge) based on their experiences.

The households discussed their systems and its various quirks with their neighbours, sharing anecdotes about what they had done and the results based on their experiences and "operating habits" transmitting 'folk' knowledge between themselves and the other groups on the development. This was often framed in a competitive "my technology is better than yours" manner yet also acted as an inclusionary bonding experience between the different households.

In addition to the transmission of 'folk' knowledge, for each of the different technologies one individual became resident 'folk' expert and a focal point for knowledge and advice. Each came to be assigned this role by different routes. With the GSHP homes GSHP12 came to have specialist knowledge due to an expert coaching her prior to having a media interview. Subsequently she was engaged by each of the other households to set up their systems.

> *"I mean the only reason I knew about the summer mode was because <GSHP12> had done it... because she had visit and a run through... she has been the only one and she had explained. So it's been other tenants explaining to everybody else how it's going." (GSHP13)*

With the Active Solar homes SOLAR 6 spend a great deal of time during the training day prior to moving in with the expert asking many questions. She subsequently became the point for referral not only by the tenants but also by the housing association:

> *"When we came to have a look around and they went through everything and I was actually with the guy, and he went through every single setting with me and he spent a long while going through how everything worked. Because I think when <SOLAR2> moved in she didn't know how to set hers and she must have phone and spoke to Steve (housing officer) and he said ask <SOLAR 6> because he knew that I was there for quite some time. And that the man had gone through it all with me." (SOLAR6).*

Within the MVHR group MVHR8 took time to understand the system by his own observations, often taking the lead role in discussing the operation with the other households, gathering information on how they used it, correcting them if he thought their understanding was wrong and adding to his own knowledge and passing that knowledge on in an iterative way.

> *"He (indicates partner) has understood it but I don't. I mean you was out there the other day talking to <MVHR9> the new guy that's just moved in yeah and I don't get it even when he was out there explaining it... still don't understand it even when I listen to it. But and he's like yeah I need more information." (MVHR8f)*

Despite the different routes to the resident expert role each of these individuals shared a common characteristic of interest in the technology, an inquisitive attitude and a desire to understand how it worked.

6.4.2. Adoption: The ways in which technology was altered to meet household needs

The majority of households had altered their systems to some degree to meet their needs (Table 6-1) from switching a setting from winter to summer, using the thermostats and thermostatic radiator valves (TRV's), altering boiler and heating timings and settings, through to a more extreme tinkering of overriding default settings on the solar hot water and GSHP.

To do this the household used various strategies including: exploiting their wider network of more knowledgeable or 'expert' friends and relations; doing it in-house with their own expertise; and trial and error.

6.4.2.1. Knowledgeable network

> *"My dad, he always thinks he knows about these things and he set it. He's like an electrician so he's like oop yeah ...he knows about these things and he did it." (MVHR7)*

Some households, particularly those with a single female parent and the more exotic technologies, e.g. the GSHP systems, were more fearful of 'doing something wrong' and were more timid in their approach preferring to leave the technology to its own devises so long as it provided adequate service. This group relied on the input from their wider network of more knowledgeable friends and relations particularly in those households that perceived themselves not technically competent:

> *"I mean obviously I've set up on my wall ...you know the times when I've wanted it to go on and come off. My friend came round and did that for me... all the times are right and the days on that on are right when I want my heating to come on and off and my water to come on and off." (SOLAR4)*

In cases of need they found the expert information provided was inadequate and perceived themselves as not qualified preferring to call on the resident 'folk' expert to pop in to alter the settings switch:

> *"I haven't touched it. Too many buttons... Although I did mess about with the dial once and that stopped the hot water for a little while right when I needed to use it. But <GSHP12> come round and reset it and put it back together for me" (GSHP14)*

6.4.2.2. In-house trial and error

> *I just went upstairs and looked at it and thought oh there's a switch there and let's turn it on and see what happens." (SOLAR5)*

For some households, in the absence of other information, a process of trial and error was used until satisfactory levels of service were established. For households with conventional gas boiler technology it was familiar and presented no new problems:

> *"We actually knew how to do <this> as, well my husband did, as it was very similar to the one in our old one...I think he did look at the manual just to make sure" (CONTROL2)*

However, the more exotic technologies were outside the realms of experience for both these householders and their wider network, and, in the absence of 'expert' input or useable information, relied on trial and error, which, as one householder noted was not perhaps the most efficient approach:

> *"I suppose it doesn't take all that much you know common sense to sort it out but it is just trial and error really and seeing what suits what houses...Which is a bit of a shame as no one's learning the full potential of how to use them or getting them to work as efficiently as possible." (GSHP13)*

In the absence of expert knowledge households observed their technologies and the signals that were available to them to build up an understanding of how it worked. For example:

> *"I do sort of look at how much it's gone up by and then, because it flashes when it's in use or collecting the energy and then it stops. And it has been interesting to watch and see what time it actually stops flashing and the light is on because it is quite late in the evening. Whereas I thought it would be nearer tea time when it gets cooler it would then stop but then the suns still out and that amazed me because the sun goes done over there but it's still collecting energy. It's all so pie in the sky." (SOLAR6)*

This knowledge was used in a process of trial and error which revolved around testing out different scenarios and theories building up and adding to their understanding and the fund of knowledge within the community, working within the limits of the controls that were available to them.

For example, in the case of the solar hot water and its relationship with the gas fired boiler:

> *"I was sort of looking at the monitor or whatever you call it up in the airing cupboard and I was sort of keeping an eye on the temperature of it and it wasn't...you did need to boost it with the gas. But then again it was maybe an hour here and there. At first I had it set on the timer but then I thought I don't need it set on a timer because the tank does keep it hot. So once it is hot then that's fine but then once you use it obviously, you then... because you top it up with cold water again aren't you, in theory. I just boosted it whenever I needed it. So that's all I did in the end." SOLAR6*

In this example the first attempt lead to an inefficient use of both gas boiler and solar systems, what could be described as a misuse from an experts point of view. The initial alteration of the timing of the gas boiler pre-heated the water in the thermal store in the morning before the solar panels had an opportunity to heat it therefore reducing the contribution the solar could make. However the later adjustment, to one of *adhoc* heating from the gas boiler topping up the solar contribution after use when necessary, lead to an increase in the contribution from the solar hot water system and a more efficient relationship between the two systems.

