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The use of digital technology to encourage householders in the energy sector to retrofit their properties and adopt sustainable heating behaviours

By

CHRISTOPHER WEEKS

Industrial Doctorate Centre in Systems
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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of DOCTOR OF ENGINEERING in the Faculty of Engineering.

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ABSTRACT

In the drive to build a more sustainable world, we know that we must make a significant change in the way that householders heat their properties. To this end, this thesis focuses on first, better understanding the decision process behind the installation of energy efficiency measures; second, to enhance our knowledge about the reasons behind unsustainable heating patterns; and finally, to highlight the role digital technology can play in helping us move towards a more sustainable domestic energy system.

The thesis has five contributions to knowledge. First, we highlight that the Sustainable Human Computer Interaction (HCI) and ICT for Sustainability (ICT4S) research communities need to focus more of their attention on retrofitting and space heating behaviours due to their large potential for energy and CO_2 savings. The second contribution to knowledge is a novel theoretical framework called "the power law of engagement for energy saving", which shows how we can convert disengaged householders into engaged householders that install energy efficiency measures. We then build on the power law of engagement for energy saving by exploring a number of the reasons for the slow adoption of energy efficiency measures by householders. The results extend the literature on the drivers and barriers to the installation of energy efficiency measures. The third contribution is an in-depth evaluation of the role that householders' sustainability views have in determining their heating patterns. We extend the academic literature by highlighting that there is no significant correlation between a householder's sustainability values and pro-environmental self-identity (seeing oneself as pro-environmental) and their objective scheduled and actual heating patterns. We also show the role a householder's technology self-identity (seeing oneself as an early adopter of new technology) can play in predicting self-reported pro-environmental behaviours, but that it has limited predictive influence on objective scheduled and actual heating patterns. The final contribution is the implementation of a unique smartphone application designed to help develop school pupils' knowledge on a number of key energy sustainability (reducing the impact the energy sector has on the environment) topics. The application was then used to collect data about school pupils' levels of knowledge, awareness of, and engagement with energy sustainability, which showcased a significant knowledge about certain topics, but also a significant lack of knowledge in other vital sustainability topics.

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I would like to say a massive thank you to all of my supervisors for all their help throughout my EngD, which included insightful discussions, pushing my work to a higher level and always being there for emotional support: Professor Chris Preist (main academic supervisor), Dr Theo Tryfonas (second academic supervisor), Professor Lorraine Whitmarsh (supporting supervisor), Dr Charles Delalonde (first industrial supervisor) and David Ferguson (second industrial supervisor). I also want to say thank you to all those at EDF Energy who I have worked with on different projects, especially Alastair Byrne, Jordan Murkin, Thibaut Possompès, Alexandre Nicol, Jean-Michel Daignan, Huma Arif, Irena Yanachkova, Louis Guitton, Emmanuel Dupriez, Ben Johnston, Pierre Boulic, Cedric Alexandre, Will Selby, Nguyen Nguyen, Baptiste Ingrand, Noeleen Keane, Carole Peylaire, Dominique Bertin, Xavier Mamo and Emily Kneil. Finally, I would like to thank my partner, Hannah Rich, for all her loving support and consistent encouragement over the past four years, and especially supporting me during the write up.

AUTHOR'S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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GLOSSARY

connected home a home with multiple devices that are connected to the internet, and which can be automated and easily controlled. 11, 77

decoupling refers to the ability to separate economic growth from the impact that it has on the environment. 25

digital natives individuals brought up during the age of of digital technology, therefore knowing how to use computers, mobile devices and the internet. 48

energy efficiency gap is defined as society not taking advantage of a number of energy efficiency measures, even when the measures can save significant energy at a low cost. 100

energy efficiency measures are defined as any technology that, once implemented, reduce the consumption of energy in the building. i, 2, 11, 13, 14, 26, 33, 35, 37, 38, 40–42, 45, 48, 53–56, 60, 69–71, 73, 75–78, 80, 91, 95, 99, 104–107, 109, 110, 113–116, 136, 145, 172–179

environmental limit once a renewable natural system has been reduced by external pressures to a point where its reduction in benefit is no longer acceptable or tolerable to humans. 23, 25

environmental threshold the point where a sudden collapse happens in a renewable natural system due to external pressures. 23

Green Deal UK government's scheme to help householders or small businesses install energy efficiency improvements on their property without the upfront cost. 37, 104–107, 109, 110, 113, 172

renovation making improvements to a building that cost more than 25% of the building value, or more than 25% of the surface of the building envelope is changed (European Commission 2010*a*). 35, 53, 54, 113, 114, 116

retrofitting adding, enhancing or maintaining energy efficiency measures on a property. i, 17, 34, 48, 53, 54, 65–67, 69–71, 73, 75–84, 86, 88, 90, 91, 93–97, 99, 100, 103–105, 110, 113–116, 136, 144, 172–176, 178, 181, 182

six large suppliers the former incumbent energy suppliers, which include British Gas, EDF Energy, E.ON, npower, ScottishPower and Southern Electric (SSE). 44

smart heating control heating controls (thermostats) that include feature such as zonal control, learning algorithms, internet connection or remote control. 11, 39–41, 46, 59–61, 63, 71, 78, 114, 115, 143, 172–176, 179

smart meter is an electric or gas meter that has two characteristics: first, the ability to measure and store data at intervals, and second, to enable two-way communication between energy suppliers and the householder and the Automated Meter Management (AMM) (Darby 2010). 38–42, 45, 46, 66, 71, 125, 174

space heating the heating of a space especially for human comfort through natural gas or electricity. 6, 143

The Paris Agreement is an agreement between 195 countries within the United Nations Framework Convention on Climate Change (UNFCCC) that deals with the reduction of greenhouse gases starting in the year 2020. 33

u-value represents the rate of transfer of heat in watts per meter squared kelvin or watts per meter squared Celsius of a building envelope divided by the difference in temperature of the inside and outside of the building. 50

wet appliances appliances in the home that utilise water in their operation, this is mainly washing machines and dishwashers. 6

ACRONYMS

AI Artificial Intelligence. 63

AMM Automated Meter Management. xx, 38

BEIS Department for Business, Energy and Industrial Strategy. 36, 39, 40, 49

CCC Committee on Climate Change. 36, 41

CERO Carbon Emissions Reduction Obligation. 38

CERT Carbon Emission Reduction Target. 104

CESP Community Energy Saving Obligation. 42, 104

CMA Competition and Market Authority. 46

CMS Content Management System. 127

CSCL Computer-Supported Collaborative Learning. 123

CSCO Carbon Saving Community Obligation. 38

CSS Cascading Style Sheets. 127

DCC Data Communications Company. 38

DECC Department of Energy and Climate Change. 36, 37, 39

DEFRA Department for Environment, Food and Rural Affairs. 76

EC European Commission. 34, 53

ECO Energy Company Obligation. 38, 41, 42, 46, 104, 105, 172

EDF Électricité de France. 3, 13, 42, 44, 46, 48, 106, 125–128, 135–137, 147, 174, 182, 183

EED Energy Efficiency Directive. 34, 35

EPBD Energy Performance of Building Directive. 34, 35, 40, 52, 54

EPC Energy Performance Certificate. 40, 166

EPSRC Engineering and Physical Sciences Research Council. 3

ESCII IEA Energy Sector Carbon Intensity Index. 28

EU European Union. vii, 1, 2, 11, 26, 33–37, 39, 40, 45, 49, 50, 52–54, 78

FBM Fogg's Behaviour Model. 80, 81, 84, 86, 176

GHG Greenhouse Gases. xv, 1–3, 6, 11, 21–23, 26, 28, 33, 34, 36, 78

HCI Human Computer Interaction. i, viii, 13, 65–70, 73, 75–78, 80, 172, 173, 177, 182

HHCRO Home Heating Cost Reduction Obligation (affordable warmth obligation). 38

HTML5 Hypertext Markup Language 5. 127

IBM International Business Machines Corporation. 46

ICT Information and Communications Technology. ix, xvi, 11, 13, 35, 44, 46, 61, 65, 71, 73, 75, 76, 79, 92, 94, 96, 97, 99, 105–107, 114–116, 122, 124–126, 134, 137, 171, 172, 174–179, 181, 182

ICT4E ICT for Energy. 70, 76

ICT4S ICT for Sustainability. i, viii, 13, 65, 70, 73, 75–78, 172, 173, 177, 182

IEA International Energy Agency. xv, 29, 41, 53

IHD In-Home Display. 11

INDC Intended Nationally Determined Contributions. 33

IPCC Intergovenmental Panel on Climate Change. 23

LCOE Levelised Cost of Electricity. 30

LED Light-emitting Diode. 105, 135

NEP New Ecological Paradigm. 144, 151, 159–163

PC Personal Computer. 127

PV Photovoltaic. 71, 178

REHC Renewable Energy Heating and Cooling. 41, 59

RHI Renewable Heat Incentive. 41

SAP Standard Assessment Procedure. 52

SMS Short Message Service. 122

SSE Southern Electric. xix, 44

TRVs Thermostatic Radiator Valves. 11, 60, 78

UAVs Unmanned Aerial Vehicles. 73, 74

UK United Kingdom. vii, xvi, xvii, 1–3, 6, 11, 26, 33–42, 44, 45, 48–50, 52, 53, 56, 60, 78, 88, 104, 105, 107, 109, 121, 129, 143, 172, 173

UN United Nations. vii, 33, 35, 37, 39

UNEP United Nations Environment Programme. 25

UNFCCC United Nations Framework Convention on Climate Change. xx, 1, 33

USA United States of America. 26

VBN Value Belief Norm model. 144

VIF Variance Inflation Factor. 153

LIST OF PUBLICATIONS

The first section lists all research that has been written by the author, and has been submitted to international conference or journals that have been peer reviewed. The second section contains a list of extended research that has been submitted as workshop papers, conference posters or presentations.

Peer reviewed conferences papers and journals

1. ICT for Sustainability 2014 — Nominated for best paper award (Chapter 4).

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Power law of engagement: Transforming disengaged householders into retrofitting energy savers.

   2nd International Conference on ICT for Sustainability (ICT4S 2014)

2. EnviroInfo2015 and ICT for Sustainability 2015 (Chapter 5)

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help?

   29th International Conference on Informatics for Environmental Protection (EnviroInfo 2015) and 3rd International Conference on ICT for Sustainability (ICT4S 2015)

3. CHI2016 - Late-Breaking Work (Chapter 6)

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. The use of Digital Technology to Evaluate School Pupils' Grasp of Energy Sustainability.

4. Environment and Behavior (Chapter 7) — under review

   (Main Author) Weeks, C., Ferguson, D., Preist, C., and Whitmarash, L. Exploring the relationship between householders' pro-environmental values, identities and heating patterns.

Workshops papers and extended abstracts

1. NordiCHI 2014 - Workshop 8: Is there a European strand of sustainable HCI? (Chapter 3)

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Sustainable HCI and Encouraging Retrofitting.

   8th Nordic Conference on Human-Computer Interaction

2. TEDDINET - 1st Energy Feedback Symposium - The surge of energy data: What does it mean for EDF Energy employees and householders? - Christopher Weeks

Poster

1. 6th Annual IDC in Systems Research Conference 2015 - Best poster award.

   Domestic Energy Saving through Engaging Digital Technologies - Weeks, C.

CHAPTER 1

INTRODUCTION

"The idea of a non-growing economy may be an anathema to an economist. But the idea of a continually growing economy is an anathema to an ecologist." — Jackson (2009) — Prosperity without growth — Economics for a finite planet

In this initial chapter of the thesis we define the core problem statement that this thesis looks to address and we define the underlying motivation of the researcher. We then introduce the research design and activities including: the research philosophy, research aims and activities, research questions and research approach.

1.1 Problem statement

Anthropogenic climate change is reshaping the environment around us. Its effects are felt around the globe, and scientific consensus has identified the issue as serious and urgent (Stern 2007). Tackling it requires cooperation by all countries to make rapid changes in the way we manage our relationship with the environment (United Nations 2015*a*), and these changes must be at both the micro and macro level (United Nations 2015*b*, European Commission 2010*a*, 2012). In an effort to start tackling climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was formulated in Rio de Janeiro in 1992. The UNFCCC has led to the generation of a number of core agreements and protocols to help mitigate the impact of climate change, including the Kyoto Protocol (United Nations Framework Convention on Climate Change 2008) and more recently the Paris Agreement (United Nations 2015*a*). In the formulation of these international treaties, the focus has been on the stabilisation and reduction of the overall concentration of Greenhouse Gases (GHG) in the atmosphere. To help meet this goal, the EU and the UK government have set themselves a number of key targets to achieve a reduction in GHG. Firstly, the EU committed to a 20% reduction in its GHG emissions and to achieving a target of deriving 20% of the EU's final energy consumption from renewable sources, both by 2020 (Freeman et al. 2008). Secondly, the UK government made it the duty of the Secretary of State to ensure that the new UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline (Parliament of the United Kingdom 2008). In meeting the targets set by EU and UK policy, plus the UK government's overall climate change ambitions, a rapid reduction in the country's overall domestic energy consumption is paramount. In 2014, 27% of the UK's overall energy consumption was attributed to the domestic sector; 38% to transport; 17% to the industrial sector; 13% to the services sector; and finally 5% is used for non-energy purposes (Department of Energy and Climate Change 2015*a*). In 2014, the domestic sector accounted for 23.5% of the CO_2 emissions created, if taken from the point of "end-use" (Department of Energy and Climate Change 2015*e*).

Social, economic and political factors are aligning to make the reduction of energy in the domestic sector both possible and desirable, with a number of stakeholders desiring or benefiting from such reduction. On the macro level, member states of the EU have been putting direct requirements on energy suppliers through energy saving obligations and white certificate schemes (Bertoldi & Rezessy 2009). The schemes predominantly focus on the end-use sector (excluding generation and network savings) (Bertoldi & Rezessy 2009), and therefore both national governments and energy companies are driven to help reduce the overall impact of the domestic energy sector on the environment. Substantial fines can also be imposed on the energy companies that fail to meet these obligations. Meanwhile, on the micro level, there has been a growing concern around energy costs in households and a desire to reduce bills. However, this does not always translate into a reduction of a household's overall consumption through behaviour change or the implementation of energy efficiency measures. In between the macro and micro levels sit local and regional government bodies, who often have carbon emissions reduction targets for their areas. They want to actively stimulate an overall reduction in domestic energy consumption to help them meet the targets.

As highlighted above, the domestic energy sector provides a significant opportunity to reduce the overall impact of GHG on the environment through the minimisation of energy generation and use. Reducing the overall energy consumption of the domestic energy sector involves complex interactions between both technology (hard systems) and people (soft systems), which defines it as a socio-technical system. Soft system includes the individuals feelings, relationships and social interactions. On top of this, the problem is constantly changing, is full of incomplete data and has complex interdependences, which Rittel & Webber (1973) define as key characteristics of a "wicked problem". The combination of pressing environmental and political needs coupled with the complex socio-technical relationship makes it a worthwhile research topic for investigation.

1.2 Reason for research

In this project there are two main factors that inspired the initial research questions and the subsequent investigations.

Firstly, the environment provides all the resources necessary for life on the planet. It can mesmerise us with its beauty, it provides us with shelter and warmth, it can provide an abundance of food, and it provides us a playground to socialise with our fellow humans. However, it is finite and limited; it can be damaged and planets and animals can go extinct. Therefore we need to protect the environment and ensure that our use of the planet's resources is sustainable. This drive towards a more sustainable society was of interest to me at the beginning of the research, but as I have engaged more with the literature and ventured into the facts behind the rapidly increasing temperature of earth, the vast consumption of natural resources and the huge amount of GHG we are placing in our atmosphere, it convinced me that we must radically change the way we treat and manage the environment.

Secondly, throughout my early education I have always been interested in the way that people behave, especially when it comes to digital technology. Digital technology is an inevitable part of our lives. It shapes the way we form relationships, educate ourselves, meet our physiological needs and build a prosperous society. However, even with all our great leaps forward in technology, we overlook the relationship between technology and the environment. The steam engine led to a rapid increase in coal extraction and the burning of highly polluting fossil fuel; jet engines likewise led to a huge increase in oil burning; and now the huge data centres that power the internet are only just becoming clean. Technology can cause huge paradigm shifts in our society-after all, it is strange to think of a world without the internet, but I think it is time for us to start using technology to improve our relationship with the environment, not damage it. It is understanding and trying to find a solution across people, technology and the environment that I find fascinating.

This work is supported by two partners, Électricité de France (EDF) Energy and the Systems Centre, through the Engineering and Physical Sciences Research Council (EPSRC) funded Industrial Doctorate Centre in Systems (Grant EP/G037353/1).

EDF Energy is the UK's biggest electricity supplier; the operations of the company span from electric generation, sale of gas and electricity to the domestic and commercial markets, and providing energy services. EDF Energy has over 13,500 employees, and has five million residential and business customers (EDF Energy 2016). EDF Energy produces this energy through its eight nuclear plants, two coal plants and 25 wind farms (EDF Energy 2016).

Throughout the project EDF Energy provided access to: experts throughout the company; smart heating data; energy consumption data; software; their UK officers; data collected from both their employees and customers; mentorship and support through my two industrial supervisors; and resources to run trials and experiments. EDF Energy provided this support throughout the whole five years of the EngD. During the EngD my time was split, with me spending 75% of the time with EDF Energy and 25% of the time with the University of Bristol. Most of the research completed in this thesis was completed in EDF Energy's Brighton office, where I was physically based throughout the EngD.

EDF Energy support this research as there core mission is to be the largest generator of low-carbon energy, and as part of that mission they want to find methods of helping customers be more effective with their energy consumption.

The Systems Doctorate Centre is a leader in the development and application of Systems Thinking to create value within socio-technical complexity. It works in partnership with industry and government to enhance performance through Systems practice. It has four core aims (University of Bristol 2016):

1. working with industry to enhance performance
2. training future leaders of industry
3. developing systems generic research programme
4. working with academics to develop industrial collaboration

1.3 Overview of research design

In this section we provide a high-level overview of the research philosophy, the approach to bounding the problem space, research aims and goals, research questions and an overview of each chapter's research approach.

1.3.1 Research philosophy

This research is grounded in the view of the critical realism philosophical paradigm. This paradigm allows for the combination of both the philosophy of science and social science. Realism defines that what our senses show us as reality is the truth, and it defines that there is a reality quite independent from our mind (Saunders et al. 2009). In expanding on realism, critical realism can be defined as:

> *Critical realism is a specific form of realism whose manifesto is to recognize the reality of natural order and the events and discourses of the social world and holds that 'we will only be able to understand - and so change - the social world if we identify the structures at work that generate those events and discourses. These structures are not spontaneously apparent in the observable patterns of events; they can only be identified through the practical and theoretical work of the social sciences* - (Bryman & Bell 2007) (Bhaskar 1989)

Critical realism enables an epistemological assumption similar to positivism in that a scientific approach can be used for the development of knowledge (Saunders et al. 2009), but unlike direct realism, critical realism goes one step further in that epistemological formulation cannot happen separately from the social context. In the foundation of critical realism, it argues that there are social phenomena such as language, decisions, conflicts and hierarchies that exist objectively and have an influence over us, and therefore can be studied (Dobson 2001). We also have an axiological assumption that, as a researcher, our worldviews, assumptions and biases have an impact on our research. Therefore, we must define our motivation and reasoning behind completing the research as highlighted in section 1.2 and section 1.3.3. It is also important to understand that critical realism takes the ontological assumption that there exists a reality independent of observers (Easton 2010).

The combination of orthodox philosophy of science and the ability to investigate social systems makes the paradigm of critical realism suitable for the proposed research outlined in this thesis. This is because the research requires the understanding of the technology and the environment (hard systems), in combination with the social structures (soft systems) that they are embedded within.

1.3.2 Bounding the problem space

In this section we will bound the problem space of the thesis.

1.3.2.1 The global energy system

Energy is an essential part of our lives; it is necessary for our social development and it powers our economy. It can be defined as the ability to complete work, whether this be the kinetic energy that moves electrons, drives a motor, turns a drill, allows us to dig a tunnel for a new road, or the energy that sends an electrical signal to our muscles that allows us to type, which sends an electrical signal to our computer resulting in words being presented on our computer screen. The modern world has mainly been built on energy generated from fossil fuels (petroleum, coal, betumes, natural gas, shale oil), fissile sources (uranium, thorium), and a few renewable sources (biomass, hydro, wind, solar, geothermal, marine, hydrogen). Energy production has a vital role to play in our society as it is a key input into all other consumption and production processes; it is therefore a crucial controller of growth and a major determinate in a large proportion of human activity (Bilgen 2014). However, it is also the largest driver of anthropogenic climate change which is reshaping our environment. The global demand for energy continues to grow rapidly (Newell et al. 2015), whether used to heat our homes, charge our smartphones or build new office blocks. The way the global energy system generates energy is changing towards renewables due to their reduced costs and pressure from governments to produce clean energy (FS-UNEP Collaborating Centre for Climate and Sustainability Energy Finance 2016). However, a huge amount of our energy system still relies on energy generated by extractivism activities, with oil and gas production in North America growing more rapidly than experts expected, and companies having to invest in more high-cost prospects such as deepwater, oil sands, or in the Arctic, to meet our global need for fossil fuels (Newell et al. 2015).

The rise in demand has also driven a change in the way energy is supplied, with new technology enabling supply networks to become more intelligent, leading to the modern smart grids that are using demand-side management to enable energy savings (Department for Business Energy and Industrial Strategy 2016*d*), and are helping to develop a more decentralised energy system. However, similar to our reliance on fossil fuels, the energy supply system is still predominately centralised. Finally, the last area that makes up a large proportion of our global energy system is the final “end user”, whether this is industrial energy consumption, or domestic energy consumption. This thesis will focus on the domestic energy sector, which will be discussed next.

1.3.2.2 The UK domestic energy sector

In the UK domestic energy sector there are three methods in which a householder is supplied with energy:

1. **Natural gas** is mainly used for hot water and space heating. In 2014 it accounted for 67.64% of the UK's domestic energy supply (Department of Energy and Climate Change 2015*b*).
2. **Electricity (including renewable electricity)** made up 22.27% of the overall domestic energy consumption in 2014, and is predominately used for consumer applications, wet appliances and cooking (Department of Energy and Climate Change 2015*b*).
3. **Alternative fuels (petroleum, bioenergy and waste, solid fuels and heat sold)** counts for 10.09% of the overall energy supplied to the domestic energy sector (Department of Energy and Climate Change 2015*b*).

The research presented in this thesis will mainly focus on the use of natural gas and electricity as they represent the largest proportion of the overall energy consumption, and therefore provide the best opportunity for a reduction in overall GHG emissions. There are four core components in the simple standard representation of the supply of natural gas and electricity:

1. Generation,
2. Regional transmission,
3. Local distribution,
4. End-user consumption in businesses or homes.

A simple representation for this process is provided in Figure 1.1. It must be noted that this representation is a high-level overview of a typical centralised energy system. As we move towards a more distributed generation model through micro-generation, smart metering and storage, the lines between generation, supply and consumption start to become blurred.

In bounding the problem space further, we will mainly focus on the end-user consumption, specifically domestic households. The advantage of choosing this part of the overall supply chain is that for every 1 kWh of energy saved at the end-user, you get compounding savings generated back up the supply chain, due to large energy losses, conversion and distribution, as seen in Figure 1.2.

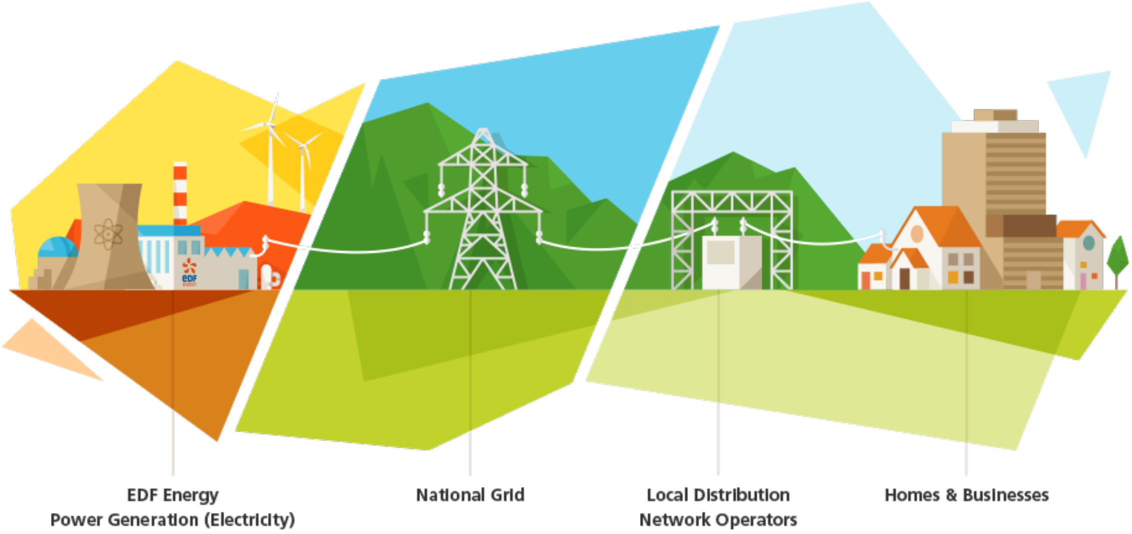
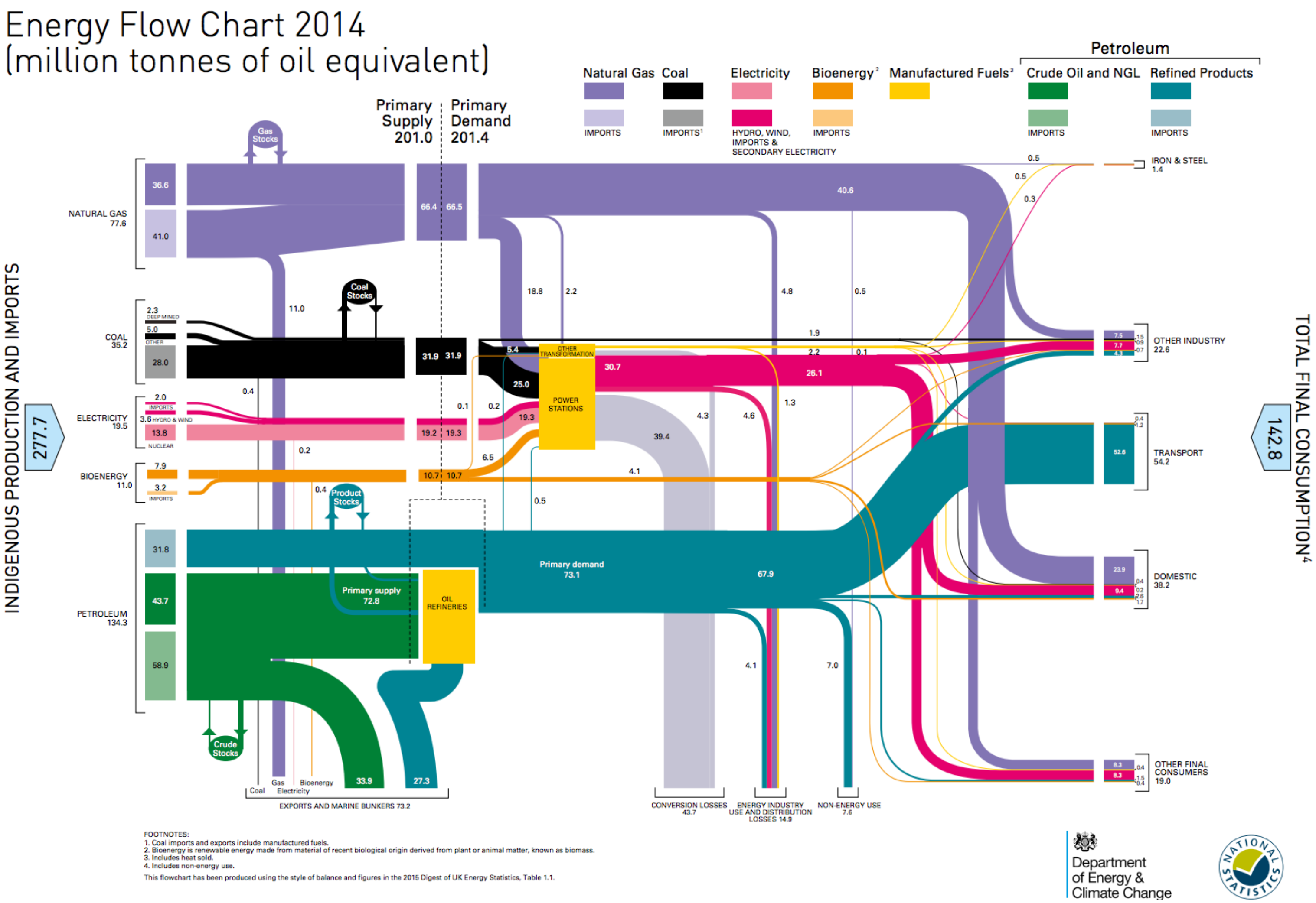


Figure 1.1: EDF Energy (2016), *Simple representation of electricity generation, supply and consumption.*



FOOTNOTES:
1. Coal imports and exports include manufactured fuels.
2. Bioenergy is renewable energy made from material of recent biological origin derived from plant or animal matter, known as biomass.
3. Includes heat sold.
4. Includes non-energy use.

This flowchart has been produced using the style of balance and figures in the 2015 Digest of UK Energy Statistics, Table 1.1.

Figure 1.2: Department of Energy and Climate Change (2014, p.2), *Energy flow chart 2014 (million tonnes of oil equivalent).*

To understand the domestic energy system better and to have an overall, holistic view of the problem space, we developed a system of interest diagram to help develop the boundary of the thesis; this is highlighted in Figure 1.3. In this diagram we start with the environment which our whole system sits within, then we have the simple energy generation, transmission, distribution and end-user consumption. In the system of interest we then expand upon the area of end-user consumption in the domestic sector, and as we do this we start to explore a number of the core topics of interest to the thesis, both from a technology and householder standpoint. Finally, within this system we also have the role of governmental policy that has a large impact on the system all the way from generation to end-user consumption.

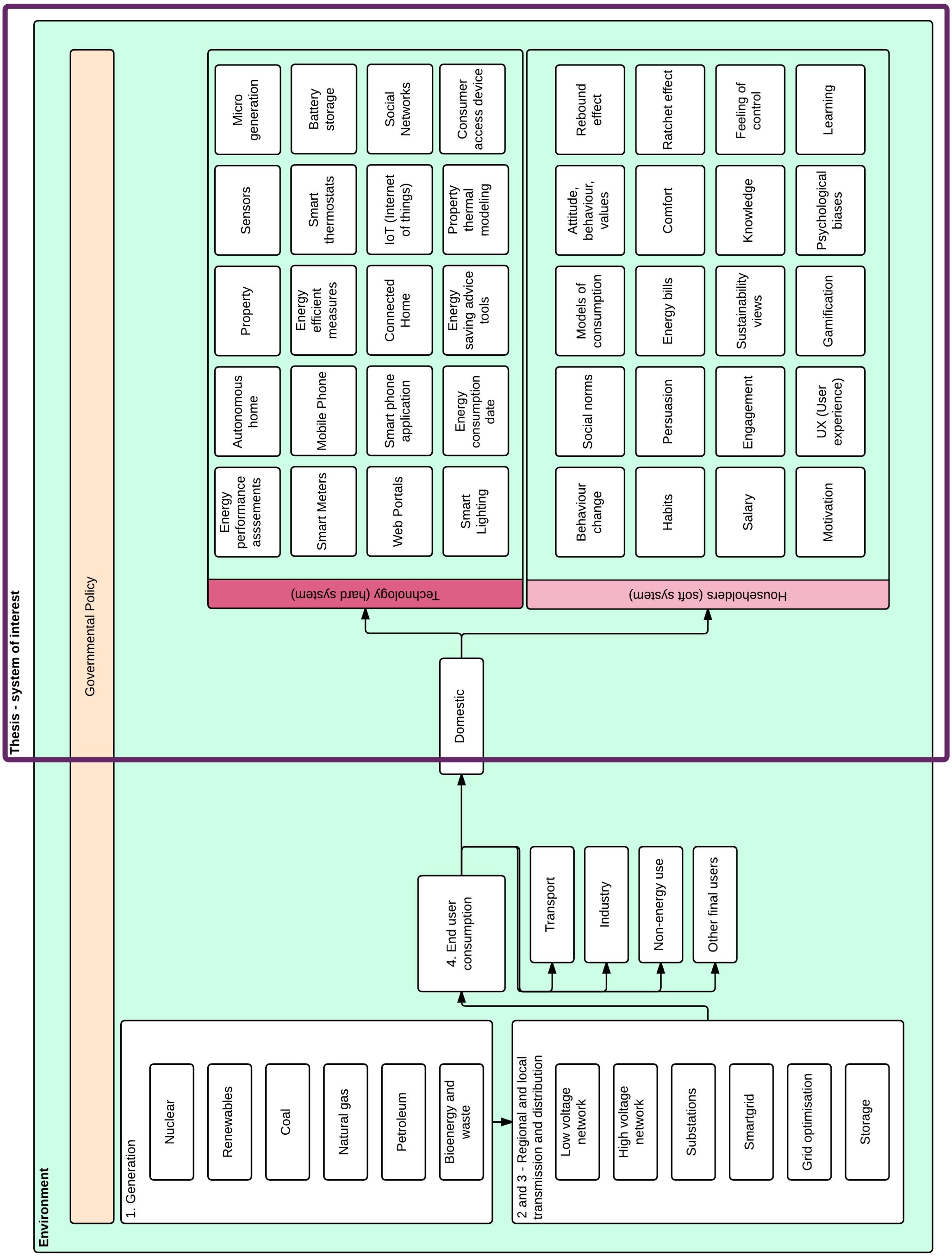


Figure 1.3: Thesis system of interest.

As part of the research we also focus on the role that digital technology plays within the domestic energy sector as it is a huge component within our daily life. For example, according to Ofcom (2015*a*) UK mobile use for adults hit 89% in 2014, of which 66% is smartphone usage; the average volume of internet use per week hit 20.5 hours, and 72% of adults have a social media portfolio, with over 81% checking it at least once a day. Finally, 68% of adults have used online services for banking or paying bills (Ofcom 2015*a*). The overview of the changing digital landscape is presented in Figure 1.4. The numbers for digital technology start to become even more interesting when you investigate usage behaviour for children; 81% of 5-15 year olds have access to a tablet computer at home, with 40% owning their own tablet. The hours of internet use for 8-11s and 12-15s has doubled since 2005, hitting a high of 11.1 hours a week and 18.9 respectively (Ofcom 2015*b*). These facts highlight the enormous impact that digital technology is already having on society, while also demonstrating that the impact of digital technology will only continue to increase as current and future generations grow up. To help understand the role ICT can play with future generations in Chapter 6 we explore how it can be used to help engage school pupils to discuss sustainability and energy.

In parallel, the role of digital technology is also playing a larger part in the domestic energy sector with the increased adoption of connected home products like smart heating controls, smart lighting, weather stations and Thermostatic Radiator Valves (TRVs). The smart meter rollout is also planned to be completed in 2020 (Department of Energy and Climate Change 2015*d*), and this will cause a rapid increase in the amount of data collected on householders, giving energy companies the ability to provide more engaging and personalised feedback mechanisms like smartphone applications, In-Home Display (IHD) and web portals (Darby 2006). The push towards more digital smart homes is driven both by government policy mandating and encouraging energy efficiency measures to meet EU and national level climate change objectives, and also by the rapid increase in low-cost, high-speed internet (Balta-Ozkan et al. 2013). It is vital that we understand the role that digital technology can play to help engage, communicate, teach, and lead householders to a more sustainable level of domestic energy consumption.

1.3.3 Research aims and activities

The main aim of this research is to evaluate how digital technology can be used as a way of encouraging householders to reduce their overall energy consumption, thereby reducing the overall amount of GHG emissions generated and leading to a reduction in householder's impact on the environment. In the thesis our first focus is on the installation of energy efficiency measures (investment behaviours) (Chapter 3-5), as these measures can have a large, sustainable impact on householders' overall energy consumption, as highlighted in Chapter 3. Please also see section 8.3 for a discussion on the difference between investment vs habitual behaviour change. The second focus has been on whether householders' sustainability views affect their heating a patterns (Chapter 7). Space heating is the largest consumer of energy and makes up the biggest proportion of the CO_2 generated in the domestic energy sector, as shown in section 2.1.2. Space heating requirements are also predominately satisfied through the burning

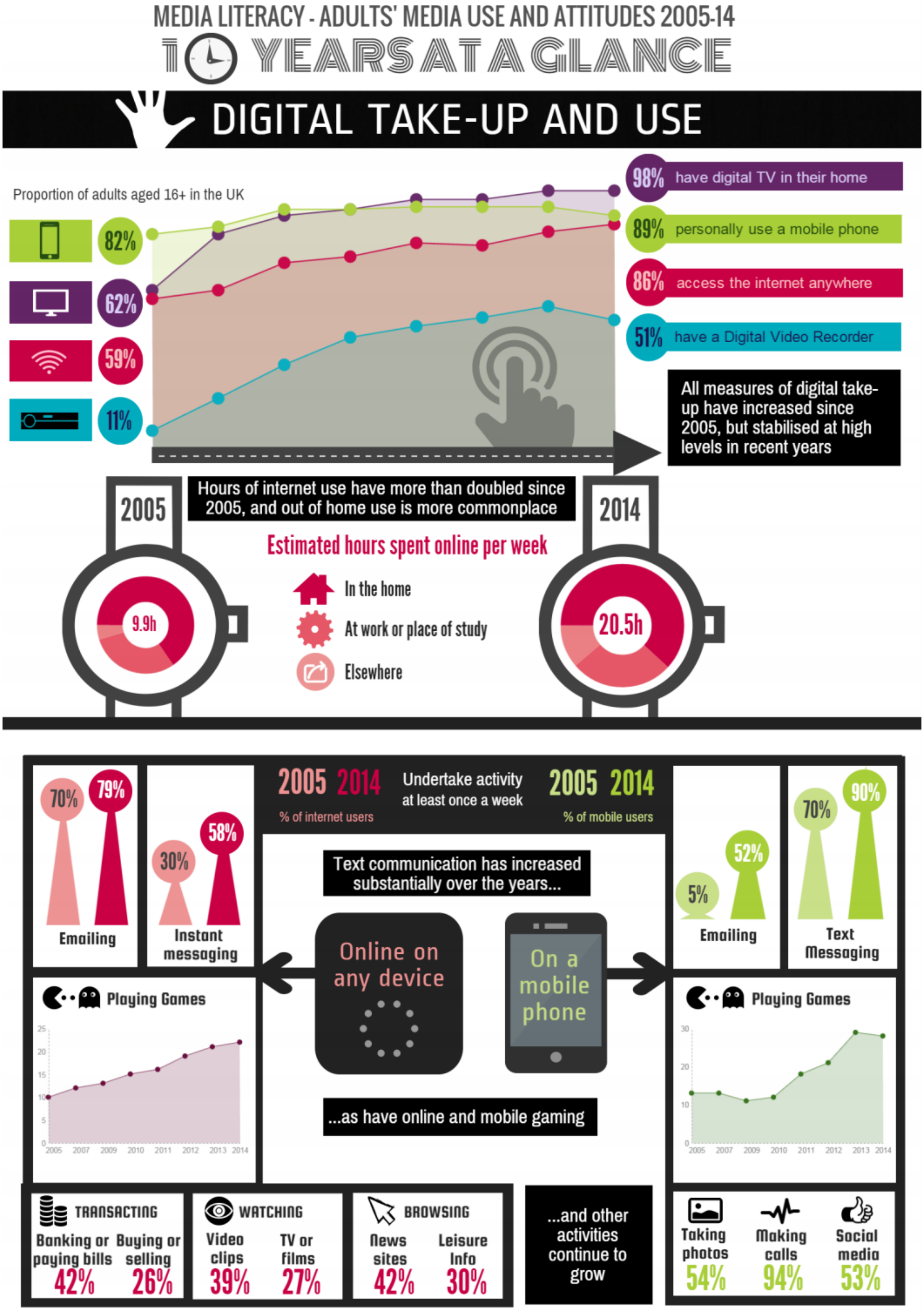


Figure 1.4: Ofcom (2015*a*, p.25), *Digital media take-up and use (2005 - 2014)*.

of gas, and therefore, can't easily be transitioned to renewable sources. It is therefore important that we understand the psychological drivers behind householders heating behaviours. Finally, we have also explored methods of helping school teachers teach pupils about energy sustainability, which is presented in Chapter 6. It must be noted that all activities presented in this thesis were undertaken in the industrial context of EDF Energy. The main activities throughout the EngD have been:

1. Chapter 3 — explored how the sustainable HCI and ICT4S communities could focus more of their attention on the installation of energy efficiency measures as these generate large energy savings that can be sustained over a longer period of time.
2. Chapter 4 — investigated the behaviour-change literature and proposed a householder engagement framework (power law of engagement for energy saving) that defines the different stages householders can be in when it comes to making decisions about retrofitting. We also map the role digital technology can play within each stage of the framework.
3. Chapter 5 — undertook a two-month longitudinal trial to explore the drivers and barriers of retrofitting, then suggested a number of ways in which ICT can help with the uptake of energy efficiency measures.
4. Chapter 6 — explored how digital technology can help teach the core energy topics to school pupils, through the development of a smartphone application to link teachers with EDF Energy experts.
5. Chapter 7 — undertook a trial with 206 participants to explore the relationship between householders' pro-environmental values, identities and heating patterns.

1.3.4 Research questions

The research presented in this thesis answers five core questions:

1. How can we encourage householders to implement physical changes to their property through energy efficiency measures? (Chapter 3 to 5)
    a) What decision-making processes do the householders go through when deciding to install energy efficiency measures?
    b) What are the core barriers and drivers for householders implementing energy efficiency measures?
    c) What interventions can we use to help remove the barriers that householders have when it comes to energy efficiency measures, and what interventions can we use to enhance the drivers?
2. What role can digital technology play in encouraging householders to implement energy efficiency measures? (Chapter 3 to 5)

   a) How can digital technology be used to empower householders and remove the barriers to installing energy efficiency measures?
   b) What digital technologies are needed to help householders during the decision-making process of installing energy efficiency measures?
   c) How do householders use digital technology within their property to save energy, and how do their values, beliefs and attitudes affect the way they use this technology?

3. Which energy topics do school pupils' have high levels of knowledge, engagement and awareness of already, and which topics do they need to learn more about? (Chapter 6)
   a) Does linking school teachers with experts at EDF Energy help teachers teach pupils about sustainability and energy issues?
   b) Can the use of ICT help develop collaborative learning around sustainability?
   c) Can the application of the spacing effect and habit formation techniques help encourage school pupils to develop sustainability habits?
4. To what extent do householders' pro-environmental values, pro-environmental self-identities and technology self-identities influence their: (Chapter 7)
   a) self-reported pro-environmental behaviours, including space heating behaviours?
   b) objective programmed heating schedules?
   c) objective actual heating patterns?
   d) adoption of smart thermostats?
5. Do householders who self-report undertaking sustainable heating behaviours actually undertake those behaviours? (Chapter 7)

1.3.5 Research approach

The problem of encouraging individuals in the domestic energy sector to reduce their overall energy consumption involves a large number of stakeholders, each with different perspectives, conflicting interests and alternative solutions. This causes an inherent pluralism that needs to be managed. Likewise, as highlighted above, the problem space is a “wicked problem”. In this type of problem situation we need to manage the dimensions of complexity. In addition, the problem space is dynamic and consists of a large number of behavioural elements, which have interconnecting relationships that influence each other. Therefore, in exploring a problem of this complexity we need to understand the influence we: "as the researcher" have on the problem. Taking a critical evaluation of our research approach, paradigms and methodologies enables us to define our research assumptions. In Table 1.5 we provide an overview of the research strategy used for each paper presented in this thesis; the formulation of the table is based on Saunders et al.'s (2009) research onion. Saunders et al.'s (2009) research onion defines the stages that a researcher must cover when designing a research study. It helps the researcher makes sure they go through all the stages from research philosophy to defining the analysis techniques and procedures that will be used on the data collected.

Chapter:	Research philosophies:	Research approach:	Research strategies:	Time horizons	Techniques and procedures
3. Sustainable HCI and Encouraging Retrofitting This chapter takes an inductive grounded theory approach based on the wide literature reviewed to formulate a proposition that the Sustainable HCI community is spending too much time investigating behaviour change that leads to simple action change, rather than focusing on behaviour change that leads to physical changes in a householder's property. This enables us to have a phenomenological research paradigm.	Phenomenological	Inductive (theory building)	Grounded theory - based on current literature.	Longitudinal: Literature reviewed throughout a two year period.	Academic literature - Literature review.
4. Power law of engagement and the ICT Cycle of engagement The power law of engagement is a theoretical framework that was based on the current academic literature, therefore it was developed using grounded theory and action research while at EDF Energy. The research took an inductive approach as we look to develop a new theory, and this enabled us to have a phenomenological research paradigm.	Phenomenological	Inductive (theory building)	Grounded theory - based on current literature.	Longitudinal: Literature reviewed throughout a two year period.	Academic literature - Literature review.
5. Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help? The monitoring trials and interviews were developed to test a small section of the power law of engagement framework. The approach was to take a positivist and deductive research approach as the theoretical framework had already been developed. To achieve this, over a two month period, interviews, questionnaires and sensor data was collected and analysed.	Positivism	Deductive (theory testing)	Questionnaires, interviews and sensor data.	Longitudinal: 2 months logging period.	1. Sensor data 2. People's' views through questionnaires and interviews.
6. The use of digital technology to evaluate school pupils' grasp of energy sustainability This chapter evaluates a new method of teaching school pupils about energy sustainability while testing their overall grasp of a number of the core energy sustainability topics. We took both a positivist deductive approach to test our new method of teaching, while also taking a more phenomenological grounded theory approach to learn more about the school pupils' overall grasp of energy sustainability.	Positivism / Phenomenological	Deductive (theory testing) / Inductive (theory building)	Questionnaires and Google Analytics data, alongside grounded theory to do thematic analysis of the catch all questions.	Longitudinal: 1 month logging period.	1. Teacher's evaluation of school pupils 2. Google Analytics data collected from the smartphone application.
7. Exploring the relationship between householders' pro-environmental values, identities and heating patterns In this chapter we have used a deductive approach to explore our key research questions. In the trial we have taken a mixed-method approach by collecting both sensor data and questionnaires from the householders.	Positivism	Deductive (theory testing)	Questionnaires and sensor data.	Longitudinal: 6 months logging period.	1. Sensor data 2. People's' views through questionnaires.

Figure 1.5: Overview of research approaches broken down by chapter using Saunders et al.'s (2009) research onion.

1.4 Research contributions

This thesis has a number of core contributions to the academic community. These are outlined below, and it must be noted that the contributions are ordered in terms of significance, rather than their order within the thesis.

1. **Contribution 1 — Chapter 7**

   Undertook an in-depth evaluation of the role that householders' sustainability views have over their heating patterns. This was achieved by completing a trial that included 206 participants. We extend the academic literature by first highlighting that there is no significant correlation between a householder's sustainability values and pro-environmental self-identity and their objective scheduled and actual heating patterns. Secondly, we highlight the role a householder's technology self-identity can play in predicting self-reported pro-environmental behaviours, but determine that it has a limited predictive influence on objective scheduled and actual heating patterns. Finally, we discovered that a householder's pro-environmental self-identity has a negative influence on smart thermostat ownership.

   Research areas of contribution — heating behaviours, pro-environmental values, pro-environmental self-identity, pro-environmental behaviours, technology self-identity

   Publication — Environment and Behavior journal - under review

   (Main Author) Weeks, C., Ferguson, D., Preist, C., and Whitmarash, L. Exploring the relationship between householders' pro-environmental values, identities and heating patterns.

   Collaborative authors

   a) David Ferguson (2$^{\text{nd}}$ industrial supervisor who replaced Charles Delalonde)

   b) Chris Preist (Academic supervisor)

   c) Lorraine Whitmarsh (2$^{\text{nd}}$ supporting supervisor) provided additional supervision due to her expertise in psychology which is the related discipline in which we made the contribution. She also provided advice on statistics and contributed to the reviewing and editing of the paper.

2. **Contribution 2 — Chapter 5**

   Extended the literature on the drivers and barriers faced by householders when it comes to installing energy efficiency measures. This was achieved through a two-month longitudinal study of householders' decision process during the Green Deal, the UK government's policy to increase uptake of retrofitting. We concluded that there are a number of drivers; in descending order of impact they are: potential financial savings, increased comfort, subsidies, accurate information and broken products. The largest barriers were: initial cost, limited expert knowledge, time-consuming, resignation (in the current state of their property) and bad communication.

Research areas of contribution — retrofitting, Green Deal, householder engagement, energy efficiency measures, ICT

Publication — EnviroInfo2015 and ICT for Sustainability 2015

(Main Author) Weeks, C., Delalonde, C., and Preist, C. Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help?

Collaborative authors

a) Charles Delalonde (1st industrial supervisor)
b) Chris Preist (Academic supervisor)

3. **Contribution 3 — Chapter 3**

   We present how the sustainable HCI community is focusing on research into persuasive psychological techniques to change householders' behaviours to be more sustainable. Nevertheless, behaviour change has limited energy saving potential and can be hard to sustain. Therefore, we propose an area of research which has had limited attention so far in the HCI sustainability community — namely encouraging retrofitting, which provides greater energy efficiency savings and is a more sustainable change. We then propose a number of areas of exploration for the sustainable HCI community.

   Research areas of contribution — sustainable HCI, energy efficiency measures, retrofitting, persuasive sustainability, sustainability, ICT

   Publication — NordiCHI 2014

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Sustainable HCI and Encouraging Retrofitting

   Collaborative authors

   a) Charles Delalonde (1st industrial supervisor)
   b) Chris Preist (Academic supervisor)

4. **Contribution 4 — Chapter 4**

   Developed a novel theoretical framework called the power law of engagement for energy saving, which looks to highlight how we can convert disengaged householders into engaged householders who install energy efficiency measures.

   Research areas of contribution — retrofitting, energy efficiency measures, energy consumption, householder engagement, behaviour change, householder commitment, ICT

   Publication — ICT for Sustainability 2014 — Nominated for best paper award

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Power law of engagement: Transforming disengaged householders into retrofitting energy savers.

Collaborative authors

a) Charles Delalonde (1st industrial supervisor)
b) Chris Preist (Academic supervisor)

5. **Contribution 5 — Chapter 6**

   The implementation of a unique smartphone application designed to help develop school pupils' knowledge on a number of the key energy sustainability questions by spreading the expert knowledge of EDF Energy's staff members to school teachers. The application was then used to collect data about school pupils' levels of knowledge and awareness of — and engagement with — energy sustainability, which highlighted that school pupils' have a significant knowledge and awareness of wind farms and the sustainable action of turning off lights. However, they had limited knowledge and awareness of alternative forms of renewable energy generation. The application was shown to be successful at spreading the expert knowledge of EDF Energy's staff, but due to lack of repeated engagement from school pupils the application was unsuccessful at generating habitual discussions about sustainability.

   Research areas of contribution — environmental education, education for sustainable development, sustainability, energy education

   Publication — CHI2016 - Late-Breaking Work

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. The use of Digital Technology to Evaluate School Pupils' Grasp of Energy Sustainability.

   Collaborative authors

   a) Charles Delalonde (1st industrial supervisor)
   b) Chris Preist (Academic supervisor)

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

"If we don't change where we're going, we may get there. If we want to go somewhere else, we need stars to steer by. Perhaps the first step is to describe the sort of destination we want to reach" — Hawken et al. (2013) — Natural Capitalism — The next industrial revolution

Contained in this chapter is an overview of the background to the thesis and a high-level literature review. The chapter sets the scene for the topics that will be covered throughout the thesis, and each individual chapter will have a more in-depth literature review to highlight the core academic material relevant to each chapter's topic.

2.1 Human impact on the environment

It is not new knowledge that human beings have a significant impact on the natural environment. To sustain our modern way of living we are generating huge amounts of GHG emissions through burning fossil fuels for energy, transportation, industry and residential purposes. The rapid rise in GHG emissions can be seen in Figure 2.1; the alarming part of this graph is that we are seeing larger decadal increases toward the end of the graph, even with new government policies and stricter regulations on GHG emissions. In the graph there is also a hidden, alarming effect: in 2010, 77% of the GHG emissions were CO_2, and the nature of CO_2 is that it has a long lag effect. Firstly, this is caused by the atmospheric nature of physics, which means it can take CO_2 up to 25-30 years to reach the upper atmosphere where it starts to have an impact known as the greenhouse effect (New Climate Economy 2014). Secondly, it is caused by human infrastructure, which means our decisions now will only have a major impact on future generations. This is due to our current legacy power stations that will take 40-50 years to replace (New Climate Economy 2014). This is known as "carbon lock-in", and it is driven by our technological systems and societal institutions that rely on fossil fuels. It is also important to highlight that carbon lock-in also causes the slow diffusion of carbon-saving technologies as we get stuck in the dominant design paradigm of burning fossil fuels (Unruh 2000).

The overall rise in the levels of GHG is accelerating the process of climate change, leaving us with a large range of global phenomena including: global temperature increases (Figure 2.2), global sea level

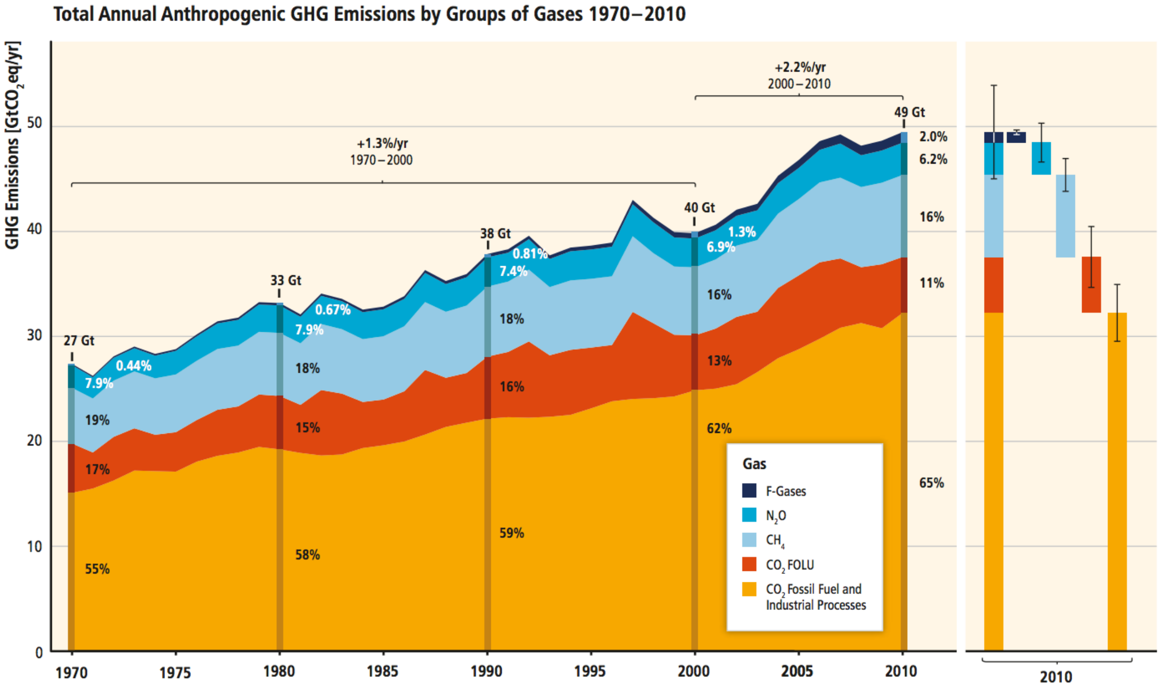


Figure 2.1: IPCC (2014*b*, p.7), *Total annual anthropogenic GHG emissions (GtCO$_2$eq/yr) by groups of gases 1970-2010.*

rises (Figure 2.3), coral bleaching and disease (Hughes et al. 2003), ice mass loss (Figure 2.4) and an increase in extreme weather events (Coumou & Rahmstorf 2012).

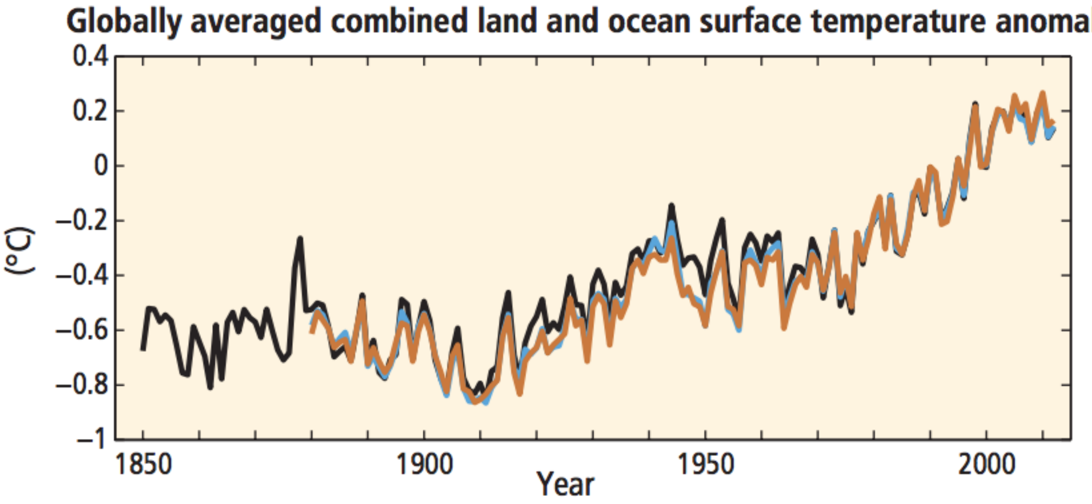


Figure 2.2: IPCC (2014*a*, p.3), *Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colours indicate different data sets.*

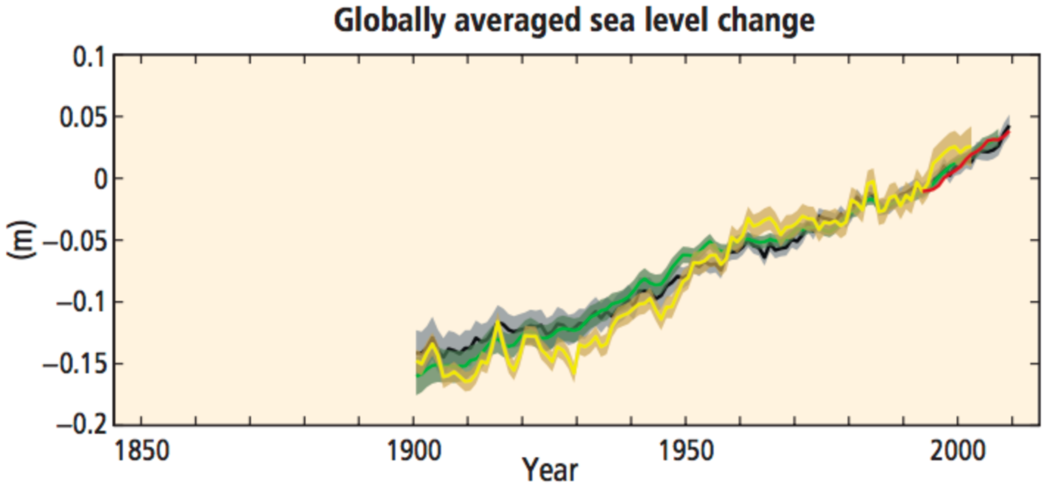


Figure 2.3: IPCC (2014*a*, p.3), *Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset. Colours indicate different data sets. All datasets are aligned to have the same value in 1993, the first year of satellite altimetry data (red). Where assessed, uncertainties are indicated by coloured shading*

It is clear that humans are having a dramatic effect on our climate system, and this can be observed across all continents and oceans. The Intergovenmental Panel on Climate Change (IPCC) even went as far as stating that they are now 95% certain that humans are the main cause of current global warming (IPCC 2014*a*). The energy sector has a vital role to play in moving society towards a more sustainable level of GHG emissions, especially as Figure 2.1 shows that CO_2 from burning fossil fuel is the primary driver of GHG emissions. In building on this we must also understand the bounded environmental limits of our planet, which will be the main topic of the next section.

2.1.1 Environmental limits and thresholds, economic growth and decoupling

As individuals we rely on a large number of renewable natural resource systems, including: the water cycle, the nitrogen, sulphur and phosphorus nutrient cycles, the production of food and fibre, and the protection of communities from hazards. As highlighted above in section 2.1, we are putting a large amount of external pressure on these natural resource systems through pollution and overuse. These external pressures lead to a reduction in the benefits that these natural systems provide, and eventually we could find the reduction in benefit is no longer acceptable or tolerable. At this critical point we have reached what is known as the "environmental limit" of the natural resource system (Haines-Young et al. 2006). In a number of cases these natural systems can have a rapid shift in state which causes the system to collapse; in this case, the system is said to have surpassed its "environmental threshold" (Haines-Young et al. 2006). Figure 2.5 shows a graphical representation of environmental limits. In understanding that the natural resource systems have environmental limits and environmental thresholds, Meadows et al.'s (1972) *Limits of Growth* showed that we cannot continue our growth trends in world

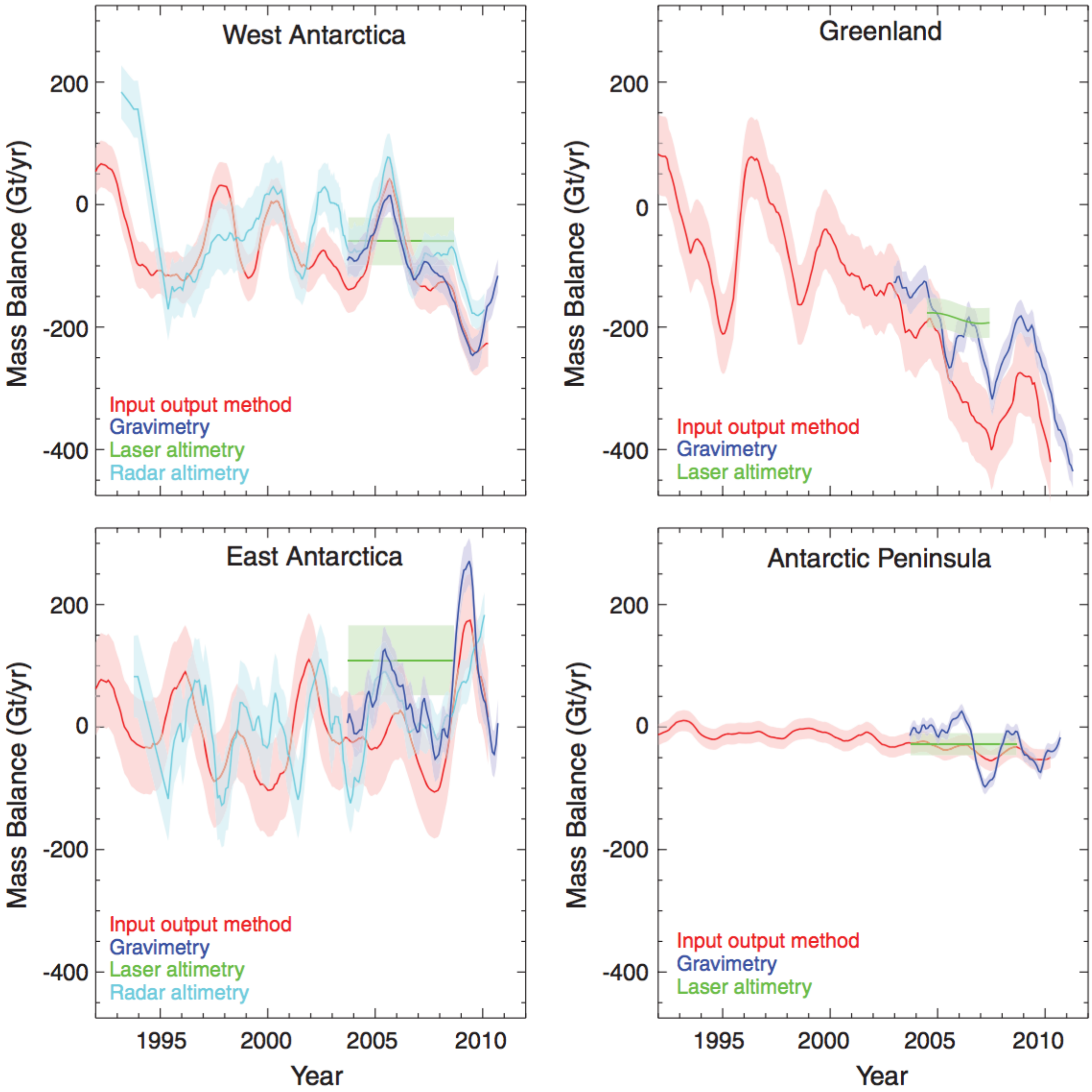


Figure 2.4: Shepherd et al. (2012, p.1187), *Rate of mass change of the four main ice-sheet regions, as derived from the four techniques of satellite RA (cyan), IOM (red), LA (green), and gravimetry (blue), with uncertainty ranges (light shading).*

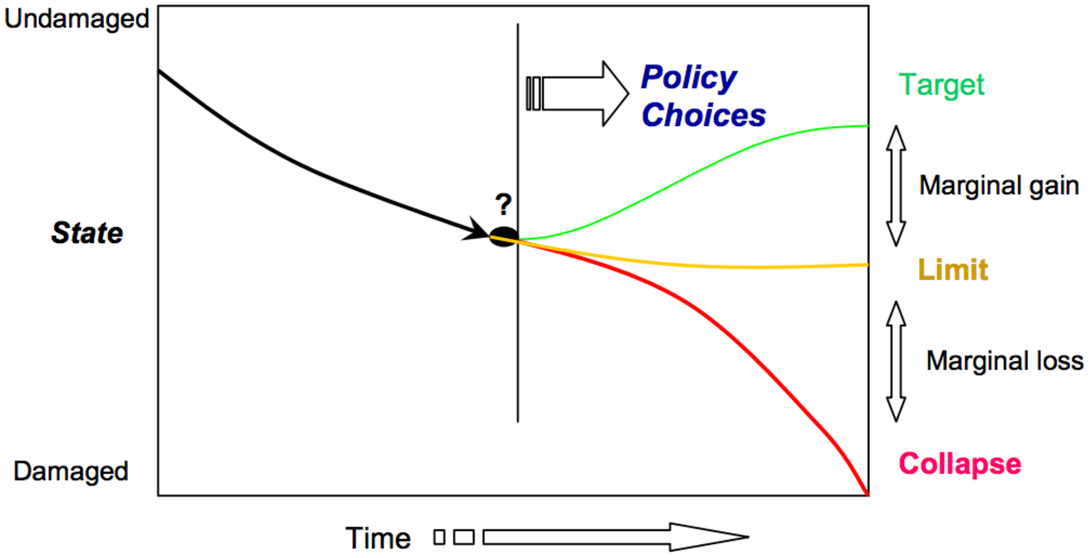


Figure 2.5: Haines-Young et al. (2006, p.5), *Understanding Limits and Values.*

population, industrialisation, pollution, food production and resource depletion without hitting the limits to growth on this planet.

In the mid-19th century, economist William Stanley Jenvons sounded an early alarm about relying on a finite resource with his book that touches upon sustainability, *The Coal Question* (Jevons 1866). In a similar tone of warning, Jackson's book *Prosperity Without Growth: Economics for a Finite Planet* (Jackson 2009) highlights the challenge that we face in building both an economic system and a new mental model of prosperity that can work within a planet that has environmental limits. Jackson argues that it is our obsession with novelty and consumerism that is driving us to live unsustainable lives. A key response to the issues of growth is to look at the possibility of separating economic growth and human prosperity from the impact it has on the environment (Jackson 2009); this is known as decoupling.

In looking at decoupling we have to examine both 'relative decoupling', which states we can produce the same economic gain with less environmental damages, and 'absolute decoupling', which refers to an overall decline in our resource use while the economy grows (Jackson 2009). Decoupling is at the heart of the mission of the International Resource Panel, which was set up by the United Nations Environment Programme (UNEP) (Weizsäcker et al. 2014). So far there are limited examples of relative decoupling, while absolute decoupling is even rarer and has only happened at points when the resource productivity growth rate exceeds the growth rate of the economy (United Nations Environment Programme 2011). In a quest to achieve decoupling, nations are looking at scientific and technological advances to help them enable a certain level of decoupling that will help us stay within our environmental limits *and* have economic growth and prosperity. Estimating the impact of technological advances was highlighted as a limiting factor in Meadows's early research (Meadows et al. 1972). However, as described by Jevons paradox (section 2.4.5), most advances in the efficiency of a technology led to greater resource consumption due to an increased demand for the technology (Jevons 1866, Fischer Kowalski & von Weizsäcker 2011). Two articles that support Jevons paradox in the energy sector include: Fouquet & Pearson's (2003) study on lighting efficiency, and Dahmus's (2014) review on the effectiveness of efficiency improvements in reducing consumption of energy resources.

Therefore, to achieve decoupling we need to change governmental policies, corporate behaviour, consumption patterns of the public (Fischer Kowalski & von Weizsäcker 2011) and finally, increase energy efficiency measures, which have shown to have some success in achieving decoupling (International Energy Agency 2015*b*). It is these two final factors, consumption patterns and energy efficiency measures, that will be the focus of this thesis.

Jackson (2009) highlights that the increase in affluence is driving resource throughput at a higher rate than overall population growth. This means given our finite planet and diminishing stocks of non-renewable resources, we must become accepting of the principle that a growth in the number of people will eventually imply a lower standard of living (Meadows et al. 1972). If we do not want to get used to a lower standard of living and want to maintain our level of prosperity, we need to make radical changes in how we view the consumption of resources and, in particular, the levels of CO_2 we generate through our daily consumption.

2.1.2 Breaking down the CO_2

We have seen that the overall level of CO_2 is rising on a global scale and is the largest contributor to our total annual anthropogenic GHG (Figure 2.1). In 2016 the concentration of CO_2 hit 403 ppm, which is 40% higher than the mid-1800s, meaning that over the last ten years we have seen an average growth rate of 2ppm/year (International Energy Agency 2017). What is driving this rapid increase? In looking at the breakdown of the world's overall CO_2 generation, there are three activities that contribute the largest amount of CO_2: transport, and electricity and heat (see Figure 2.6).

The primary focus of this thesis will be the reduction of electricity and heating within the 11% represented by the residential sector. In looking at just the UK, if we breakdown CO_2 emissions by source of where the "end-use" occurred, the residential sector created 133.5 $MtCO_2e$ in 2013, which represents 23.5% of total UK CO_2 emissions (Department of Energy and Climate Change 2015*e*). This is only surpassed by the transport and business sector. This is also replicated in the United States of America (USA), where the residential sector attributes to 1,085 $MMtCO_2e$ and represents 15.8% of "end-use" CO_2 emissions (U.S. Environmental Proctection Agency 2016). Finally, you also see a similar pattern in the "end-use" across the EU-27 where we find that the residential sector makes up 25% of all GHG emissions in the EU, again only surpassed by transportation and industry (Fernandez & Watterson 2012) (please note: this last figure is all GHG emissions, not just CO_2 emissions).

As we can see, the residential sector makes up a substantial amount of our CO_2 emissions. The next step is to start to break down the residential sector into the core activities that generate CO_2; this can be seen in Figure 2.7. Based on these figures, space heating accounted for 64 $MtCO_2e$ in 2009, which is about 73% of all CO_2 generated from the residential sector. In looking deeper at just the impact of

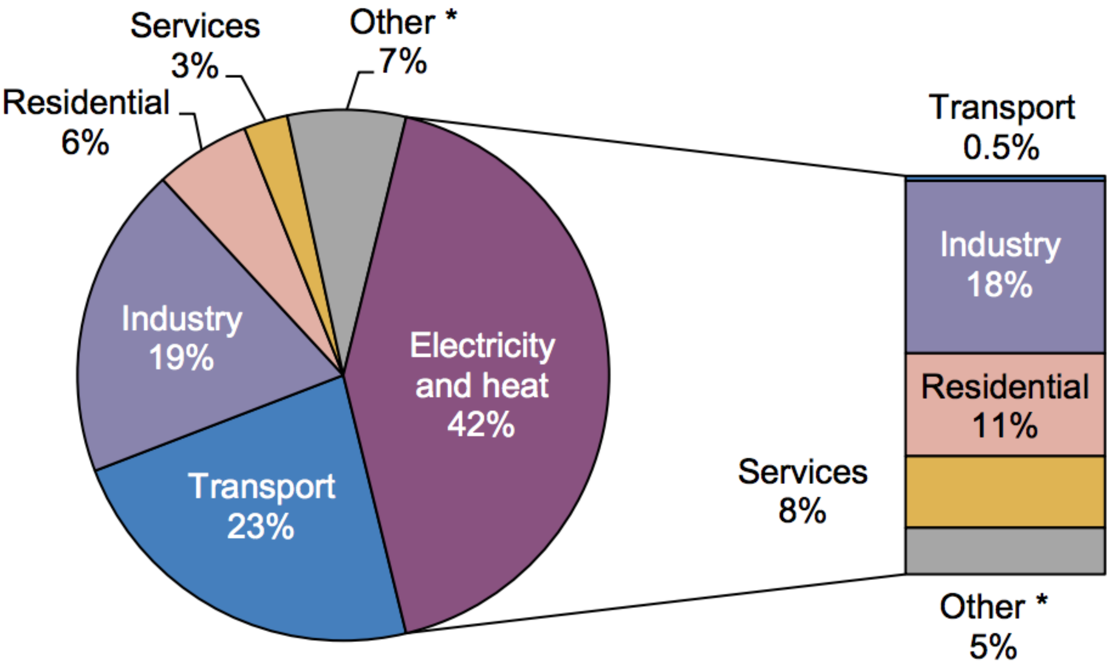


Figure 2.6: International Energy Agency (2015*a*, p.6), *World CO_2 emissions by sector in 2013.*

residential space heating, the significant change in our residential sector heating systems and levels of comfort expectations have significantly transformed the amount of CO_2 generated from space heating (Palmer et al. 2013). The key determinants over the CO_2 impact of space heating is the householders' demand temperature (setpoint) and heating duration; a 1% setpoint temperature rise is estimated to increase CO_2 emissions by 1.55% and a 1% rise in heating hours is equivalent to 0.62% increase in CO_2 emissions (Shipworth et al. 2010). Within the UK we have an increased expectation around the level of comfort householders desire: in 1970 the average household temperature was 12°C and it has risen to 17.6°C in 2011 (Palmer et al. 2013). These levels of comfort are replicated across Europe, with Nordic countries having the highest average indoor temperatures in the EU (22°C in Swedish houses), while southern Europe has an average indoor temperature of 20°C (Kemna 2014).

This breakdown of CO_2 highlights the huge impact our residential sector has on the environment as well as the significant role that space heating has to play in the generation of CO_2 emissions. In conjunction, in this section we have also highlighted the direct CO_2 impact of householders' heating demands (setpoint and heating hours). In moving forward, if our expectations about comfort levels continue to rise, it must be noted that this will have a direct impact on the levels of CO_2 generated.

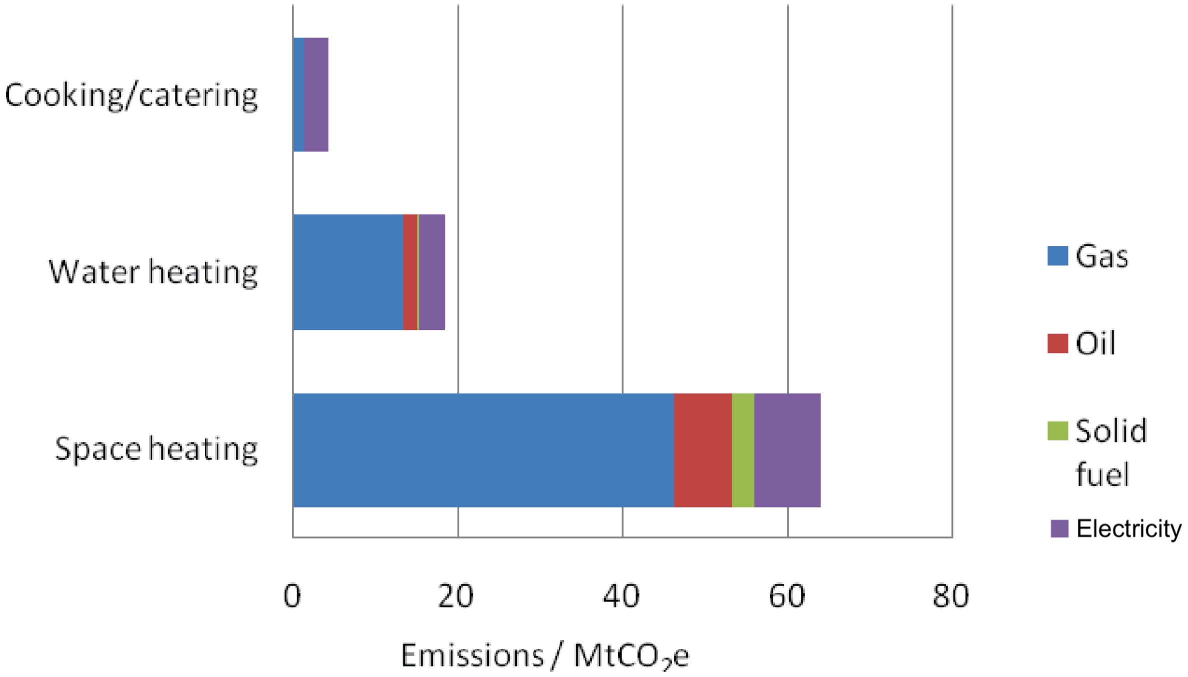


Figure 2.7: Department of Energy and Climate Change (2012*a*, p.5), *Domestic sector, by end-use and fuel, breakdown of* CO_2

2.1.3 Energy: The rise of consumption

The causal factors that are driving the large increase in GHG emission that are seen in Figure 2.1 can be hard to measure, but it is without doubt that our rapidly increasing level of energy consumption is playing a role. The energy supply sector accounts for about 35% of the total GHG emissions (IPCC 2014*b*), and over the last three decades there has been a steady increase in the world's requirements for energy; the level of energy consumption is predicted to continue to grow for the next three decades (Figure 2.8). A key factor driving this increase is that our global per capita primary energy use has risen by 31% from 1971 to 2010, which was caused by growing income per capita and the changes in our energy intensity (IPCC 2014*b*). This rapid rise in per capita primary energy use, in combination with the high carbon intensity factor (carbon emission per unit of energy), is the primary driver behind the energy sector's huge contribution to global CO_2 emissions. The IEA Energy Sector Carbon Intensity Index (ESCII) has essentially remained static since the 1990s (Figure 2.9); this is mainly due to our continued reliance on fossil fuels and coal in particular (International Energy Agency 2014). If we are to meet our global CO_2 targets we must see a dramatic decline in the ESCII.

Energy consumption and carbon intensity factor trends over the last 40 years are alarming, but there are signs of change. In 2015, energy-related CO_2 emissions stalled due to a 1.8% improvement in energy intensity of the global economy, driven by improvements in energy efficiency and the increase in the installation and development of clean energy sources worldwide such as renewables (International

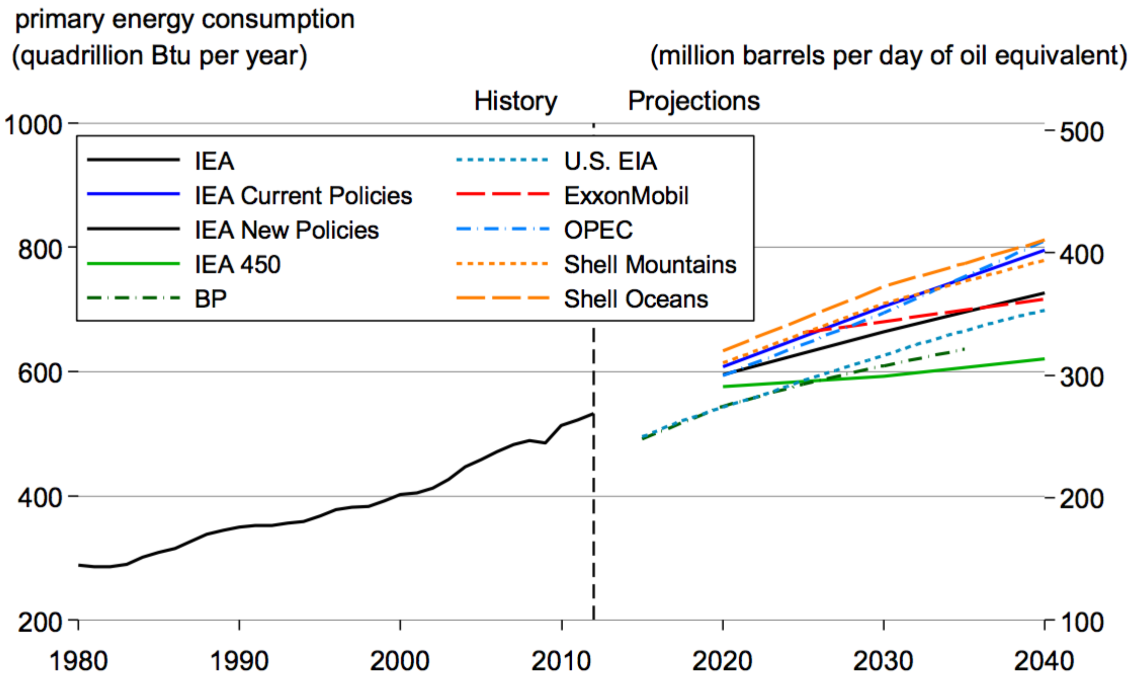


Figure 2.8: Newell et al. (2015, p.10), *World primary energy consumption taken from the IEA report and projections from BP, U.S. EIA, ExxonMobil, IEA, OPEC and Shell.*

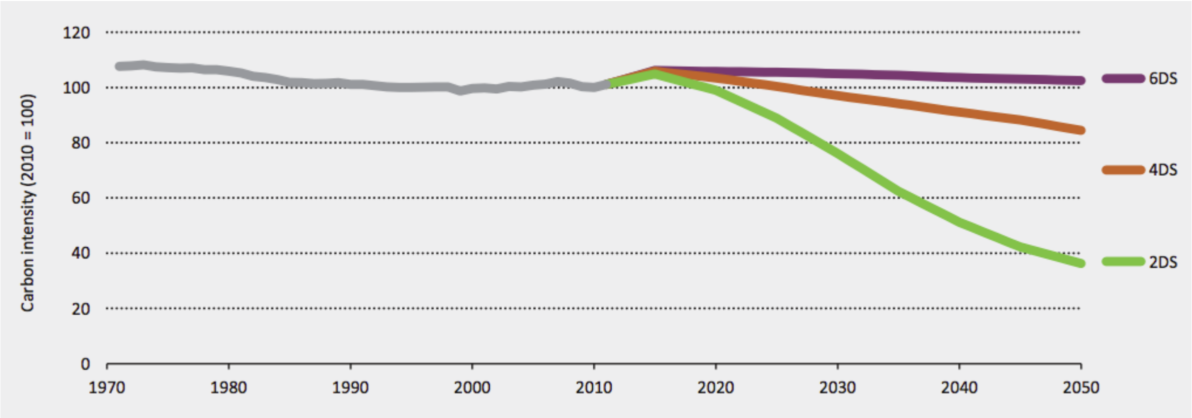


Figure 2.9: International Energy Agency (2014, p.13), *The IEA Energy Sector Carbon Intensity Index (ESCII) from 1970 to 2050 with predicted value from 2014 to 2050, including required change in ESCII to keep global temperatures below 2^{o}C (2DS), 4^{o}C (4DS) and 6^{o}C (6DS).*

Energy Agency 2016*b*). Governmental policies that aimed to improve energy security, reduce local pollution concerns and reduce the impact of climate change have supported the uptake of renewables, and in 2015 renewable energy accounted for 23% of total electricity generation globally (International Energy Agency 2016*a*). Figure 2.10 shows the steady increase in renewables over the last decade; this has been mainly driven by solar and wind power, which accounted for about 77% of new renewable installations in 2016 (Kristin et al. 2016). The growth in renewables has been increasing year on year (Figure 2.11), which is driven by large government and private investment. Such investment hit a record of $285.9 billion in 2015, compared to only $130 billion invested in coal and gas generation (FS-UNEP Collaborating Centre for Climate and Sustainability Energy Finance 2016). Advances in technology have increased efficiency and reduced the capital cost of renewables; the global Levelised Cost of Electricity (LCOE) of solar has dropped from $315/MWh in 2009 to $122/MWh in 2015. Onshore wind energy has also seen a 14% reduction from $96/MWh in 2009 to $83/MWh in 2015 (FS-UNEP Collaborating Centre for Climate and Sustainability Energy Finance 2016); this compares to coal, which stood at $58/MWh and gas at $62/MWh in 2016 (Dowling & Gray 2015). This trend in the reduction of the LCOE is expected to continue in the future, with onshore wind expected to drop 41% by 2040 and utility-scale solar is expected to drop by 60% to a central estimate of around $40/MWh worldwide by 2040 (Bloomberg 2016).