The MVHR system had relatively simple controls but had a high number of them which made the system appear more complex. There were two on/off switches, one just below the loft hatch and the other in the kitchen, neither were marked or indicated anywhere as belonging to the MVHR system, and an air flow controller with a 3 speed dial showing 1, 2, 3 and a small red light. This complexity led to confusion in what was appropriate use:

> *"It was very much I don't know what this does; I found a switch do you know what I mean. Then we find another switch thinking there's another switch we haven't found. I remember at one point thinking what is all this doing? What's it for?" (MVHR8)*

The response was to experiment with the various controls and switches until an appropriate level of service was achieved:

> *"I turned it up and it got more draughty and then I turned it down and I thought oh that helped and then I turned it back down to one and it's been on one ever since I haven't needed to change it." (MVHR7)*

What these findings indicate is there is an initial period of experimentation by passively adopting households in which the controls and management systems available to them are altered until a satisfactory level of service or comfort is achieved or a satisfactory compromise is reached. In the absence of adequate knowledge or expertise this may be in ways that compromise the effectiveness of the LZC technologies particularly where there are multiple systems supplying the same service (e.g. hot water).

6.4.3. Adaptation: The ways in which tenants accommodated their systems

> *"I mean when you have a lifestyle that you can't physically change, with like central heating and that, you can only negotiate what you are going to do about it to the best of your ability and when you are living there all the time with it you have to just get on a deal with it." (GSHP13)*

The changes experienced by passively adopting households may not be simply one way technological changes as households adopt new LZC technologies. The process may be in both directions with the technologies influencing the households in return.

In these households changes in behaviour were observed, particularly in those households with the most visible or different technologies, including SOLAR and GSHP households respectively. Each of these groups included households that ranged from disengaged to highly engaged with their technologies. Both these groups talked at length about the changes that they had made to accommodate the quirks of their system or maximise the 'free energy' in the case of solar.

For most of the technologies any metering equipment was discretely hidden in cupboards and buried in control functions. The exception was the PV solar where a meter was installed above the front door that met eye height as you descended the stairs. Each of the solar households commented on looking at it when coming down stairs:

> *"Yeah I look every time I 'm up and down the stairs I will look and see if it's changed" (SOLAR6)*

For one of the less engaged Solar homes (SOLAR4) the solar meter was a catalyst for guilt driven waste reducing behaviour reminiscent of Hondo's mottainai (Hondo and Baba 2010) . Whilst her understanding of energy and the way in which it is generated and connected with the PV system remained diffuse and her level of engagement with the technologies in her home was low, she was observant of the meter.

She also confessed to becoming obsessed with switching things off and monitoring the behaviour of her sons:

> *"Them phone charger! I'm like turn it off, switch it off and that since I've been here. Even things that don't really matter, cos the kettle doesn't like does it and that… I'm just switching switches of and that's ever since I been here. I don't touch, I don't normally bother with all that <the entertainment centre> but you know what I mean we do turn it off properly there's not standby or anything. So but yeah, chargers I'm forever telling them two to turn it off cost that's using!" (SOLAR4)*

However, this level of engagement was not expressed by this tenant about the solar hot water system. There was little discussion of the system and no change in patterns of hot water consumption with life continuing as before. Suggesting that this cognitive effect is not equivalent across technologies.

In the more engaged SOLAR households both power use and hot water use patterns were shaped by the availability of the solar. With regards to PV two of the households interviewed had changed the timing of activities to correspond with generation. For example, where the home was occupied during the day:

> *"All my stuff gets done during the day and I try to cook dinner before it starts getting dark."* When asked why: *"because it's free!" (SOLAR5)*

In the case of a household which was unoccupied often during peak hours timers were installed on washing machines:

"yes I do my washing during the day and there's a timer on my machine so I will set the timer on my washing machine as well. Yeah so what I can do in the mornings if not sunny or anything I can set it for a couple of hours later if I am not going to be there." (SOLAR6)

SOLAR5 had also switched off their gas boiler as soon as the solar could generate enough hot water and relied entirely on the solar hot water provision for the majority of the year. SOLAR6 took a more pragmatic approach:

"If I know that there's no hot water for a shower in the morning then I will probably wait until later. So I won't necessarily wait and flick on the boiler just for me to have a shower if I don't really need one. But if I do really need to have a shower in the morning then I will flick it on. But then generally I will go with the flow." (SOLAR6)

This household also altered their water based routines to maximise the use of hot water:

"I just leave it until the evening because then there's the hot water...I tend to shower. And then <SOLAR6m> has a shower and I put the plug in then the little one jumps in the bath. I mean it's ridiculous not to do it that way really." (SOLAR6)

Furthermore, she also recognised their purchasing choices would have been different in hindsight regretting the choice of a gas oven over an electric one.

"But at the time it was all I could afford and I do wish that I had gone for an electric not just to save energy but also to get an electric fan over because I prefer it for cooking. And I though what an idiot you get a nice day you could put on a programmer and timer... but you learn don't you. Next time. I need an upgrade..." (SOLAR6)

The SOLAR technologies were never contextualised in reference to anything else and were perceived as something separate and different and visible. Whereas, the GSHP was often referenced in the context of conventional central heating, in particular comparing its responsiveness, the simplicity of only having one power source (electric) to deal with and the underfloor heating with the GSHP perceived as being a special and more "luxurious" heat.

All the GSHP households commented that the system was not as responsive as conventional central heating. This is particularly noticeable during the transitional seasons (spring and autumn) where the weather can be extremely variable. This resulted in comments relating to either overheating or being too cold. Each household responded differently changing their behaviour to adapt to this quirk in the technology. One household's response was to plan ahead and set the controls accordingly by becoming more aware of what the weather is going to do in a 48 hour time window:

> *"Yeah it was really cold then and then of course you turn it on and then it takes a while to heat up and by the time it's heated up its gone hot again and it's I'm hot now. It's like, well you have to kind of predict the weather before you know...I try and look at the weather forecast."* (GSHP12)

Another response was to just accept its limitations and use blankets rather than overheat:

> *"It was quite difficult… we all turned it onto the summer settings when we had that really nice weather and then it was like 'oh no' and it took like a whole day for the whole house to heat up afterwards by which time it's like it's too late now it's warm again and it is frustrating in that if you have a cold day and your house is cold you can't get instant heat so I guess you just put up with it really... I just have blankets around instead. I just put up with the cold and blankets."* (GSHP15)

For the more conventional CONTROL homes, no changes in behaviour were raised or referenced. For these households the patterns of life continued as it had before.

Within the changes in patterns of energy use and living with the limitations of their systems there were no evident changes in terms of reducing absolute energy consumption. With the exception of SOLAR6 and their on-going inter-household battle with switching things off, there was no evident changes in either expectation of service (e.g. reducing thermostat temperatures and wearing seasonally appropriate clothes) or behaviour changes aimed at reducing overall energy demand (e.g. reducing the number of appliances or using them less often, washing clothes less or showering less). This suggests that the technologies are affecting a superficial shift only in terms of timing of consumption to exploit the economic advantages of 'free' energy rather than effecting a reduction in overall consumption.