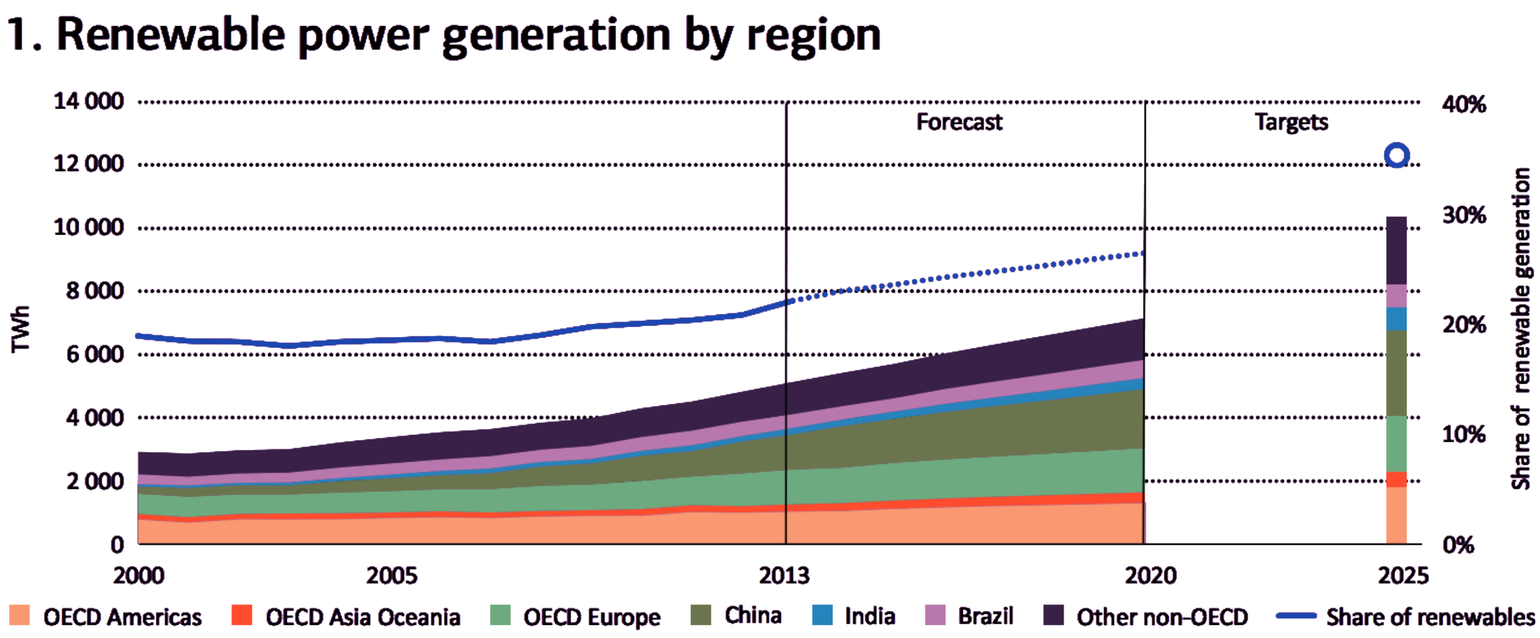
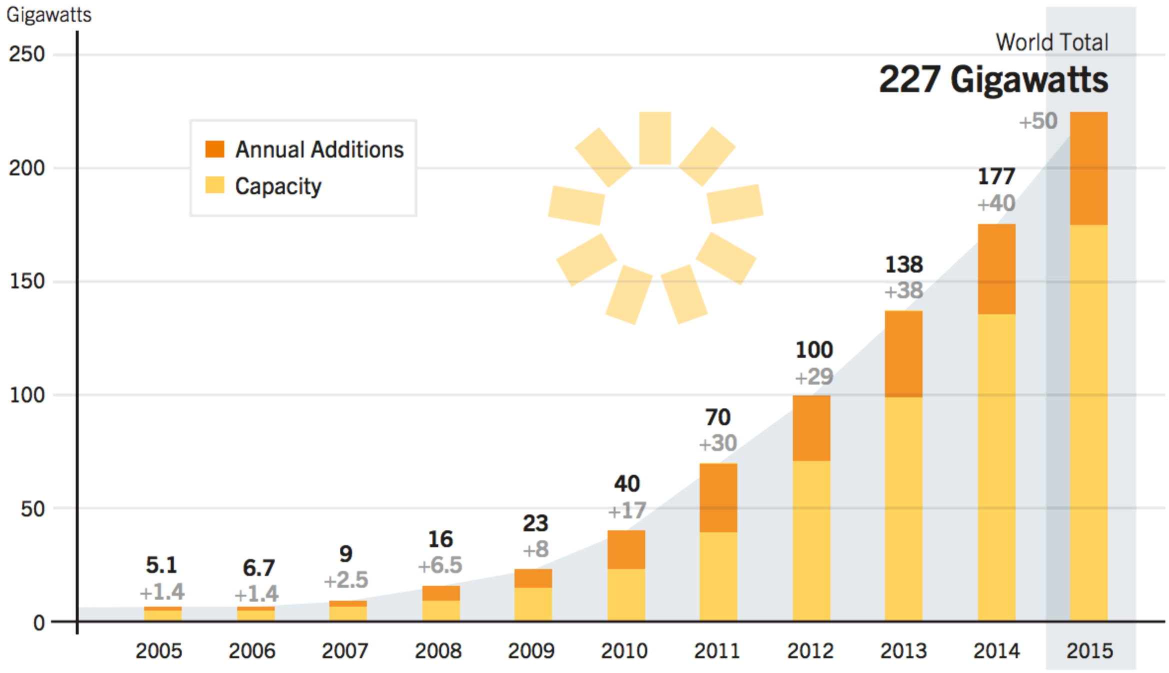
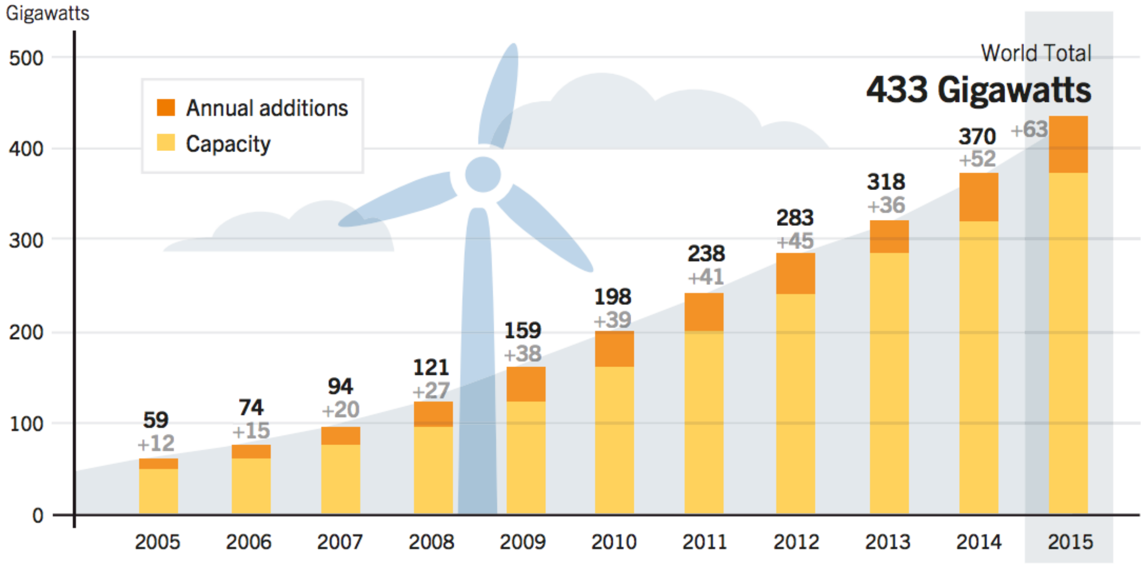


Figure 2.10: International Energy Agency (2016*a*, p.19), *Renewable power generation by region.*



(a) Solar PV Global Capacity and Annual Additions, 2005-2015.



(b) Wind Power Global Capacity and Annual Additions, 2005-2015.

Figure 2.11: Kristin et al. (2016, p.62 and p.77), *Solar PV and Wind Power Global Capacity and Annual Additions, 2005-2015.*

The rapid increase in renewables is making our electricity system less carbon intensive. However, even as we rapidly move towards a renewable energy system, space heating and cooling in buildings and industry cause major issues as approximately only 8% of heating and cooling demand worldwide is met by renewables, and three-quarters of global energy used for heating is powered by fossil fuel (Kristin et al. 2016). This means that even as we move towards a world of renewables the environmental impact from the energy needed for space heating and cooling will still be significant. Therefore, we cannot rely on the transition to renewable sources of energy to help solve our space heating demand, and we must investigate potential alternative solutions to help reduce the impact that space heating and cooling has on the environment.

2.2 What is the plan? — UN, EU and UK policy

In the knowledge that we cannot continue on our current path when it comes to the generation of both GHG emissions and CO_2 emissions in particular, we have seen large changes in governmental policy and regulations to help speed up the transition to a low-carbon society and reduce humanity's impact on the environment. In this section we first provide an overview of the current international agreements to tackle climate change. This is followed by an overview on the EU and UK policies, with an increased focus on policies affecting the domestic energy sector, installation of energy efficiency measures and space heating. Alongside presenting the policies, we also bring in key literature that supports or critiques the policies to help develop a full picture of the impact the policy or regulation can have on the environment.

2.2.1 The Paris Agreement

On 12^{th} December 2015, the landmark Paris Agreement was agreed between 195 nations. The Paris Agreement recognised that cooperation by all countries is required to accelerate the rapid reduction in GHG emissions to help address climate change. It emphasises that we must take action to build a pathway that keeps the global average temperature below $2^{o}C$ above pre-industrial levels and to pursue efforts to limit the temperature increase to $1.5^{o}C$ above pre-industrial levels (United Nations 2015*b*). The global temperature was recently recorded at $1.1^{o}C$ above pre-industrial levels in 2016 (MetOffice 2017), which highlights the significant challenge we are facing, especially as the Paris Agreement does not come into effect until 2020. The agreement also highlights that we need to increase our ability to adapt to the large impact of climate change, and start to make finances available to help us move towards low levels of GHG emissions (United Nations 2015*b*). To achieve the required reduction in GHG emissions, the UNFCCC members each submit Intended Nationally Determined Contributions (INDC), which define the actions each member will take post-2020. The Paris Agreement has caused some controversy among researchers, as some support the agreement as a historical achievement with ambitious targets, strong transparency and a better approach to differentiation between party members' responsibilities (Rogelj et al. 2016, Rajamani 2016, Savaresi 2016). However, others emphasise the lack of GHG emissions reduction targets, top-down legal bindings set on party members' contributions, and financial support for developing countries as key issues (Clemencon 2016, Spash 2016). The Paris Agreement has been ratified by 131 of 197 parties (United Nations 2017), and it provides a framework for countries to submit their INDCs and report their progress towards these targets on a five-year basis, making individual countries accountable and transparent, and in turn affecting governmental policy. In the next section we will discuss the governmental policy of the EU before moving onto the UK.

2.2.2 EU policy

The EU implemented their first energy and climate policy package in 2008, when they proposed the 20/20/20 targets. That stated that the EU would reduce GHG emissions by 20%, increase the share of energy produced by renewables to 20%, and make a 20% improvement in energy efficiency by 2020 (European Commission 2010*b*). The EU has made a substantial move towards the targets. By 2012 they reduced the levels of GHG emissions by 18% and increased the amount of energy generated by renewables to 13%; the energy intensity (energy per unit of GDP) of the EU has dropped 24% between 1995 and 2011 (European Commision 2014). The success of the EU 20/20/20 targets have prompted an extension of the targets to 2030, where the EU will look to reduce the levels of GHG emissions to 40% below 1990 levels, increase the share of energy produced by renewables to 27% and increase the level of energy savings to approximately 25% (European Commision 2014). Finally, by 2050 the EU plans to reduce the level of GHG emissions to 80-90% below 1990 levels (European Commission 2011).

To help achieve these targets, the EU has made a number of keystone policies that directly affect the domestic energy sector and look to accelerate the cost-effective retrofitting of existing buildings; these policies include the Energy Performance of Building Directive (EPBD) (European Commission 2010*a*) and the Energy Efficiency Directive (EED) (European Commission 2012). The first directive we will look at is the EPBD (European Commission 2010*a*). The European Commission (EC) highlights that approximately 75% of EU buildings are energy inefficient and, in addition, only 0.4-1.2% of the EU building stock is retrofitted each year (European Commission 2016*a*). Therefore, to help improve these figures the directive highlights the need to:

1. develop a general framework for a methodology for calculating the integrated energy performance of building and building units,
2. set minimum requirements to the energy performance of new buildings,
3. apply minimum requirements to the energy performance of:
    a) existing buildings,
    b) building elements that form part of the building envelop and that have a large impact on the energy performance of the building,
    c) technical building systems whenever they are installed replaced or upgraded,
4. develop a national plan to increase the level of nearly zero-energy buildings,
5. set up an energy certification system for buildings,
6. implement a system to undertake regular inspection of heating and cooling systems in buildings,

7. install independent control system for energy performance certificates and inspection reports (European Commission 2010*a*).

In 2016, EPBD was amended to:

1. increase the focus on long-term building renovations,
2. encourage the use of ICT and smart technologies to monitor building efficiency,
3. streamline resources where they are not delivering results and incentivise increased building renovation to tackle energy poverty (European Commission 2016*a*).

The EPBD has a strong focus on the need to monitor the energy performance of buildings, increase the minimum energy performance of buildings and build ICT to help monitor building performance. The second directive, EED, works in conjunction with the EPBD, and the policy looks to help reduce the energy consumption in the domestic energy sector by asking member states to:

1. develop a long-term strategy for mobilising investment in the renovation of the nation's stock of residential buildings,
2. set up energy efficiency obligation schemes that ensure that energy distributors and retailers achieve energy efficiency savings of 1.5% each year through energy efficiency measures,
3. promote the availability of high quality energy audits to householders that are carried out by independent authorities,
4. empower householders to better manage their energy consumption, including providing easy and free access to data on consumption through individual metering,
5. evaluate and, if necessary, take appropriate measures to remove regulatory and non-regulatory barriers that stop the installation of energy efficiency measures (European Commission 2012).

Please note that we have only highlighted the policies in the directive that apply to the content of this thesis. Again, the EED puts a large focus on the ability to monitor building performance and the use of ICT, and, in addition, it also looks to help householders gain a better understanding of their energy consumption. It has been highlighted that even with these directives being placed on member states, it will be difficult to meet the required uptake of energy efficiency measures (Sandberg et al. 2016). Likewise, the current financial instruments to accelerate energy efficiency measures only achieve a business-as-usual case and are not significant enough to meet the EU's 2050 aspirations (Buildings Performance Institute Europe 2011, Filippidou et al. 2016). Meanwhile, a number of member states now have a strong residential energy efficiency market due to the policies (Germany, Denmark, France, and in Flanders (BE)), and there are emerging residential energy efficiency markets in Hungary, Romania and the UK (Labanca et al. 2015). These markets are driving the uptake of energy efficiency measures, but rely on governmental subsidies or incentives developed to meet member states' EU targets. Therefore, it is important to understand the factors holding back these energy efficiency markets. It is clear from the EU's policies that both technology and energy efficiency measures are going to play a critical role in the low-carbon transformation, and both these topics will be explored within this thesis. In the next section we will look at how the UK is taking a similar strategy to the EU to help stimulate their low-carbon transformation.

2.2.3 Climate Change Act 2008

The UK's Climate Change Act 2008 made it the duty of the Secretary of the State to ensure that the UK's carbon account for the year 2050 is at least 80% lower than the 1990 baseline, which includes both carbon dioxide and the six GHG emissions stated by the Kyoto Protocol (Parliament of the United Kingdom 2008). In addition, the Act set out the development of an independent advisory committee called the Committee on Climate Change (CCC) (Committee on Climate Change 2017*b*). The Act highlights the need for the UK government to set out carbon budgets for the years leading up to 2050, which stand at 29% from 2013 to 2017, 35% by 2020, 50% by 2025 and 57% by 2030 (Committee on Climate Change 2017*a*). The UK has been steadily working towards the 2050 goal, as in 2015 emissions fell by 3% relative to 2014 levels and are now 38% below the 1990 baseline level (Committee on Climate Change 2016). However, it has been highlighted that the current policies do not go far enough to meet the carbon budgets set by the UK government (Committee on Climate Change 2016) and the reduction required to meet the Climate Change Act is unprecedented (Anderson et al. 2008). The Committee on Climate Change sent out a warning in their recent progress report that a large amount of the UK's CO_2 savings are coming from the power sector, as seen in Figure 2.12. Meanwhile, the residential building sector has seen limited reductions due to the *"slow uptake of low-carbon technologies and behaviours in the building sector (i.e. low rates of insulation improvements, low take-up of low-carbon heat)"*(Committee on Climate Change 2016). In conjunction, Ekins & Lees (2008) highlight that improvements are required in UK policy to help the building sector deliver the large CO_2 emissions reductions necessary to meet the Climate Change Act. In the quest to generate a more significant reduction in GHG emissions from the domestic sector, the UK government has set out two core policies for the Department of Energy and Climate Change (DECC) and now the Department for Business, Energy and Industrial Strategy (BEIS) to implement, which includes: household energy and the energy efficiency of buildings.

In each policy, BEIS sets out key policy and consultation papers, and produces national statistics on the topic on energy in the domestic sector. These documents will be reviewed and discussed throughout the next sections.

2.2.4 Household energy

The household energy policy has a core focus on helping domestic householders use less energy, get the best deal from their energy supplier, help vulnerable householders with their energy bills, build the Big Energy Saving Network, help reform the energy market and secure the UK's energy supply (UK

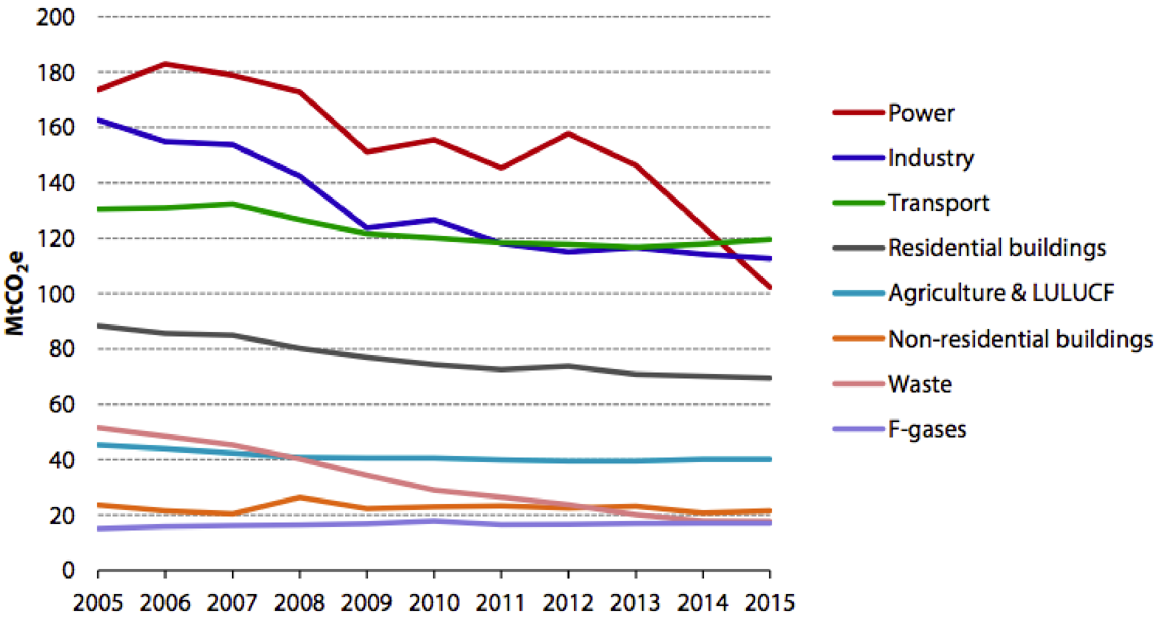


Figure 2.12: Committee on Climate Change (2016, p.12), *Progress reducing emissions since 2012 has been almost entirely due to the power sector - chart shows temperature-adjusted emission in power, residential and non-residential buildings.*

Government 2017*a*). In helping householders use less energy, DECC has set six key initiatives. These initiatives include:

1. **Green Deal —** Helps householders or small businesses to install energy efficiency improvements on their property without the upfront cost. To achieve this, a broad range of energy efficiency measures can be financed, or partly financed through the government. The government provides loans to householders or small businesses on the basis that they will be paid back through the savings generated from the measures being installed. The fundamental goal of the measures are to:

    a) reduce the impact of rising energy prices,
    b) maintain or increase levels of comfort,
    c) deliver fuel bill savings (Department of Energy and Climate Change 2012*c*).

    The Green Deal was launched in January 2013 and has been rolled out through energy companies and Green Deal providers. In November 2016 a total of 681,723 Green Deal Assessments had taken place, with 20,677 Green Deal measures installed (UK Government 2017*c*), which made a small saving of 0.4 $MtCO_2$ (Gooding & Gul 2017). However, due to low uptake and concerns about industry standards, DECC have decided to provide no further funding to the Green Deal Finance Company (UK Government 2017*b*), bringing an end to the Green Deal. It has been mentioned in this literature review as this policy was active throughout the work completed in this thesis.

2. **Energy Company Obligation (ECO) —** Supports vulnerable householders or householders living in fuel poverty by funding the installation of energy efficiency measures. ECO is fully funded and administrated by the large energy companies that supply energy to the domestic sector (this includes those that have 250,000 domestic customers, supply 400 GWh of electric or 2,000 GWh of gas). ECO's key aim is to help vulnerable householder groups and hard to treat homes, which it achieves through three obligations:

    a) Carbon Emissions Reduction Obligation (CERO) — Provides solid wall, cavity wall, loft installation, connection to district heating systems, double glazing and draught proofing to hard to treat homes that cannot be fully funded through the Green Deal.

    b) Carbon Saving Community Obligation (CSCO) — Administers the installation of energy efficiency measures to householders in low income areas or vulnerable householders.

    c) Home Heating Cost Reduction Obligation (affordable warmth obligation) (HHCRO) — Installs heating and insulation energy efficiency measures to householders living in private tenure homes that receive means tested benefits, which in turn reduces the impact of cold homes on vulnerable householders (UK Government 2017*a*).

    ECO has been successful and achieved 2,041,909 installations of energy efficiency measures by December 2016 (UK Government 2017*c*). However, Rosenow et al. (2013) highlights that there can be tensions between ECO and helping fuel poverty, as the cost of the obligation results in higher energy bills that impact the fuel poor. Only a fraction of the beneficiaries of the obligation are fuel poor, and the process of establishing which householders could benefit from HHCRO is tedious and costly for suppliers, whilst being intrusive for householders (Rosenow et al. 2013).

3. **Smart metering —** Will replace over 53 million gas and electricity meters between now and 2020, and involve 30 million homes and small businesses (UK Government 2017*a*). The general definition of a smart meter is an electric or gas meter that has two characteristics: a) the ability to measure and store data at intervals, and b) to enable two-way communication between energy suppliers and the householder and the AMM (Darby 2010), which in the UK is the Data Communications Company (DCC). The dominant motivation behind the smart meter rollout is to provide householders with:

    a) increased feedback through real-time information on energy use,

    b) more control of their energy use,

    c) the end of estimated bills,

    d) a more straightforward way of switching between energy companies (UK Government 2017*a*).

In September 2017, over 8.61 million smart meters were operated by large energy suppliers in the domestic sector (Department for Business Energy and Industrial Strategy 2017). The installation of smart meters is the first step toward a smart grid, and the smart grid will provide large social benefits through service quality enhancements, improved feedback, demand response programs, new products and energy services, and externality benefits; smart meters also have a positive macroeconomic impact (Neenan & Hemphill 2008). It has been estimated that smart grid technology could globally reduce CO_2 emissions by 2.03 $GtCO_2e$ by 2020 (The Climate Group 2008), and direct feedback to householders from a smart meter with an associated display can produce energy savings of between 5-15% (Darby 2010).

4. **Smarter heating controls research programme** — Sets out to determine if smart heating controls can save a significant amount of energy in the domestic sector. It has four core aims:

   a) to find out if smart heating controls reduces the energy consumed by householders, and why they do or do not,

   b) understand the best method to harness the energy saving potential of new smart heating controls,

   c) improve our understanding of the role smart heating controls play in different socio-technical situations to help maximise the energy savings from smart heating controls in a broad range of contexts,

   d) identify potential adoption paths for smart heating controls (Department of Energy and Climate Change 2015*f*).

   Throughout 2016, DECC undertook a review of the potential role that smart heating controls could play in the UK government's policy to de-carbonise heating, and it highlighted a lack of evidence relating to the energy savings, cost effectiveness and usability of smart heating controls (Department of Energy and Climate Change 2016). In conjunction, the recent "Heating in Buildings" (Department for Business Energy and Industrial Strategy 2016*c*) consultation released by BEIS proposes to increase heating control requirements. These new requirements are: first, that all new heating systems should include independent time control, a room thermostat (or programmable thermostat) and individual radiator control; and second, that all householders who upgrade or replace their existing boiler would have to be provided with a heating control that allows them to control hours of heating and the desired temperature (setpoint) in the home (Department for Business Energy and Industrial Strategy 2016*c*). The implementation of these changes in energy policy by BEIS mean that more householders will have greater control over their heating schedules and heating patterns.

5. **The central heating fund** — Supports local authorities to deliver central heating systems to fuel poor householders. This is achieved through a £25 million capital funding programme (Department

of Energy and Climate Change 2015*g*). The programme helps cut bills and increase comfort for non-gas fuel-poor householders.

The household energy policy is driving to make buildings more energy efficient and implement core technologies like smart meters and smart heating controls to engage householders and help them manage their energy consumption better. The research presented in this thesis plays a complementary role to the householder energy policy by exploring why individuals install energy efficiency measures and investigating the relationship between householders' sustainability views and their heating patterns.

2.2.5 Energy efficiency in buildings

The energy efficiency in buildings policy covers a broad range of topics regarding the environmental impact of buildings on the environment, including waste management, tree preservation, flooding, and energy performance. Therefore, throughout this section we only discuss the core initiatives that are applicable to this thesis:

1. **Heat in buildings — The future of heat consultation —** Recent consultations by BEIS set out to better understand from householders, installers and manufacturers policy options that can:

    a) maintain householder energy bills as low as possible,

    b) ensure a secure and resilient energy system within the UK,

    c) find cost-effective methods of reducing CO_2 emissions from domestic buildings,

    d) avoid unreasonable upfront cost for householders that could discourage home improvements (Department for Business Energy and Industrial Strategy 2016*c*).

    To achieve this, the consultation looks to take advantage of the fact that 1.2 million boilers are installed in the UK each year. Therefore, they propose to increase boiler standards, provide improved control of space heating through smart heating controls (as highlighted under the smart heating controls research programme), and apply weather compensator devices to boilers to improve efficiency (Department for Business Energy and Industrial Strategy 2016*c*). These small devices measure outside temperature and reduce load on the boilers when the weather is mild. However, the consultation does not provide any suggestion for alternative energy efficiency measures beyond boilers and heating controls.

2. **Energy Performance Certificate (EPC) —** must be carried out for all houses that are sold, built or rented. They are undertaken by qualified energy assessors using standard methods of assessing a building's energy performance; householders are then provided with a list of cost-effective measures to improve the building's energy performance (Department for Communities and Local Government 2017). EPCs are required as part of the EU's EPBD set out in section 2.2.2. The awareness and understanding of EPCs has been shown to be strong, but they only have a moderate effect when it comes to helping householders incorporate energy efficiency information into their

purchasing decision (Amecke 2012). They have also been shown to have limited impact on the price a householder is willing to pay for a property (Hårsman et al. 2016).

3. **Renewable Heat Incentive (RHI) —** aims to help householders move from transitional heating technologies to low-carbon alternatives. Since 2014 the incentive has helped over 50,000 households make the transition (Department for Business Energy and Industrial Strategy 2016*e*). Renewable Energy Heating and Cooling (REHC) was described as the "sleeping giant" of renewables energy potential from the global prescriptivist, the IEA (International Energy Agency 2007). In their study they highlighted that REHC have received little attention compared to the generation of electricity and production of transport fuel, and that the potential to increase REHC systems is significant. However, there are a number of large barriers to REHC, including high-cost of installation, a lack of investor awareness, existing infrastructure constraints, landlord / tenant incentive splits and difficulties obtaining planning consent (Seyboth et al. 2008). The incentive looks to help reduce these barriers for four key technologies: biomass boilers and stoves, ground source heat pumps, air source heat pumps and solar thermal (Department for Business Energy and Industrial Strategy 2016*e*).

The combination of the energy efficiency in buildings and household energy policy aims to help the UK transition to a low-carbon domestic energy sector. However, in the CCC's recent report on the UK's progress towards delivery of energy efficiency measures, they highlighted a significant setback in policy by the failure of the Green Deal, funding and targets of the successor to ECO being reduced, and the zero-carbon homes regulations being abandoned (Committee on Climate Change 2016). In this next section we look at the role that energy companies play in the domestic sector and how the policies highlighted above impact energy companies and householders.

2.3 Position of energy companies

In the domestic energy sector, energy companies play a central role in the way householders interact with energy. First, the energy company is the key interface between the householder and their energy use. This interface consists of a number of core activities, such as setting energy tariffs, maintaining 24/7 support for customers, and providing householders' energy bills in both paper and digital formats. In addition, energy companies undertake a number of extra activities, including the promotion of additional energy services such as boiler insurance and the selling of smart heating controls or connected home devices. Second, energy companies are the core method though which the UK government implements their energy policies highlighted in section 2.2. This includes providing finance for ECO, implementing the smart meter rollout, enhancing householders' energy knowledge and helping engage householders to reduce their energy bills by changing their behaviours or installing energy efficiency measures. In this section we provide an overview of the energy companies' viewpoint and how they manage their relationships with householders to provide an insight into the industrial context of the thesis. It must be noted that this section has a slight bias towards the industrial changes happening within EDF Energy, as this was the industrial sponsor for this thesis.

2.3.1 Impact of energy obligations

Energy obligations require energy companies to deliver a certain amount of CO_2 savings for householders; these are normally achieved through incentivising householders to install energy efficiency measures through subsidies (Rosenow et al. 2013). A chronology of UK energy obligations can be seen in Figure 2.13. The cost of meeting energy obligations is split between energy suppliers and householders, who pay through an increase in their energy bills. In breaking down a householder's average duel fuel bill in 2016/2017, 13% of the cost is due to environmental and social policy costs; this breaks down into 6% on top of a gas bill and 20% on top of an electricity bill (Figure 2.14). The added costs help to deliver the ECO, smart meter rollout, warm home discount, feed-in-tariffs and investment in low-carbon electric generation and security of supply (Energy UK 2017). Energy obligations place a huge pressure on energy companies to effectively deliver significant energy savings in the domestic sector or face significant fines. This was the case for InterGen, who undelivered on 38.8% of its Community Energy Saving Obligation (CESP), leading to a fine of £11 million (Ofgem 2015*b*). Likewise, British Gas only met 37.6% of its CESP, leading to fines of £10.6 million (Ofgem 2015*a*). This pressure of regulatory fines required that energy companies divert a significant amount of their resources to meeting their regulatory requirements and delivering their obligation targets. This pressure is also amplified by the scale and financial costs involved in meeting the required obligations; it is estimated that the smart meter rollout will cost £10.98 billion (Department for Business Energy and Industrial Strategy 2016*d*) to complete, and since ECO launched in September 2016, it has cost energy companies ≈£3.5 billion (UK Government 2017*c*). Therefore energy companies have to find innovative methods to minimise the impact of obligations on their operations costs and, in turn, on the householders' energy bills.

Name of scheme	Energy Efficiency Standards of Performance 1	Energy Efficiency Standards of Performance 2	Energy Efficiency Standards of Performance 3	Energy Efficiency Commitment 1	Energy Efficiency Commitment 1	Carbon Emissions Reduction Target	Community Energy Savings Programme	Energy Company Obligation
Abbreviation	EESoP 1	EESoP 2	EESoP 3	EEC 1	EEC 2	CERT	CESP	ECO
Period	1994–1998	1998–2000	2000–2002	2002–2005	2005–2008	2008–2012	2009–2012	2013–2015
Target (lifetime)	6.1 TW h	2.7 TW h	4.9 TW h electricity & 6.1 TW h gas	62 TW h	130 TW h	293 million t CO_2=494 TW h	19 million t CO_2=47 TW h	20.9 million t CO_2 6.8 million t CO_2 lifetime savings notional heating costs of £4.2 billion
Implicit annual target (lifetime)	1.5 TW h	1.4 TW h	5.5 TW h	21 TW h	43 TW h	~104 TW h	~15 TW h	~30 TW h
Cost of the							programme	£101.7 million
£48.1 million	£110 million (indicative)	£500 million (indicative)	£1.2 billion (indicative)	£5.6 billion (indicative)	£0.4 billion (indicative)	£2.9 billion (indicative)		
Cost per household	£1	£1	£2.40	£7.20	£18	£51	£3	£53
Per cent of savings in Priority Group	30% (expected, not compulsory)	65% of expenditure (expected, not compulsory)	67% of expenditure (expected, not compulsory)	50%	50%	40%, 15% in Super Priority Group	Lowest 10% income decile in England and 15% most income deprived areas in Scotland and Wales	25%, 20% in 15% most income deprived areas

Figure 2.13: Rosenow et al. (2013, p.2), *Chronology of UK energy supplier obligations.*

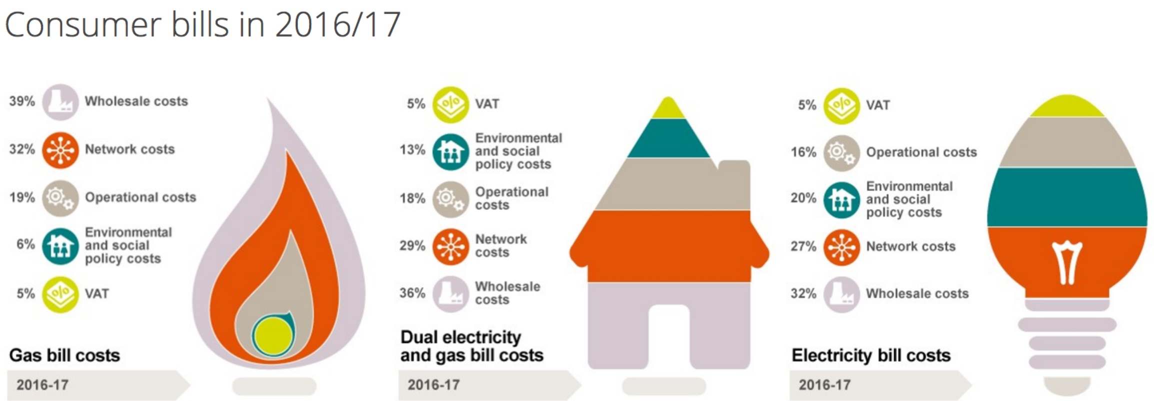


Figure 2.14: Energy UK (2017), *Energy bill breakdown in 2016/17.*

2.3.2 The rise of the small- and medium-sized entries

The energy market in the UK is undergoing a significant change, which is being driven by small- and medium-sized energy suppliers. The market share of small- and medium-sized energy suppliers has grown to 14% in March 2016, and has grown nearly 4% points from April 2015 to March 2016 while the six large suppliers continue to lose market share (Figure 2.15 (Ofgem 2016)). The rise of small- and medium-sized entries has been driven by the full liberalisation of the energy market, and such companies utilise novel business models such as not-for-profit suppliers, only renewable suppliers and local authority supplier schemes (Ofgem 2016). A large number of the new entries do not have to rely on legacy infrastructure and ICT systems, and instead use modern digital platforms. This allows them to deliver a modern user experience, provide low-cost and innovative energy tariffs, and provide higher levels of customer satisfaction (Accenture 2017). In addition, small suppliers rely on significant cost advantages that result in steep declines in wholesale prices and they are exempted from regulatory obligations highlighted in section 2.2, allowing them to provide low-cost tariffs (EDF Energy 2014*a*). The rise of small- and medium-sized entries has required that traditional vertical integrated energy suppliers have had to make radical changes within their business: first, to become highly customer focused in their supply business; second, to undertake the transition from legacy ICT systems to more modern digital solutions; third, to develop novel and interesting methods of retaining customers (EDF Energy 2015*b*); and finally, to streamline their supply business to reduce operational costs and maintain new competitive tariffs for customers (EDF Energy 2014*a*).

2.3.3 Energy vs energy services

A major growth area for energy companies is the promotion of energy services to householders, which has led to EDF's purchase of Dalkia (Dalkia 2017), SSE's acquisition of Energy Solutions Group (SSE 2014) and Centrica (owner of British Gas) to set out plans to invest £250 million into the growth of

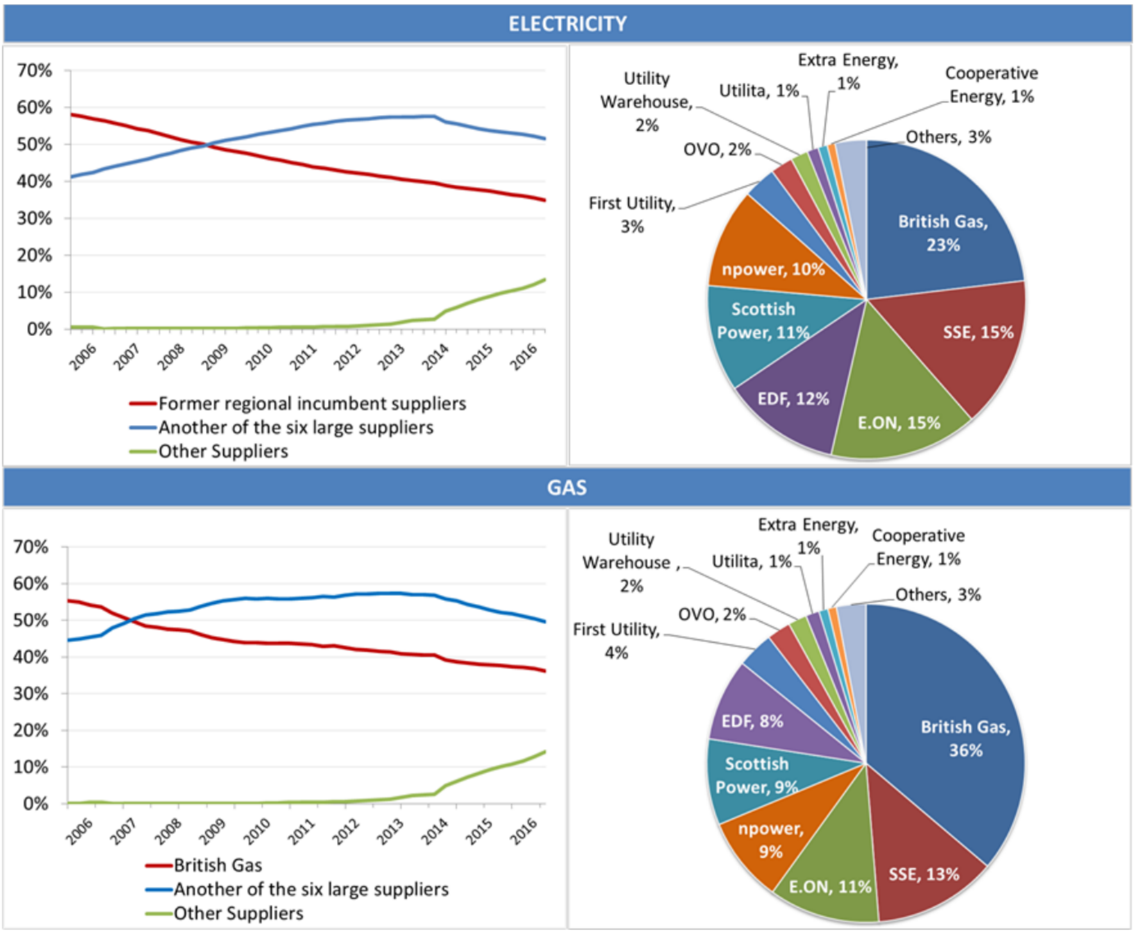


Figure 2.15: (Ofgem 2016, p.10), *Share of UK's domestic meter points served by different types of supplier - 2006 to 2016, and snapshot for March 2016.*

energy services over the next five years and £500 million in energy services in the connected homes market (Centrica 2015). The rapid rise in energy services has been driven by four core factors: first, the EU's policy requirement on energy suppliers to install and monitor energy efficiency measures (Economidou 2015); second, there has been an increase in demand for householders to make their homes connected (GSMA 2015); third, micro-generation and storage technologies have reduced in cost, leading to more householders looking to generate their own energy; and forth, the rollout of smart meters is enabling householders to better understand and manage their energy consumption through new energy services. Energy companies face volume and margin pressures on their supply of energy, and the energy supply market is being shared between a growing number of new entries, encouraging energy companies to diversify their portfolios through energy services.

2.3.4 Increased importance of householder engagement

Due to the pressures highlighted above, energy suppliers are looking to increase their level of engagement with their householders, and are looking for better methods and techniques to increase their householders' levels of engagement with energy and energy services. This is required for a number of reasons:

First, householders have a significant influence over the success or failure of energy technologies (Energy Generation and Supply Knowledge Transfer Network 2014). Increasing a householder's engagement, acceptance and perceptions can help with the installation of smart meters, ECO measures, Green Deal measures and promotion of pro-environmental behaviours, which means that energy companies can meet their obligations more effectively.

Second, the recent Competition and Market Authority (CMA) report highlighted that there is a lack of engagement in the retail energy market by many householders, which can lead householders being charged higher prices from their energy suppliers (Competition and Markets Authority 2016*b*). This was supported by Ofgem finding that one in five householders are very disengaged, on expensive standard variable tariffs, more likely to be in a vulnerable situation and have low levels of engagement with information provided by energy suppliers (Ofgem 2016). This has caused the CMA to recommend that Ofgem create a database of disengaged householders who are on standard variable tariffs for more than three years that will be shared with rival suppliers to help prompt householder engagement (Competition and Markets Authority 2016*a*). This means that energy companies that fail to stimulate householder engagement will face strong competition from rivals, especially new entries, as rivals can use the database to acquire their competitors' customers.

Finally, energy services are playing a more important role in energy companies' business models, as shown in section 2.3.3. As a result, energy suppliers are becoming more interested in having highly engaged householders that will not only be interested in energy, but also interested in energy services, connected home products, load balancing technologies and micro-generation.

2.3.5 Transition to digital

Digital technology (ICT) has started to have a massive influence on the energy sector, as it is seen as a method to solve a number of the issues highlighted throughout this section. It has become vital for energy companies to position themselves at the centre of the emerging digital energy eco-system (Figure2.16) (PwC 2016), which is being generated by the smart meter rollout and the rise of the connected home.

The digital revolution in the energy sector is being driven by the rapid increase of energy-relevant data being collected. International Business Machines Corporation (IBM) highlights that going from one meter reading a month to a reading every 15 minutes works out as a 3,000-fold increase in data, and a total of 96 million reads per day for every million smart meters installed (IBM Corporation 2012). For example, EDF Energy has 3.3 million electricity customers and 2.0 million gas customers (EDF Energy 2015*a*), which equals 508.8 million readings per day once the smart meter rollout is complete. In conjunction, the connected home is estimated to dwarf the data generated from smart meters, through smart heating controls, smart lighting, connected white appliances and smart security systems. With data

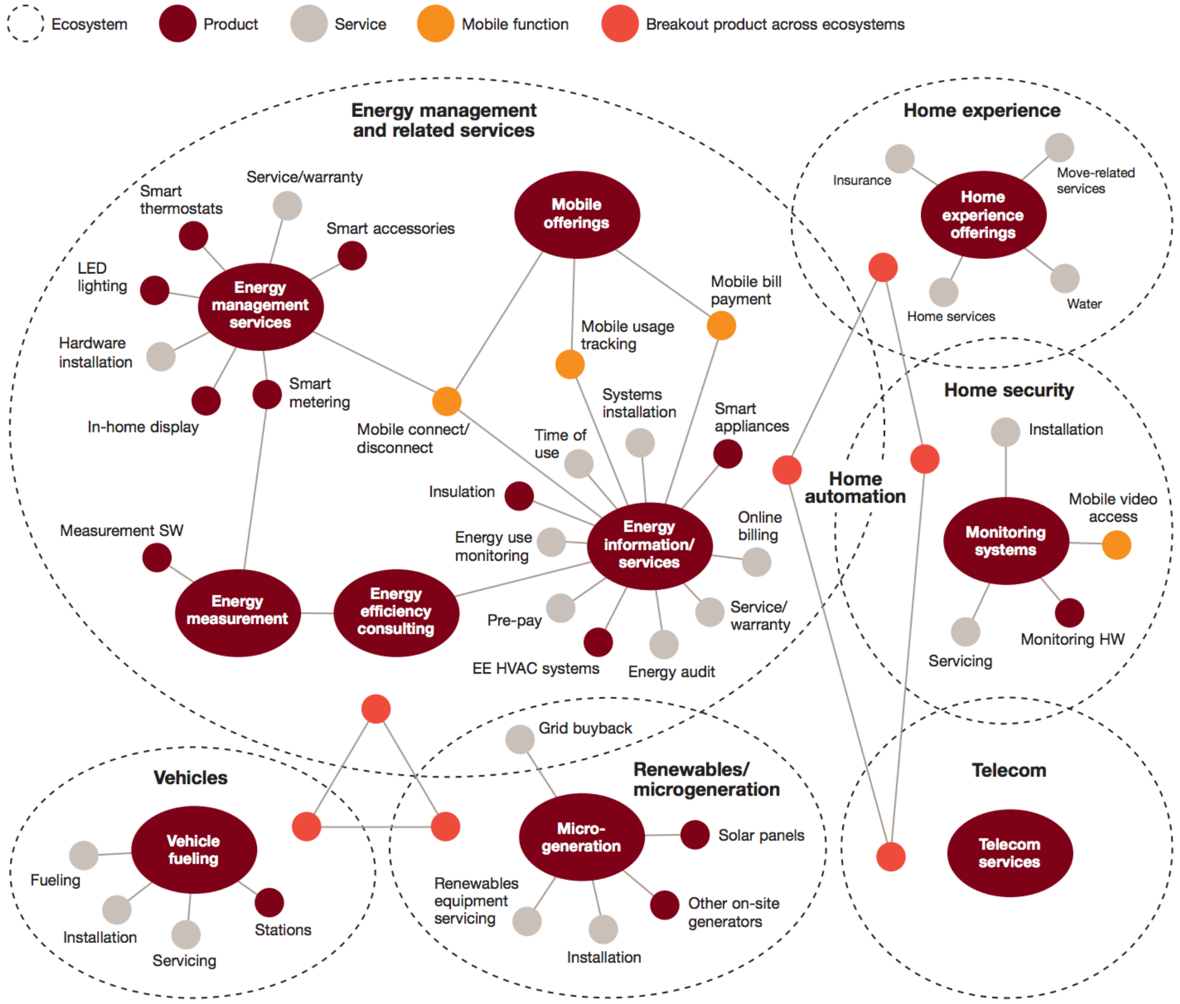


Figure 2.16: (PwC 2016, p.6), *The dynamic and complex energy eco-system.*

being seen as the new oil, the rise in data in the energy sector has not gone unnoticed by a number of pure technology companies (PwC 2016), including Alphabet's (Google's parent company) purchase of Nest Labs for $3.2 billion (Alphabet 2014) and Samsung's acquisition of SmartThings for an estimated $200 million (Samsung Newsroom 2014). The new pure technology entries are looking to control both the data generated by the energy sector and the interface that lets householders control and manage their home and, in turn, their energy consumption. Energy companies have to adapt to this new data centric method of operation.

Digital services are also helping energy companies to reduce their operational costs, increase customer satisfaction and increase the likelihood of customers signing up and buying energy services (Figure 2.17). Energy suppliers that combine advanced data collection and analytics with a strong digital strategy stand to take advantage of the digital revolution in the energy sector, while energy suppliers that fail to move fast enough will be overtaken by competitors (PwC 2015). Customers' expectations are changing as customers start to generate their own energy; get involved in monitoring and managing their energy through new and automated devices; and 'digital natives' start to represent a larger proportion of an energy suppliers' customer base (PwC 2016). As highlighted in section 1.3.2.2 this is only going to grow in importance as younger generations start to purchase energy and energy services. Educating this generation to manage energy more effective will become a key challenge for energy companies, and we explore this issue in Chapter 6. Digital technologies is requiring energy companies to make significant changes to place digital at the core of their business, and energy companies are starting to bring digital skills in house through the development of innovation teams and centres. This can be seen by EDF Energy launching Blue Lab: *"an innovation platform and incubator to develop new products, business models and services for customers — and to continue to develop the ways in which our customers can take control of their energy through digital."* — Vincent De Rivaz, Chief Executive of EDF Energy (EDF Energy 2015*b*). In a similar manner, British Gas built a team under the new brand name 'Hive' in 2012, whose mission is to help British Gas accelerate the progress of the connected home. It seeks to blend design, both digital and physical, to help customers gain control over their homes (British Gas 2017*a*).

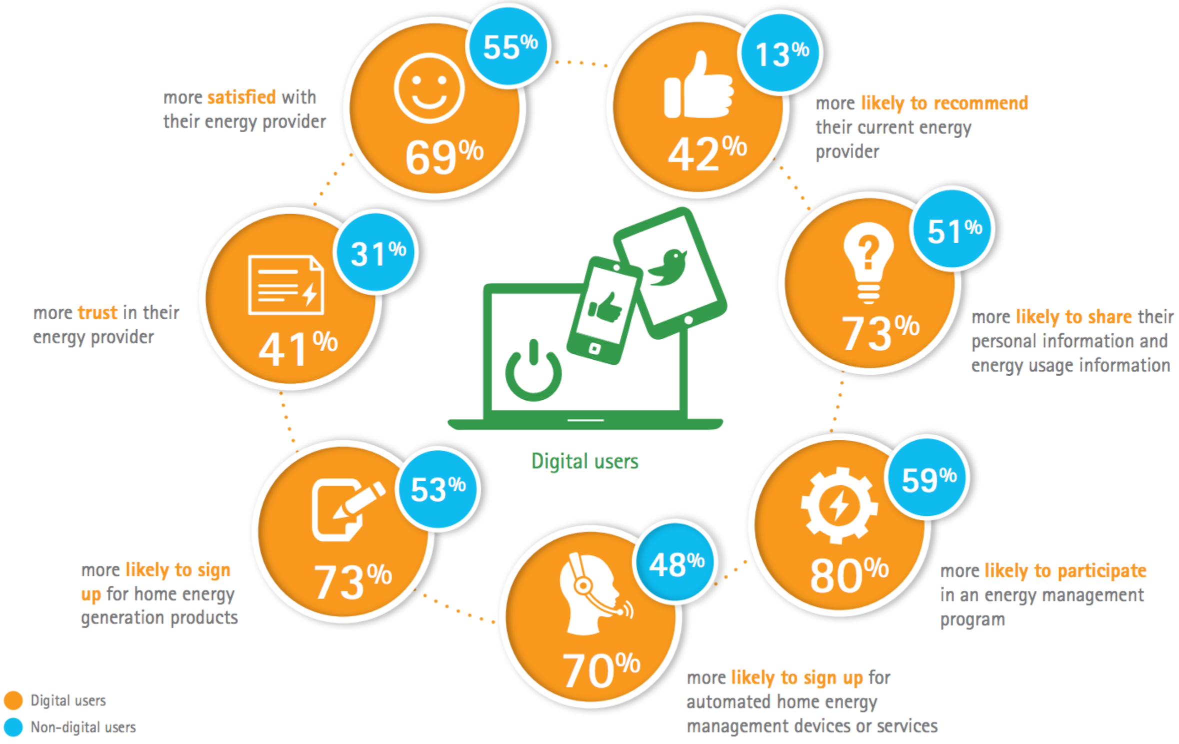


Figure 2.17: Accenture (2017, p.15), *The digitally engaged energy consumer unleashes more business value for energy providers.*

In this section a number of the core pressures faced by energy companies have been highlighted to help provide a summary of the industrial context of the thesis. The next section will provide an overview of the UK housing stock and the literature on energy efficiency measures and retrofitting.

2.4 Housing stock, energy efficiency measures and retrofitting

It is estimated that to meet the the Paris Agreement of keeping global temperatures below 2°C by 2050, the building sector (including both residential and commercial) will need to reduce the amount of direct CO_2 emissions it generates by 70-80%, and by 80-90% to maintain a temperature increase below 1.5°C (Rogelj et al. 2015, Climate Action Tracker 2016). This level of change can only be achieved through re-thinking the way buildings are heated in the residential sector, as breaking down the CO_2 generated from the residential sector (section 2.1.2) showed that space heating is the largest contributor to CO_2 emissions. In 2016, BEIS stated that: *"Hitting the UK's 2050 carbon reduction target is likely to require eliminating nearly all of the heat related emissions from buildings" (Department for Business Energy and Industrial Strategy 2016*c*)*. This transition to a significant change to minimise energy leakage from buildings, and to optimise the efficiency and sustainability of heating and cooling systems (European Commission 2016*b*). There are two main methods to achieve the transition: 1. build new energy efficient housing stock, and 2. retrofit the current housing stock to improve energy efficiency. Throughout this section, we start by highlighting the current state of the EU and UK building stock, then explore the two alternative paths to move toward a low-carbon residential housing stock.

2.4.1 EU building stocks

The EU's housing stock predominately consists of older buildings (Figure 2.18), which in most cases have a low-energy performance and require retrofitting (Buildings Performance Institute Europe 2011). Due to the age of the EU's housing stock, two-thirds of the building stock were built in a time when energy efficiency policies were limited or non-existent (European Commission 2016*b*), so have yet to be affected by new energy performance requirements (European Commission 2017).

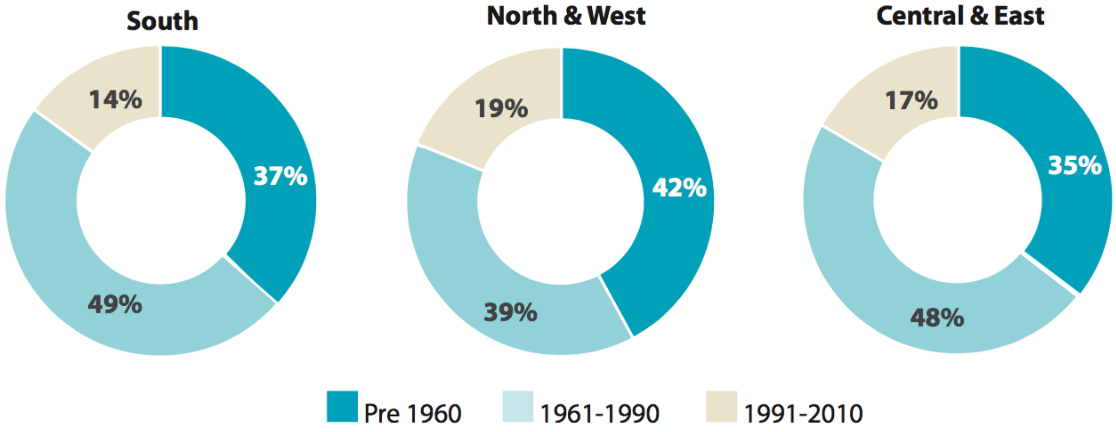


Figure 2.18: Buildings Performance Institute Europe (2011, p.9), *Age categorisation of housing stock in Europe.*

The age of the building has a large influence on the overall performance of the building, as older buildings, on average, have higher u-values caused by poor performing windows and building envelopes (Figure 2.19). Energy consumption in the EU's building stock is mainly from gas consumption at 36%, closely followed by electricity consumption at 32%, with renewables representing 10%; as we have highlighted already, space heating dominates the end-use of the energy (Figure 2.20) (European Commission 2017). A rapid change in the EU's building stock is required to meet the EU's climate change targets.

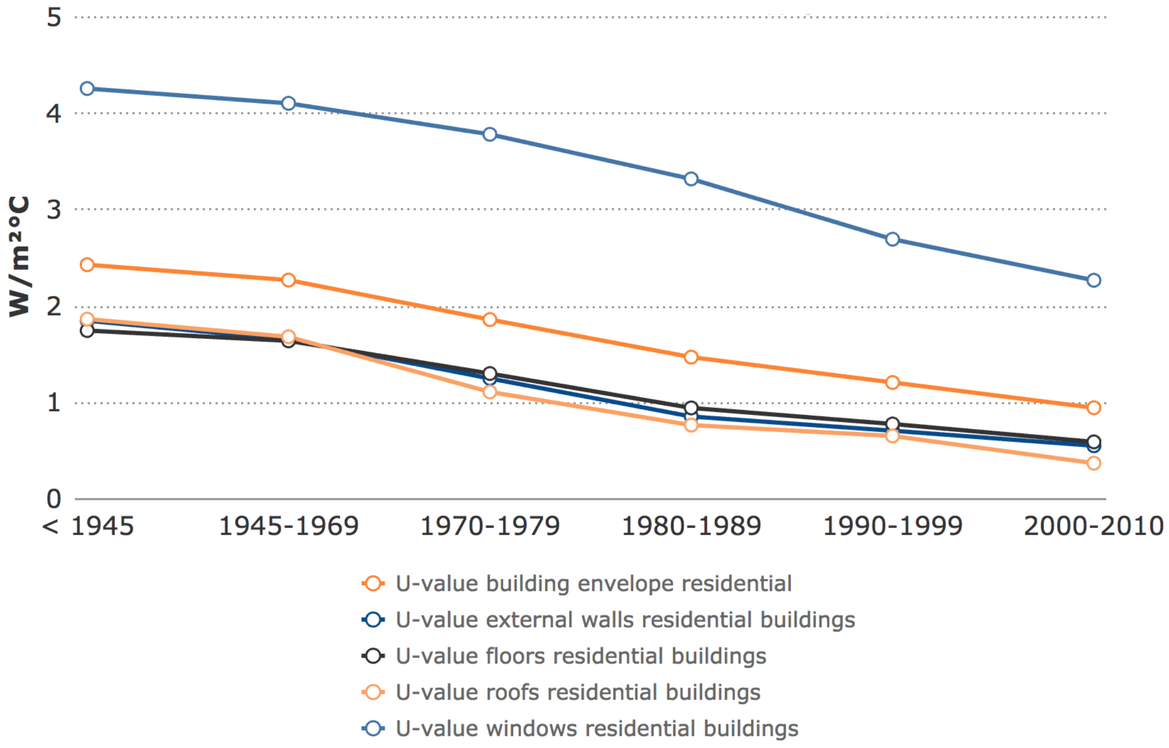


Figure 2.19: European Commission (2017), *Average U-values per age category (2014).*

2.4.2 UK building stock

The UK is one of the countries with the largest proportion of older buildings (Figure 2.21), along with Denmark, Sweden, France, the Czech Republic and Bulgaria (Buildings Performance Institute Europe 2011). As highlighted above, older buildings tend to be less efficient, and this is no different for the UK's building stock. The main housing types in the UK are semi-detached and terraced housing, which each represent just under a third of the housing stock (Palmer et al. 2013). However, over the last several decades, detached houses and flats have become more common. This is important as flats help to improve energy efficiency due to their shared external wall area, but detached houses increase inefficiency due to an increase in external wall area (Palmer et al. 2013). In the UK, the housing stock is also predominately owner occupied, with 14.7 million homes owner occupied, 4.7 million are private rented and 4.0 million are social or affordable housing (Department for Communities and Local Governments 2016). This is

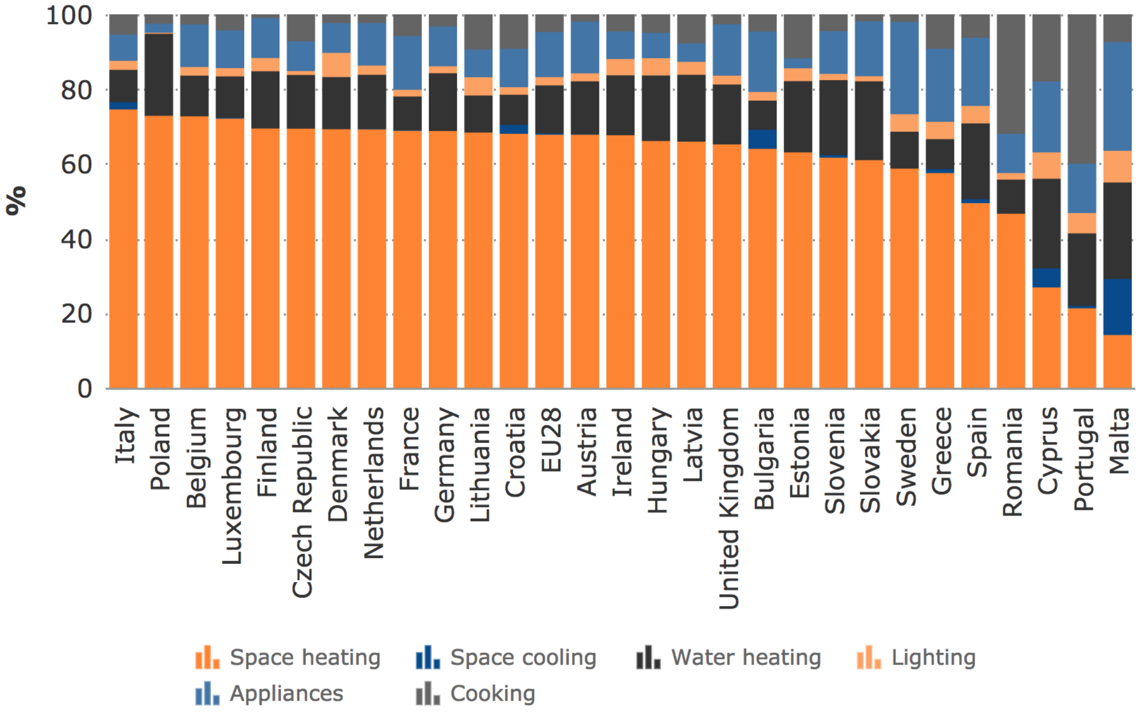


Figure 2.20: European Commission (2017), *Energy consumption by end-use in residential buildings (2013).*

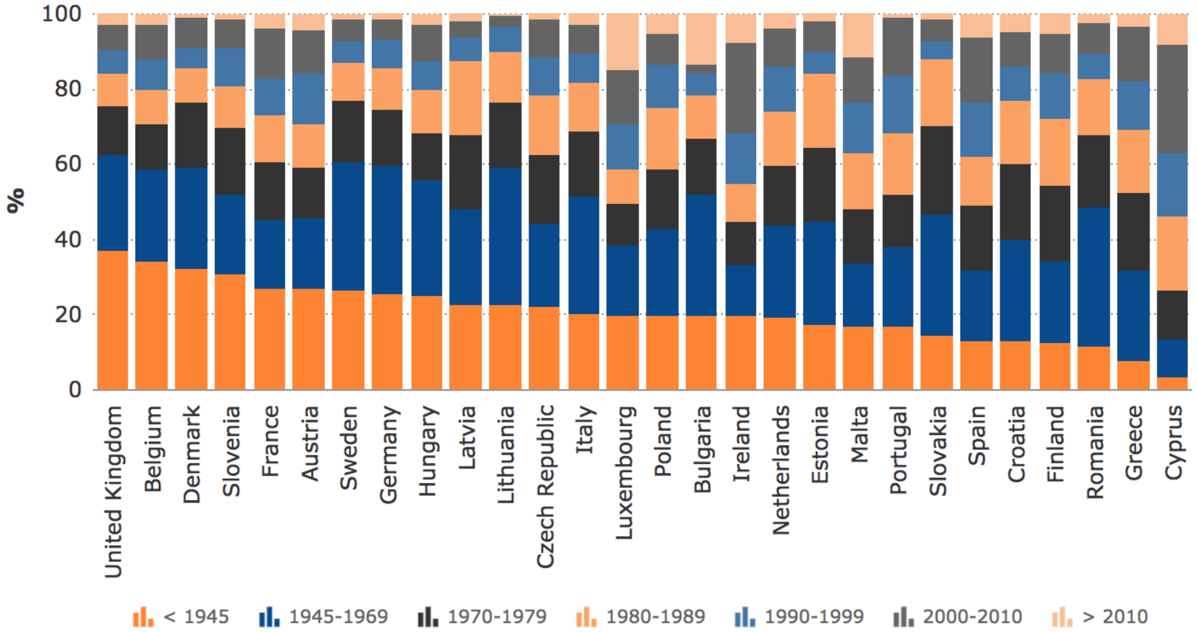


Figure 2.21: (European Commission 2017), *Breakdown of residential building by construction year (2014).*

significant as a large proportion of the UK's policies are aimed at social or affordable housing, which makes up the smallest proportion of the UK's housing stock, albeit the most in-need householders.

The energy efficiency of the UK housing stock has slowly been improving, mainly due to the increased uptake of whole house heating systems, more efficient boilers, improved glazing, and loft and cavity insulation (Eyre & Baruah 2015). This has enabled the average Standard Assessment Procedure (SAP) rating for the UK's housing stock to steadily improve, as seen in Figure 2.22 (Department of Energy and Climate Change 2015*c*), albeit at a slow rate. Unfortunately, the energy supply system within the UK has a large reliance and high penetration of natural gas, which is predominately used for space and water heating through gas boilers (Eyre & Baruah 2015, Hamilton et al. 2013). The level of gas demand also increases the older the house (Hamilton et al. 2013).

To summarise, the UK housing stock is old and inefficient, with a large reliance on a fossil fuel (gas). The housing stock is predominately composed of owner occupied semi-detached and terraced housing, which needs to be improved to increase energy efficiency.

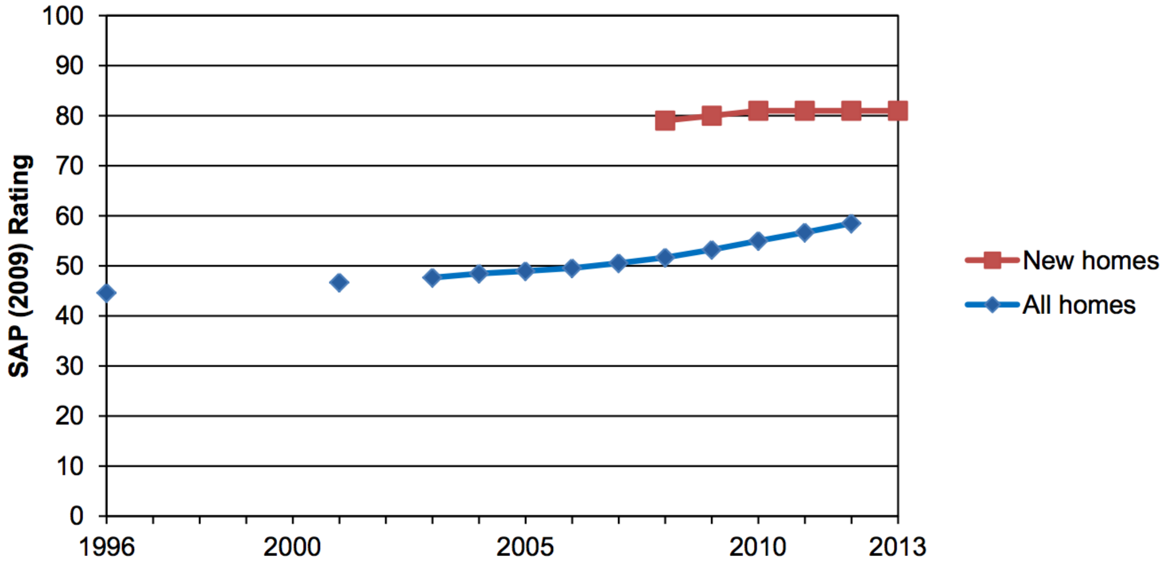


Figure 2.22: Department of Energy and Climate Change (2015*c*, p.19), *Energy efficiency rating homes in England, 1996 - 2013.*

2.4.3 Building new energy efficient housing stock

In the quest to build a new energy efficient housing stock, the EU have stated in an update to the EPBD that all new buildings constructed by 31 December 2020 must be nearly zero-energy buildings (European Commission 2010*a*). Since 2013 the UK building regulators define that new builds must have a 44% reduction in their target emission rate compared to 2006 standards (Dowson et al. 2012). However, new builds make up a limited proportion of the overall EU and UK housing stock, with the percentage of new buildings constructed since 2000 only reaching 9.79% in the UK, 7.09% in Germany, 17.33% in

France and 23.79% in Spain, as shown in Figure 2.21. It is this slow rate of replacement of around 1% in both the EU (Buildings Performance Institute Europe 2011) and UK (Swan et al. 2010) that makes relying on replacing the current building stock with new efficient housing stock and ineffective way to achieve CO_2 targets. The EU states that most of its inefficient housing stock will most likely still be standing in 2050 (European Commission 2016*b*), while the UK's Royal Academy of Engineering stated: *"Most of the houses that will exist in 2050 have already been built. New houses should be built to the highest standard of energy efficiency but that, by itself, will not be enough. If we are to meet the 2050 targets, major improvements will have to be made to the existing housing stock."*(The Royal Academy of Engineering 2012). These facts highlight the vital role that retrofitting has to play, as the EU and UK's targets are unrealistic without a significant uptake of energy efficiency measures. In the next section we analyse the current levels of retrofitting and energy efficiency measures.

2.4.4 Renovation, retrofitting and energy efficiency measures

As highlighted above, renovation and retrofitting are the only suitable options to transition towards a sustainable housing stock. The installation of energy efficiency measures is an essential contributor to all of the EU climate and energy policies (European Commision 2014). Likewise, as we have highlighted throughout this literature review, energy efficiency measures have been the primary factor in lowering energy consumption over the last decade (International Energy Agency 2015*b*, European Commission 2017). It is this factor that makes investment behaviour change so important, as discussed in section 8.3. However, both renovation and retrofitting rates are still low. The EU's renovation rate is typically around 1% per year, of which it is estimated that 85% are minor renovations (installation of one or two energy efficiency measures), 10% are moderate renovations (resulting in an energy reduction of 30% to 60%) and only 5% are major renovations (resulting in energy reductions of 60% to 90%) (Artola et al. 2016). In modelling 11 EU countries' renovation rates towards 2050, the rates still fall within the range of 0.6% to 1.6% (Sandberg et al. 2016).

In looking at the UK, the rates of energy efficiency measures being installed have reduced under the current government schemes, down 49% on 2014 and 87% on 2012 across cavity wall, loft and solid wall insulation, which is shown in Figure 2.23 (Committee on Climate Change 2016). It must be noted that the report highlights that the cause of these reductions are caused by policy implications and not market saturation. Figure 2.23 reflects the impact that weakening of energy policy can have on the overall number of installations (Committee on Climate Change 2016). Meanwhile, the EU is estimated to have up to 110 million buildings that could be renovated (Artola et al. 2016). The low installation rate of energy efficiency measures and the significant amount of households that require measures highlight the huge energy saving potential there is from retrofitting in both the EU and UK.

The European Commission (EC) states that: *"Increasing the rate, quality and effectiveness of building renovation is the biggest challenge for the coming decades."* (European Commission 2016*a*). This is echoed by the IEA, who stated that *"the rate and ambition of energy retrofits of existing buildings need to be improved."* (International Energy Agency 2016*a*). As highlighted earlier, the housing stock

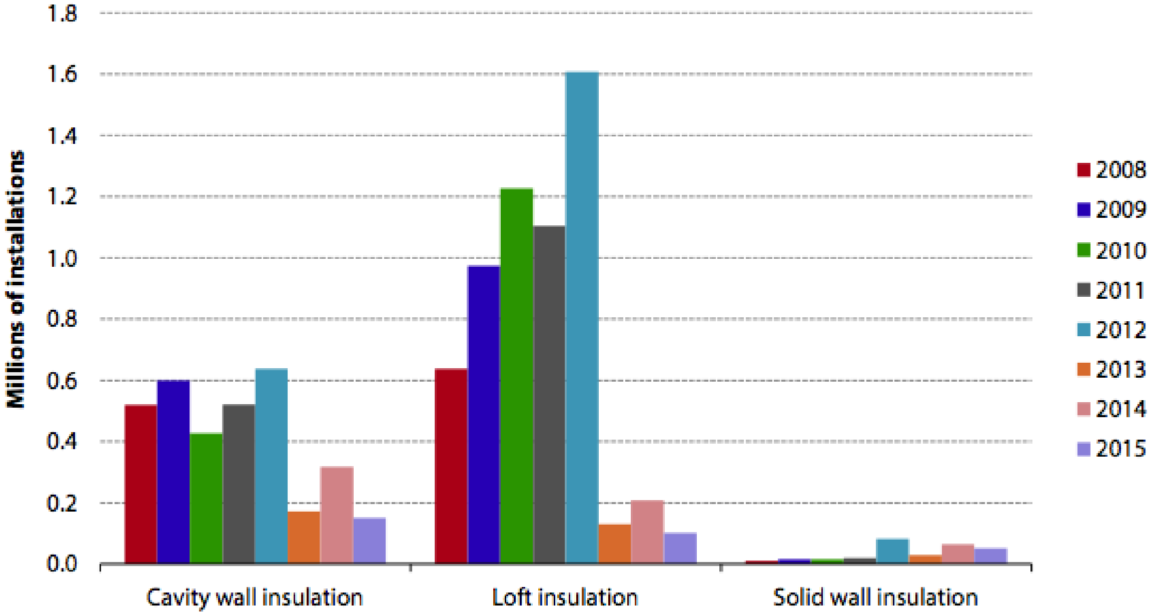


Figure 2.23: Committee on Climate Change (2016, p.97), *UK annual insulation installation rates (2008-2015).*

is old and inefficient, but there are currently a large number of simple renovations (insulation, boiler improvements and double or triple glazing) that can produce big savings (European Commission 2016*b*) and can be delivered in a cost effective manner. For example, almost half of the EU's boilers were installed before 1992, with an efficiency of 60% or less (European Commission 2016*b*), while in 2014 only 53% of households in England had a condensing-combination boiler, and only 48% had cavity or solid wall insulation (Department of Energy and Climate Change 2015*e*). The low level of adoption of energy efficiency measures highlight a shortfall in policy, eduction (Chapter 6), markets and householder acceptance (which is the main focus of the first half of this thesis and explored in Chapters 3, 4 and 5).

Please note that throughout this section we have used the terms "renovation" and "retrofitting". A major renovation is defined by the EPBD as a construction activity that changes 25% of the building's surface envelope or costs higher than 25% of the value of the building. Minor renovations, however implement one or two measures, resulting in a reduction in energy consumption (European Commission 2010*a*), similar to retrofitting. Retrofitting can be defined as adding, enhancing or maintaining energy efficiency measures on a property. As the focus of this thesis is on the improvement of the domestic housing stock to make it more energy efficient, we include major renovations that improve the energy efficiency of a property in our definition of retrofitting. Therefore, our use of retrofitting throughout the remainder of this document includes both minor, moderate and major renovations that improve the energy efficiency of the property.

2.4.5 Rebound effect and the Jevons Paradox

It is important to consider the rebound effect and the Jevons Paradox when seeking to improve energy efficiency within the domestic energy sector.

The “rebound” effect in the context of energy states that a proportion of the energy savings generated from technological improvements is lost due to an increased demand for energy. This increase in demand for energy is driven by the decrease in the price of energy resulting from the technological efficiency improvements (Greening et al. 2000). The initial idea of the “rebound” effect was presented by Jevons (1866) in *The Coal Question*, where he highlights that it is a confusing idea to suppose that the economical use of fuel results in a reduction in consumption, while the contrary is true: it is the economy of its use that results in extensive consumption. Greening et al. (2000) define four rebound effect categories when it comes to energy services, which include both microeconomic and macroeconomic effects:

1. direct rebound effect — results from the energy service being reduced in cost, leading to a householder being able to afford an increased amount of the service,

2. secondary energy use effect — is caused by the householders using the savings from one energy service to facilitate an increase in additional energy services,

3. market clearing price and quantity adjustments or wide economy-wide effects — happens when the aggregated effect of both direct and secondary effects are looked at over a long-time period, leading to investment by both consumers and governments, resulting in a change of the price of energy services,

4. transformational effects — are produced by the technology changing householders’ preferences, altering social institutions and rearranging production.

In the worst case scenario, the rebound effect can cause an increase in energy consumption known as ‘backfire’. However, research has show this does not routinely happen in energy efficiency improvements, and that the economy-wide rebound effect removes about 10% of the energy savings achieved by the energy efficiency improvement (UK Energy Research Centre 2007). The rebound effect can be higher for certain energy efficiency improvements. For example, when looking at space heating energy efficiency improvements, the effect of just direct rebound effect is estimated between 10% to 30%, while water heating improvements lose between 10% to 40% of savings due to the rebound effect (Greening et al. 2000). The rebound effect has significant policy implications as it must be incorporated in estimates of potential savings generated from energy efficiency measures (UK Energy Research Centre 2007). Incorporating the rebound effect into the effectiveness of energy efficiency measures increases the challenge that society faces, as between 10% to 30% of retrofitting energy savings will be lost as a result.

2.5 Space heating

In this chapter we have focused on the installation of energy efficiency measures that provide the background for Chapter 3 to Chapter 5. However, the literature also suggests that behavioural and social characteristics of householders and their interactions with their heating system has a large influence on heating: it is not only due to the physical characteristics of the household and the levels of energy efficiency measures installed (Kelly et al. 2013). In Chapter 7 we explore the role a householder's sustainability views has on their heating demand, and therefore in this section we provide a background to space heating, with a key focus on space heating behaviours and heating controls.

The importance of space heating in helping reduce CO_2 emissions generated from the domestic energy sector has already been highlighted throughout this chapter. However, it is important to emphasise the core facts when it comes to space heating:

1. In 2015 space heating accounted for 70% of total end-use domestic energy consumption in the UK (Department for Business Energy and Industrial Strategy 2016*b*).

2. In 2015 gas made up almost 80% of domestic space heating within the UK (Department for Business Energy and Industrial Strategy 2016*b*).

3. Only 8% of heating and cooling needs worldwide are met by renewables (Kristin et al. 2016).

4. The average household temperature in the UK has risen from 12 ^{o}C in 1970 to 17.6 ^{o}C in 2011 (Palmer et al. 2013).

In tackling these core issues it is vital to look at both energy efficiency measures and householders' space heating behaviours. When it comes to heating choices, householders have a significant influence over three heating elements:

1. heat behaviours and demand — the householder's heating schedules and patterns that provide the householder's required level of comfort.

2. selecting a heating system — the combination of technologies that generate heat and distribute it around the household, including the controls the householder uses to select their heating demand.

3. selecting an energy provider — supplies the household with gas to fuel the heating system (Department for Business Energy and Industrial Strategy 2016*a*).

In the next section we will review other researchers definitions of comfort and provide our own definition, which we use throughout the thesis. We will then review point 1 and 2 stated above, while point 3 is out of the scope of this thesis.

2.5.1 Comfort

A householders levels of comfort can vary, and this is influenced by different social and cultural norms that affect individuals habits and attitudes. Comfort can also be seen within the social dynamic of a home and individuals levels of comfort can compete (Shove 2003, Jackson 2005). Comfort can also be effected by a individual's level of activity or local climate (Fountain et al. 1996, Clear et al. 2014). All these factors and the subjective nature of comfort can make it hard to define. One method of defining comfort is to look purely at an individuals skin temperature to define comfort. This was the approach taken by Fanger (1970). His research understood that different individuals had different conditions that would make them comfortable, and therefore looks to create a model of 'optimal thermal comfort' (where most people are happy). Fanger then created two models: Predicted Mean Vote and Predicted Percentage of Dissatisfied, that can be used to define the 'optimal' air temperature, mean radiant temperature, relative velocity and air humanity for a given activity or level of clothing (Fanger 1970). This method of defining comfort has been critiqued as it puts too much emphases on mechanical heating and cooling to make individuals comfort (Shove 2003) rather than taking a more adaptive model of comfort (Clear et al. 2014). Shove (2003) argues that our models of comfort have been made, naturalised and reproduced by a sequence of events that have locked us into unsustainable requirements of comfort. Her research highlights that it is the combination of our socio-technical systems and our habits, routines, injunctions and concepts of service that define our levels of comfort. To help define the problem space and focus the research presented in this thesis, we have decided to define householder's comfort as: the clothes, local interventions (as highlighted in the adaptive model of comfort (Clear et al. 2014)) and the householders desired room temperature. In our research we also draw on a number of the psychological and social aspects of comfort to help explain and discuss the research presented throughout the thesis.