6.4.4. Experts scripts and user subversions

During the inscription process (Figure 6-1) experts impose a script based on how a technology should behave which is framed for fictive user or an idealised pattern of use. In the case of management and control systems in the domestic context engineers commission systems based on industry standards or with a specific service outcome in mind, heating timing and thermostat settings for example. This may conflict with the users' expectations. For example:

> *"I had a call from boilers manufacturer asking "can I come and take a look at it" and I said yeah. But then he came out and he really tampered with it and he was like twisting things and changing all the setting on it and he went all the way through it and like clicking stuff. But I'd noticed after he had gone that both me and Darren felt colder we were like it was not as warm now. Because he was going you don't need this high and with a house like this you don't need it like this it should only be on this. And he did it all to the most efficient but then that was tailored on coming into the warmest weather but we noticed that it was a bit colder we were like oof it's a bit chilly now since he's fiddled with it..." this households response to this discomfort: "I was like putting the thermostat up higher to sort of balance out whatever he had done to it." (MVHR7)*

This illustrates the disjoint between the fictive user as scripted and the user in reality. In this case the engineer had a pre-determined idea of the level of service that the system would deliver, without recourse to deferring to the actual users preferences and lifestyle, despite their presence in their own home. The resulting use of the thermostat in order to meet their preferences would be perceived as a misuse and the user somehow at fault. Yet, this situation could be avoided in such passively adopting households if, rather than imposing an idealised pattern of use based on a fictive user, systems were commissioned in a manner that were tailored to meet the needs of the actual household actually using it.

The imposition of 'scripts' and the conflicts caused are often unseen by designers and those in decision making roles during the development phase. This becomes particularly relevant when specifying new technologies and innovation where there will be many unknowns or areas that are not thought of, such as defining roles and responsibilities.

MVHR systems have a filter that requires regular maintenance, a relatively simple procedure of checking, cleaning or replacing filters. The air flow speed control, which is positioned outside the bathroom door below the loft hatch, has a small LED light which is programmed to go red every three months to indicate when the air filters require checking, cleaning or replacing. The filters were housed in the heat recovery unit which was housed in the loft. The loft hatch had a warning sign on it informing the tenants that the loft was out of bounds. The design team, including the architects and the housing association, had decided that the unit was not to be tampered with by the tenants. The information pack contained no information informing the tenants of this. The housing association put no protocols in place, other than declaring the loft and the unit out of bounds, for who was to undertake the task of maintaining the filter.

The product designers had scripted the prompts into the system and made assumptions that an individual with a certain level of competence would be on hand to respond to the prompt. The product was then incorporated into the designers and housing associations script and they made assumptions about the competences of the tenants and the risks to the equipment. However, whilst the script made it very clear who was not to take on this maintenance role it neglected to continue to describe who would take on this role. And the tenants pointed out:

> *"How does that leave us because he was trying to fix something that was their responsibility or ... what if I broke it then what? Because I don't' know what it is and without looking at it he doesn't even know if he can do it or not."(MVHR7)*

In the absence of any guidance, the tenants, quite naturally, as the light was a red colour typically indicating danger or fault, perceived the light as a fault which required action. This action could be reporting, dealing with or ignoring it. In this case the tenant reported the 'fault' to the housing association and, in the absence of any 'experts', switched the ventilation system off;

> *"It's one of those things that doesn't affect use as it doesn't really do anything"(MVHR7)*

For some households the lack of control available to them was particularly frustrating, leading to what could be described as 'transgressive' behaviour in order to achieve the level of service they wanted. Finding ways of tweaking or overriding the systems when what they wanted to achieve was not achievable in the scripted and therefore sanctioned or 'allowed' control functions. For example, GSHP15 expressed frustration at not being able to change the timing and temperature of the hot water:

> *"I've not been able to change the timing of it, I would like to be able to change the timing of it. There doesn't seem to be any way to doing that so in the winter all I could do was turn the thermostat down or up to control it. I mean you can switch it to the summer setting which I've got now so it just heats water but you can't change times or anything." (GSHP15)*

During a later interview, in discussing the controls she had found a way of resetting the timing to have the water heating during the day. She had also observed that:

> *"there was only one day a week when it was hot and I managed to find on the control panel in there that there was only one day a week that it was set to heat to 63°C and every other day it was set to go to 45°C which wasn't warm enough, obviously... I don't' know the water just wasn't hot enough."* And whilst changing the timing found that she could change the temperature setting to every day *"So I adjusted it to change it to heat to 63°C every day and that seems to be fine" (GSHP15)*

However, the 63°C setting is a weekly booster to kill bacteria in hot water systems. For this household it was a perfectly reasonable solution that solved her problems within the constraints of the controls available to her. But in doing so she was subverting the script as inscribed by the systems designer. Had she been able to have a finer degree of control she may have been perfectly happy with water set at 50°C. The 'closed script', enforced by removing control from the user, prevented this. The consequence of this was the user subverting the script, resulting in a reduction in the efficiency achieved by their system increasing their energy demand.

The intended script for the sunspace was as a solar 'collector' to work in conjunction with the MVHR system. It was envisaged that the tenants would perhaps *"leave shoes and school bags and maybe house some plants" (architect).* However the space was seen perceived by the households as an additional room in three out of four cases. For example:

> *"Paul and the girls tend to play out there…so it's like another room. Before it was warm they had their little table and chairs out there where they would draw. For the kids though it's fantastic because there's more space down stairs... But it's that thing of not knowing what it's for but it is very much the bike place, the scooter place...and it is nice it does make the house feel big it's like a vast space." (MVHR8)*

and

> *"it's the dog. She likes laying out there and seeing what's going on. She don't like if I shut the door on her. And if the doors shut and she's in here then she wants to be out there so we just live with the front door open. So I*

> *don't know how that would affect the actual sunspace the way that it works."*
> *(MVHR 7)*

Interestingly whilst shoes were well in evidence only one plant was observed. Only one household actively used the space in its thermal capacity by opening and closing doors, windows and vents to exploit and control heat flow from the sunspace into the home. One household used the space as a utility room, home office and smoking room, drilling through the airtight membrane to facilitate the installation of water services to a washing machine and tumble drier, this then freed up space in the kitchen for a dishwasher, the only household with one on the development. In total 9 different uses of the space where documented:

- Children's play area
- Cloakroom (coats, shoes etc.)
- Conservatory/Solarium
- Kennel for dog
- Drying space
- Home gym
- Home office
- Smoking room
- Utility room (installing washing, drying equipment)

The way in which a technology is framed changes its script. For example, MVHR is designed and used to provide clean fresh air pre warmed using extracted stale air and guarantee a healthier indoor environment in buildings. Yet, for one MVHR household the "draughts" created from the system were associated with air conditioning that she had experienced on holiday and this framed her understanding and use of the system. During the summer this was a positive special benefit of which she was very proud:

> *"It's like aircon like you're on holiday because you can feel the breeze coming through and its keeps the rooms without having to open the windows or things like that or you turn it off if you don't want the breeze to come through" (MVHR8)*

However, during the winter this became a negative and the system was switched off. She had difficulty in connecting it with heating and the sunspace and its use was entirely contradictory to its designed purpose.