2.5.2 Heating behaviours and demand

In looking at heat demand, the Energy Technologies Institute (2015) highlighted that about a third of householders (36%) claimed to reduce their energy use through turning their thermostats down, turning heating off when they went out or down in unused rooms, while approximately another third (27%) focus on ensuring that their heating demand meets the level of comfort required by them or others in the household, and the last third (37%) showed limited interest in heating demand altogether. The Department of Energy and Climate Change (2013) also highlighted five 'scales' that influence a householder's heating behaviours:

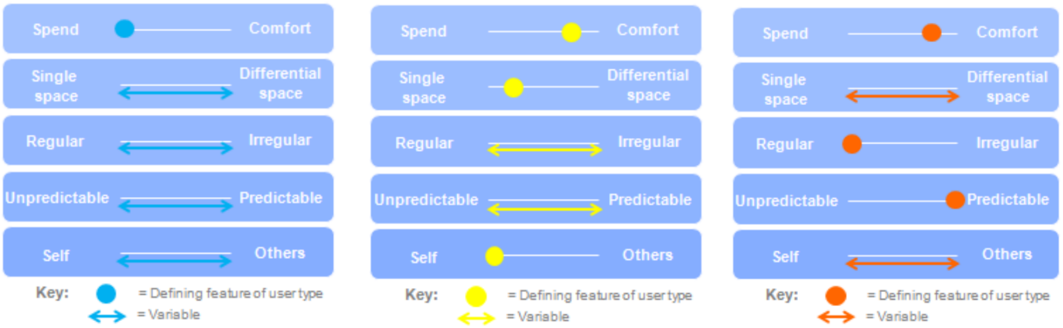
1. spending vs comfort
2. single space vs differential space
3. regular vs irregular routines
4. unpredictable vs predictable routines

5. self vs others

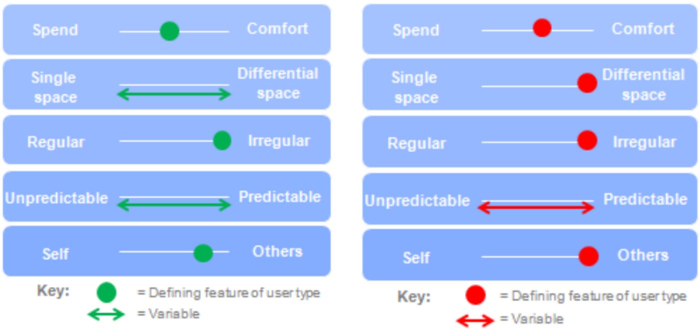
Then Department of Energy and Climate Change (2013) used these five scales to produce five heating behaviour types that can aid with thinking about heating demand and heating controls (Figure 2.24):

1. rationers — main focus is on minimising spending on heating; this tends to be driven by limited income, and they only use heating to avoid discomfort. Rationers predominately undertake manual interactions with their thermostats to reduce the cost of heating when it is not needed.
2. ego-centric — are driven by achieving their own required level of thermal comfort. They are happy to spend money to get their required level of comfort, and tend to manually interact with their thermostat. Health and well-being can also be a driving factor for this group.
3. hands off — don't want to think or interact with their heating system, and therefore have regular and predictable heating demand routines. They are focused on comfort rather than spending, and are happy to set their thermostat at one temperature all year, leading to limited interaction with their thermostat.
4. planners — try to pro-actively manage their heating, leading to a large number of interactions with their thermostat. They look to maximise both comfort vs spending, through changing their schedule and an in-depth understanding of their heating controls.
5. reactors — view their house as having many different areas or zones, which they heat separately. They react to external temperatures and struggle to achieve their required comfort without a number of interactions with their thermostat or using alternative method of gaining heat (blankets, auxiliary heating or clothes).

These profiles show the wide range of heating behaviours and demonstrate the complexity involved in understanding how householders heat their properties. This complexity is especially tricky when it comes to encouraging the 64% of householders who have picked comfort or are disengaged in heating to reduce their heating demand to save energy and reduce their impact on the environment. On top of this, householders have different social and cultural norms that influence their habits and attitude towards heating, which can lead to unsustainable heating behaviours. For example, Dimitrokali et al. (2015) found that 49.3% of householders open windows to get fresh air while the heating is on, only 32% of householders reported turning the heating off when it is not needed, and the Energy Technologies Institute (2015) reported that around 10% state leaving their heating on to try and save energy. It has also been shown by Morton et al. (2016) that householders tend to increase their level of manual interactions during the winter months, highlighting that householders do not pre-define their heating schedule for the winter period, and rely on manual overrides to get their required levels of comfort. Meanwhile, it has been shown that householders who have routine heating behaviours tend to consume more energy on heating than householders without a routine (Kelly et al. 2013). Finally, as we look to reduce householders' energy consumption from heating demand, it is vital to encourage householders



(a) rationers (b) ego-centric (c) hands off



(d) planners (e) reactors

Figure 2.24: Department of Energy and Climate Change (2013, p.25-27), *Heating demand - emerging user types.*

to reduce their internal temperature as this is the most effective behavioural change that can be made (Department of Energy and Climate Change 2012*b*).

These manual overrides, in combination with a householders' heating schedules and heating behaviours, can have a large influence on the overall CO_2 generated from a household. Therefore, it is a worthwhile area of research and we expand on the literature in this field by investigating how a householder's sustainability views affect both their heating demand and their likelihood of owning a smart heating control (Chapter 7).

2.5.3 Heating systems and smart heating controls

The second core decision area is the householder's heating system. This comprises all the required technology to provide the householder with their required thermal comfort. In this section we investigate heating controls, as this is the key research area in Chapter 7, and we count upgrades to boilers and the installations of REHC as retrofitting measures covered earlier in this chapter.

Before we start to look at the different types of technology it is important to highlight the technology / environmental debate between technophilics and technosceptics (Brand & Fischer 2012). Technophilic see technical solutions as the answer to our environmental problems. They view the proliferation of technology as a method to facilitate ecological sustainability (Nishant et al. 2014). Technosceptics on the other hand argue that we need to change our lifestyle and behaviours in over to solve environmental issues. The remainder of this section will focus on the technophilic point of view and focus on the technologies trying to reduce space heating demand.

The penetration of boilers in the UK is high, with over 95% of householder having a boiler. *"Of these, 800,000 have no controls at all, almost 8 million have no room thermostat and over 70% lack the minimum levels of controls in the 2010 building regulations. Industry estimate that installing standard controls could reduce domestic energy used for heating and hot water by 30%: ensuring all homes had a timer, room thermostat and TRVs would reduce UK CO2 emissions 4.3Mt/year by 2020, just under 1% of annual emission (Department of Energy and Climate Change 2015*f*)."* However, the evidence on the potential energy savings that can be achieved from improvements in heating control is mixed, as Shipworth et al.'s (2010) showed that households with heating controls do not have a lower heating demand (lower temperature or duration) than households that do not use controls. While other literature (Department of Energy and Climate Change 2016, Kelly et al. 2013) highlighted some evidence that whole house thermostats and TRVs can save energy, but the evidence on thermostats with a timer or that can be programmed is still unclear. In a study from Department of Energy and Climate Change (2016), the authors also conclude that there is a lack of robust evidence related to the energy savings, cost effectiveness and usability of heating controls.

One area of growing interest is smart heating controls and smart thermostats which look to learn the householder's behaviours and heating preferences, and then optimise their heating patterns to save energy. Householders see smart thermostats as intelligent (67.2%), hi-tech (49.3%) and convenient (43.3%) (Dimitrokali et al. 2015). Smart heating controls are growing in popularity with an estimated 100,000 devices being installed per year in the UK, which are being provided by energy companies, telecommunications companies and technology companies (Delta - Energy and Environment 2014, Department for Business Energy and Industrial Strategy 2016*c*). The key premise of the devices is to save householders energy, but a large number of householders find the experience of programming the smart heating control to be challenging, especially when the householder is older (Combe et al. 2012). This can lead to an increased level of energy consumption due to ineffective configurations. In addition, smart heating controls can struggle to learn the complex heating patterns and behaviours of householders, as they have limited access to occupancy, householders' activity levels and contextual information (Yang & Newman 2013). These factors define some of the challenges when it comes to smart heating controls, but they can also provide significant advantages. First, due to the increase in data collected from smart heating controls it is now possible to estimate a householder's property characteristics (heat loss rate and heat capacity), enabling customised advice on energy efficiency measures (Rogers & Wilcock 2012, Firth et al. 2013, Van Der Ham et al. 2016). Second, the data can be used to present householders with personal heating advice (Rogers & Wilcock 2012). Finally, Dimitrokali et al. (2015) showed that 70% of householders felt that the smart heating controls changed their heating behaviours. If each of these changes is towards more sustainable heating patterns then smart heating controls could meet the estimated 1% savings in the UK's annual CO_2 emissions as stated by Department of Energy and Climate

Change (2015*f*).

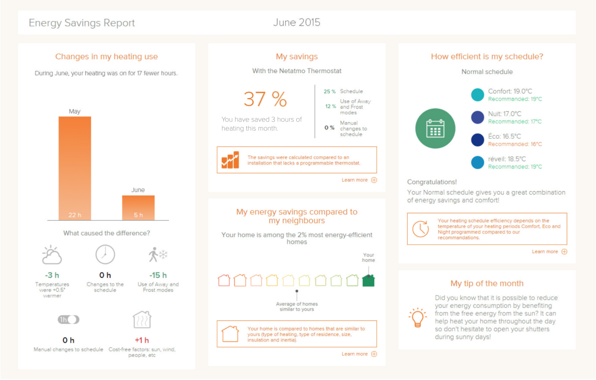
2.5.4 ICT and householders' heating patterns

Much of the academic literature has focused on the application of ICT to help householders reduce their electric energy consumption (Darby 2006, Kjeldskov et al. 2012, Paay et al. 2014, Kjeldskov et al. 2015). However, less research has been carried out on the use of ICT to help householders reduce the environmental impact of their heating patterns; this will be the core topic of this section and a core topic of Chapter 7.

2.5.4.1 Heating reports and heat coaching

A number of companies who sell smart heating controls now provide householders with a heating report Figure 2.25. The reports provide the householders with basic information about their heating patterns, including hours of heating, average setpoint, changes in their heating patterns and, finally, they provide the householder with advice and recommendations on how they can have more sustainable heating patterns to save money and energy. In Rogers & Wilcock (2012), the heating report provides householders with an estimate of the energy saving the householder could gain through lowering their setpoint. For example, if last week you heat at 19 °C instead of 23.5 °C, it would yield a 9% saving based on your heating patterns. Likewise, ThermoCoach provides a layer on top of a manual or smart thermostat to help teach the householder how to use their thermostat. It achieves this by monitoring the occupancy patterns with occupancy sensors, then provides recommendations for both a setpoint and heating schedule, resulting in energy savings of 4.7% on a manual programmable thermostat and 12.4% on the Nest learning thermostat (Pisharoty et al. 2015). Next, Ponce et al. (2017) developed a smart interface that uses artificial neural networks and fuzzy logic to classify householders based on their energy consumption, environmental sentiment and their experience of using smart thermostats. It then uses this classification to present householders with different smart thermostat interfaces and energy saving recommendations to suit their needs, e.g. a novice smart thermostat user is sent messages in order to turn them into an experienced smart thermostat user, while Green Advocates are sent more complex heating advice to save energy (Ponce et al. 2017). Finally, Opower is using heating disaggregation to enable householders to compare themselves to similar households in their neighbourhood to stimulate engagement, and then provides the householders with targeted energy saving advice (Laskey & Kavazovic 2011).

Just these few applications of ICT show the potential of smart heating controls to increase householders' knowledge and understanding of their heating schedules, patterns and behaviours. However, do householders need to understand their heating patterns, or can smart heating control automation of householder heating patterns remove the need for this knowledge? In the next section we look at the current role of ICT to automate heating patterns.



Energy Savings Report June 2015

Changes in my heating use

During June, your heating was on for 17 fewer hours.

What caused the difference?

-3 h Temperatures were +0.5° warmer

0 h Changes to the schedule

-15 h Use of Away and Frost modes

0 h Manual changes to schedule

+1 h Cost-free factors: sun, wind, people, etc

My savings

With the Netatmo Thermostat

37 %

You have saved 3 hours of heating this month.

25 % Schedule

12 % Use of Away and Frost modes

0 % Manual changes to schedule

The savings were calculated compared to an installation that lacks a programmable thermostat.

Learn more ⊕

My energy savings compared to my neighbours

Your home is among the 2% most energy-efficient homes

Your home is compared to homes that are similar to yours (type of heating, type of residence, size, insulation and inertia).

Learn more ⊕

How efficient is my schedule?

Normal schedule

Confort: 19.0°C Recommanded: 19°C

Nuit: 17.0°C Recommanded: 17°C

Éco: 16.5°C Recommanded: 16°C

réveil: 18.5°C Recommanded: 19°C

Congratulations!

Your Normal schedule gives you a great combination of energy savings and comfort!

Your heating schedule efficiency depends on the temperature of your heating periods Comfort, Eco and Night programmed compared to our recommandations.

Learn more ⊕

My tip of the month

Did you know that it is possible to reduce your energy consumption by benefiting from the free energy from the sun? It can help heat your home throughout the day so don't hesitate to open your shutters during sunny days!

(a) Netatmo (2017), *Netatmo energy saving report.*

Kudos!

You've done an amazing job changing the temperature to save energy.

November Energy Report

energy@nest.com

Since October 2011, all Nests together have saved

224,348,732 kWh

That's the same amount of energy it would take to power the Empire State Building for over four years.

Welcome to your Nest Energy Report. It tells you how much energy you've used to heat or cool your home and has tips to help you save more.

Here's how you did:

This month you used 8 hours more than last month +8 hrs

Why did your energy use change?

We looked at a lot of reasons for energy changes - from weather to Auto-Away - and these are the ones that made the biggest difference for you this month. Learn more >

+16 hrs Cooler weather meant more energy use.

-6 hrs Kudos! Your schedule was more efficient this month.

-3 hrs Auto-Away turned on more often.

A tip for you:

Try turning down the temperature just 1°F

Energy use is rising as the weather cools, but we've found it takes about a week to get used to a slightly lower temperature. So try turning down the temperature across your schedule by 1°F. After a few days you'll feel just as comfortable at 69°F as you did at 70°F.

Interesting fact:

Your Away temperature is currently 57° F - the average for California is 58.1° F and the average for the US is 59.3° F. Save more for California - and your wallet - by turning your Away temp down for the holiday season.

A look at your Leafs:

You get a Leaf when you choose an energy-efficient temperature. Here's how many you got this month.

In November you earned: 29 4 more than October

You're in the top: 5% of Nesters Kudos!

What else is happening at Nest:

Nest at Best Buy > We're in stores across the US

Warm up to True Radiant > Perfect for radiant and radiator systems.

© 2012 Nest Labs Inc. 900 Hansen Way Palo Alto, CA 94304

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(b) Nest Labs (2017), *Nest thermostat energy report.*

Figure 2.25: Examples of heating reports.

2.5.4.2 Automation, machine learning and Artificial Intelligence (AI)

There has been a drive to develop automated algorithms that can replace the need for the householder to understand or schedule their heating patterns. To use the vocabulary of Pierce et al. (2010) the algorithms achieve this by "cutting" overall levels of heating, "trimming" the householder's setpoint or hours of heating, and "shifting" heating and cooling to times of less demand (Lu et al. 2010, Ellis et al. 2012, Scott et al. 2011, Jensen et al. 2016, Koehler et al. 2013). For example: Ellis et al.'s (2012) algorithm aims to predict when householders are leaving their property and then turns the heating off before the householder leaves, resulting in a 1-8% saving in gas consumption. Likewise, the PreHeat algorithm (Scott et al. 2011) sensed and predicted householder occupancy to automatically set heating schedules, which was shown to reduce gas consumption and reduce MissTime (householders present but the temperature is not at the required setpoint). The algorithm also predicted per-room occupancy, allowing for further reductions in heating. Next, HeatDial (Jensen et al. 2016) allows householders to set up internal setpoint tolerance ranges for heat pumps, which enables the heating system to automatically load shift electricity consumption to make heating more energy efficient. However, the authors highlight how householders' had misconceptions regarding how the system worked, and they warned that automated systems must provide feedback to householders on their intended actions. The concept of householders misunderstanding the action of automated systems was also shown as an issue when looking at smart thermostats by Yang & Newman (2013), and Yang et al. (2014).

Although the effectiveness of smart heating controls are questionable, they are still a vital area of research to explore and will be the core topic of Chapter 7.

CHAPTER 3

SUSTAINABLE HCI, ICT4S AND ENCOURAGING RETROFITTING

"We have to make the momentous choice between brief greatness and longer continued mediocrity" — Jevons (1866) — The Coal Question

3.1 Introduction

The research communities of sustainable HCI and ICT4S have grown considerably in the past several years, with researchers investigating topics ranging from persuasive technologies for electric energy consumption to participatory sensing for energy management. However, are these the most effective routes to generating sustainability? This chapter presents how these communities are focusing on research into persuasive psychological techniques to encourage householders to change their day-to-day behaviours. Nevertheless, behaviour change techniques have limited energy saving potential and can themselves be hard to sustain on a daily basis. Therefore, we propose an area of research that has received limited attention: encouraging household retrofitting to provide greater energy efficiency savings and create a more sustainable change. The use of sustainable HCI and ICT to encourage retrofitting sets a unique challenge that is very different in character from the traditional focus on everyday behaviours and habits because retrofitting requires a considerable commitment from both individuals and society. Finally, we suggest four key areas where these research communities can help support retrofitting: 1. psychological encouragement of retrofitting; 2. information provision for retrofitting; 3. energy efficiency participatory sensing; and 4. increased focus on sustainable interaction design for household heating systems.

The content of this chapter is an extended version of the author's workshop paper that was published and presented at the 8th Nordic Conference on Human-Computer Interaction (NordiCHI 2014).

3.2 Background

In this section we will present the background literature to the research contained in this chapter.

3.2.1 Sustainable HCI

In recent years there have been a number of studies that review the state of sustainable HCI. One of the first was the research completed by Goodman (2009), who highlighted three core areas of environmental discourse: sustainable interaction design, re-visioning consumption and citizen sensing. This research was then further developed by DiSalvo et al. (2010), who took these discussion topics and segmented them into five genres of sustainable HCI, which are explored below:

1. **Persuasive technology** — The research focuses largely on the use of psychological techniques to encourage individuals to behave in a more sustainable manner. The genre is grounded by the research completed by Fogg (2002). Much of the research regarding persuasive sustainable HCI about sustainability in terms of reducing wasted resources, and the success criteria of sustainable HCI is to change an individual's behaviours (DiSalvo et al. 2010). In the quest to persuade customers in the energy sector to reduce their energy usage, the focus has been primarily on feedback of energy consumption (Mattern et al. 2010). A variety of different persuasion techniques have been used, including social comparison (Foster et al. 2010, Graml et al. 2011, Laskey & Kavazovic 2011, Petkov et al. 2012), social proof (Mankoff, Matthews, Fussell & Johnson 2007, Mankoff et al. 2010), providing thought-provoking information (Milenkovic et al. 2013) and gamification techniques such as competition, rewards and leaderboards (Foster et al. 2010, Gamberini et al. 2012). There are three drivers that have propelled the rapid rise in persuasive feedback. First, the increase of readily available data being collected from smart meters that enables researchers to develop novel and engaging methods of presenting the householder's energy consumption. Second, the rise of social media has enabled researchers to apply persuasion techniques involving social influence; and thirdly, the rapid rise of smart phones and smart phone applications have provided a simple and elegant method of delivering persuasive messaging (Petkov et al. 2012). However, the field of persuasive eco-feedback has faced some criticism due to its lack of applying rigorous comparative controls, through establishing baseline data or implementing control groups to test interventions (Froehlich et al. 2010). In addition, a number of studies have highlighted that a large number of householders struggle to understand eco-feedback surrounding energy consumption, as householders do not think like resource managers (Strengers 2011, Broms et al. 2010). The application of persuasion techniques also narrows the framing of sustainability to individuals' behaviours and their interrelationships, rather than focusing on the broader systemic view of sustainability (Knowles et al. 2013, Brynjarsdottir & Håkansson 2012). Finally, the field of persuasive technologies focuses on the curtailment of behaviours, which can draw attention away from encouraging longer lasting efficiency behaviours like retrofitting, which we will highlight as an issue throughout this chapter.

2. **Ambient awareness** — This technique tries to draw the individual's attention to the topic of sustainability through the use of visualisations. Ambient awareness can come in two types: direct visibility, which draws the user's attention to the unsustainable behaviour (two examples of this

include the Power-Aware Cord (Gustafsson & Gyllenswärd 2005) and the Energy Orb (Faruqui & Sergici 2009)); and desired visibility, which looks to highlight the desired behaviour through visualisation (DiSalvo et al. 2010). The field of ambient awareness looks to remove the cognitive burden on the householder by presenting the undesired or desired behaviour through ambient media (sound, light, airflow or water movement) that makes it easier for individuals to process, leading to behaviour change. Providing householders with coloured light feedback when selecting heating settings has been shown to increase the amount of energy saved compare to standard numerical feedback while lowering the householder's cognitive load (Maan et al. 2011). Likewise, Lu et al.'s (2016) results showed that participants who received colour-based energy feedback (different coloured radiators from red to blue) decreased their energy consumption more, and they showed that red is a key indicator of high energy consumption compared to blue. Lu et al.'s (2015) work has also shown that manipulation of room lighting can influence an individuals' judgement of room temperature. Ambient awareness has also been used to present householders with new methods of displaying their electricity consumption (Broms et al. 2010). There are limited applications of ambient awareness in the area of retrofitting, but as we will see in section 3.2.3.2, thermography can be seen as an application of ambient awareness through using heating patterns to remove the cognitive burden of understanding heat loss within a property.

3. **Sustainable interaction design** — This strand looks to push sustainability through industrial design philosophy (Blevis 2007), which drives a change to manufacturing, use and disposal practices (Goodman 2009). Sustainable interaction design also argues that sustainability should be the main focus of interaction design through motivating sustainable behaviours, rather than solely relying on legislation and governmental policy. Blevis's (2007) research highlights the need for sustainable interaction design to promote both a link between the design of new artefacts and their effects (displacement or obsolescence) on currently used artefacts, and an understanding of how new artefacts can be designed to promote renewal or reuse. Key areas of the sustainable interaction design field have included: investigating why individuals preserve objects (Hanks et al. 2008, Odom et al. 2009), the growth in mobile phone obsolescence (Huang & Truong 2008, Bates et al. 2015) and exploring the link between fashion and sustainable interaction design (Pan et al. 2012, 2014). Sustainable interaction design research has expanded to investigate the role end-users can play in the design of digital artefacts long after their development by professionals to meet their everyday needs (Wakkary & Tanenbaum 2011, Maestri & Wakkary 2011). The field of sustainable interaction design is of particular interest when considering retrofitting: houses have a lifespan of 50-100 years, so they undergo a large amount of renewal and reuse, which are key principles of sustainable interaction design. However, similar to other areas within the sustainable HCI community, limited work has been done linking the two fields.

4. **Formative user studies** — This takes a more bottom-up approach through trying to understand householders' and users' cultural values, beliefs and norms towards being sustainable. The research focuses more on the assessment of the users, rather than directly looking to change

their behaviours and actions as is done with persuasive technologies, ambient awareness and sustainable interaction design. Formative user studies focus on the use of ethnography, interviews, surveys and questionnaires to undertake a grounded theory approach to understanding the causal effects of unsustainable or sustainable behaviours. The technique has been applied to energy consumption behaviours (Strengers 2008, Pierce et al. 2010), and highlighted that householders' energy consumption behaviours are more strongly linked to mirco and macro level systems rather than being the results of conscious and motivated actions. Likewise, Woodruff et al.'s (2008) research evaluated individuals who have a high tendency to undertake sustainable actions and behaviours. The research showed that sustainable individuals make large sacrifices in terms of time, attention and effort to achieve their green lifestyles; they also undertake complex calculations to share, learn and partake in friendly competition with similar sustainable individuals. The research also highlighted that an individual's path to being sustainable was an evolving and continuous journey over time. Finally, in Strengers's (2008) study about comfort and cleanliness behaviours, she found that householders struggle to reduce their resource usage through social norms, as individuals do not have the required social knowledge; often this information is hard to collect due to discussions around resource management being considered private and personal topics.

5. **Pervasive and participatory sensing** — Burke et al. (2006) use a clear and concise definition for participatory sensing:

   "Participatory sensing will task deployed mobile devices to form interactive, participatory sensor networks that enable public and professional users to gather, analyse and share local knowledge."

   The increase in participatory sensing has been driven by the reduced cost of smart phones and the large reduction in low-cost sensors. These factors allow for large amounts of data to be collected, (e.g. body movements (Nike 2017), home temperature (Nest Labs 2011) and sleep quality (Hello 2017)) to be collected by a wide range of sources (individuals, employees and community groups). This rise in data has allowed the sustainable HCI community to implement more adventurous citizen science projects. The projects have shown the key role participants and communities can play in helping with the collection of data to improve their surrounding environment. Similar to community environmental information systems (DiSalvo et al. 2010), an advantage of participatory sensing is that individuals are included in the data collection and analysis. This provides them with a greater sense of control, which means they are more likely to be satisfied (Tiwari et al. 2010). Participatory sensing has been used in a number of applications to reduce energy consumption, including: to help optimise thermal comfort in commercial buildings (Hang-yat & Wang 2013, Jazizadeh & Becerik-Gerber 2012, Erickson & Cerpa 2012) and to reduce energy wasted by local shops that leave their doors open (Massung 2013). Participatory sensing has also been applied to a number of alternative sustainability challenges: air quality (Miyaki & Rekimoto 2008, Dutta et al. 2009), transportation (Mun et al. 2009, Ganti et al. 2010, Jacobi et al. 2015, Hasselqvist et al. 2016) and water and trash management (Kim et al. 2015, ChuckMo 2016). However, pervasive and participatory sensing has had limited application when it comes to retrofitting. Few householders share their data openly, unless part of a scientific trial. A key area where householders do share data is through open home events, but to conduct a large-scale citizen science project, householders need to be more willing to share their energy data.

The five genres laid out by DiSalvo et al. (2010) provide a good overview of sustainable HCI. However, their research highlights the focus on changing an individual's behaviour through persuasion, which was also supported by Knowles et al.'s (2013) review of sustainability research in computing. In the sub-genres of sustainable HCI, there is little mention of persuading individuals or groups to change the physical characteristics of their environment or consideration of large, one-off decisions which reduce environmental impact (e.g. the installation of energy efficiency measures). Knowles et al.'s (2013) review also has limited mention of the role computing can play in helping communities and individuals change the physical characteristics of their environment to promote more sustainable lifestyles. This chapter looks to expand the sustainable HCI literature by investigating sustainable HCI in the context of retrofitting.

Finally, the sustainable HCI community has highlighted that they need to expand their focus beyond technology itself to consider the role technology plays in particular social contexts, especially in governmental policy and causing larger systemic change rather than incremental changes (Dourish 2010, Silberman et al. 2014, Knowles et al. 2014). This has prompted sustainable HCI researchers to investigate their role in environmental policy (Dourish 2010, Thomas et al. 2017), with a key focus on climate change, green ICT procurement policies, and waste electrical and electronic equipment. This chapter will highlight that it is logical to expand the role of sustainable HCI to include retrofitting, installation of energy efficiency measures, and their wider social and political impacts. To continue the evaluation of related work, the next section will take a more in-depth look at sustainability in design vs sustainability through design.

3.2.2 Sustainability in design vs sustainability through design

The original research by Mankoff, Blevis & Borning (2007) split the concept of sustainable HCI into two divisions:

1. **Sustainability in design** — Focuses on how we can design the physical products around us to be more sustainable, and is closely related to sustainable interaction design, but looks in further detail at the life-cycle of products. Sustainability principles are increasingly being used throughout the design and manufacturing process of digital products (Apple 2016, HP 2017), and the same changes are happening in the built environment (European Commission 2012, Pelsmakers 2014). Blevis (2007) defines the need for the designer to take into consideration not only the impact of the product during use but also in disposal, and they must understand the displacement and obsolescence effect the item has on other products. Sustainability in design has concentrated on

re-use (Hanks et al. 2008, Huh et al. 2010), disposal (Huang & Truong 2008) and attachment to objects (Odom et al. 2009, Pan et al. 2014). More recently, the field of sustainability in design has expanded to focus on the environmental impact of the infrastructure which supports artefacts being designed, especially digital artefacts (Bates & Hazas 2013, Schien et al. 2013, Preist et al. 2016).

2. **Sustainability through design** — States that it is the role of the designer to engage in solving wicked problems (Rittel & Webber 1973) by creating and manipulating artefacts to help transform the world from our current state to a more preferable state (Zimmerman et al. 2007). In sustainable HCI, sustainability through design looks at the role artefacts can have in supporting a more sustainable lifestyle, and how design can help individuals to make the right sustainable decisions. Sustainability through design includes the persuasive technologies, ambient awareness and the participatory sensing genres from the research outlined above. The key outputs of research through design are: a clear problem framing and definition of the preferred world state, a set of artefacts (designs, prototypes, products) and a clear understanding of the design process (Zimmerman et al. 2007).

The research completed by Mankoff, Blevis & Borning (2007) and the role that the two design principles (sustainability in design vs sustainability through design) play within the sustainable HCI community is of key relevance when it comes to energy consumption and retrofitting. As highlighted by DiSalvo et al. (2010), most of the research completed by the sustainable HCI community is focused on sustainability through design, especially when it comes to reducing energy consumption. In this chapter we highlight the need for the sustainable HCI community to further investigate using sustainability through design to get individuals and community groups to change the design of their environment (sustainability in design). Changing this focus will also cause the individuals and groups to become the designers of their own sustainable environment. As discussed by Kaplan (2000), allowing individuals to participate is a key element in behaviour change: *“People want to participate, to play a role, in what is going on around them; they hate being incompetent or helpless."* In conjunction, if we can encourage individuals to think of sustainability in the design of their household and in their environmental choice around products, we can start to generate more durable sustainability; this is where we feel the application of retrofitting fits into the sustainable HCI community. This combination of using sustainable HCI applied to retrofitting and applying it to help householders design their own sustainable environment is the key contribution of this chapter.

Next, alongside the work being completed within the sustainable HCI community, there is a large body of research that is developed by the ICT4S and ICT for Energy (ICT4E) communities that focuses more on the installation of energy efficiency measures and retrofitting; these will be highlighted in the next section. It must be noted that from now on when we refer to ICT4S we are also including the relevant literature from the ICT4E community.

3.2.3 ICT and retrofitting

The review presented below will explore a number of the ways in which ICT is being used to promote retrofitting.

3.2.3.1 Advice tools for energy efficiency measures

ICT can be a powerful tool when it comes to providing householders with information about energy efficiency measures. The first tools developed allowed householders to input basic property information. This would then be used to calculate a list of general recommendations for energy efficiency measures including their cost, potential energy savings and cost savings. Examples include: Energy Savings Trust's (2017*a*) home energy check (Figure 3.1a) and npower's Home Energy Survey (npower 2017) (Figure 3.1b). These tools provide the householder with a general view of the potential options when it comes to retrofitting, but the information is not tailored to the householder. To further improve these tools researchers started to include data collected from both smart meters (Beckel 2015, Energy Savings Trust 2017*b*) and smart heating controls (Firth et al. 2013). This meant that individual property characteristics (leakage rate, heating capacity) would be determined without relying on householders to input large amounts of data. These improvements allowed for personalised energy efficiency recommendations for householders. This led to householders having a better understanding of the best option based on their personal context.

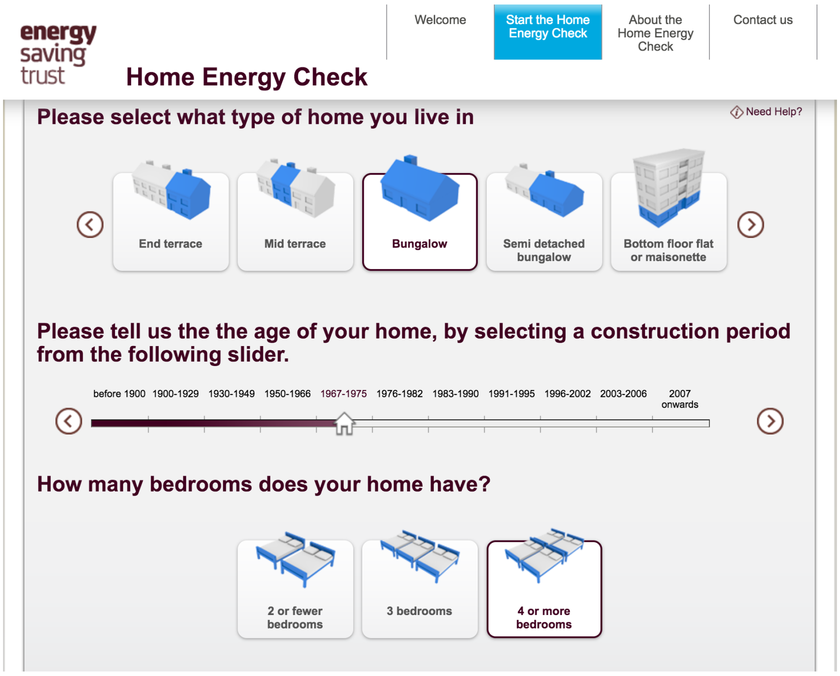
There has also been a growing development in tools that provide advice on the potential of Photovoltaic (PV) installations (Megujulo Energiapark 2016, Google 2017, Solar Guide 2017). Google's Project Sunroof is a good example of reducing householder friction to installing energy efficiency measures (PV) as, from a single postcode input, it calculates customised savings based on roof size and shape, shaded roof areas, local weather, local electricity prices, solar costs, and estimated incentives over time (Google 2017).

The final area in which ICT is helping householders gain advice on energy efficiency measures is to enhance and support eco-home open days. For example, "The Green Doors App" (Massung et al. 2014) and the SuperHomes retrofitting online database (SuperHomes 2017) provide a simple method for householders to gain practical information on different energy efficiency measures, and help build a community around retrofitting through shared learning.

3.2.3.2 Building modelling

To provide householders with the best advice possible, there are a number of applications of ICT to improve building modelling.

Firstly, the use of data from smart heating controls or low-cost temperature sensors can be used to gain data on internal temperatures, householders' desired setpoint, boiler usage and external temperature. This data can then be converted into a thermal model of the property (Rogers & Wilcock 2012, Beckel 2015, Ghosh et al. 2015). The increase in data collected on space heating is allowing for the development

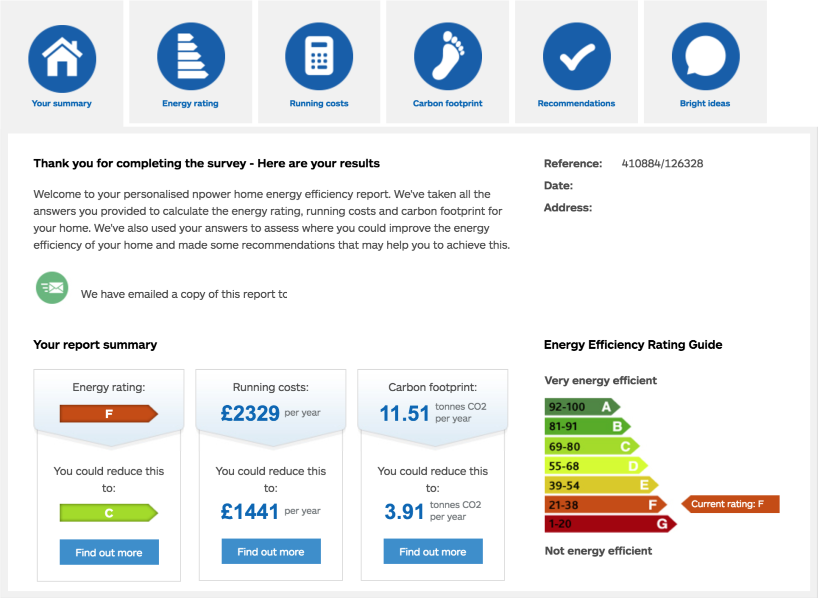


Please select what type of home you live in

Please tell us the the age of your home, by selecting a construction period from the following slider.

How many bedrooms does your home have?

(a) Energy Saving Trust - Home energy check (Energy Savings Trust 2017*a*).



Thank you for completing the survey - Here are your results

Welcome to your personalised npower home energy efficiency report. We've taken all the answers you provided to calculate the energy rating, running costs and carbon footprint for your home. We've also used your answers to assess where you could improve the energy efficiency of your home and made some recommendations that may help you to achieve this.

Reference: 410884/126328
Date:
Address:

We have emailed a copy of this report tc

Your report summary

Energy rating: F
You could reduce this to: C

Running costs: £2329 per year
You could reduce this to: £1441 per year

Carbon footprint: 11.51 tonnes CO2 per year
You could reduce this to: 3.91 tonnes CO2 per year

Energy Efficiency Rating Guide

(b) npower - Home Energy Survey - results (npower 2017).

Figure 3.1: General energy efficiency measures recommendation tools.

of more complex thermal models. The new models can estimate: building characteristics (Rogers & Wilcock 2012, Beckel 2015, Ghosh et al. 2015), householders' personal level of thermal comfort (Shann & Seuken 2013, Auffenberg et al. 2015) and householders' heating habits and routines (Ge & Ho 2014). A much clearer understanding of the factors that influence a householder's energy consumption can be developed through the models and estimates. This has only become possible due to the increased amount of ICT being installed within households.

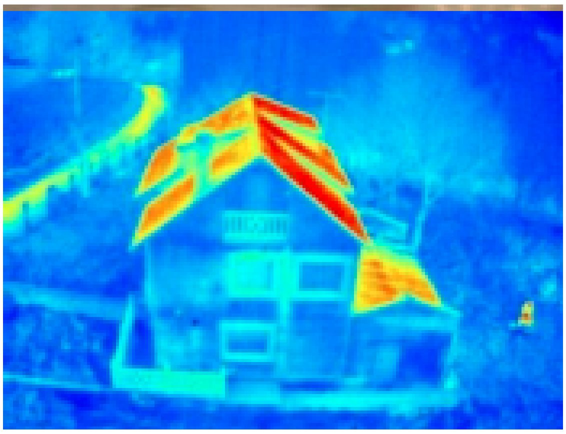
The second area of development is the application of low-cost thermal imaging technology (thermography; Figure 3.2) (Goodhew et al. 2014, Mauriello et al. 2015, 2016, Essess 2017, Mauriello et al. 2017). Thermography allows householders to see the heat flows that are normally invisible. Householders can then understand where their property is losing heat, and in turn know which areas of their property need improving. Presenting householders with a thermograph during a property energy audit has been shown to increase carbon savings, increase the number of energy-saving behaviours undertaken by the householders and, most importantly, has been shown to increase the levels of retrofitting (Goodhew et al. 2014). The decrease in cost of thermal and infrared cameras are helping make thermography quicker and cheaper. It can now be achieved with a standard smartphone and an extension camera (Figure 3.2b). This enables householders to undertake their own energy audits (Mauriello et al. 2016). However, it has been shown that novice users taking thermographic images can struggle with interpreting the images and lack the confidence to understand the severity of the heat loss presented in the images (Mauriello et al. 2017).

Finally, researchers have started to use robotics as a method of undertaking automated thermography, using both Unmanned Aerial Vehicles (UAVs) and indoor robots (Mauriello et al. 2015). This approach has helped scale up the process of undertaking energy audits, and has helped improve the models of the buildings. Recently, Essess's thermal imaging technology managed to map the building envelopes of 17,000 buildings in Cambridge, Massachusetts through their fleet of customised road vehicles (Essess 2017). The increased scale and reduction in cost means that thermography should have a significant impact on the uptake of energy efficiency measures.

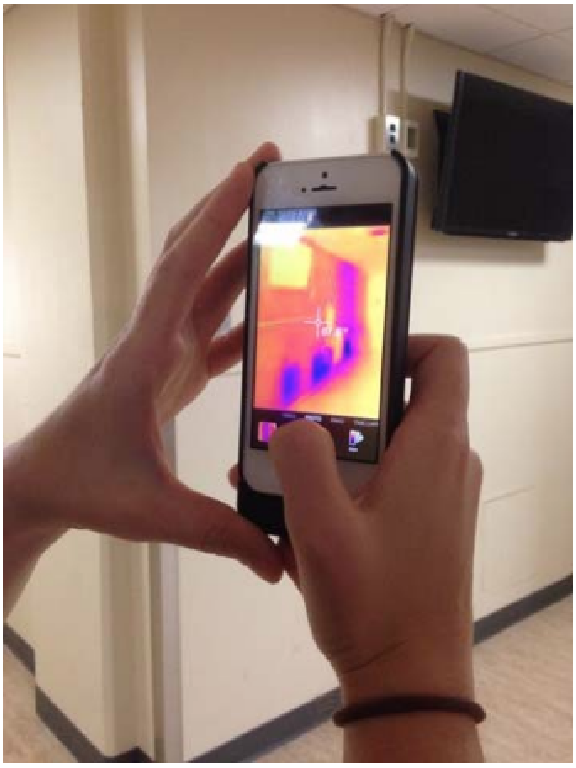
The projects presented throughout this section highlight the huge potential ICT can have in providing householders with simple, clear and relevant information when it comes to retrofitting. The next section will look to define a number of the core reasons why retrofitting should become a more integral part of both the sustainable HCI and ICT4S communities.

3.3 Why retrofitting?

In the background section above we have highlighted that there is an overwhelming focus in the sustainable HCI and ICT4S community on helping to change individuals' behaviours, especially with regards to the reduction of electrical consumption. This is supported by DiSalvo et al.'s (2010) paper showing that 70% of the 157 papers they reviewed were targeted at individual householders. However, simple behaviour change in the domestic energy sector can only save a limited amount of energy. For example, turning your thermostat down by 1°C from 19 to 18°C saves about 13% per year on energy



(a) Mauriello et al. (2016, p.4), *Thermal image of domestic home from a UAVs with a mounted thermal camera.*



(b) Mauriello et al. (2016, p.1), *A FLIR One connected to a iPhone 5s being used to assess a hallway in a building on the University of Maryland's campus.*

Figure 3.2: Examples of thermography technology

used for space heating (Department of Energy and Climate Change 2012*b*), and turning off radiator valves in unused rooms saves around 4% per year (Department of Energy and Climate Change 2012*b*). Providing visual feedback of energy consumption can also provide limited results of between 5% - 15% (Darby 2006). On top of this, it has also been shown that simple behaviour change techniques used to reduce energy consumption can be reliable in the short-term but struggle to achieve durable change (Young 1993); this was also an issue in the persuasive sustainability community (Brynjarsdottir & Håkansson 2012). These facts show that individual behaviour change can save energy, and it is beneficial for a proportion of the sustainable HCI and ICT4S communities to research the advantages of behaviour change. However, the relatively low potential energy savings highlight the need to drive these communities in a different direction: considering how to encourage and support citizens and authorities to rework the infrastructure of their communities to be fundamentally more sustainable. This can lead to significantly more transformative and lasting solutions than those addressed at specific ongoing behaviours within the existing infrastructure, but are also significantly more challenging to enable. Changing infrastructure requires investment of money and time, as well as the commitment of individuals, authorities and infrastructure providers. The level of infrastructure transformation required and the speed at which the transformation has to happen helps provide a significantly wicked problem to apply research through design philosophy (Zimmerman et al. 2007). Retrofitting of properties is one example of infrastructure transformation. The aim should be to get householders to make larger commitments through the installation of energy efficiency measures in their property, for instance through the installation of improved insulation, heat recovery systems and low-carbon and renewable energy sources. The application of sustainable HCI and ICT4S to retrofitting is a fundamental part of the rest of this thesis (Chapter 4 and 5).

The advantage of focusing on retrofitting and energy efficiency measures is that these topics can generate higher CO_2 savings. Research has shown that retrofitting can yield potential energy savings ranging from 45% (Ballarini et al. 2012) up to 80% in some cases (Stafford et al. 2011). Correspondingly, retrofitting also results in long-term energy savings, as once the measure is installed it will save energy for subsequent years (Hamilton et al. 2013), including when new occupants take over the household or office space. Despite the positive benefits it provides, retrofitting requires a major commitment of time, energy and money by householders and businesses, and this provides an interesting challenge for these academic research communities to tackle. On top of this challenge, society is currently locked into a social norm of not considering energy efficiency measures when undertaking construction (beyond a legal minimum), and only those who are seriously committed for environmental reasons go against this norm. As has been discussed before, ICT has a role in changing community norms (Massung et al. 2013), and this could also be a key area where the sustainable HCI and ICT4S communities can provide insight by changing the way retrofitting is portrayed in our society. In turn, this can help change the norm over time to one in which retrofitting is actively considered and often implemented. For these reasons, more researchers in these communities need to focus more of their expertise and attention towards retrofitting, both at an individual householder and community level.

3.4 How sustainable HCI and ICT4S can support retrofitting

From an environmental perspective, the potential impact of retrofitting is high, and so these energy efficiency measures are a good application for the overall sustainable HCI and ICT4S communities. In this section, we provide a number of recommendations for the way these communities can encourage an increase in retrofitting.

1. **Psychological encouragement of retrofitting** — This investigates the potential use of psychological techniques to promote individuals or groups to change their physical environment to make it more sustainable. Researchers can take the ideas and techniques developed in the fields of persuasive technologies and apply them to larger infrastructure decisions, especially the persuasive technology research that has grown from Fogg's behaviour model Fogg (2002). It is also vital to investigate how current behaviour change frameworks can provide increased insight into a householder's decision process when it comes to retrofitting, as well as the barriers and drivers for householders. Department for Environment, Food and Rural Affairs (DEFRA)'s pro-environmental behaviour framework (Department for Environment & Affairs 2008) and the power law of engagement for energy saving in Chapter 4 are two examples of behaviour change frameworks that help provide insights around retrofitting.

   The field would allow researchers to explore the wider sociological techniques that can promote retrofitting within our society. This would help the sustainable HCI community move away from focusing on the individual, which Pierce & Strengers (2013) highlighted as an issue.

   Finally, as retrofitting requires a large commitment by the householder in terms of time, finance, or lifestyle change, the sustainable HCI community will have to take a slightly different approach to behaviour change. It will have to start to look at psychological techniques that encourage the purchase of high-priced items and large one-off decisions, rather than small habitual behaviour change. It will also have to explore new applications of ICT to support these new psychological techniques and models. This will be explored throughout both Chapter 4 and Chapter 5.

2. **Information provision for retrofitting** — This technique explores the way sustainable HCI and ICT4S can be used to increase both the awareness and knowledge of retrofitting. Massung et al. (2014) proposed a number of barriers to retrofitting, which include a number of informational barriers, such as:

   - Lack of reliable information about products;
   - Difficulty in finding trusted builders to carry out the work;
   - Lack of understanding about levels of disruption required in the work.

   Digital technologies can be used to help reduce the barriers highlighted above, and a number of the applications of ICT4E highlighted within section 3.2.3 are starting to provide this information. By providing householders with the right information that answers their concerns about retrofitting, we can improve the probability of householders installing energy efficiency measures. However, it is important that we do not just present householders with their energy consumption and presume a change in behaviours. This has already been attempted in a number of applications (Mankoff et al. 2010, Foster et al. 2010, 2011). Researchers need to go further by providing data that informs the householders how to re-design their own household to make it more sustainable. The rise of the connected home is making it easier to collect data that enables the presentation of information tailored to the individual householders rather than general information applied to all householders. It is key that this tailored information also includes a plan of action the householder can follow. Finally, to help the transfer of learning between information provision projects, it is important to take research presented in section 3.2.3 and apply rigorous design techniques to the artefacts being developed.

3. **Energy efficiency participatory sensing** — Participatory sensing has been applied to a number of environmental sustainability problems, but currently it has limited applications in the domestic energy sector. The rise of the connected home is going to allow more householders to collect a wide range of datasets about internal temperatures, energy consumption, air quality and noise levels within the household. This provides the perfect opportunity for sustainable HCI researchers to apply their current work in participatory sensing to a different setting, especially when it comes to sharing knowledge and learning from installing and maintaining energy efficiency measures. As the work completed by Woodruff et al. (2008) showed, individuals who have a high tendency to undertake sustainable actions are also willing to share and participate in helping the sustainability community. These individuals would make ideal lead participants for energy efficiency participatory sensing projects. The projects would help semi-engaged householders who are thinking of undertaking retrofitting to feel more empowered through contributing data, asking questions and highlighting retrofitting challenges. This would also lead to a greater level of satisfaction with installed energy efficiency measures due to the higher sense of control over the installation (Tiwari et al. 2010).

4. **Increased focus on sustainable interaction design for household heating systems** — Chapter 2 showed that space heating accounts for a large percentage of domestic energy consumption. Therefore it is important from a sustainability in design point of view to increase our understanding of the environmental impact of new heating system artefacts. A number of areas of investigation would be to explore:

    a) How do current smart heating system artefacts displace or make obsolescent, more traditional or adaptive methods of heating?

    b) How does the design of new heating system artefacts encourage users to minimise energy consumption over the lifetime of the artefact?

    c) What are the infrastructural effects of increased supply and control over heating demand?

d) What are the disposal practices needed to help encourage the rapid change from unsustainable heating systems to more efficient heating systems?

e) How can heating system artefacts help householders understand the environmental impacts of increasing levels of comfort, and provide householders with guidance towards suitable energy efficiency measures?

> The above questions provide initial areas of research, but this list is not an exhaustive view of the applications of both sustainable interaction design and sustainability in design practices.

Retrofitting is an opportunity to apply current and new sustainable HCI and ICT4S techniques to the problem space of increasing the number of householders re-designing their physical environment to make it more sustainable. The field should look at both the installation of large energy efficiency measures like heat pumps, solar panels or heat recovery systems, and small measures including smart heating controls, energy saving light bulbs or TRVs. It is also important to note that the main focus of researchers should be on the current housing stock rather than looking at changing regulation surrounding new builds. Chapter 2 highlighted the slow rate of building replacement, especially in the UK, where most of the housing stock will still exist in 2050. Therefore this should be the main focus of the four research areas highlighted above, and the regulation around new buildings should be left to the sub-genres of sustainable HCI that are focused on policy and wider systemic change.

Finally, throughout this chapter the focus has been on individuals or groups changing the physical properties of their household. However, retrofitting does not have to be limited by this boundary: future research can look into the evaluation of implementing physical changes in co-working spaces or community shared spaces, like offices, village halls or local churches. Individuals have less control over the property in these spaces as they are not the owner. Therefore researchers will need to look at systems that work with a number of stakeholders to reach an agreement to retrofit.

3.5 Conclusion

This chapter has investigated the current landscape of sustainable HCI and ICT4S. We have proposed that there is a valuable opportunity for both communities to apply their current research to retrofitting, especially as retrofitting in the domestic energy sector can generate large energy savings and reduce the amount of GHG emissions produced. The contributions to knowledge of this chapter is, firstly, highlighting to the sustainable HCI and ICT4S communities the opportunities to use their current research in a more effective way to reach the required EU emissions targets. Secondly, to stimulate discussion and propose a number of core areas where these communities can already contribute towards increasing the rate of retrofitting.

To help stimulate these new areas in Chapter 4 and 5, research is carried out to help better understand the use of using psychological encouragement to increase levels of retrofitting. Chapter 7 will then explore some of the behavioural factors influencing household heating systems.

CHAPTER 4

POWER LAW OF ENGAGEMENT FOR ENERGY SAVING FRAMEWORK—TRANSFORMING DISENGAGED HOUSEHOLDERS INTO RETROFITTING ENERGY SAVERS

“In the face of an absolutely unprecedented emergency, society has no choice but to take dramatic action to avert a collapse of civilization. Either we will change our ways and build an entirely new kind of global society, or they will be changed for us. ” — Brundtland & Ehrlich (2012)

4.1 Introduction

How can we transform householders from being disengaged, passive energy consumers and turn them into highly motivated, retrofitting energy-saving masters? In this chapter the power law of engagement for energy saving framework is introduced, which breaks down the process of engaging householders into eight defined stages. The framework is based on the householder’s level of engagement and commitment, but applies Fogg’s behaviour model at key stages to help evaluate the decision-making process of the householder. The focus of the framework is both to build up the individual’s level of commitment and engagement, and to allow them to provide feedback to the community to build a greater culture of retrofitting. The research takes a similar approach to Strengers’s (2014) ‘Resource Man’ through creating a number of personas (e.g. stages in the framework) to help simplify and generalise our knowledge and understanding of the retrofitting process. The chapter also describes a set of tools that can be used to take the householder on a journey to reduce their overall energy consumption and help them progress through the eight stages. Throughout these descriptions key examples of where ICT can help are highlighted.

The content of the chapter is an edited version of the author’s paper that was published and presented at the 2nd ICT for Sustainability Conference (ICT4S 2014), where it was nominated for a best paper award.

4.2 Background

A number of theories of behaviour change have been proposed in the academic literature, and this section highlights the key literature and summarises the insights they offer to the particular problem explored in this chapter.

To begin, Lewin's (1951) influential change theory defines behaviour change as having three states: freezing, unfreezing and refreezing (Jackson 2005). In applying this to retrofitting, householders face a number of 'steps' of unfreezing and refreezing as their levels of commitment to retrofitting change and their willingness to undertake energy efficiency measures change. Building on this, Kaplan (2000) adopts an evolutionary psychology perspective on behaviour change. He emphasises three key elements that affect our behaviour and motivation:

1. *"People are motivated to know, to understand what is going on; they hate being confused or disoriented.*
2. *People also are motivated to learn, to discover, to explore; they prefer acquiring information at their own pace and in answer to their own questions.*
3. *People want to participate, to play a role, in what is going on around them; they hate being incompetent or helpless."*

The key factor of Kaplan's (2000) research is that it is not about telling people what to do, but about encouraging people to learn about and discover new behaviours, and along the process to guide them to more environmentally responsible behaviours. In addition, his research also provides insight about appropriate empowerment strategies to move individuals between the different stages of engagement.

The next model of persuasive behaviour change that has gained attention for its simplicity is Fogg's Behaviour Model (FBM) (Fogg 2009) (Figure 4.1). As highlighted in Chapter 3, the FBM has promoted a sub-genre of persuasive technologies within sustainable HCI. It looks to break down behaviour into three factors: motivation, ability and trigger. In Fogg's (2009) research, he shows that you need either high motivation or high ability in order to perform a task, but without a trigger to set the action in motion, the behaviour change will fail. This model provides a good framework for considering the psychological and environmental factors which encourage particular behaviours.

Both the FBM and Kaplan's (2000) research provide insights into short-term factors influencing an alternate behaviour. An alternative model, the transtheorectical model (Prochaska & Velicer 1997), considers the longer term processes involved in unfreezing and refreezing at a given level. It was originally designed to be applied to health behaviour change, but has also been applied to provide insights into domestic energy consumption (He et al. 2010). The model proposes six stages to behaviour change: 1. pre-contemplation, 2. contemplation, 3. preparation, 4. action, 5. maintenance and 6. termination.

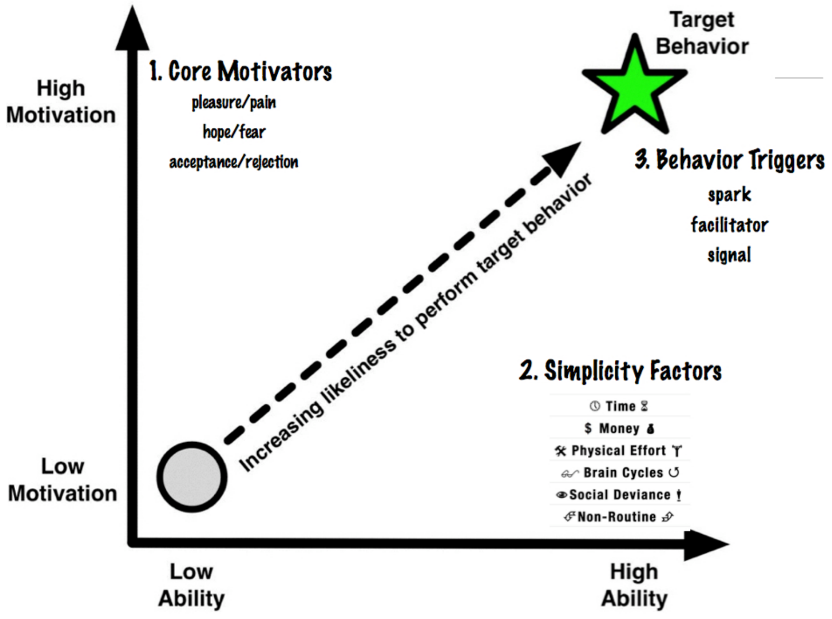


Figure 4.1: Fogg (2009, p.5), *Fogg's behaviour model.*

The model is interesting for a number of reasons: firstly, it breaks down the process of behaviour change into a number of sequential stages. Secondly, the work illustrates the importance of the stages before and after an action. Finally, it defines the need to apply different approaches of behaviour change at different stages in order to encourage individuals to make sustainable change in their behaviours.

All the models presented so far have been mainly focused on behaviour change for individuals rather than for wider society. However, one interesting area of research is community-based social marketing (McKenzie-Mohr 2000). The research in this area takes a slightly different approach, identifying all the barriers that could stop a pro-environmental action from taking place. It describes five tools that can be used for behaviour change, including:

1. Commitment - It is hard to get people to commit to the large change of retrofitting. However, we can increase the likelihood of doing so through asking people to make a small initial commitment, then following it up with a larger commitment (Freedman & Fraser 1966).

2. Prompts - Prompts can be used in a similar way to triggers within the FBM: they can catalyse the behaviour change.

3. Social Norms - The people around us have a major influence on our behaviour (Cialdini et al. 1990), and it is therefore important that these social influences push neighbourhoods towards retrofitting. It has been shown that up to a 6% reduction in energy consumption can be achieved through the application of social norms (Dolan & Metcalfe 2013).

4. Communication - In community-based marketing there are a number of key communication principles, including: captive information, using credible sources, framing of the message, making the message easy to remember, providing personal or community goals, emphasising the personal context and providing feedback (McKenzie-Mohr 2000).

5. Incentives - When it comes to energy usage, incentives are broken down into two main types: financial and moral (Dolan & Metcalfe 2013). Incentives need to be used close to the delivered behaviour, and must be used only when the behaviour is positive. However, care must be taken both when removing incentives and when deciding the size of the incentive (McKenzie-Mohr 2000).

The defining feature of the community-based social marketing approach is that it includes social elements to increase people's engagement. This can be through commitments, social norms and communication, but this is only part of the story when it comes to engagement. One interesting area of research on engagement is looking at the work in social media and open source projects. In this field, a ladder of participation is presented (Li 2007), which splits people into a number of groups, including: inactive, spectators, joiners, collectors, critics and creators. The idea behind the ladder of participation is the way it represents people's engagement. At one end of the scale we have a large proportion of people who are inactive or just spectators. These people have a low engagement threshold and low motivation when it comes to social media. However, at the other end of the scale we have the creators and critics; these are at the highest level of engagement or motivation, and provide a vast amount of knowledge to the social media world. The best graphical representation of the power law of participation can be found on Ross's (2006) blog (Ross 2006) Figure 4.2.

The power law of participation can guide us to a structure for promoting long-term householder engagement which has been shown to be an issue in a number of pro-environmental behaviour change projects (Young 1993, Wood & Newborough 2003). If we ask householders to make little commitments to begin with (spectator), then build to making the large commitment of retrofitting (collectors), to finally encouraging the householder to become an energy saving master (creators), we can start to develop sustained behaviour change. This idea will be further addressed in section 4.3. Summarising the insight of the theories explored in this section, we see:

1. The importance of guiding householders to discover and learn more about sustainable behaviour;

2. That the right level of ability or motivation along with the right trigger can cause behaviour change;

3. That we need to look not only at the desired behaviour change, but also at the time before and after;

4. The importance of social aspects on a householder's decision, plus the importance of allowing people to demonstrate their behaviour change;

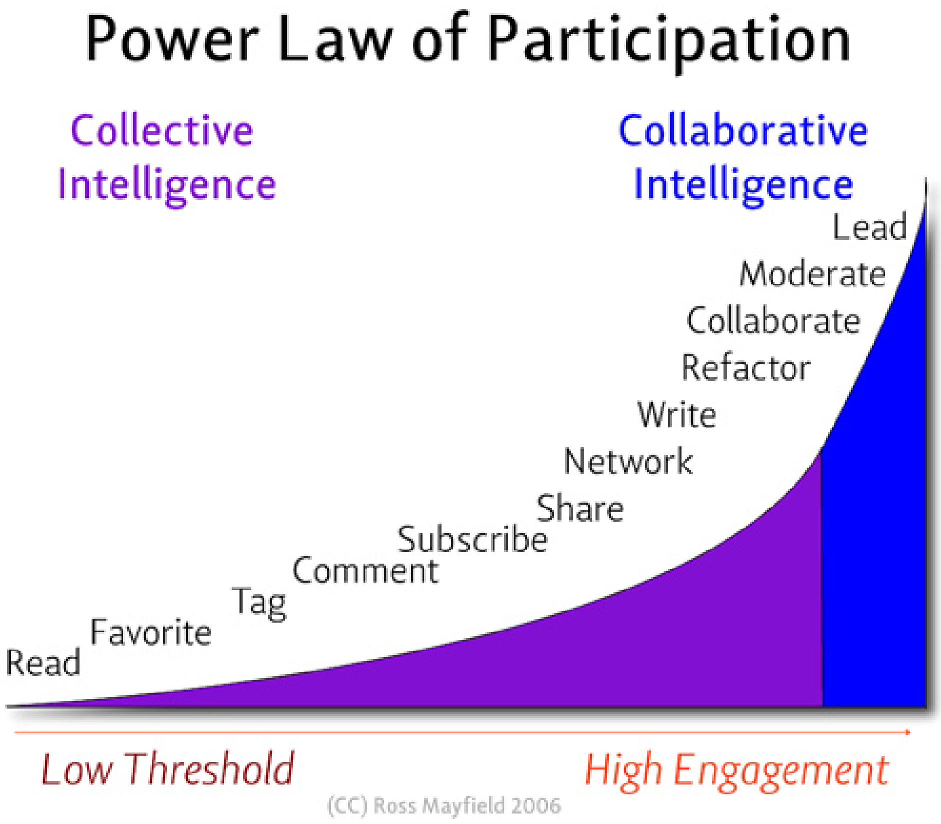


Figure 4.2: Ross (2006), *Power law of participation.* Inspired by Li (2007).

5. That a long-term vision, with the right structure, can play a vital role in encouraging retrofitting.

These five points are the defining reason for developing the power law of engagement framework, which will be expounded next.

4.3 Power law of engagement for energy saving

In this section we present a novel framework of householder engagement called "power law of engagement for energy saving" (Figure 4.3), which captures the insights of the theories presented above and applies them to retrofitting. The first element of the framework, its defining structure, is taken from the power law of participation model (Ross 2006), but instead of looking at the levels of collective intelligence it looks at both the levels of engagement and commitment towards energy saving. The advantage of this structure is that it draws attention to the idea that different householders can play different roles within the community. It also promotes the concept that if householders are given the right tools and support, we can start to generate a communication feedback loop as happens with online content. Once a critical mass is reached it will sustain itself without constant support. The second element, stages of engagement, looks to generate a similar staging approach to the one found within the transtheorectical model (McKenzie-Mohr 2000), but the stages are defined in terms of commitment to retrofitting. The stages are discussed in detail in section 4.3.2. The staged approach has a number of benefits; firstly, it provides the concept of a journey, with set milestones for the householder to reach. Secondly, individual techniques and tools can be defined for each stage. The importance of communication, community and social norms must be recognised within the framework. The framework depends on householders at the later stages providing guidance and support to those at the earlier stages, which is consistent with the community-based social marketing approach. Finally, it is extremely important to understand that at each stage the householder has a different level of motivation and ability, and that different triggers will be needed for behaviour change at each stage. Therefore, an interpretation of the FBM (Figure 4.1) has been applied to key stages throughout the framework. This will be presented in section 4.3.2. The interpretation of the FBM is made up of two elements: the two axes which are taken from the FBM (ability and motivation) (Figure 4.1), and the operating environment the householder is working within. This can include a large number of defining parameters that affect the actions of the householder, including salary, time and environmental views. As each householder's operating environment is different, it can be hard to define all of the parameters contained within it. However, defining the key factors would be an interesting area for future research.

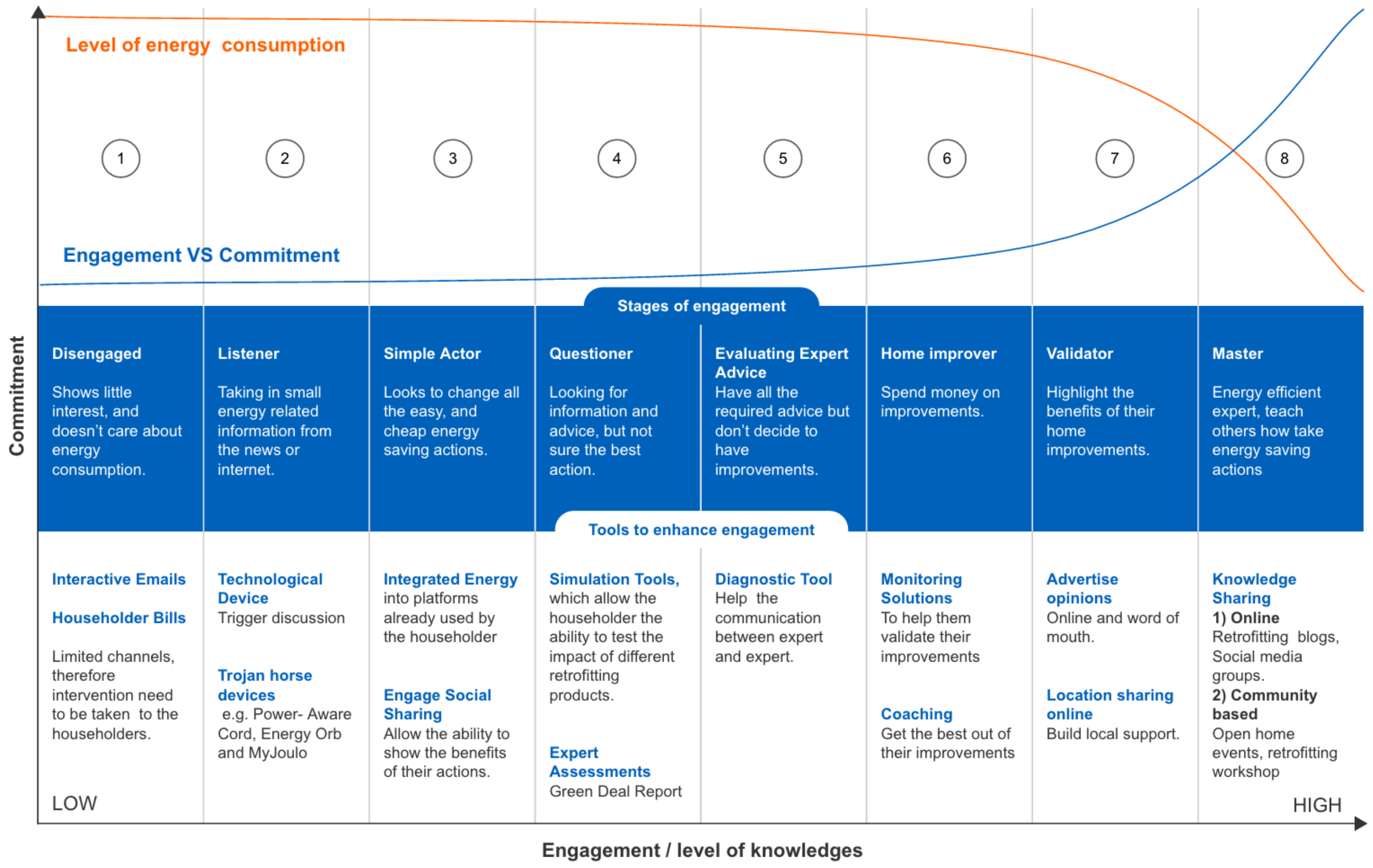


Figure 4.3: Power law of engagement for energy saving — a novel framework to better understand householders' engagement when it comes to retrofitting.

4.3.1 Engagement, commitment and energy consumption

Figure 4.3 illustrates the framework and provides a qualitative plot of level of commitment and energy consumption against stages of engagement. This illustrates that as householders' engagement increases, so does their commitment at a rapid rate, especially in the later stages. Householders can make a number of small commitments in the early stages, but a point comes where they have to start making substantial commitments with regards to time, finance, or lifestyle changes. If the relationship between commitment and engagement can be understood, then it becomes easier to support the householder through the process of retrofitting. The second line plotted on the graph looks at the relationship between the stages of engagement and the level of energy consumption. At each stage there will be a minimum and maximum amount of energy that can be saved. Knowing these boundaries is important for two reasons:

1. It shows householders the potential savings that can be achieved with greater commitment;
2. It can be used to demonstrate the limits of energy saving to householders in the lower stages of engagement.

Characterising these two relationships is a key area of research that needs to be developed.

4.3.2 Stages of engagement

The stages of engagement looks to break down the journey of retrofitting, allowing for an evaluation of the decisions faced by a householder. At the lowest level of engagement we have disengaged householders, while at the top end of the scale we have the energy masters. A householder can remain in a single state for a long period of time, and it will take an increase in both commitment and engagement to move into the higher stages. Householders can also move down stages similar to relapsing in the transtheorectical model (McKenzie-Mohr 2000). There are eight defined stages:

4.3.2.1 Disengaged

As implied by the name, householders at this level have extremely low levels of engagement and their commitment to energy saving is minimal. They do not care about their energy usage and rarely discuss it with friends or family. To create a graphical representation of their views on energy saving, we can start by applying the adapted FBM as shown in Figure 4.4. This representation of the model allows us to start looking at which energy saving action would be most successful for the individual. It has already been shown that the initial cost of retrofitting can be very unattractive to householders (Faiers et al. 2007), and this barrier is heightened when you have a householder within the stage shown in Figure 4.4. In this case, it does not matter how effective the message presented to them is nor how well we use persuasion techniques. The combination of a highly disengaged householder and the large financial commitment required renders retrofitting nearly impossible. However, if work can be done to get Disengaged householders to start being aware of energy (this could be through community-based engagement or through the bills they receive), this can start an increase in both motivation and engagement. It is critical to present the proposed behaviour change in terms of triggers which motivate the Disengaged householder. For example, Disengaged householders are not naturally pro-environmental, therefore showing CO_2 savings is unlikely to work, whereas demonstrating monetary savings could have a greater effect. Finally, interventions must be pro-actively brought to Disengaged householders, as they do not seek out energy related content by themselves.

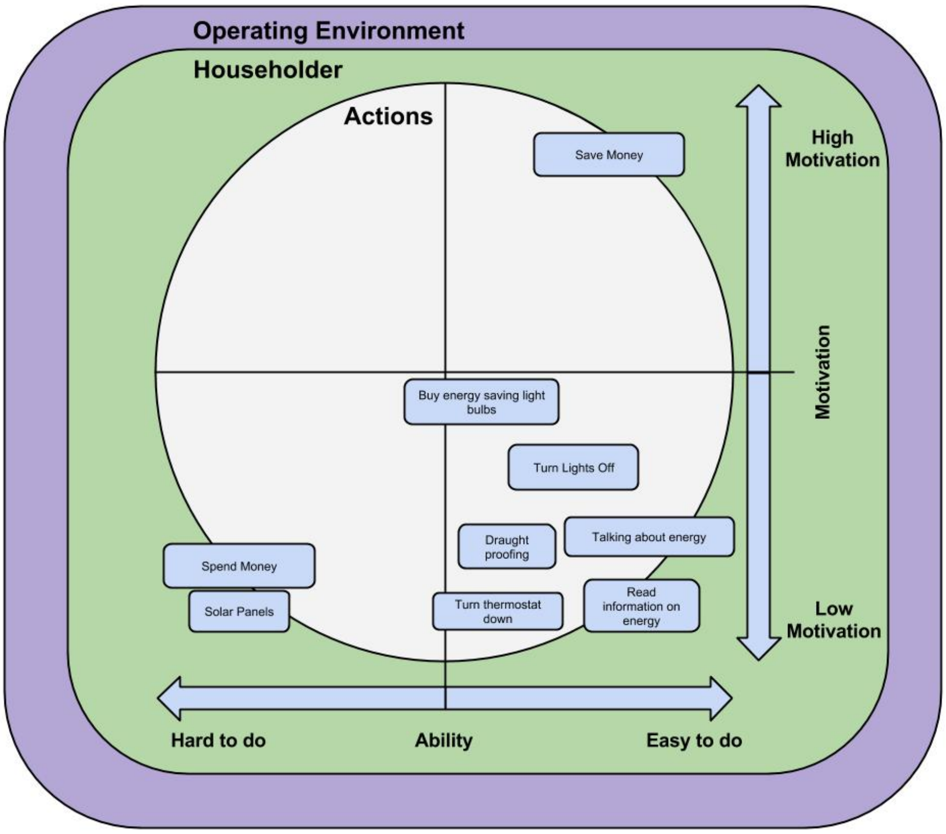


Figure 4.4: Disengaged householder — stage 1 of the power law of engagement for energy saving framework.

4.3.2.2 Listener

Those at this level have a heightened awareness of energy-related media consisting of news, bills and promotional material. The benefit of this is that necessary information can start to be presented to the Listener, but it is important to keep adding social pressure. Due to their level of engagement and commitment, the Listener does not take any actions toward saving energy yet. To get the householder to move to the next stage we need a well-placed trigger that will encourage them to take simple actions (lower thermostat setpoint to save energy, turn off heating in unused rooms). The trigger could be a piece of hardware or a new billing method, but it must be something that disrupts their usual interaction with energy, and lifts both their motivation and perceived ability.

4.3.2.3 Simple Actor

This level still has a relatively low level of engagement and limited energy knowledge. This means that some of their actions may actually consume more energy instead of less; for instance, there is still a belief in myths such as turning a thermostat up higher will heat a room quicker (Foster et al. 2010). Two things must be noted: first, the householder will only take actions on the easy-to-do ability spectrum; and second, the householder is willing to learn if information is presented in an engaging way. The vital point here is that once the householder has taken simple actions they, must be provided with immediate feedback. The feedback should provide the householder with enough information to begin exploring and learning about their property and retrofitting. Utilising a similar method to the way Kaplan (2000) describes behaviour change, the feedback should work as a triggering method to start the householder questioning their energy consumption, which helps them move onto the next stage.

4.3.2.4 Questioner

At this point the householder has completed a number of small actions, but with limited energy saving potential. To achieve larger savings, the householder needs to make physical changes to their property. To make these changes it requires the householder to undertake investment behaviours rather than habitual behaviours. The physical change to a householder's property can throw up a large number of barriers (Dowson et al. 2012). Therefore the householder seeks more information and looks towards advice services such as the UK's Energy Saving Trust (Energy Savings Trust 2017*a*). This information-gathering process allows the householder to build up evidence to support their commitment to retrofit. However, if a well-timed trigger is supplied during this moment, it can increase the likelihood of energy actions. In this stage we need an increase in communication from energy companies, suppliers, installers, and also from individuals who are close to the householder. Individuals close to the householder are very important, as they are a credible information source and have a large influence on the householders' decision-making process (McKenzie-Mohr 2000). The householder in this stage has a different set of decisions to make compared to the Disengaged (see Figure 4.4 and Figure 4.5 to compare). The Questioner is focused on which type of retrofitting will be best for them. In Figure 4.5, a larger proportion of the decisions are now towards the right-hand side of the ability scale, and have risen up on the motivation scale including willingness to spend money. The final point on the Questioner is that the right information must be presented to them *without* giving them information overload or analysis paralysis (Schwartz 2009).

4.3.2.5 Evaluating expert advice

This householder has gathered a large amount of information through public and expert sources. However, there is still a state where the householder fails to retrofit (Reddy 1991). There could be a number of

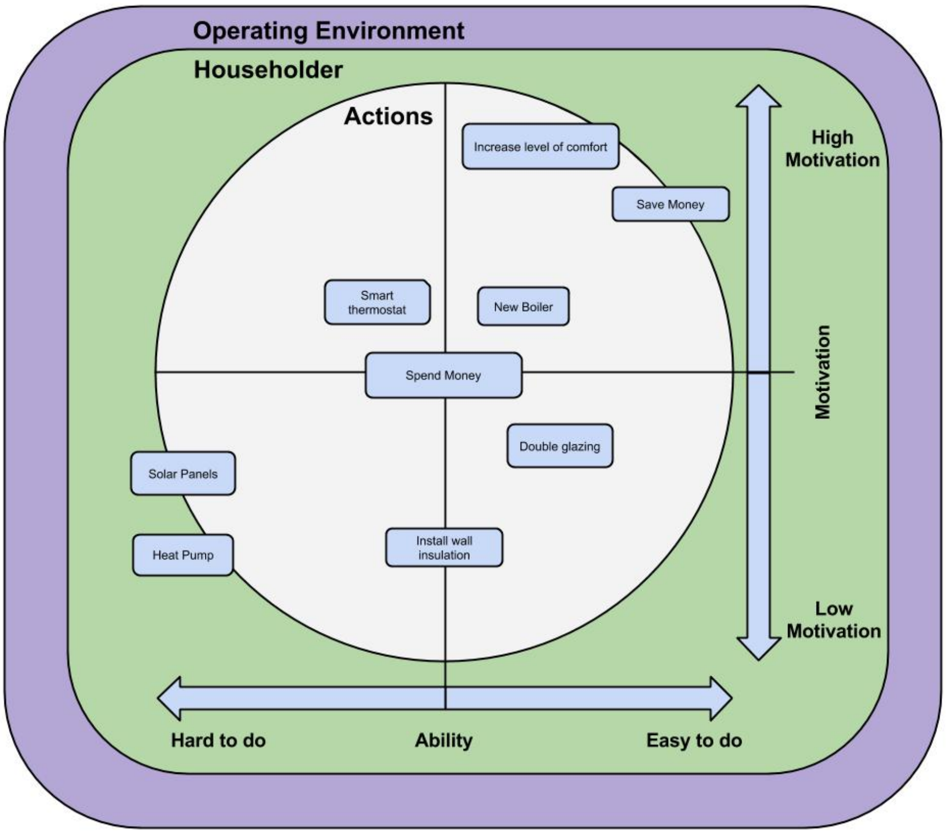


Figure 4.5: Questioner householder — stage 4 of the power law of engagement for energy saving framework.

reasons for this: initial cost, disruption caused by building work, and poor integration of supply chains (Rosenow & Eyre 2012). At this stage a great amount of effort needs to be made to help reduce the impact on the householder, and it is important to maintain their levels of motivation and commitment. It is key to create a set of targeted triggers to push the householder's level of commitment upward and take them into the Home Improver stage. It is essential to have a set of tools, as one solution will not fit all householders. The triggers also need to look at approaching the problem from a number of angles, both on a personal and social level.

4.3.2.6 Home Improver

At this stage, the householder has taken on board all the expert information and has made the decision to retrofit. This is a significant step, as the Home Improver has shown a large level of commitment and a genuine level of engagement. It is important to show the Home Improver all possible improvements, as they have the right level of commitment and engagement to retrofit. It is in this stage where the most progress can be made toward reducing CO_2 emissions, with estimated reductions of about 50% and, in some cases, up to 80% (Stafford et al. 2011). However, the householder's biggest concern is to prove that the changes to their property are both financially and environmentally beneficial. This is where monitoring tools can be advantageous. If they can start to validate the rewards of retrofitting both their level of engagement and commitment intensify, thus pushing them on to the next stage: Validator.

4.3.2.7 Validator

This householder has undertaken retrofitting and seen the benefits. Their levels of motivation are considerable, and they have already shown a substantial level of commitment. The Validator has limited decisions to make about energy improvements, as the only actions left to take are on the hard-to-do scale of ability, or not possible without a sizeable change to their life (e.g. moving home). The Validators play a vital role through sharing their knowledge and experience with the rest of society. Validators must be given a platform to display their accomplishments to other householders, as they provide information which is both credible and from a trusted source, thus improving their ability to change other householders' behaviour (McKenzie-Mohr 2000). The process of providing feedback plays two vital roles: firstly, social pressure is built upon disengaged householders as the norm moves (Dolan & Metcalfe 2013); and secondly, according to Bandura & McClelland's (1977) social learning theory other householders have a chance to take onboard the learnings of others without the large commitment. As the householder starts to become established in providing feedback into society they start to develop into the final stage of the framework: the Master.

4.3.2.8 Master

This householder pushes the limits of their property to make it as environmentally friendly as possible. Similar to the Validators, they are very engaged and highly motivated. Therefore, the only improvements left to make are on the very hard-to-do scale of ability (Figure 4.6). Their level of commitment is excessively high, which means they are willing to spend large amounts of money to save energy. Their decisions are driven by the environmental benefits rather than money saved or levels of comfort in their property. They are likely to be what is characterised as 'positive green' in attitude (Department for Environment & Affairs 2008). Their story of retrofitting can be used to provide information and experience to householders in less engaged stages. To take advantage of this, work must be done to harness their intense commitment and allow them to share their experiences through public engagement (lectures, workshops, and open home events). As the householder migrates to the Master stage, the pressure of social norms will start to change along with the values of disengaged householders. This process of giving back to the community must be stimulated to build energy leaders. It has been shown that people like to work with experts rather than on their own (Kaplan 2000), and if there is a set of leaders who distribute information, they could work in a similar way to Burn's recycling "block leaders" (Burn 1991).

The eight stages of the framework have now been defined. However, it is important that the concept of communication and community is emphasised within the framework. The framework depends on householders at the later stages providing guidance and support to householders in the earlier stages, driving them to retrofit their properties. Without this, the framework begins to breakdown. At each stage,

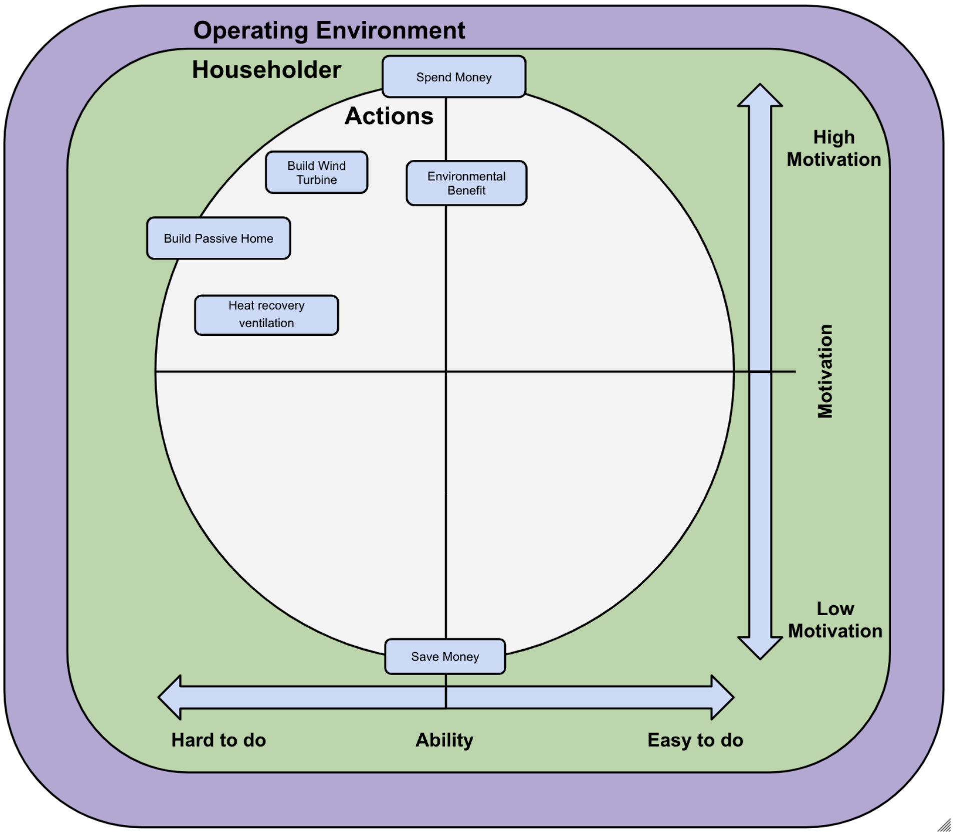


Figure 4.6: Master householder — stage 8 of the power law of engagement for energy saving framework.

the householder has a different mindset and it allows for the development of tailored tools for each stage (Department for Environment & Affairs 2008). The tools should be seen as bread crumbs that lead us both towards the perfect energy saving property and towards householders who are highly energy conscious. The tools must connect to each other and be provided in a structured order based on the householder. These tools to move a householder from one stage to another will be different, and will be considered in the next section.