6.5. Effects on energy consumption

For the households characterised as low energy (SOLAR5, SOLAR6, GSHP12, GSHP14 and GSHP15 (Table 6-1) there were two distinct groups. The first group, for example GSHP14 and GSHP15, it is technology rather than any intrinsic characteristics or behaviour of these households, that appears to be the predominant factor in reducing their total consumption. All the GSHP households were relatively low energy households. GSHP14 was not engaged with her system, hadn't read the information, did not significantly adapt the system, or adapt her behaviour in any way. For her, and households like her, the GSHP was an ideal technology quietly tucked away in the background with no requirement to interact with it and no requirement to change.

The second distinctive low energy group are characterised by being:

1. Informed and knowledgeable
2. Interested in understanding what their technologies do and how they work
3. Adaptive to working with the system for their benefit
4. Pro-active in experimenting with their system

Two of these cases, GSHP12 and SOLAR6, were also the resident 'folk' experts for their technology group. However, possessing these characteristics does not necessarily translate into low energy behaviour as demonstrated by MVHR8, who, despite being the resident 'folk' expert for their group is characterised as having a high energy demand. This illustrates that engagement and interest does not necessarily lead to action and adaptive behaviour.

For households classified as high energy consumers, CONTROL1, CONTROL2, and MVHR8 there is only one common shared characteristic. These households showed no demonstrable changes in overall energy use behaviour prompted by living in a low energy home. CONTROL1 and CONTROL2 where the control cases representative of conventional new homes with convention gas boiler central heating system (albeit highly efficient). For these households their conventional technology required no real changes to how they operated their homes and the technological innovation was hidden within the design and construction. MVHR households, with the addition of mechanical ventilation with heat recovery system and a solar sunspace, were the most visibly different of all the four groups. Yet this visible prompt of low energy credentials did not prompt any discernible difference in energy consumption behaviour in household MVHR8.

Conversely, the households with the most visible generating technologies, the SOLAR households (SOLAR4, SOLAR5 and SOLAR6), despite having the same boiler and identical internal house design had altered their patterns of energy use, demonstrating adaptive (or load shifting not reduction) behaviours. This suggests that some technologies can have a positive ‘double dividend’ effect on energy use behaviour (Keirstead 2007). However there is no evidence that any of the technologies deployed were implicated as a stimulus for low energy behaviour merely that the solar technologies presented an opportunity for ‘free’ energy.

6.6. Conclusions

It is clear from this study that new LZC technologies are both adapted by households to meet their needs and, in turn, households adapt patterns of behaviour to accommodate new technologies. However, the majority of these households did not change their patterns of energy consumption, lifestyles or behaviours to exploit the full potential of the low energy technologies provided for them. This is not a failing of these households. Other than the budgetary constraints of living on low incomes these households have no invested interest in reducing their carbon footprint or reducing their energy consumption. They are interested in the water being hot and in sufficient quantities when required, the homes internal climate being comfortable and that they are able to meet the costs of achieving these services. However this study found that of some LZC technologies can have a ‘double-dividend’ and be a lever for positive changes in energy use behaviour. But this is not equal to all technologies and not for all people. In these households this effect was associated with those technologies that generate 'free' heat and power and appear to make the link between energy and service tangible. The trigger for this may not be attributed to visibility but a sense of the Mottanai and the waste of a free resource (Hondo and Baba 2010).

The absence of usable information was problematic for the majority of these households. Information can only be effective if it is a) usable and b) read and applied by the system user. Firstly, information needs to be aimed at the user and be provided in formats that are accessible. In producing the material provided, the experts failed to account for 1) technical competency of the users and 2) diversity in literacy in the users. Secondly, in prescribing the provisioning of information it was assumed to be a universal solution assuring the optimum running of systems. This was clearly not the case in these households. Some households used the information to alter the commissioned settings; others only used the information when the system failed to provide adequate service, while others never used the information. The latter group of households preferred to either put up with poor service or divest control to experts or those they trusted, family members or their wider network.

Energy efficient homes and LZC technologies are essential components in reducing energy consumption and carbon emissions. Technical assessments indicate that their potential is not being optimised. The user is fundamental in how successful, or otherwise these technologies are in achieving the goals of their designers. Yet the user is viewed as a systemic component to be constrained or manipulated into behaving in the correct way. Using the conceptual lens of scripts, the way in which users are actually using these new technologies, subverting, re-imagining or rejecting them, has been highlighted.

Designers of systems and controls need to pay more attention to the knowledge and experience of users of LZC technologies in the early days of ‘passive’ mainstream adoption. Studies have concentrated on technical evaluation of technologies, viewing the user as a passive protagonist in this process. Yet, in experiencing living with these new systems these households developed a significant amount of folk knowledge. Much of this 'folk' knowledge is hugely valuable in understanding how users actually think about their homes and their systems rather than what designers assume. Yet, their experience, expertise and understanding has no value in this process. Listening to this knowledge can help designers and experts clarify where there is a disjunct between their assumptions of the users’ understandings that are scripted and that in actuality. This would enable modification of those scripts that are used in order to optimise the performance of these systems.

Variability between households and users is inevitable. Yet, experts are commissioning systems based on their own scripts and not those of the user. Commissioning and set up of new technologies needs to be right for the user and be household specific and not according to those imposed by an engineer working to a predefined human cipher institutionalised in regulations and codes. Furthermore, households vary in competence, knowledge and capacity. Some households desire a high degree of control of their systems and others desire to not engage with it at all. Systems and their controls need to be scripted for this diversity. Closing out control will lead to the user exerting control in ways that may run contrary to that scripted by the designer. Understanding how users interact with their systems may enable designers to pre-empt the points where users will 'subvert' these scripts. This is most pertinent in the design of controls, their usability, the level of control available, and where they are installed in the home.

Low energy developments are designed and constructed by experts, whose primary objective is to deliver their contract as per the brief, meeting regulatory demands as cost effectively as possible. Yet, these experts never ask people how they really live before making the design decisions that deliver the clients brief. What this research shows is that people are perfectly capable of articulating their needs and to develop the skills to fulfil them. The logical outcome from this suggests that a more active role for the eventual users in determining how new low carbon technologies are designed, installed and commissioned could contribute to an improved outcome for both resource use in the home but also for policy outcomes. However, the way homes and technologies are produced may be a significant barrier to achieving this.