It must be noted that the framework is defining a householders approach towards retrofitting and the installation of energy efficiency measures. Therefore, someone could be pro-environmental in certain behaviours like recycling or air travel. But can still be in the disengaged stage when it comes to the installation of energy efficiency measures. With the same logic, it also means that a householder can be a retrofitting master and help teach others about retrofitting. But can live an unsustainable lifestyle outside of their property. This is why the stages from Questioner to Master are all focused on retrofitting improvements, and the early stages are focused on the habitual behaviours that lead up to a householder installing energy efficiency measures.

4.4 Tools to enhance engagement and the role ICT plays

In this section, the tools and techniques which could be used to enhance engagement at each stage of the process will be introduced, with a focus on the role ICT plays. These tools should not be disconnected from each other; instead they should create an homogeneous solution which expands over a long time frame.

4.4.1 Disengaged

The challenge at this stage is that there are limited points of contact with the householder. This is due firstly to the move to online billing and direct debit payments, allowing householders to effectively ignore their energy consumption should they choose. Secondly, the most vulnerable householders are provided with heating benefits through fixed payments, which removes the link between energy consumption and cost. Therefore, the message of energy saving has to be taken to the householder and any interaction must be used to develop their engagement. In online billing, we need to look at embedding engagement techniques into the emails the householder receives. The techniques must encourage the householder into finding out more information. The emails must be interactive and start a two-way conversation between the householder and the energy company. The interactive element could be a graphical representation of a thermostat that the householder can adjust and see the potential cost savings. Alternatively, householders could be provided with interactive games in which they must guess which applications consumed the most energy last month (similar to Power Agent (Gustafsson, Katzeff & Bång 2009) and Power Explorer (Gustafsson, Bång & Svahn 2009)). In the final stage the householder should have the ability to share the email with friends and family to help develop the communication feedback loop. On top of this, as bills are the only other channel for reaching the Disengaged, work must be done to improve the information presented. As demonstrated by Wilhite & Ling (1995), more informative bills result in energy savings of about 10%, but more interestingly their research showed that householders were more likely to spend time discussing their bills with others; again, this stimulates the communication feedback loop.

4.4.2 Listener

Once the householder starts to take in information, their knowledge begins to develop. However, the householder does not know the best course of action yet. Therefore, in this stage it is key to get the householder connecting to the community of people who have more knowledge, and encourage them to take simple actions. A technological device can be used as a trigger to start the conversation between householders, providing comparable data and triggering a discussion about the device. In order for the device to be successful with householders who have low levels of engagement it must be:

1. Aesthetically pleasing, exciting and new; this provides an instant hit of engagement;
2. Simple to use, as the householder will only undertake tasks which are low on the ability scale;
3. Provide simple feedback on actions taken;

4. Cheap, due to low commitment levels the householder will not spend money.

There are currently a number of tools which meet some of the criteria stated above: Power-Aware Cord (Gustafsson & Gyllenswärd 2005), Energy Orb (Faruqui & Sergici 2009) and MyJoulo (Rogers & Wilcock 2012). These tools can work as a catalyst to start householders getting used to both monitoring energy consumption, while only requiring a low level of commitment. Engagement with these tools can drop off rapidly. Therefore it is important to understand what will be the next tool or next steps for the householder to take.

4.4.3 Simple actor

Keeping the householder moving forward can be a challenge. To counter this, work must be done to integrate energy consumption into the householder's daily routines, and a new dimension of social interaction must be added. Modern social networks (Twitter, Facebook) and online tools (Google Calendar, web browser plug-ins) meet both these needs, meaning that integration with these technologies is essential at this stage. Some good examples include "Power Ballads", which deploys aversive energy feedback through Facebook (Foster et al. 2011), and stepgreen.org, which provides plugins for both MySpace and Facebook (Mankoff et al. 2010). Applying these tools offers two benefits: firstly, householders are provided with constant feedback on their energy consumption and secondly, the social element increases the feedback into the community through online sharing. Similar technologies have been used outside the energy sector to help already motivated runners to increase their levels of exercise (Trevorrow 2012, Nike 2017), and help individuals learn new languages (Vesselinov & Grego 2012, Duolingo 2017).

4.4.4 Questioner

In this stage the tools must allow the householder to discover and explore the possible retrofitting scenarios, as Kaplan (2000) highlighted these as key factors in behaviour change from both a behavioural and motivational point of view. It is vital that the tools meet a number of requirements:

1. Display benefits and drawbacks of retrofitting;
2. Show information based on the householder's property;
3. Allow simulation of different scenarios to help the householder find the best solution;
4. Incorporate data collected from the householder's property;
5. Be freely available and easy to access, as the levels of motivation are still low.

A tool that meets these requirements allows the householder to build up evidence to support their decision to retrofit. Two examples of websites that work well are the Energy Saving Trust's "Home Energy Check" (Energy Savings Trust 2017*a*), which allows the householder to see the potential savings of retrofitting, and “Heat Bleed” (Energy Response Corps 2012), which calculates the heat loss of your property. However, both tools are limited on the simulation of different scenarios and the ability to include data collected from the householder’s property. At this point it would also be interesting to show householders thermographic images of their property, as illustrated in Figure 3.2, to help increase engagement and to let the householder understand where their property is losing heat. The tools should look to not only show money or CO_2 savings, but it would be beneficial to include other factors like level of comfort, level of disruption and the time to install, as these factors could be more important to certain householders. The tools allow the householder to build up their knowledge, but there is only so much information that can be provided by ICT tools. Therefore, the next step is for the householder to organise an expert evaluation, for example by engaging Green Deal Advisers (Department of Energy and Climate Change 2017) or Parity Projects (Parity Projects 2017), which requires an increase in both time and financial commitment.

4.4.5 Evaluating expert advice

At this stage the householder is right on the edge of retrofitting and the experts have told them the best solution. However, the householder can start to feel helpless in this stage, as it may appear that the experts are controlling their decisions. As discussed by Kaplan (2000), helplessness can have a big effect on the decision process. To help with this issue, the householder needs to be provided with a diagnostic tool (e.g. small sensor equipment) to help them evaluate their property and, more importantly, to help stimulate the negotiation between the householder and the expert. The negotiation will help the householder gain more control over the decision-making process, plus help the expert to understand the householder’s requirements. It is important that the communication turnaround time between the expert and householder is quick, as in this stage the householder is very close to retrofitting; to achieve the necessary speed in communication, a shared online portal would be beneficial. The diagnostic tool can also be a trigger that increases both their motivation and removes the fear of retrofitting. The tool should apply Freedman & Fraser’s (1966) and Cialdini’s (2007) concept that if someone has agreed to a small request he is more likely to comply with a larger request. The small request can be getting diagnostic sensors installed, which in turn can lead them into agreeing with the large request, retrofitting. Finally, getting the necessary follow-on information must be simple: if the householder has to wait for a quote or pay for another evaluation, this will cause their motivation to decrease and they will relapse back into the Questioner stage.

4.4.6 Home Improver

In this stage the main driver for the householder is validation that the decisions they made were both financially and environmentally rewarding. To enable this they need to be provided with monitoring tools. The monitoring tools need to perform a number of tasks to be successful:

1. Facilitate the ability to compare energy usage before and after retrofitting;

2. Provide regular feedback to the householder over a long time frame (Fischer 2008);
3. Integrate with smart devices installed in the household; this allows for a breakdown of energy usage (Fischer 2008);
4. Provide methods to share their feedback with other householders.

There are already a number of monitoring tools both in the academic community and provided by industry that could meet these requirements with few adaptations, e.g. Foster et al.'s (2010) "WattsUps" Facebook application and the "engage" platform Engage (2017). Finally, the Home Improver needs to be connected to a community expert. The community expert will help the householder learn about the equipment that has been installed and highlight any lifestyle changes that are required to get the best energy savings.

4.4.7 Validator

The Validator has seen the benefits of retrofitting. Therefore it is important to get the householder to start broadcasting their opinions in the community. The first type of advertising is the householder's opinions, which could be reviews of installers, suppliers or equipment, or it could include their opinions on the process of retrofitting in general. The two most trusted advertising methods are word of mouth through friends and family, followed by online content; both have been shown to be completely or somewhat trusted a majority of the time (92% and 72% representatively (Nielsen 2012)). The second channel of feedback should be through sharing their location on an interactive online map; this can help other householders see what energy efficiency measures have been made within their local area and how successful these measures have been. These techniques both increase the communication feedback loop and help encourage the Disengaged to think about retrofitting.

4.4.8 Master

In the Master stage, the householder wants to help other householders, and they want to share their experience and knowledge to less engaged households. We can help this in a number of ways, both through online media (energy blogs, Facebook groups, or retrofitting websites) or through public events (open home events, retrofitting workshops, or community drop in sessions). Two examples of these type of tools include "SuperHomes Network" (SuperHomes 2017) and "Bristol Green Doors" (Bristol Green Doors 2015), which both organise open home events and provide online information. However, with the development of smart devices, these platforms need to evolve to include the ability to allow people to compare energy consumption and temperature data from householders' properties. The smart devices can also be used to allow the Master to share their location when holding open home events or presenting lectures. This has been shown to be successful in the "Bristol Green Doors" project with the development of the "Green Doors App" (Massung et al. 2014).

In this section a number of different techniques and tools have been introduced to help stimulate the progress from one stage to the next. However, it must be noted that these tool are a guideline and that each householder is different. Therefore, we must build up a collection of tools to meet each householder's motivation (He et al. 2010).

Breaking down the different types of ICT that will be applicable to different stages of the retrofitting process enables further research to build upon the power law of engagement for energy saving framework. A graphical representation of the different ICT solutions for each stage can be seen in Figure 4.7.

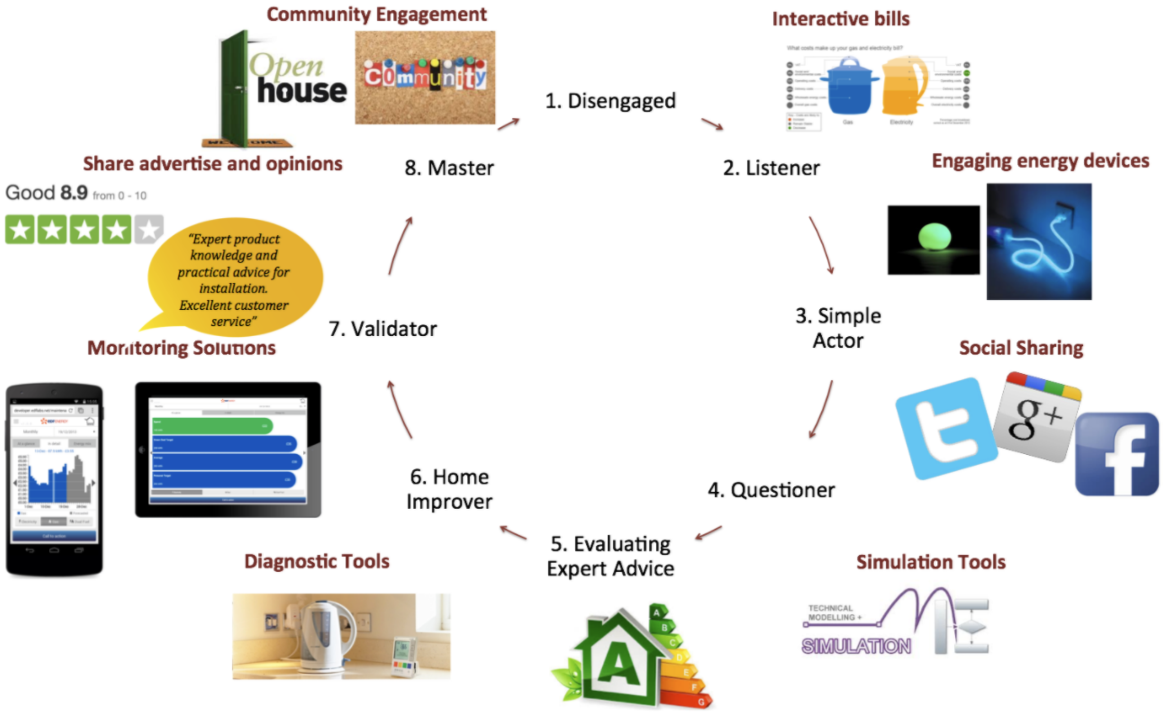


Figure 4.7: Power law of engagement for energy saving framework stages mapped to relevant ICT solutions.

4.5 Discussion

This chapter has presented the power law of engagement for energy saving framework and a number of ICT tools have been introduced that can be used at different stages in the framework. However, the integrated solution is missing. The framework presented in the chapter sets out a solid foundation for future research to develop on and work with, but a number of areas still need to be developed.

Firstly, a methodology must be defined that determines at what stage the householder is in. When defining the methodology, we must be aware that householders can state pro-environmental intentions but actually behave differently. For example, it has been shown that 20% of householders are willing to pay a premium of 10-20% for environmentally friendly electricity, however the market share is often below 1% Truffer et al. (2001). Therefore asking the householder directly could yield misleading results.

To solve this issue, future research needs to look at logging objective consumption or both heating data from a householder's property as well as getting them to provide their views through questionnaires. This is developed further when looking at heating patterns in Chapter 7.

Secondly, the chapter has suggested a number of ICT tools which could be applied to each stage. In the process it has raised a number of questions that researchers need to think about when developing tools to engage householders, including:

1. What level of commitment, ability and motivation is required to use the tool?
2. Which tool is most effective for the householder at this current time?
3. What is the lifetime of the tool? (How quickly does the householder get bored of it?)
4. Does the tool increase the likelihood of pushing the householder to retrofit?
5. Can this tool be used to introduce more advanced tools, which have the potential to save more energy?

The power law of engagement for energy saving provides the framework to map tools to the householder's level of engagement. Answering the above questions will help future researchers maximise the take up of ICT tools that look to stimulate engagement and lead to more long-term solutions for retrofitting.

Finally, it is important to understand the householder's operating environment at each stage, as these can vary between individuals. Finding the key barriers and drivers within the householder's environment will allow for the development of techniques that both minimise the barriers and maximise the drivers. This is the core topic of Chapter 5.

4.6 Conclusion

This chapter presents the power law of engagement for energy saving, a novel framework that provides a method for encouraging disengaged householders to retrofit their properties. The framework is built on existing models that have been shown to stimulate behaviour change and increase engagement. However, the proposed model focuses on the the development of a communication feedback loop, driving the highly engaged to help disengaged householders.

CHAPTER 5

INVESTIGATION INTO THE SLOW ADOPTION OF RETROFITTING — WHAT ARE THE BARRIERS AND DRIVERS TO RETROFITTING, AND HOW CAN ICT HELP?

"Too many of us now tend to worship self-indulgence and consumption. Human identity is no longer defined by what one does, but by what one owns. But we've discovered that owning things and consuming things does not satisfy our longing for meaning. We've learned that piling up material goods cannot fill the emptiness of lives which have no confidence or purpose." — Jimmy Carter (1979) — Energy and the National Goals — Crisis of Confidence

5.1 Introduction

In this chapter we build on the work completed in Chapter 4 by exploring the reasons for the slow adoption of energy efficiency measures by householders. We use primary research collected over a two-month longitudinal trial to define a number of the core barriers and drivers to retrofitting. The trial logged participants who were interested in energy efficiency measures but were still undecided about whether or not to install. We conclude the chapter by supplying a number of recommendations about how ICT can be used to help remove the barriers and enhance the drivers during this critical period.

The content of the chapter is an edited version of the author's paper that was published and presented at the 29th International Conference on Informatics for Environmental Protection (EnviroInfo 2015) and 3rd International Conference on ICT for Sustainability (ICT4S2015).

5.2 Background

In this review we will focus on the core decision process undertaken by householders when they are thinking about retrofitting. To achieve this we have broken the review into two sections, barriers and drivers of retrofitting, which link directly to our research questions for this thesis.

5.2.1 Barriers

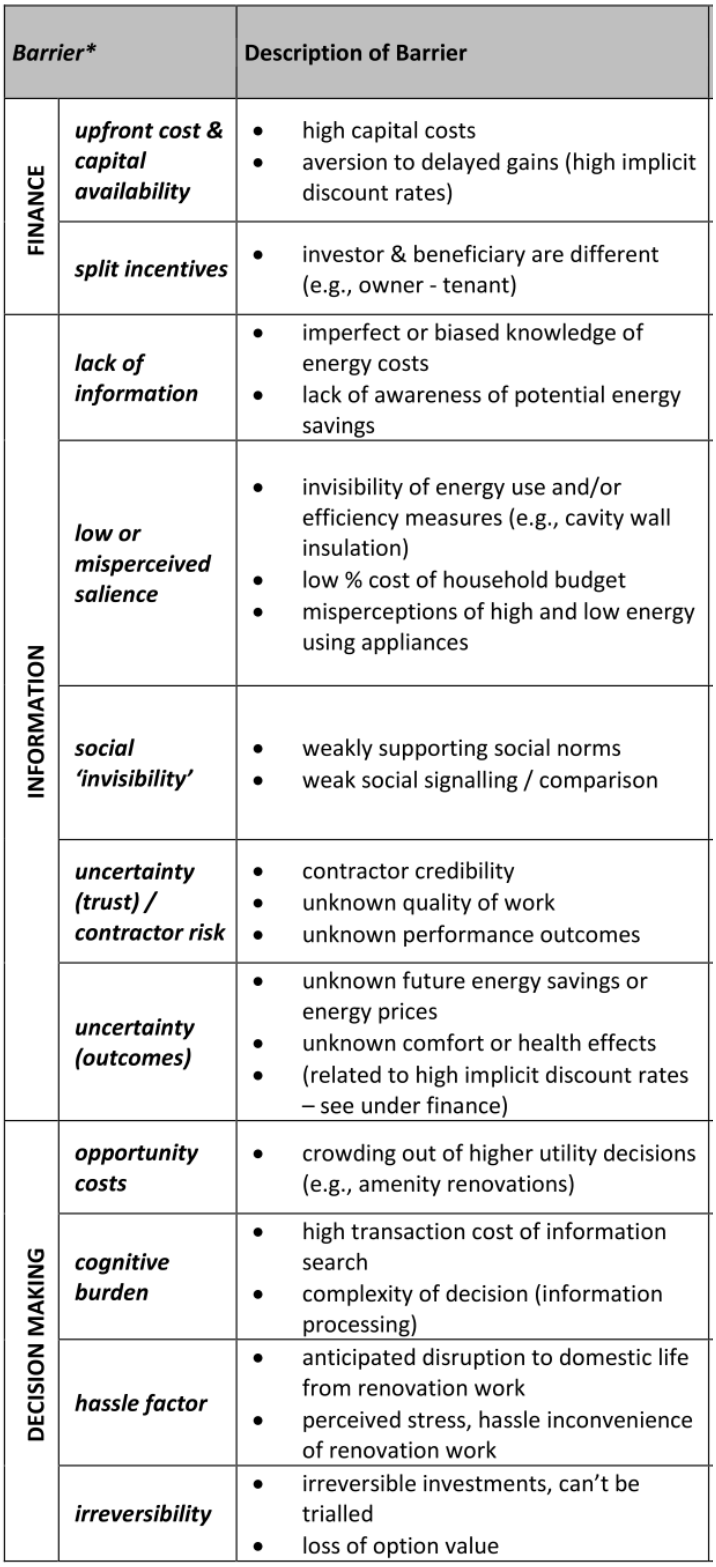
In investigating the reasons behind what prevents individual householders from retrofitting, Wilson et al. (2014) produced a table that summarises the barriers (Figure 5.1): finance, information and decision making. These core themes have also been supported by research conducted by Massung et al. (2014). In the descriptions of the barriers we start to see the issues facing householders and the hurdles that need to be removed to help increase the level of retrofitting. The barriers described in Figure 5.1 are focused on the householder and define the terms in relation to the responsibility faced by the householder, e.g. hassle factor, cognitive burden. However, in evaluating the barriers we must also explore the impact the external environment has on the householder, and start to investigate the failures that could be limiting the householder. In drilling further into the literature, we start to see two types of failures: market failures and behavioural mismatches (Gillingham et al. 2009).

5.2.1.1 Market failures

Market failures can be defined by the energy efficiency gap: that energy efficiency technologies exist, and that simple net present value calculations show them to be cost effective at current prices, but they nevertheless have limited impact in the market (Jaffe & Stavins 1994). In this context, individual householders are seen as rational agents based on rational choice theory (Scott 2000), and they look to maximise their own expected utility. Consequently, the decision to have retrofitting measures comes down to the relationship between initial capital cost, expected future savings, and the increased utility provided to the householder. This will be described within section 5.2.2. The market failures can be caused by a combination of factors, including:

1. misplaced incentives;
2. discretionary fiscal and regulatory policies;
3. unpriced cost;
4. unpriced benefits;
5. insufficient and inaccurate information (Brown 2001).

It is widely argued that to resolve these market failures there needs to be market interventions, which can come in a number of forms including emissions pricing, financing programmes or increased investment in information distribution (Gillingham et al. 2009). A large number of market failure interventions happen on the macro-level and typically involve governmental organisations, who look to reduce the overall financial impact faced by householders. In designing the trial explained in section 5.4, we want to explore the impact these market failures and market interventions have on individual householders.



*Barrier**		**Description of Barrier**
FINANCE	***upfront cost & capital availability***	high capital costs aversion to delayed gains (high implicit discount rates)
	split incentives	investor & beneficiary are different (e.g., owner - tenant)
INFORMATION	***lack of information***	imperfect or biased knowledge of energy costs lack of awareness of potential energy savings
	low or misperceived salience	invisibility of energy use and/or efficiency measures (e.g., cavity wall insulation) low % cost of household budget misperceptions of high and low energy using appliances
	social 'invisibility'	weakly supporting social norms weak social signalling / comparison
	uncertainty (trust) / contractor risk	contractor credibility unknown quality of work unknown performance outcomes
	uncertainty (outcomes)	unknown future energy savings or energy prices unknown comfort or health effects (related to high implicit discount rates – see under finance)
DECISION MAKING	***opportunity costs***	crowding out of higher utility decisions (e.g., amenity renovations)
	cognitive burden	high transaction cost of information search complexity of decision (information processing)
	hassle factor	anticipated disruption to domestic life from renovation work perceived stress, hassle inconvenience of renovation work
	irreversibility	irreversible investments, can't be trialled loss of option value

Figure 5.1: Wilson et al. (2014, p.5), *The Energy Efficiency Gap: Barriers to Energy Efficient Renovations.*

5.2.1.2 Behavioural mismatch

Behavioural mismatch occurs when householders' behaviour is inconsistent with utility maximisation, as Howarth & Andersson (1993) states: *"Consumers are 'irrational' in the sense that they do not evaluate energy-using technologies in a manner consistent with life-cycle cost criteria."* Householders are individuals that have different values, attitudes and beliefs towards energy and the environment, which makes them 'irrational agents' in the sense they do not behave like the utility maximisers expected by economic theory. Humans in general are considered irrational (Ariely 2010, Kahneman 2011). In this context we need to use analytical techniques that derive from the psychology and behavioural economics fields of research, and we need to evaluate cognitive biases and behavioural anomalies. Frederiks et al. (2015) composed a list of 11 cognitive biases that are related to householders' view of energy and that are predictable tendencies; below, we have selected the core cognitive biases that have an influence on the decision to undertake retrofitting measures:

1. Status quo — householders resist change, and look to go with pre-set options, even in the context where alternative options would lead to greater personal and collective outcomes.

2. Loss averse — individuals commonly focus on losses associated with a new behaviour, whether it be financial, physical, social, ecological, or time related, and tend to discount the potential gains. In risky and uncertain choices losses loom larger than gains (Tversky & Kahneman 1992).

3. Risk averse and risk seeking — householders are more risk averse when faced with high probability gains or low probability losses, but are more risk seeking when faced with high probability losses or low probability gains. This means householders avoid risk given the prospect of gains, but will take risks when there is the prospect of losses.

4. Temporal or spatial discounting — householders tend to avoid actions that are costly in the short-term but could be beneficial in the long-term. They feel things are less valuable if they are further away in time or space.

5. Conform to social norms — householders tend towards the behaviours and actions that are approved or done within society. This is through injunctive or descriptive norms. Injunctive norms refer to actions that most others approve or disprove of, e.g. individuals do what ought to be done. Descriptive norms refer to what most others do, e.g. individuals do what most other people are doing (Cialdini et al. 1990).

6. Rewards or incentives — look to increase individuals' extrinsic motivation. However, they can be short-lived and inconsistent, and individuals may respond negatively toward them.

7. Trust (source dependence) — expertise, experience, openness, honesty and concern for others all help householders in their decision-making heuristic. It helps them assess risk and influences their cost-benefit appraisals.

In understanding the cognitive biases, and realising that householders are not rational agents, we can start to see the problem from a different perspective and understand the behavioural mismatch that underlies it. Gillingham et al. (2009) summarise the behavioural mismatch into three core areas of research:

1. Prospect theory — States that individuals base their decision on the potential gains and losses rather than the final outcome. An idea introduced by prospect theory is that individuals underweight outcomes that are probable compared with outcomes that are certain (certainty effect) (Kahneman & Tversky 1979). Prospect theory has also been used to explain the isolation effect; when individuals remember stimulus that differ from the rest of multiple homogeneous stimuli (Kahneman & Tversky 1979). Prospect theory has been expanded to create cumulative prospect theory, which includes five phenomena of choice: framing effects, non-linear preferences, source dependence, risk seeking and loss averse (Tversky & Kahneman 1992).
2. Bounded rationality — Defines that individuals have limits to their rationality, which is driven by two limiting factors: our cognitive ability and the available time to make the decision. The limits of rationality are increased during risky and uncertain decisions due to the introduction of incomplete information that makes it challenging to compare alternative choices (Simon 1972).
3. Heuristic decision making — Heuristics are a subset of strategies that speed up the process of making a decision by ignoring certain information or being more frugal with information (Gigerenzer & Gaissmaier 2011). Heuristic decision making develops rules that work in most situations, but are not always rational or logical. Heuristic decision making can lead to severe and systematic errors due to insensitivity to prior probability of outcomes, insensitivity to sample size, misconceptions of chance, insensitivity to predictability, illusion of validity and misconceptions of regression (Tversky & Kahneman 1973).

It must be noted that these areas of research cover the 11 cognitive biases described by Frederiks et al. (2015). In developing interventions to minimise behavioural mismatch, more focus must be placed on education, information distribution and community-led social change.

5.2.2 Drivers

In parallel to the barriers, we must also understand the drivers: what is it that causes householders to install energy efficiency measures? The drivers that lead to energy efficiency measures are less explored within the academic literature (Mills & Rosenfeld 1996), and this is an area we are looking to advance throughout this chapter.

Pelenur (2013) defined seven motivations that lead to retrofitting: saving money, reducing environmental emissions, resource efficiency, warmth and comfort, aesthetics and space, health and safety and time convenience. Similar non-energy benefits were highlighted by Mills & Rosenfeld (1996). In Oxera's (2006) report, the key finding was that future energy savings was of little importance in the householder's decision process; other non-energy factors had a greater influence. The terms used to describe these motivations may have different connotations for each householder. For example, Huebner et al. (2013) explored the meaning of comfort to householders, and found a whole range of definitions: warmth, space, light and cleanliness. Likewise, in evaluating the drivers that motivate householders, there must be a key distinction between which drivers are intrinsic or extrinsic motivators (Ryan & Deci 2000):

1. intrinsic — “the doing of an activity for its inherent satisfactions rather than for some separable consequence”
2. extrinsic — “the doing of an activity in order to attain some separable outcome”

The two types of motivation have been explored in studies looking at energy reduction through behaviour change, but less attention has been applied to their impact on retrofitting.

5.3 The problem

In Chapter 2 we defined the core reasons behind promoting retrofitting, and showed that stakeholders seek to benefit from the re-design of our current housing stock. However, as we explored in section 5.2.1, the uptake of energy efficiency measures is still slow, and there are a number of barriers and drivers influencing householder behaviour. It seems a large number of householders don’t transition from the evaluating expert advice stage to the home improver stage of the power law of engagement for energy saving (Figure 4.3). As we highlighted in section 2.2, the UK government has put together a set of schemes to help promote the uptake of energy efficiency measures: ECO and Green Deal. The schemes look to correct the market failures described in 5.2.1, and they also look to remove the problem faced by large initial upfront capital costs. Rosenow & Eyre (2012) defined six criticisms of the Green Deal and ECO:

1. Contribution to carbon reduction — Green Deal and ECO are estimated to deliver only 26% of the carbon savings of previous policies (Carbon Emission Reduction Target (CERT) and CESP).
2. Potential barriers to uptake — Currently the Green Deal finance deals with the problem of initial upfront cost, however it does not affect other potential barriers like disruption, householders’ time commitment or poor integration of the supply chain.
3. Scheme design choices made and their implications — On a number of occasions it has been highlighted that poor scheme design choices have been made. For example, initially ECO was going to be predominately focused on high cost measures like solid wall installation, but due to its impact on the established cavity wall and loft insulation markets only certain householders can apply for solid wall insulation under ECO. This has led to limited funding for solid wall insulation that comes at a high cost but has a high impact on building energy performance. In conjunction, subsidies have been removed for all lighting and appliance energy efficiency measures. Replacing

tungsten halogen lighting with new Light-emitting Diode (LED) is now possible and would have an impact on energy use, and the support for efficient lighting should not be abandoned.

4. Supply chain capacity to deliver — The capacity of the supply chain can limit the number of installations. Due to the supply chain not being ready for the rapid increase of solid wall installation, the government modified the initial proposal and now only certain solid wall installations will be covered by ECO.

5. Credit default risk — Under the Green Deal program, householders are taking out a loan on their property and if householders are not able to repay the loan, this can cause a default on the loan; the risk then lies fully on the Green Deal provider.

6. Fuel poverty — ECO aims to take 125,000 - 250,00 households out of fuel poverty by 2023. However, currently there are about 20 - 40 times this figure currently in fuel poverty. Under Green Deal and ECO The Association for Conservation of Energy showed that there would be a 29% reduction in the total funding for fuel poverty, compare to the previous government schemes.

In reviewing the criticism of the UK government's schemes and researching the barriers and drivers, we want to explore the householder's decision process in more detail, and in particular answer questions surrounding retrofitting in the context of the two government schemes highlighted above. These questions are:

1. What is the householder's view of the slow uptake of retrofitting?

2. Do we find the same barriers and drivers highlighted in section 5.2 with the UK government's retrofitting schemes?

3. What stops householders taking out retrofitting measures during the process of the UK government's schemes?

4. What actions could be taken to increase the uptake of retrofitting?

5. How can ICT be used to remove a number of the barriers faced by householders when it comes to retrofitting?

6. How could ICT be used to increase the uptake of retrofitting?

To evaluate the research questions above we undertook a two-month trial with a number of householders who were at the time trying to decide whether to undertake energy efficiency measures, e.g. in the questioner stage or evaluating expert advice stage of the power law of engagement for energy saving framework (Figure 4.3). Throughout this period we captured qualitative data through questionnaires and interviews. The participants were also provided with a smartphone application to view and input their energy data.

5.4 Monitoring trial

In this section we present the trial participants selection, smartphone application designs, and the design of the interview and questionnaires.

5.4.1 Participants

Participants were recruited through EDF Energy's Employee Green Deal trial. Each participant was in the process of evaluating whether to install energy efficiency measures through the Green Deal scheme described in section 2.2.4. Participants had already shown an interest in energy efficiency measures and therefore were already in a state of high engagement. Overall we recruited 12 participants: 58% females and 42% males. We also evaluated each participant's level of engagement with energy and ICT (Figure 5.2). The results showed that our participant sample was engaged in both energy and ICT, but more engaged in ICT than energy.

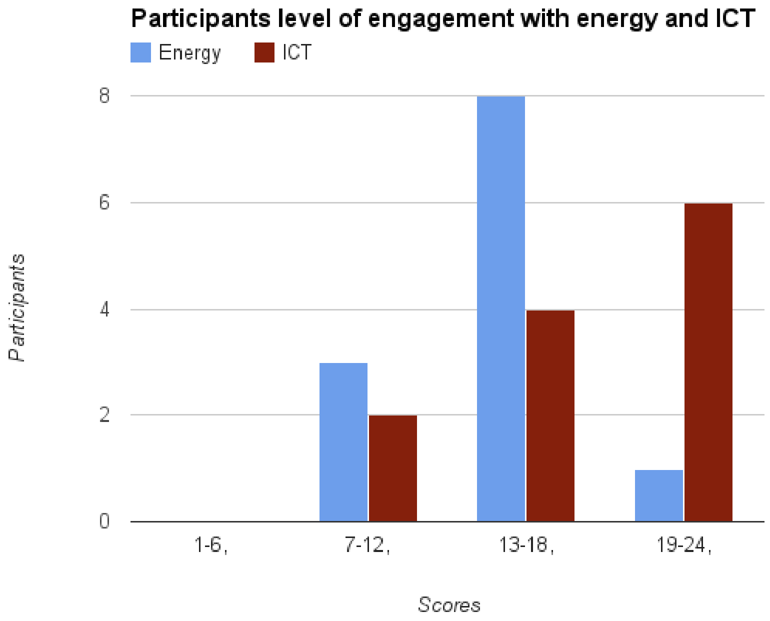


Figure 5.2: Participants' level of engagement with energy and ICT.

5.4.2 Smart phone application

The smart phone application provides a method of displaying energy and temperature data to the householders, while enabling the householder to input energy meter readings. In the trial we were not evaluating the level of engagement with the smart phone application; it was only used as a tool to present data to the participants. The application contained two main sections, that can be viewed in Figure 5.3:

1. Meter reading page — provides a method for the householder to supply their energy meter readings on a regular basis throughout the trial. It was highlighted to the trial participants that they should take both a gas and an electric meter reading once a week. We decided to allow householders to enter their meter readings manually, as when this research was conducted there was still a low penetration of smart meters within the domestic energy market.

2. MyDashboard page — provides the householders with a method of looking at their energy consumption and temperature data. MyDashboard is split into three main screens:

   a) At a glance — displays the householder's total energy consumption for the selected period as well as the average internal and external temperature for the period in a simple view that can be accessed quickly.
   b) In Detail — allows householders to see a graph of their energy consumption for the selected period, as well as internal and external temperature data. The view provides the householder a more comprehensive view of their data, and allows them to see the relationship between their energy consumption and temperature over time.
   c) Energy Mix — provides householders with a ratio of the amount they have spent on electricity and gas, which helps householders to start to infer where they could be saving energy.

5.4.3 Questionnaires and semi-structured interviews

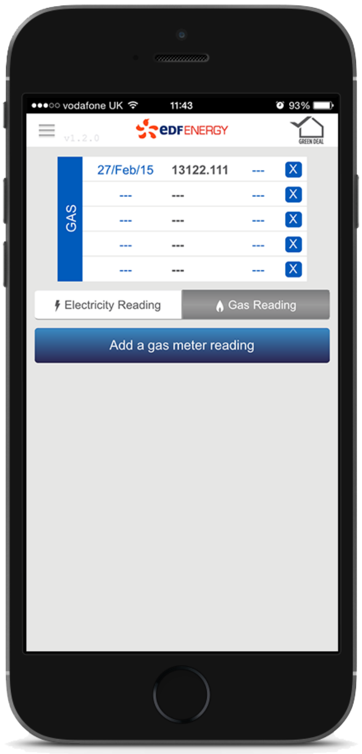
The key method of collecting data throughout the trial was questionnaires and semi-structured interviews. We collected 38 questionnaires and six 45-minute interviews throughout the trial:

1. Preliminary questionnaire — investigated participants' current level of engagement in ICT and energy. The questions took the form of a six point Likert scale, and included questions such as: "How often do you review your energy bills?" and "How often do you use online banking on a mobile device?"

2. Trial questionnaires — each participant would take the trial questionnaire three times: once at the start, once at the midway point and once at the end of the trial. The focus of the questionnaire was to allow us to evaluate how householders' views change throughout the trial. The questions used a Likert scale to assess the householders' opinions, and the questionnaire was split into two sections. The first section evaluated participants' likelihood to install energy efficiency measures, and the second section gauged participants' views on a number of the barriers and drivers highlighted in section 7.2. The barriers investigated included initial cost, disruption and uncertainty of savings. The drivers included environmental views, level of comfort and Green Deal / UK government's schemes.

3. Semi-structured interviews — at the end of the trial, each participant was asked if they would like to take part in a semi-structured interview. Six of the participants agreed. Each interview lasted

(a) At a glance (b) In detail (c) Energy mix



(d) Meter reading

Figure 5.3: Monitoring trial smart phone app.

45 minutes and was split into two sections: current energy efficiency measures and future Green Deal measures. In the first section, we asked participants to describe the current energy efficiency measures they installed in their property and focused on encouraging the participants to discuss the reasons why they chose these measures. In part two, we evaluated the participants' views toward potential new measures that could be installed, with a key focus on exploring the barriers currently stopping them from installing the energy efficiency measures.

5.5 Results and discussion

This section presents the results of the trial and discusses there implications.

5.5.1 Trial questionnaires

A symmetric Likert scale was presented to the participants for each barrier and driver. The householders were presented with both positive and negatively oriented statements, for example:

- Positive statement — I would be willing to put up with disruption if the benefit of an improvement is great enough.
- Negative statement — I am unlikely to have an improvement done due to the disruption it causes.

Each participant would express their opinion about each statement as either “strongly disagree”, “disagree”, “neither”, “agree” or “strongly agree”. If the statement was positive, the assigned values for the answers would be 1 to 5 in order stated above; if the statement was negative, the assigned values would be inverted 5 to 1. Finally, all the values from both the positive and negative statements were summed to create the participant's overall view; this was completed for all three trial questionnaires.

5.5.1.1 Results and analysis

In analysing the results from the trial questionnaire, we can start to evaluate the participants' views towards each of the barriers and drivers presented in the questionnaire. The results can be seen in Figure 5.4. Figure 5.4b shows that disruption was the largest barrier stopping our participants from installing energy efficiency measures. This was closely followed by uncertainty in savings and initial cost. It is interesting to see that disruption was the largest barrier on participants' minds, especially as a large number of the UK government's schemes look to reduce the initial cost barrier rather than disruption. One potential reason for disruption being selected as the primary barrier is that householders were already taking part in the Green Deal process. As a result they likely had already factored the initial cost of the energy efficiency measures into their decision process, including the financial incentive from the Green Deal. This would then focus their attention on the installation process itself.

If we investigate the drivers, we can see that comfort is the biggest driver, followed closely by the environment and Green Deal scheme. The Green Deal was approximately a third less important a driver for householders than comfort and the environment, which highlights that even participants involved in the Green Deal do not see it as a key driver in their decision process.

Finally, there were no significant changes to the participants' views throughout the two-month trial. This was a surprising result as a fluctuation in participants' views around the initial cost and disruption was expected as householders proceeded to install or organise the installation of energy efficiency measures. As discussed in Chapter 4, a householder's decision process is not a static event, but instead occurs over a period of time. Therefore, we need to evaluate the thought process before (questioner stage), during (home improver stage) and after the installation of energy efficiency measures (validator and master) in order to improve our understanding of the decision process.

5.5.2 Interview results and analysis

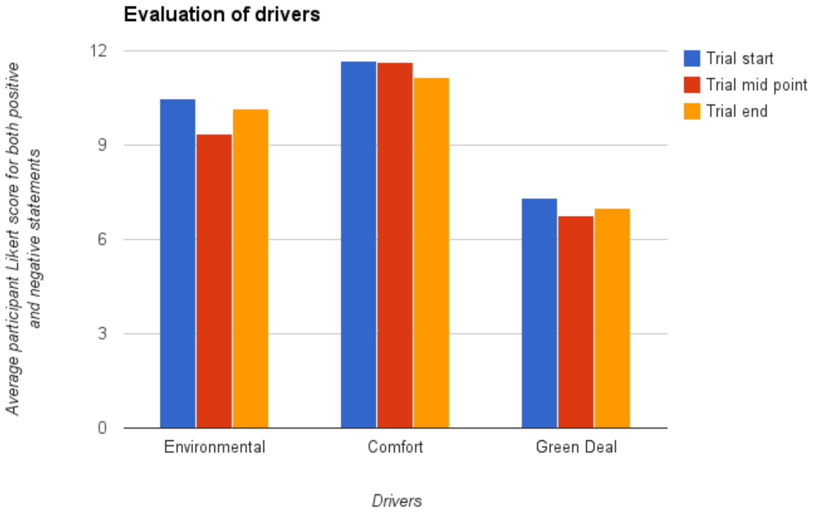
At the conclusion of the trial, six participants undertook semi-structured interviews, each lasting around 45 minutes. The interviews were recorded in audio format, then transcribed to provide our data corpus. The data corpus was then imported into Atlas and we undertook thematic analysis (Braun & Clarke 2006) with two overarching perspective themes — retrofitting barriers and drivers — that were taken from the design of the interviews. We then took a grounded approach to create the initial codes and patterns. This was an iterative approach of reading the data corpus, assigning preliminary codes, then looked to collapsing the preliminary codes into core themes that would lie within our two overarching themes. We then cross-analysed these themes with the academic literature highlighted in section 7.2. This provided us with a final set of sub-topics under each of the overarching themes of drivers and barriers. Finally, through Atlas we analysed the co-occurrence between retrofitting and each of the drivers and barriers. Co-occurrence refers to the chance that two terms in a text corpus appear alongside each other. Co-occurrence analysis allows us to learn more about the structure and the relationship between themes in the data corpus. This is the reason that we used this analysis technique. The higher the co-occurrence value, the larger the importance to the trial participants, and the more it related to the overarching themes of drivers and barriers.