6.7. References

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7. Reflections and concluding remarks

The aim of this research was to evaluate the carbon consequences of constructing low energy homes and assess the effectiveness of the housebuilding industries response to regulatory drivers and its ability to meet policy targets. This was explored using the following three research questions, set out in Chapter 1 and addressed in Chapters 2 to 6:

What are the embodied energy and carbon consequences of constructing new low energy homes compared with conventional construction?

The second question considered the contribution that new low carbon technologies can make and asks:

Are the innovations currently being deployed by mainstream housing providers in response to regulatory changes capable of meeting policy carbon targets?

The third question considered the reality of how these technological innovations are actually used in the real world and asks:

What is the influence of passively adopting households on the overall energy and carbon outcomes of mainstream new low carbon homes as they adopt and adapt to new LZC technologies?

This chapter draws this thesis to a close by summarising the key findings and discussing their relevance to policy. This chapter begins with summarising the main findings of this research with reference to these research questions. Section 7.2 reflects on the implication of these findings for policy, evaluating how well UK policy on new build housing is contributing to achieving energy and carbon reduction targets. Section 7.3 follows with specific recommendations for UK policymakers. Section 7.4 reflects critically on the research and discusses the limitations of the research and suggests directions for continuation of this research. This chapter closes this thesis with concluding reflections on this research project in section 7.4.

7.1. Key findings

This section summarises the key findings of 5 studies presented in Chapters 2 – 6 using the three research questions as a framework to discuss the implications of these findings.

7.1.1. Question 1: Embodied energy and carbon

The embodied carbon study (Chapter 2) estimated that between 110 – 167MtCO_2 will result from the policy aspiration to build 3 million new homes. This could equal or exceed the annual carbon emissions arising from the total existing housing stock. Yet, a significant proportion of this embodied carbon lies outside national accounting frameworks, concealed within imported materials and products. In addressing carbon mitigation the UK's policy focus on energy efficiency and clean energy excludes embodied carbon, a crucial omission.

The choices in materials used were found to have a significant effect on the energy and carbon impacts of these homes. The embodied energy and carbon consequences of construction innovation using MMC revealed that this approach significantly reduced the carbon costs of construction compared with conventional masonry construction (by 34% in this case). This was largely attributed to the use of timber in both the structure and cladding suggesting that these materials and construction innovation will result in a lower carbon burden than traditional materials and construction.

However, the comparative lifecycle methodology used in this research was narrow in its scope (excluding maintenance, and end of life phases). This is problematic for two reasons. Firstly, the findings in this research are dependent upon the manufacture and construction alone. Without including the impacts from maintenance and end of life disposal the picture remains incomplete and could, potentially, be radically different if a full lifecycle, including maintenance and end of life, is considered. Which leads on to the second point, high embodied energy materials, such as concrete and brick, the example discussed in Chapter 3, also have a high mass, which, if deployed effectively in the design will assist in levelling out thermal loads, reducing heating and cooling requirements and reducing the amount of energy required in occupation. However, under the limits of the boundaries used in this research (Chapter 2), the findings suggest that such materials are to be avoided. Consequently, decision making based on the outcomes of a limited approach could be misleading and potentially counterproductive in the long run. A comparative full lifecycle study would contribute enormously to this knowledge.

Decisions on materials to be used are the responsibility of the design team. In the case study this research describes the environmental impacts of the materials used was a design principle, this is not typically standard practise. Incorporating the impacts of material choices into design decisions has been problematic. Undertaking lifecycle assessments of materials have been difficult and time consuming, principally due to the availability of reliable and relevant data. However, since the embodied energy and carbon study described in this research (Chapter 2) was undertaken embodied energy and embodied carbon data and numerous tools and software, both open access and commercial, have become readily available. As a consequence, lifecycle studies of housing are increasingly being undertaken. If, as this research found, the consequences of material choices taken during the design process have such a significant effect on the lifecycle energy and carbon associated with a building then it makes sense to include it within policy and regulation.

7.1.2. Question 2: Innovation outcomes and policy targets

Innovation in housing construction in response to regulation is unequivocally reducing the energy demand of new housing (Chapter 3). All the four house types within the case study had lower energy demand for space heating compared with the contemporary industry standard, clearly demonstrating that increasingly stringent regulations will result in significant energy reductions. However, the extent of reductions achieved by regulation may be limited by how they are achieved. For example, in the case study

(Chapter 3) the use of all electric systems was found to be counterproductive for environmental and social policies. Whilst such systems were found to lead to relatively low energy demand they had the highest carbon and monetary costs. This research found that none of the systems approached the performance claimed by manufacturers, highlighting that the relationship between energy and carbon is not always straightforward. Whilst ground sourced heat pumps were found to be beneficial in energy terms, due to the high carbon factor of grid electricity, their carbon performance was comparatively poor and will remain so until either integrated renewable energy systems come as part of the household package or the UK's grid power supply significantly decarbonises. This research suggests that the extent of carbon reductions achievable will be dependent upon the technology used and wider contextual factors, particularly that of the UK's energy supply.

This research also found, in achieving lower carbon emissions, homes and their systems are becoming increasingly complex (Chapter 3 and Chapter 4). The range of technologies used and the need for additional controls is increasing. For example, Chapter 4 considered a specific example of industry response to policy: that of the increasing adopting of mechanised ventilation in relation to building regulations part L1a and Part F. This study considered how resolving one problem, reducing heat loss through increased insulation and airtightness, can create other problems, such as the requirement for adequate ventilation to compensate for that lost due to increased airtightness or the need for compensatory mechanisms to cope with overheating caused by limiting heat loss, that require solutions (Chapter 4).

The findings of this study suggest that MVHR systems as currently deployed in new build homes are not meeting their intended aims of providing adequate ventilation in an energy efficient manner. On the evidence presented in this case study, it is of critical concern that 1) the systems are being specified inappropriately, 2) the systems may not be used as intended, if they are used at all, risking a potential increase in significantly impoverished indoor environments. These findings agreed with that found in the literature. Furthermore, this research also suggests a third point: there is a risk of institutionalising the notion that ventilation and indoor comfort is provided by mechanical means rather than passive. As a result the net effect on energy demand may be one of increasing energy demand associated with a new and additional technology rather than a net energy reduction associated with the synergistic efficiencies of two systems, heating, and ventilation, working together.

Industry and regulation has responded to this increasing complexity by fragmentation and specialisation of the production process. This approach suits the way in which homes are traditionally produced. Regulatory changes have been accommodated by incremental changes to the basic product or production process (e.g. in this case MMC) and specialised systems and new technologies which can be bolted on (e.g. solar hot water and PV) or replace old ones (e.g. heat pumps) without recourse to questioning the basic product or production process. This could lead one to consider the innovations currently being introduced as over-engineered or overly complex solutions that: increase the costs of achieving significant carbon reductions; creating conflicts between different functions and services; and increasing the likelihood of misunderstanding between the designer and user, placing unnecessary demands upon the user, leading to conflicts and, for want of a better word, ‘misuse’.

7.1.3. Question 3: Passively adopting households

One of the most surprising findings of this research shows that, despite the energy and carbon reductions demonstrated, none of the homes and their technologies performed as well as predicted in terms of heat (Chapter 3). This performance gap was found to be the consequence of differences in household energy demand (Chapter 5). The explanatory factors for this observed variance were found to be complex but can be attributed to three main aspects: technical; physical; and use. Whilst each household was found to involve a unique complex of explanatory factors the occupants themselves and how they used these new technologies and homes was found to be the key contributing factor.

Interestingly, overall there was no discernible difference found in electrical appliance related energy consumption between these case study households and the average UK household (Chapter 3). This finding suggests that the occupants themselves may be contributing little or nothing towards the energy reductions found in these homes. In these homes the energy reductions were principally be attributed to technology and the physical thermal structure of the home. It can therefore be surmised that the energy and carbon reductions found in these particular homes is derived from material and technological innovations and not from passively adopting households becoming more energy aware and shifting towards low energy use behaviour. This finding suggests that fast effective carbon reduction may lie with design and technology rather than increasing efforts to effect individually motivated behaviour change.

In reality these homes and technologies were adapted by the households to meet their service expectations and not vice versa (Chapter 6). This study found that all the households adapted and used their systems in ways that met their needs (Chapter 6). Often the adaptation was in ways that could be construed from an engineering perspective as ‘misuse’, perceiving the user as a systemic defect requiring correction. Information, or rather the lack of usable and relevant information, was found to be important to these case study households. Without usable information, and even in cases where it was provided, households were found to be using systems and their controls in ways that were unintended by the systems designers and commissioners to produce results that were satisfactory and made sense to those households.

During this early stage of adoption of these new technologies understanding how users are interacting with their systems and listening to their experience, knowledge, and expertise could be hugely valuable in helping designers and commissioners to optimise the design of systems, controls, their usability, and how and where they are installed in the home. However, the households that will live in these homes will have no part in the decisions made during the production of their homes and the technologies that are put in them. They are, for the most part, virtually absent from the production process, represented either in an abstract way as formula or bands of acceptable environmental parameters or as a source of potential system failure to be controlled for in some way. If passively adopting households were included in the design process of both mainstream volume housebuilding design and the systems that will go in them, then the opportunities for misunderstandings may be reduced and energy and carbon outcomes improved.

However, there was, and will continue to be, a disparity between predicted and reality (Chapter 5). The principle agent for this disparity is the occupants themselves and how they elect to live in and use these new homes and new technologies. As regulation moves housing toward ever lower comfort related energy consumption the importance of the user becomes increasingly critical. The evidence of this research suggests that the occupant behavioural component of the performance gap may be inevitable and is difficult, if not impossible, to close without very stringent and draconian legislation and social engineering (Chapter 5). This research has shown that these new homes and new technologies were not enough to effect cognitive changes leading to behaviour change and energy conscious behaviour in individuals and households (Chapter 6). It is suggested that a more palatable solution may lie with smarter design, appropriate technology, and improvements to how homes are commissioned. If design and technology are the principle mechanisms in influencing significant energy demand and carbon reductions in mainstream new build housing, then it makes sense to exploit this through design, material choice, technology, and usability. This has implications for 1) how homes are designed and 2) for policy and regulatory focus.

Firstly, regulation is reducing the energy and carbon required by new build housing, particularly that associated with heating. These savings will be limited by what is counted, how the home and its technologies are designed and produced, and how these homes and their technologies are used. Furthermore, radical cuts require a broadening of what is regulated to include the construction material and a more holistic approach to the design of homes. This will require a deeper institutional change that requires energy and carbon literacy to permeate all levels of thinking, designing and producing homes and the technologies within them. Whilst regulation is good at defining minimum performance standards for specific elements in the desired direction it does not prescribe how these standards are to be met so cannot institute the changes that are required to institute this level of change.

Secondly, how homes are designed and constructed, the materials used and the technologies deployed to meet the energy service demands of the households that live in them are the responsibility of those that design and produce housing in the UK. Yet, designers, once their visions have taken form in the real world, do not usually find out how their houses perform or if there are any problems arising from design unless there is a major flaw that arises across multiple homes. Furthermore, they also have little, if any, influence over either how these homes and technologies are used or the appliances that households elect to have and how they are used. Therefore, it is logical for policy and regulation to limit the responsibilities of actors involved in producing new build housing, including architects, designers and specifiers, to the areas that they are a) professionally responsible for and b) able to influence. This is almost exclusively limited to the physical structure of the home itself. The zero carbon policy and the building regulations, by limiting to those emissions currently accounted for within regulations (i.e. space heating, hot water, lighting and ventilation) does this. However, I would argue that this focus on regulated emissions remains too narrow. As discussed above, designers also have responsibility for the material choices made. Therefore, if further radical cuts in emissions are to happen policy also needs to take account of and incorporate into regulation indirect emissions embodied in materials.

Finally, this research also tells us how critical the earlier, pre- production design phase was to the energy and carbon outcomes. It's clear from the research findings (Chapters 2 – 6) that the decisions made during the design and construction process were critical. These outcomes relate not just to the material and technical (Chapters 2 and 3) but also to how these technologies are used (Chapter 6). For example, the decisions taken by the production team (including architects and the housing association) on the delegation of responsibilities, including the maintenance and control of the LZC technical systems, influenced the decisions made by the contractors (including the construction contractors and LZC specialists) not only where the relevant equipment was placed but also who was to have access and how much control they could have (Chapters 4 and 6). This affected how households used their technologies and this in turn shaped the effectiveness of the technology (Chapter 6). Unfortunately this part of the process was outside the boundaries of this research but would make an interesting area for future investigation.

7.2. Policy recommendations

Each of the five results chapters and the above discussion of key findings suggest a number of recommendations for policy, changes, and future direction. These are:

1. Currently, the environmental impacts of materials are one area where designers and specifiers can have huge influence yet is largely ignored. These material aspects of new build housing offer a fruitful avenue for further radical reductions of both energy and carbon, increasing the sustainability of homes, and effecting a more holistic approach to how our homes are designed and constructed. Whilst it is mentioned briefly in the most recent carbon budget report (CCC 2010) embodied energy and carbon is firmly outside the remit of policy and regulation. I would argue that policy, in pursuing the radical levels of carbon reduction required, needs to expand its focus to include the lifecycle environmental impacts of materials. This suggests that a

broadened definition of zero carbon that encompasses the environmental impacts of the material aspects of buildings is needed.

2. The performance gap needs to be narrowed. This can be achieved by:

    a. Measurement of actual performance compared with design performance needs to become standard practise. The performance gap relating to physical and technical performance needs to be minimised prior to occupation. This can be achieved by a commissioning process in which the home is considered a whole system and which has three levels: measurement of fabric performance (e.g. air leakage and co-heating tests); monitoring of energy performance and measurement of technology performance; and inclusion of the households themselves as a unique unit and not a generic entity. This would require systems to be commissioned and programmed with the participation of the household.

    b. The way information is provided to households needs to improve. Not only improving the quality and relevance of the information provided but also a broader range of formats is required. Including: written; other visual media (i.e. DVD or online support); and face to face tuition in the home particularly at handover.

    c. Improving the accuracy of the models used in design and performance calculations by accounting for households in a more realistic manner. More research is required to increase the understanding of how occupants actually use new homes and new technologies and the impact upon energy consumption. This is needed to improve the accuracy with which energy consumption in the home can be predicted minimising the performance gap and increasing the likelihood of more realistic policy targets for energy and carbon emissions from new build homes.

3. Individual behaviour change and societal shifts towards low carbon behaviour is difficult and may not be effective or fast enough to deliver radical carbon reductions. Shaping of energy demand and carbon reduction by smarter design of new homes, technologies, and controls is needed. This requires energy and carbon thinking to be institutionalised at a basic level in how designers are trained and educated.

7.3. Original research contribution

This research was original in two ways: the methodological approach; and the contribution to knowledge.

Firstly, this research was undertaken using an interdisciplinary approach new to the study of energy and carbon arising from housing. This approach combined quantitative and qualitative methods from different disciplines in an original way. This approach proved to have merit in showing the quantities and attribution of energy and carbon emissions arising from new build low carbon homes but also the underlying factors and experiences of passively adopting households that inform the figures. The limitations of this approach are discussed below in section 1.4.3.

Secondly, this research generated new knowledge by applying existing methods. This included:

- first to apply LCA to offsite construction methods
- first comparative energy study of new LZC technology in UK housing
- first to apply conceptual lens of scripting to understanding how passively adopting households use new LZC technologies in new low carbon homes

7.4. Critical reflections on the limitations of this thesis

Discussion of limitations within the context of a thesis has two functions, both constructive in nature. Firstly, with the benefit of experience, to critically reflect on the research in order to extend learning and suggest where improvements could be made. Secondly, to indicate areas that could prove fruitful for further investigation. This research project, as in all research projects, has its limitations. Those of significance are: limitations related to time; scope; and methods plus the practical aspects of undertaking the research.

7.4.1. Limitations related to time

Limitations related to time were concerned with the relatively short period of time in which data were collected. This limited the research in two ways: longitudinally and the 'snap shot' nature of the research during a period of rapid transition in the policy arena.

Firstly, the gathering of empirical data occurred over the first year of occupation, beginning on 21st January 2008 until the 21st January 2009. This period was set by the housing partnership. This was problematic for a number of reasons. Foremost, the initial period of occupation is, by necessity, a period of transition, disruption, adjustment, and steep learning curves for the occupants and the housing association personnel. In addition, common to all new homes regardless of their innovative nature, there is a protracted period of problems or 'snagging' which will have an effect on energy consumption and occupant behaviour. Furthermore, rather than a full heating season the period of study covered two partial heating seasons. A greater longitudinal aspect encompassing at least another full heating season would enable a fuller exploration of the interaction of the occupants and their technologies as these technologies have become fully domesticated to the point of being taken for granted and 'invisible'.

Secondly, the research presented here is a snap shot taken during a time of significant and dynamic period of policy making and a resulting flux within the house building industry.

This has been further complicated by a global economic crisis and a general election in 2010 that have occurred since the research began. The global economic crisis that began in 2008 and continues to date has seen a significant reduction in the number of new homes constructed. The general election in 2010 bought the coalition government in to power resulting in a political shift in policy. The policy commitment to achieving the zero carbon standard by 2016 for all new build housing remains in place. However, the definition of zero carbon has been significantly weakened:

"Government will hold house builders accountable only for those emissions that are covered by Building Regulations" (BIS 2011) p117

How this will affect the emissions reductions achievable compared with predicted remains unknown. The findings of this thesis are limited to that found in the case study at a specific point in time. Ongoing research is needed to address how these subtle shifts in policy will affect the zero carbon aspiration and its effectiveness in contributing to the UKs 80% carbon reduction targets by 2050.

7.4.2. Limitations related to scope

Limitations related to scope are concerned with: sample size; breadth of study; and scope of issues included in study.

This case study draws upon a small number of homes with a variety of different technologies that made the sample sizes very small resulting in a high number of variables. However, whilst this made the study more challenging it also made it much richer. In addition, the households were relatively homogeneous and did not reflect the diversity found in the wider population. The use of a case study has inherent problems of generalisation and replicability over the level of detail necessary to answer the research questions posed. On the other hand, case study research provides a fine grain of detail obscured by other methods which draw on larger more representative population samples. However this level of detail is only practically managed in small sample groups.

Nevertheless small sample groups are not representative and cannot be used to draw generalisations nor can they be replicated. Furthermore, these homes and the households within them are not free market but social housing. Whilst they are produced to the same regulations as mainstream free market housing, they are produced by partners with a different agenda and different responsibilities to mainstream free market homes. The response to regulation may, therefore, be subtly different.

This research is limited in scope of the breadth of study focussing on the buildings as constructed entities. How these buildings came to be as they were finally constructed is outside the scope of this research. Yet the findings suggest that the role of the designers, architects and other decision makers is significant. The design process and how these parties make decisions shaped by their professional knowledge, regulatory constraints, negotiations, and compromises would be a fruitful avenue of investigation.

This thesis, other than briefly touching on running costs in Chapter 3, makes no attempt to address economics of either construction or LZC technologies specified. The economic data were commercially sensitive and not made available for this case study. Common to many housing development projects, the construction of the case study houses was tendered to a third party contractor. Innovation in construction and technology comes with significant risk to the contractor who has to balance competitiveness, the risks associated with inexperience and the need to remain profitable. Consequently, there will be additional costs associated with the risk which increases the cost of construction. Furthermore, the relatively low numbers of low carbon construction projects make such highly commercial data difficult to anonymise which makes it unlikely that such data would be available from mainstream construction. However, the lack of economic analysis is a large gap. If economic data became available a comparative study using whole lifecycle costing would be informative.

7.4.3. Limitations related to methods used

The limitations related to methods consist of issues related to external factors and internal factors.

External factors are those of a technical nature that are outside the control of the researcher. In this research serious failure of the metering technology and problems within the contracted company jeopardised a significant part of the quantitative research programme. With the incredibly short time scales available an alternative could not be found.

Internal factors relate to undertaking interdisciplinarity/multi-disciplinarity research. Interdisciplinary research such as that undertaken is complex and relies on the individual researcher to gain the required skills and to apply them in areas outside of their expertise (engineering or natural scientists into social sciences and vice versa). This is problematic in two ways. Firstly, the researcher needs to acquire the necessary skills from multiple disciplines. This takes not just time but also necessitates having to resolve conflicting languages, philosophies, and approaches that may arise. Interdisciplinarity within an individual researcher may be too demanding and lead to questions of competence to undertake such research. Secondly, the researcher will have acquired such a unique skill set that the ability of another researcher to repeat that research may be difficult raising questions on the replication of the research. Interdisciplinary research, as applied in this research, does offer many advantages but for the reasons discussed above may be more beneficial applied in energy and carbon studies at a team level rather than individual.

7.5. Future research arising from this research

There are three areas of interest arising from this thesis that would make a fruitful continuation of this research:

- An extension of the embodied carbon study to a full lifecycle comparative study encompassing end of life and maintenance during occupation to include those from different MMC approaches.

- An extension of the research into how users are actually using new homes and technologies compared with that of models and assumptions that designs are based upon. This relates to and has implications for improvements in how users are understood and modelled during the design of homes, technologies, and controls.
- Research into the design and decision making process, from inception to culmination, that takes place leading up to the construction of new build housing. These decisions have an effect on the energy and carbon outcomes of construction and occupation. In addition to the quantification of energy from construction and occupation this also requires an understanding where the principle decision points are, who the key decision makers are, what compromises are made and why.

7.6. Concluding remark

Government policy and its expression via regulation are leading to improvements in the energy and carbon performance in new build housing. However, the results produced in reality fall short of that predicted by the models on which government carbon targets are based. On the basis of the evidence of this thesis it is unlikely that these targets will be fully realised and will remain aspirational.

7.7. References

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8. Appendices

8.1. Appendix 1: Questionnaires

Table 8-1: Case study initial occupancy questionnaire

Previous Postcode:____________________Reference House number:_______________________				
About household:				
How many adults live in your household (aged 18 years of age and over)?				
	Age:	**Gender**	**Employment status (full time/part-time/unwaged/retired)**	**Occupation type**
1				
2				
3				
4				

How many children (under 18 years of age)?			Number	
Ages:	Child one	Child two	Child three	Child four
What is your approximate total household annual income?				
Under £10,000	£10,001 – £20,000	£20,001 - £30,000	£30,001 - £50,000	Over £50,000
How many hours would you say your household is out of the home during the typical working day?				
Do any members of your household work shifts/permanent nights?			Yes	No
0 – 3 hours 0%	4 – 8 hours 25%	9 – 12 hours50%	13 – 18 hours 75%	19 – 24 hours 100%
Notes:				

Energy use in the home:					
Do you know how much your energy bills were in your previous home?				£	Day/wk/mth/yr
Do you know who supplied your: gas				electric	
How many low energy light bulbs <u>DID</u> you have in your previous home?					
None 0%	A few 25%	Half 50%	Mostly 75%	All 100%	Comments:
Which, and how many, of the following appliances did your household use:					

Appliance	**Number**	**Energy Rating**
Washing machine		
Tumble drier		
Washer Drier		

Fridge		
Fridge Freezer		
Chest freezer		
Microwave		
TV’s		
DVD player		
Video player		
Set top receivers (eg satellite)		
Games consoles		
Computer: PC’		
Computer: laptop		
Computer: printer		

In the past three years have you switched energy supplier?	Yes	No
In your last home were you on a green energy tariff?	Yes	No

Recycling:

Does your household recycle?	Yes	No

Which of the following recycling facilities have you used and when did you last use them?

Local authority doorstep collection (e.g. wheelie bin, box)	Supermarket	Local authority waste handling facilities (i.e. the tip)

Which of the following materials have you recycled in the past 6 months?

Glass	Cans	Paper/cardboard
Plastic bottles	Plastic bags	Clothing/fabrics
Batteries	Comments:	

Do you compost your garden and food waste?	Yes	No

Notes:

Transport:

How many cars/vans do your household use?	Number:

What regular (i.e. commute or school run) journeys do members of your household take:

	Destination/ distance	Reason	Car	Motorb/sco’er	Bus	Train	Walk	Bicycle	other
1									
2									
3									
4									
5									
6									

Notes:

How many bicycles does your household have?	Number:

If >0 In general how often are the bicycles used?

	Very frequently	Frequent	Occasional	Rarely	Never
Bike 1					
Bike 2					
Bike 3					
Bike 4					

Typically for short trips which of the following forms of transport would members of your household use?

Car/van	Motorcyc/ Scooter	Bus	Train	Walk	Bicycle	other

Do you use the local train station/service?	Yes	No
Do you use the local bus service?	Yes	No

Notes:

Table 8-2: NEP questionnaire

Reference number:_________________ Gender: M F Age:_________________					
The following are a set of short statements that comment on how humans behave towards the environment. Please can you read each of these statements and then mark the response that you feel most represents how you feel about that statement. The responses to each of the statements are the same: Strongly agree, mildly agree, neither agree nor disagree, mildly disagree and strongly disagree.					
	Strongly Agree	Mildly Agree	Neither	Mildly Disagree	Strongly Disgree
1. We are approaching the limit of the number of people the earth can support					
2. Humans have the right to change the natural environment to suit their needs					
3. When humans interfere with nature it often produces disastrous results					
4. Human ingenuity will insure that we do NOT make the earth unliveable					
5. Humans are severely damaging the environment					
6. The earth has plenty of natural resources if we just learn how to develop them					
7. Plants and animals have as much right as humans to exist					
8. The balance of nature is strong enough to cope with the impacts of modern industrial nations					
9. Despite our special abilities humans are still subject to the laws of nature					
10. The so-called "environmental crisis" facing humankind has been greatly exaggerated					
11. The earth is like a spaceship with very limited room and resources					
12. Humans were meant to rule over the rest of nature					
13. The balance of nature is very delicate and easily upset					
14. Humans will eventually learn enough about how nature works to be able to control it					
15. If things continue on their present course, we will soon experience a major environmental catastrophe					

Thank you for your time.

8.2. Appendix 2: Published journal articles