5.5.2.1 Results and analysis

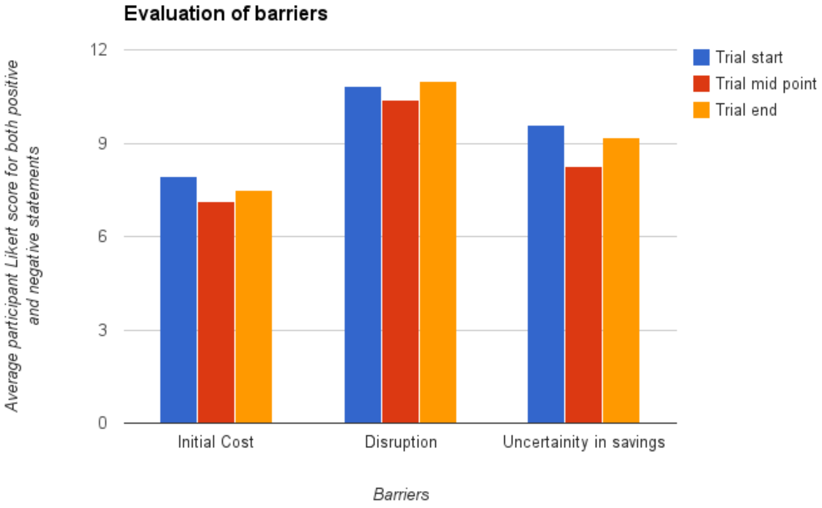
The evaluation of the interviews generated 235 coded examples that were divided into ten drivers and nine barriers. The results are represented in Table 5.1 and Table 5.2.

In analysing the results, the first thing noted is that a number of the barriers and drivers mentioned in the interviews reflect prior retrofitting research (Mills & Rosenfeld 1996, Pelenur 2013, Wilson et al. 2014, Massung et al. 2014). Finance was the largest influence on householders, both in terms of being a driver and a barrier. On the drivers side, it was highlighted a number of times that the participants see energy efficiency measures as a method for reducing the amount of money they spend on energy. For example: in response to *"What were the key factors for getting energy efficiency measures?"*, participants answered:

Participant 2: *"I think the monetary savings still is a big part."*



(a) Householders evaluation of the drivers: environmental, comfort and Green Deal.



(b) Householders evaluation of the drivers: initial cost, disruption and uncertainty of savings.

Figure 5.4: Graphs showing householders' evaluation of key barriers and drivers at the start, mid point and end of the trial.

Drivers	Co-occurrence value (similarity value)
Potential financial savings	0.27
Increased comfort	0.23
Subsidies / Discounts	0.15
Good accurate information	0.10
Current product broken	0.09
Environmental issues	0.08
Renovation already taking place	0.06
Trusted company or brand	0.05
Improve aesthetics	0.03
Social Influence	0.02

Table 5.1: List of householders’ drivers to retrofitting, generated from semi-structured interviews.

Barriers	Co-occurrence value (similarity value)
Initial cost	0.21
Limited expert knowledge	0.19
Time consuming	0.13
Resignation	0.11
Bad communication	0.09
Limited control	0.08
Disruption	0.07
Damage to the aesthetics of household	0.07
Green Deal loan	0.07

Table 5.2: List of householders’ barriers to retrofitting, generated from semi-structured interviews.

Participant 6: *"Saving money and being warmer."*

In evaluating the relationship on the barriers side, a number of participants found the initial cost of a number of measures was too much, even under the Green Deal scheme:

Participant 5: *"Would like micro-generation but the up front costs are a barrier."*

Participant 2: *"Solid wall insulation which is too unaffordable really."*

This could highlight a failing in the Green Deal scheme, as one of its key features is to help remove the initial cost barrier, but it is still present in the results from our interviews. Additionally, in a small number of cases the Green Deal loan was seen as a barrier, due to the idea that the loan may cause problems when the participants sell their house:

Participant 2: *"I would go 'Oh, don't want to pay that [Green Deal loan], you pay that [Green Deal loan] off and then I will talk about buying the property from you.' I don't want to take on somebody else's debt, even though it is a property I am buying."*

The next key factor to note in our analysis of the questionnaires was that comfort was a large driver for retrofitting. This aspect could play a larger role than it does at present in encouraging individual householders to implement energy efficiency measures; how this can be achieved will be discussed in section 5.6.

In comparing the results from our semi-structured interviews with the rest of the academic literature highlighted in section 7.2, there are two key factors in our results that are under explored in the academic literature:

1. Renovation or broken products as a driver — In a number of cases, participants showed an interest in implementing energy efficiency measures as part of a renovation, or to replace existing faulty or broken products within their household:

   Participant 5: *"We were just finishing some renovations actually so we wanted to get our loft cleared out and because we were doing that then it made an ideal opportunity [for Green Deal]."*

   Participant 6: *"So it's like we need to get things done and then incorporate them [energy efficiency measures] at the same time."*

   This poses a great opportunity if we can evaluate when householders are planning to renovate their property, or if we could evaluate when products are likely to fail or need replacing.

2. Resignation as a barrier — Participants displayed feelings of resignation towards both their current levels of comfort, and their ability to change the state of their household:

   Participant 1: *"The building is over 100 years old so it's going to be prone to damp."*

   Participant 3: *"You can see [the boiler] is old, you know it is old, it heats the water in a strange way, it works just about."*

   In Energy Technologies Institute (2015) customer research they also showed two-thirds of householders complained about heating problems, but that only 11% took the action of replacing their heating system to address the issue. It is important to take into consideration the householder's resignation about what is possible in their household. We must develop strategies that empower the householder to take on the challenges facing them. This could also help reduce the “limited control” barrier highlighted in Table 5.2.

In this section the results from the trial questionnaires and interviews have been presented. The results are shown to support a number of the drivers and barriers already found in the academic literature, but the results have also highlighted additional drivers and barriers that extend the literature.

5.6 Recommendations for the role ICT can play in encouraging retrofitting

In this section we will take a retrospective view on the previous sections, and look to define a number of recommendations about the role ICT can play in encouraging retrofitting.

The first area of interest is looking at the ability to build upon the driver of comfort and to help reduce the barrier of initial cost, as these were seen as core factors throughout our qualitative research. A proportion of energy savings from energy efficiency measures is taken back by the householder as part of the ‘rebound effect’ (section 2.4.5). It provides the householder with improved comfort, rather than direct financial savings. However, in a number of cases this value is not represented in the initial cost or expressed through the information provided to householders. The rise in the number of smart heating controls entering the market, such as the Netatmo (Netatmo 2017) and Nest (Nest Labs 2017), provide a great opportunity to begin evaluating the levels of comfort that each energy efficiency measure provides to the householder. We can start to display the increased level of comfort as a return on investment on the householder’s initial costs. This could really help householders in the questioner, evaluating expert advice and validator stages of the power law of engagement for energy saving framework (Figure 4.3). As comfort is subjective, the models of comfort would need to include quantitative temperature data collected from smart heating controls and qualitative data on the householders comfort preferences. In developing these models of comfort, we can start to provide householders with smart phone applications and improved heating reports that allow them to monitor their level of comfort rather than energy consumption. The concept could be pushed further to the point where a level of comfort is sold to a householder rather than energy e.g. 21^{o}C of heating for 10 hours a week. This would leave the responsibility of installing energy efficiency measures to the energy companies rather than the householder, as installing energy efficiency measures would reduce the energy companies’ cost to serve. The concept of comfort must also include improving the aesthetics of energy efficiency measures as this was seen as a barrier for our participants. Householders must feel comfortable with the aesthetics of their property with energy efficiency measures installed.

Secondly, ICT can be used as a method of discovering when householders are thinking about getting renovation work completed or when a product in their home is under performing (questioner stage). In the former scenario, renovation is a key opportunity as our results have shown renovation is a key driver. According to Energy Technologies Institute (2015), 35% of householders are planning renovations and it takes 70% of householders over a year to finalise their renovation plans. Therefore, it is vital that options and advantages of energy efficiency measures are presented to householders during this planning phase. Renovation can be equated to a lifestyle change and, as demonstrated by Duhigg (2012), this is also great opportunity to change householders' habits. In the latter, we see the development of low-cost sensors and smart heating controls that will allow householders to discover a large number of under-performing products, whether it be boilers (British Gas 2017*b*), insulation, single glazing or domestic products such as washing machines, refrigerators, or TVs. These are all opportunities to encourage householders to start thinking about more energy efficient options. We can also apply the concept developed by Freedman & Fraser (1966) and Cialdini (2007), where getting householders to agree and commit to small energy efficiency measures (replace washing machine to A+ model, replace broken boiler) can lead to the acceptance of large energy efficiency measures (micro-generation, solid wall insulation), as this will make their action consistent with their previous commitments. This will help push the householders to the later stages of the power law of engagement for energy saving framework (Figure 4.3). Finally, ICT could help build a database of product registrations, which would keep a register of new products bought by householders. They could then opt-in to be sent brochures or advice on how to upgrade old products to more energy efficient versions when they are no longer in warranty.

Thirdly, as we have seen in our results, retrofitting requires a large commitment in terms of initial cost, time, and disruption. Retrofitting comprises a major decision, and can only work if the householder has the right advice available (Economidou et al. 2011). The high price of energy efficiency measures makes the purchasing process similar to buying a new car, family holiday or renovating part of your home. This means that researchers need to take a different approach to changing habitual behaviours. Researchers need to investigate the psychological models that are appropriate to large, one-off purchases. In parallel, this will change the role ICT plays in encouraging retrofitting. Firstly, householders increase their time commitment to investigate the alternatives when it comes to making large purchases, as they want to make sure their £2,000-£15,000 is spent appropriately. Secondly, the decision-making process is taken over time, rather than at a single point, as shown in Chapter 4. ICT tools for retrofitting must take into consideration this longer decision time and allow the householder to interact multiple times over a prolonged period as they make their decision. This concept was the driver for our previous research in Chapter 4, and our interviews have supported the long and challenging decision process householders undertake when it comes to installing energy efficiency measures. Finally, householders have limited finances and the high price of energy efficiency measures means that retrofitting has stiff competition with other life objectives. We must be aware of these challenges. As one trial participant puts it:

Participant 3: *"There are many more priorities including fun, I think, and that is the trouble. [The boiler] is a long way down the list of priorities."*

The final recommendation focuses on the barriers of resignation and lack of control. Kaplan (2000) showed that helplessness can have a big effect on an individual's decision process. Therefore, one area of interest is how a householder can be empowered not to feel helpless when it comes to retrofitting, and how they can be encouraged to become the designers of their own energy efficient household? In looking to answer these questions we feel that we need to look at our research in Chapter 3, which highlighted that we need to focus more on using sustainability through design to get householders and groups to change the design of their environment (sustainability in design). The change in focus will cause householders and groups to become the designers of their own sustainable environment. In this approach, ICT needs to provide an engaging method for householders to experiment with different designs and different energy efficiency measures. This could take the form of simulations where the householders can experiment with different energy efficiency measures and different designs, and view their impact in terms of potential drivers (potential savings, comfort and environmental impact), and barriers (initial cost, time investment and disruption).

5.7 Conclusion

We have presented the results from a two-month longitudinal trial that evaluated householders' decision-making process during a period when our participants showed interest in energy efficiency measures, but remained undecided. Our results support and extend the literature on the drivers and barriers to retrofitting. We highlighted the importance of renovation or replacing broken products as drivers, and householders' resignation as a barrier. Finally, a number of recommendations have been presented on how ICT can help remove the barriers and enhance the drivers of retrofitting.

5.8 Appendix

Please find below the questionnaires and semi-structured interview questions used throughout the trial. The schedule of the questionnaires and interviews have also been added to this section.

5.8.1 Preliminary questionnaire

1. How often do you participate in the following activities? (Daily, weekly, monthly, quarterly, yearly or never)
    a) Review your energy bills
    b) Take gas or electric meter readings
    c) Seek out news on energy related topics
    d) Discuss energy saving with friends and family
    e) Download an application to a mobile device
    f) Use online banking services on a mobile device
    g) Check your emails on a mobile device
    h) Use online banking services on your PC or laptop
2. Have you taken any energy saving measures on your property within the last 5 years?

3. How many times have you changed your energy supplier within the last 5 years?
4. If you answered 1 or more in the question above (switched energy supplier in the last 5 years), please state the reasons for changing.
5. Please list the computers and smart devices you own:
6. On a scale from 1 to 10, 1 being inaccessible and 10 being easily accessible, how easy is it to access and read your gas meter?
7. On a scale from 1 to 10, 1 being inaccessible and 10 being easily accessible, how easy is it to access and read your electric meter?
8. What temperature is your thermostat set at during the day?
9. What temperature is your thermostat set at during the evening?
10. What is your first heating period? e.g. 07:00 - 09:00. If you don't have a set heating period, please state "No first heating period".
11. What is your second heating period? e.g. 17:00 - 20:00. If you don't have a set heating period, please state "No second heating period".
12. In one or two sentences describe your house's heating regime. Example 1: No regular heating patterns, only turn on heating when house feels cold. Example 2: Heating comes on at set times in the morning and in the evening, at a defined temperature.
13. Where is your thermostat located within your property? (In the hallway, living room, etc.). State N/A if you have no thermostat

5.8.2 Trial questionnaire

1. Please define which stage in the Green Deal process you are at: (Initial interest, assessment, received Green Deal advice report, chosen measures for installation, install or payment).
2. How likely are you to take the following actions within the next 12 months? (very probably not, probably not, possibly, probably, very probably or definitely)
    a) Install a smart meter (replacement meter which automatically submits your meter readings)
    b) Install a smart thermostat (allows automated control of your heating)
    c) Install solar panels
    d) Install roof or loft insulation
    e) Install cavity wall insulation
    f) Install external wall insulation

   g) Install a new, more energy efficient, boiler

3. To what extent do you agree or disagree with the following statements: (Strongly disagree, disagree, neither agree nor disagree, agree or strongly agree)

   a) The initial cost of improvements seem attractively priced
   b) Subsidies will help with the initial cost of improvement
   c) The upfront costs should be included in monthly repayments
   d) I am unlikely to have an improvement done due to the disruption it causes
   e) I don't mind the disruption caused by the installation of improvements
   f) I would consider having an improvement done if it didn't cause any disruption
   g) The benefit to the environment is a key driver to having the improvement installed
   h) My property will be more environmentally friendly after the improvement
   i) It is important that my property will be more environmentally friendly after the improvement
   j) The estimated savings from the improvement are very attractive
   k) I am worried about the potential savings won't meet the predictions
   l) The potential savings are the reason I am having the improvement done
   m) The increased level of comfort in my property is a positive reason to have the improvement
   n) I don't mind if the improvement doesn't increase the level of comfort in my property
   o) It is important that the improvement gives me a higher level of comfort
   p) Green Deal is making the decision to have an improvement easier
   q) I would have an improvement even if Green Deal weren't providing finance
   r) I didn't think about improvements until the Green Deal
   s) I want real time feedback on my energy usage
   t) I wish there were a simple way to view my energy usage
   u) I don't want to see how much energy my property is using
   v) I have enough information about how my property performs in terms of energy consumption

4. Please describe any reasons why you would not or can't have energy efficiency improvements. These could be, for example, issues you have encountered, or problems you have foreseen with having energy efficiency improvements performed.

5. Please describe the any reasons you would have an energy efficiency improvement. These could be anything that motivates you to have energy efficiency improvements performed.

6. Do you feel that you monitor your energy usage enough? (yes or no)

7. If no to question above, what, if anything, do you think would make it easier to monitor you home's energy usage?
8. Is there anything else you'd like to share?

5.8.3 Semi-structured interview questions

1. Main topic question:
    a) Improvements:
        i. Please describe current energy efficiency improvement you have in your property?
        ii. What was the reasoning to have them?
        iii. What were the major problems with getting your improvements?
        iv. Can you describe the key factors which concern you about having energy efficient improvements?
        v. What would be the main reasons for you to carry out a energy efficient improvement?
        vi. How easy is it to find information about energy efficiency improvements?
    b) Green Deal:
        i. Please could you describe your process through the Green Deal? What has been good, what has been bad?
        ii. What could be improved?
    c) Monitoring:
        i. How easy do you find it to understand your energy consumption?
        ii. What do you think would help you understand your energy consumption?
        iii. How do you think technology could help you learn more about your energy consumption?
        iv. Has technology already helped you understand your energy consumption?
        v. Have you found the monitoring application and MyJoulo helpful in the monitoring process?

5.8.4 Questionnaire and interview schedule

Please find the schedule for the trial questionnaires and interviews.

1. Identify potential participant
2. Recruit participant
3. Receive trial intro email and T&Cs

4. Sign and return T&Cs
5. Trial start drop in sessions:
   a) Introduce the trial
   b) Set up user accounts
   c) Get participants to sign T&Cs if they haven't already
   d) Complete preliminary questionnaire
   e) Complete trial questionnaire
6. Conduct semi-structured interview for selected participants
7. Wait 4 weeks
8. Complete trail questionnaire for the second time
9. Wait 4 weeks
10. Complete trail questionnaire for the third time.
11. Send thank you emails

CHAPTER 6

THE USE OF DIGITAL TECHNOLOGY TO EVALUATE SCHOOL PUPILS' GRASP OF ENERGY SUSTAINABILITY

"The development of ecological understanding is not simply another subject to be learnt but a fundamental change in the way we view the world." — Lyle (1996)

6.1 Introduction

Sustainability is often defined as "meeting the needs of the present without compromising the ability of future generations to meet their own" (World Commission on Environment and Development 1987). However, as highlighted in section 2.1, the current generation have been pushing the ecological boundaries of our environment to near breaking point, and we are only just starting to make the changes required to secure the planet's future. In the quest to build a society that sees sustainability as a way of life, it is critical that sustainable education plays a vital role in helping future generations learn from our mistakes. It must help them to develop the knowledge and skills to keep our earth within its ecological boundaries (Spiropoulou et al. 2007). Therefore, how do we achieve this fundamental change in school pupils?

In this chapter we discuss our development of a smartphone application that helps teachers stimulate discussion about environmental energy topics. In the application we look to incorporate a number of core learning and teaching techniques to help the application succeed in increasing the school pupils' level of engagement, knowledge and awareness about energy topics, and help them build habitual, sustainable behaviours.

The content of the chapter is an extended version of the author's Late-Breaking Work paper that was published and presented at the ACM 2016 CHI Conference on Human Factors in Computing Systems (CHI2016).

6.2 Background

In the development of the UK's 2000 revision of the National Curriculum, there was an increased focus on education regarding environmental issues, not only in science and geography but throughout the complete curriculum (Summers et al. 2000). This has helped to transform environmental education from an optional subject into a fundamental topic that is applied across disciplines. However, even with the increased focus on sustainable education, teachers and school pupils still have misconceptions about many environmental and sustainability issues (Summers et al. 2000, Spiropoulou et al. 2007). It is understandable that there are misconceptions; sustainability is a complex subject. Even in the academic community, the meaning of sustainability and the term itself are heavily debated (Chasin 2014). When looking to develop the mindset of pupils at school, it is vital that we look at both developing the computational thinking of solutionism, while including the wider systems thinking approach to help guide school pupils to a more holistic, sustainable thinking mindset (Warburton & Kevin 2003, Easterbrook 2014). Taking this approach will enable pupils to extract the social and economic impact of both their own environmental decisions and those decisions taken by wider society.

In looking to develop the smartphone application to help school pupils we incorporated a number of core learning and teaching techniques, which are presented throughout this section. The section then concludes by presenting an evaluation of the use of ICT in energy and sustainability education.

6.2.1 Spacing effect and habit formation

The spacing effect refers to: *"the finding that for a given amount of study time, spaced presentations yield significantly better learning than do presentations that are massed more closely together in time." (Dempster 1989)*. The spacing effect has been applied within school classrooms: both Sobel et al. (2011) and Bloom & Shuell (1981) showed that it produced superior long-term retention. Bloom & Shuell's (1981) study on teaching French contained two student groups: the first studied unfamiliar words for 30 minutes, and the second studied for 10 minutes on three consecutive days; the second group had a 35% increase in their ability to recall the words four days later. In a similar manner, Cepeda et al. (2008) used the spacing effect to teach facts and visual objects. The spacing effect has also been used in digital format (emails and Short Message Service (SMS)) to help Japanese students learn English vocabulary (Thornton & Houser 2004, 2005) and to help medical students learn clinical knowledge (Kerfoot et al. 2007). However, it has been noted that the spacing effect is underused both within schools (Dempster 1989) and in the textbooks we provide students (Rohrer & Taylor 2006). In understanding the large impact the spacing effect can have on information retention, it was important for the solution to provide students with content multiple times, with a discrete time frame between each occasion. The proposed solution in the chapter looks to extend the literature on the spacing effect by using a smartphone application to present students with regular repeated lessons on sustainability.

Next, habitual behaviours can be described as automated responses that are cued by a set performance context (time, environment or preceding action) (Neal et al. 2006). The repetition behaviours in the past leads to the behaviour being increasingly under control of an automatised process in the future (Aarts & Dijksterhuis 2000). In teaching sustainability, deciding the right response can be a complex decision involving many different viewpoints, and therefore it can be harder to formulate into an automatic responses compared to simple behaviours (Verplanken 2006). However, there is nothing stopping the concept of habits being applied to mental processes, e.g. thinking about the environmental impacts of actions (Trafimow & Miller 1996, Verplanken 2006). In looking to help school pupils form sustainable attitudes, values and beliefs, it is important that they get into the habit of thinking about the environmental impact of their actions. To achieve this we need to expose the pupils to contexts where the discussion can be focused on sustainability, and the students can start to learn the correct sustainable responses. In repeating this exposure, the pupils will start to feel more in control, and over time it will become a habit for them to think about the sustainable issues surrounding their actions. It is not necessarily about getting the students to undertake sustainability behaviours, but getting them into the habit of thinking about the environmental impact of their behaviours, which will in turn lead to greater understanding about sustainability. This chapter looks to broaden the understanding of habit formation when it comes to mental processes by applying it to sustainable thinking.

6.2.2 Collaborative learning and expertise

Collaborative learning is a personal philosophy that enables groups of people to come together and share the understanding that individual group members have different abilities, contributions and ideas (Panitz 1999). It aims to build a shared world view for the plenary group, and through this process each group member has to question, analyse and structure their existing knowledge. It is this engagement in explanations that helps develop conceptual understanding (Roschelle et al. 2010). Students who have been taught to use collaboration as a way to facilitate each other's learning show an increased level of cooperation, helpfulness towards each other, an increased use of 'we' and also showed more autonomy in their learning (Gillies & Ashman 1996). Developing these attributes is vital for helping school pupils understand that sustainability involves a significant amount of collaborative behaviour, as resources need to be shared to become more sustainable. The role that technology plays in collaborative learning has been slowly increasing due to a growing interest in Computer-Supported Collaborative Learning (CSCL) (Resta & Laferrière 2007), and has been applied to learning mathematics (Roschelle et al. 2010) and language (Zurita & Nussbaum 2004). It has also been highlighted that CSCL research needs to focus more on higher-order thinking, deep understanding, and knowledge creation (Resta & Laferrière 2007). This chapter expands the literature in this area by providing a novel method of linking experts with a deep understanding and knowledge of energy and sustainability with teachers, and in turn school pupils.

Vygotsky et al.'s (2012) has two perspectives on the internalisation of knowledge. Firstly, the "zone of proximal development" that represents the difference in what can be achieved by a child independently, compared to an "expert" partner. The key to the "zone of proximal development" is to provide students with educational material that is slightly too hard to be completed individually, but can be achieved with support from a teacher or expert (Wass & Golding 2014). To help aid the students' learning, teachers or experts should provide the structure and scaffolding to help the student learn to complete the task (Figure 6.1; in this situation, scaffolding is defined as *"the support, guidance, advice, prompts, direction or resources a learner is given that otherwise out of reach."* (Wass & Golding 2014). The research presented in this chapter looks to help provide such structure and scaffolding for teachers to help them teach their pupils about a number of energy issues. Vygotsky et al.'s (2012) second perspective is inter-subjectivity, which relates to the combined internalisation of knowledge from the expression of each individual's different viewpoint (Fawcett & Garton 2005). Inter-subjectivity is the product of multiple individuals sharing their different viewpoints through participating in discourse towards a goal of activity. It is this discourse that forms the product of knowledge (Hall 2010). In building on Vygotsky et al.'s (2012) research, Summers et al. (2000) also state that: *"Good subject knowledge is essential for the best teaching."* It is expertise about energy, sustainability and environmental issues that the teachers require, as this will help them remove a number of sustainability misconceptions (Summers et al. 2000, Spiropoulou et al. 2007). The teachers have the pedagogical knowledge regarding how to teach their students, therefore the proposed solution must play a supportive role rather than looking to disrupt or implement radical change to the current teaching methodology implemented by the teachers.

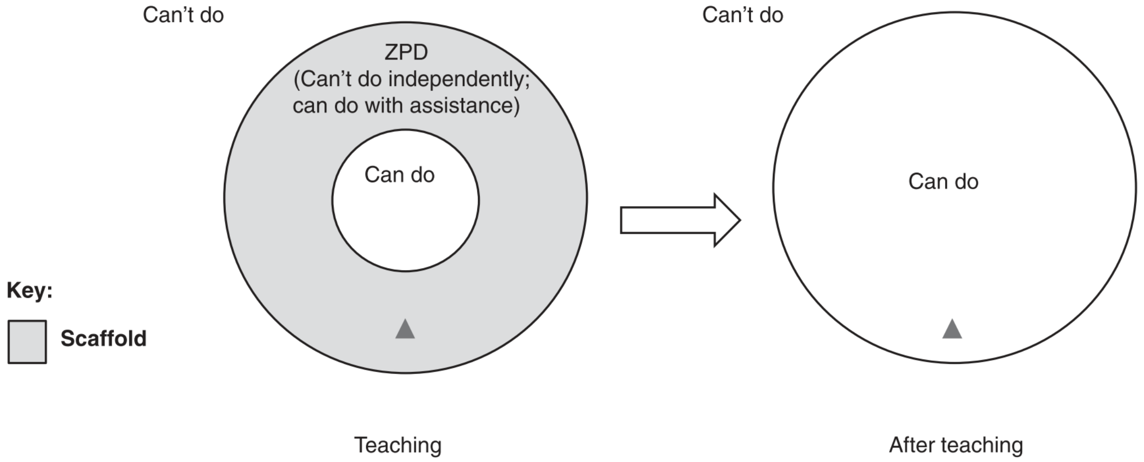


Figure 6.1: Wass & Golding (2014, p.676), *Teaching — students are scaffolded to complete a task (triangle) that is within their ZPD (zone of proximal development). After teaching — students can do this task independently.*

The final section of this review looks at the current application of ICT to help educate pupils about energy and environmental sustainability.

6.2.3 ICT in energy and sustainability education

ICT has a growing presence in children's lives, with 7 out of 10 children aged 5-15 now having access to a tablet computer at home, and 4 out of 10 owning a mobile phone; this increases to 8 out of 10 for children aged 12 - 15 (Ofcom 2014). The increase in ICT is causing schools to adapt their approach to technology in the classroom. Henderson & Yeow (2012) and Li et al. (2010) both showed that tablets provide students with a feeling of increased empowerment and engagement with their work. Chan et al. (2006) push the implementation of ICT in eduction further and show that we can create "seamless learning spaces" where pupils can learn whenever they are curious by quickly switching between different contexts: formal, informal, individual and social learning. Two examples of informal learning are the Power Agent (Gustafsson, Katzeff & Bång 2009) and Power Explorer (Gustafsson, Bång & Svahn 2009) pervasive games that look to both motivate and educate teenagers about energy conservation in the home. The games use social game mechanics, energy saving recommendations (in the form of clues) and real world smart meter data collected from the teenagers' family household to promote a transfer of energy conservation knowledge. Next, a more formal application of ICT in energy education is the SustEner initiative (Bauer & Rojko 2013, Rojko et al. 2015). The initiative has developed online tools to help secondary school teachers and students learn about key energy topics such as solar energy, wind energy, energy saving, and hybrid and electric vehicles. The solution enables experts from universities to develop online courses and remote, virtual experiments that can then be used by secondary school teachers and students, which helps spread expert knowledge of sustainable technologies and energy saving. Kalz et al. (2014) used inquiry-based learning in combination with serious games to teach students about electricity, energy consumption and energy efficiency. Finally, Meishar-Tal & Gross (2014) used smartphones to enhance experimental learning in a botanical garden, but found the use of smartphones unnecessary and potentially cumbersome.

The smartphone application solution presented in this chapter looks to extend the ICT in energy and sustainability education literature by providing a novel method of transferring expert knowledge from energy experts to school teachers, who in turn will transfer knowledge to their pupils.

6.3 Problem definition

The Pod, EDF Energy's award winning eduction programme (EDF Energy 2017*b*), approached us to help their team develop a new method of engaging pupils in energy sustainability throughout their proposed energy campaign called "Energy Month". The Energy Month campaign runs each year throughout November. It aims to get students exploring energy topics, help them learn where energy comes from, what the key issues are, why it is important to use energy efficiently and how to save it. This all helps to make students more aware of the environmental impact of energy. The Pod currently supplies teachers with curriculum-linked resources that include lesson plans, posters, games, and information packs. However, as The Pod develops it is understood that they need to move towards more digital forms of learning material to be relevant with students. In understanding The Pod's problem, we decided that there were two core areas of research — awareness and impact — each with a number of research questions to explore:

1. **Awareness**
    a) Which energy topics do school pupils' have high levels of knowledge, engagement and awareness of already, and which topics do they need to learn more about?
2. **Impact**
    a) Does linking school teachers with experts at EDF Energy help teachers teach pupils about sustainability and energy issues?

b) Can the use of ICT help develop collaborative learning around sustainability?

c) Can the application of the spacing effect and habit formation techniques help encourage school pupils to develop sustainability habits?

6.4 Daily Energy Message smartphone application

In creating the smartphone application, a number of design principles were taken from the background literature as described below:

1. The solution must take advantage of the spacing effect to increase the school pupils' overall retention of energy topics;

2. The solution must aim to encourage teachers and their students to discuss sustainability on a daily basis. This helps build a habitual mental process around sustainability;

3. The solution should help teachers increase their knowledge about sustainability, which in turn helps them transfer this knowledge to their pupils;

4. The solution must stimulate collaborative learning between the teacher and their students, but also peer-to-peer learning between the students;

5. The solution must aid the teachers by providing a "scaffolding" to combine with their pedagogical knowledge to help the students to transfer across the "zone of proximal development".

The Daily Energy Message smartphone application's core functionality is to present a daily energy fact that the teachers can read to their class to stimulate discussion around sustainability. The smartphone application aims to provide expert and up-to-date knowledge about sustainability. It allows experts at EDF Energy to generate the facts for the application, alongside additional information and resources that the teachers can use during their discussion with students. Bringing such information into classroom discussions in small, bite-size pieces that are completed on a daily basis ensures that teachers do not have to rely on out-of-date information from textbooks. The application was used throughout the whole of EDF Energy's Energy Month campaign (EDF Energy 2014*b*), which totalled 20 days of classroom time. Each day the school pupils had the opportunity to collaboratively discuss sustainability issues with the energy fact being a stimulus. The facts were distributed over the month, allowing the application to take advantage of the spacing effect, and presenting a fact each day helped make the discussion of sustainability a daily habit for the pupils during the Energy Month campaign. The goal of this format was to encourage the pupils to develop a habitual mental process around the topic of sustainability. It was key when designing the application to maximise the role EDF Energy's experts could play due to their knowledge about sustainable development, energy production and energy consumption. However, a key challenge was that EDF Energy's experts had limited time and could only visit limited locations.

This made it vital to digitalise their knowledge through the generation of the energy facts and supporting educational material.

Finally, the application was developed in Hypertext Markup Language 5 (HTML5) and Cascading Style Sheets (CSS), making it a web application that would run on mobile devices, tablets, Personal Computer (PC) and laptops. The application also had a supporting Content Management System (CMS) to allow the management of the Energy Facts and supporting teaching resources.

6.4.1 Application screens

The application contained three screens:

1. Energy Message screen (Figure 6.2a) — Contains a short catchy version of the fact that the teacher reads out to the school pupils. Examples include:
   Fact 1: *Did you know a flying wind turbine is set to take to the skies in America?*
   Fact 2: *Iceland generates 25% of its electricity through heat from geothermal sources.*

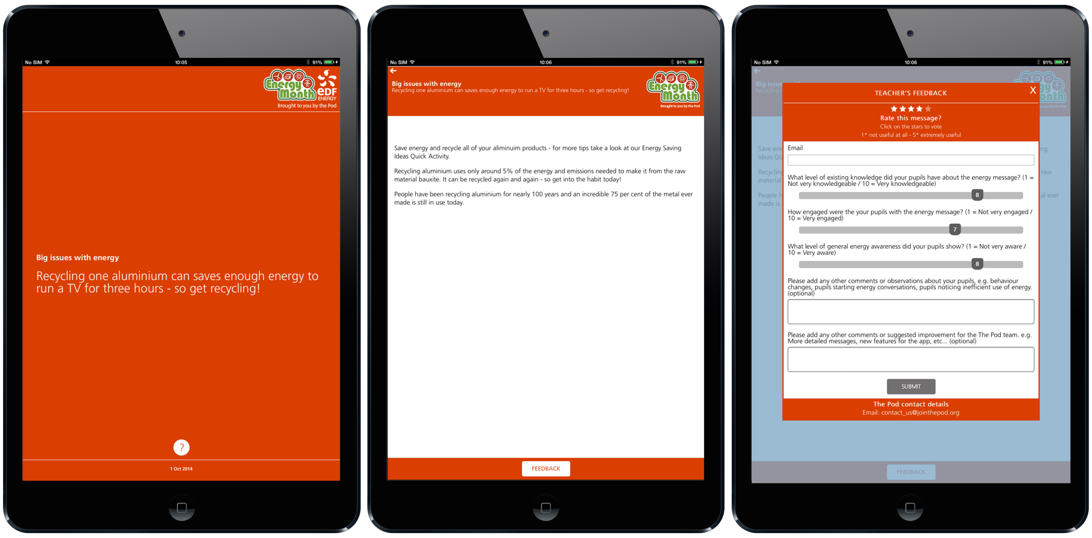
2. More detail screen (Figure 6.2b) — Presents a detailed description of the fact alongside extra teaching resources.

3. Teacher's feedback screen (Figure 6.2c) — Allows teachers to provide feedback on the resulting discussion with their students. The feedback screen was designed to allow teachers to provide feedback within two minutes, and it was designed to be completed after every teaching session where the application was used. The feedback form had a set of questions that looked at pupils' existing knowledge, engagement and awareness of the topics covered in the energy facts. It is described further below in section 6.5.2.

6.4.2 Collecting and sourcing the energy facts

To produce the facts disseminated through the application, we asked experts from EDF Energy to provide us with content. The experts were all from EDF Energy's UK based teams and from a wide range of teams within EDF Energy, including electric vehicles, sustainability, wind farms, nuclear new build and digital teams. The content was made up of four attributes: a short catchy version of a fact, a detailed description of the fact, a link to source material that validated the fact, and extra material to support the teaching of the fact.

The energy facts reduced the required impact on EDF Energy's experts as they only had to complete our set content form, which we would then review and upload through the CMS. This also reduced the impact on teachers as all required teaching material was contained within the Daily Energy Message smartphone application.



Big issues with energy

Recycling one aluminium can saves enough energy to run a TV for three hours - so get recycling!

1 Oct 2014

Save energy and recycle all of your aliminuim products - for more tips take a look at our Energy Saving Ideas Quick Activity.

Recycling aluminium uses only around 5% of the energy and emissions needed to make it from the raw material bauxite. It can be recycled again and again - so get into the habit today!

People have been recycling aluminium for nearly 100 years and an incredible 75 per cent of the metal ever made is still in use today.

TEACHER'S FEEDBACK

★★★★☆

Rate this message?

Click on the stars to vote

1* not useful at all - 5* extremely useful

Email

What level of existing knowledge did your pupils have about the energy message? (1 = Not very knowledgeable / 10 = Very knowledgeable) 8

How engaged were the your pupils with the energy message? (1 = Not very engaged / 10 = Very engaged) 7

What level of general energy awareness did your pupils show? (1 = Not very aware / 10 = Very aware) 8

Please add any other comments or observations about your pupils, e.g. behaviour changes, pupils starting energy conversations, pupils noticing inefficient use of energy. (optional)

Please add any other comments or suggested improvement for the The Pod team. e.g. More detailed messages, new features for the app, etc... (optional)

The Pod contact details

Email: contact_us@jointhepod.org

(a) Energy Message screen (b) More detail screen (c) Teacher's feedback screen

Figure 6.2: Daily Energy Message smartphone application.

6.5 Trial

In this section we outline the trial participants and design.

6.5.1 Participants

The smartphone application was trialled with school pupils in the 7-14 age group, representing key stages 2 and 3. To promote the use of the Daily Energy Message application by teachers, it was advertised through the website for The Pod, EDF Energy's education programme. Teachers were encouraged to download and use the application through a prize draw. For each day the teachers used the application and provided feedback they would get one entry to the competition. Each teacher could have a maximum of 20 entries and the winner was picked at random at the end of the month to win a school visit from a set of EDF Energy experts who would run a tailored session about one of the energy topics.

Throughout the month we had 608 sessions take place on the application, with 468 teachers using the application from 186 different cities (the distribution can be seen in Figure 6.3) and a return rate of 26%. Throughout the trial we collected 71 sets of feedback, with only one teacher providing multiple sets of feedback. This meant that around 15% of teachers provided feedback for their teaching session with the application. A majority of teachers only used the application once (74%) and only provided feedback once (99%). The low levels of retention and feedback are discussed in section 6.7.3.1.

6.5.2 Teachers' feedback

The teachers' feedback enabled a two-way communication between the teachers and EDF Energy's Pod team, and it also enabled us as researchers to start collecting data about the participating students. The

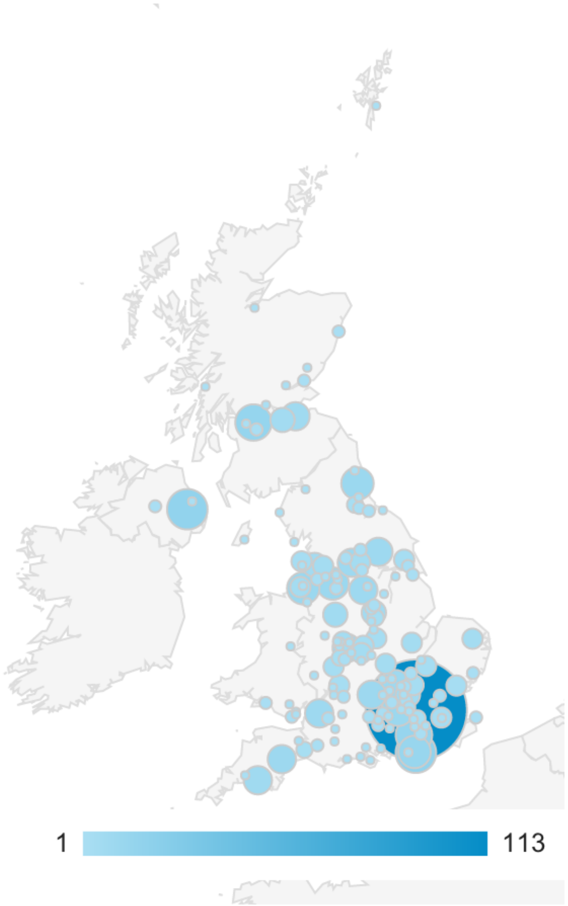


Figure 6.3: Distribution of participating teachers around the UK based on the number of sessions.

feedback form was designed to allow teachers to provide feedback within two minutes and it was aimed to be completed after every teaching session where the smartphone application was used. To reduce the impact on the teacher's time, only a small set of questions were asked:

1. Email — used to enter the school into the competition — text input box.
2. What level of existing knowledge did your pupils have about the energy message? — slider from 1-10 where: 1 = not much knowledge and 10 = very knowledgeable.
3. How engaged were your pupils with the energy message? — slider from 1-10 where: 1 = not very engaged and 10 = very engaged.
4. What level of general energy awareness did your pupils show? — slider from 1-10 where: 1 = not very aware and 10 = very aware.
5. Please add any other comments about the impact of the message on your pupils e.g. behaviour change, pupils starting energy conversations, pupils noticing inefficient use of energy. — text input box.

6. Please add any other comments or suggestions below, e.g. more detailed messages, new features, etc. — text input box.

In developing the feedback form we were able to get quantitative data from the scores provided to questions 2 to 4, while collecting qualitative data via the two catch-all questions (5 and 6).

6.5.3 Methodology

In analysing the data collected through the teachers' feedback, two methodologies were used:

1. To analyse the data collected from the three slider questions, we used simple descriptive statistics, which enabled us to look at the levels of knowledge, engagement and awareness of the school pupils. The results from this analysis are presented in the first section of our results.
2. Next, to analyse the two catch-all questions that asked the teachers to add comments on the impact of the messages and application, we used thematic analysis (Braun & Clarke 2006) with a grounded approach. This enabled us to start with no original themes and build them up as we went through the data.

Taking this two-fold approach meant that the qualitative data analysis could be added on top of the quantitative data analysis to provide more rigorous recommendations.

6.6 Results

Firstly, we looked at the pupils' overall levels of knowledge, engagement and awareness during the trial.

6.6.1 Knowledge:

Overall the level of knowledge was low, with most teachers scoring pupils at around 2-6 (Figure 6.4), and in a number of cases as low as 0. In Figure 6.5 we can see that the messages that scored the lowest were those sent on 03/11/2014, 13/11/2014 and 14/11/2014; the topics of these facts were coal, biomass and geothermal power generation respectively. The figure also highlights the highest scores as 05/11/2014, 07/11/2014 and 18/11/2014; two of these facts discuss the topic of wind farms, and likewise the fourth highest fact on 25/11/2014 was also related to wind farms. This highlights that pupils have a greater amount of knowledge on the generation of renewable energy through wind farms compared to alternative renewable energy generation sources like biomass and geothermal. Finally, overall school teachers rated their students' knowledge relatively low compared to their levels of engagement and awareness with the energy sustainability topics.

6.6.2 Engagement:

Next, the pupils' level of engagement was evaluated. Overall, the school pupils had a high level of engagement with the energy topics raised within the application, with a high proportion ranging between

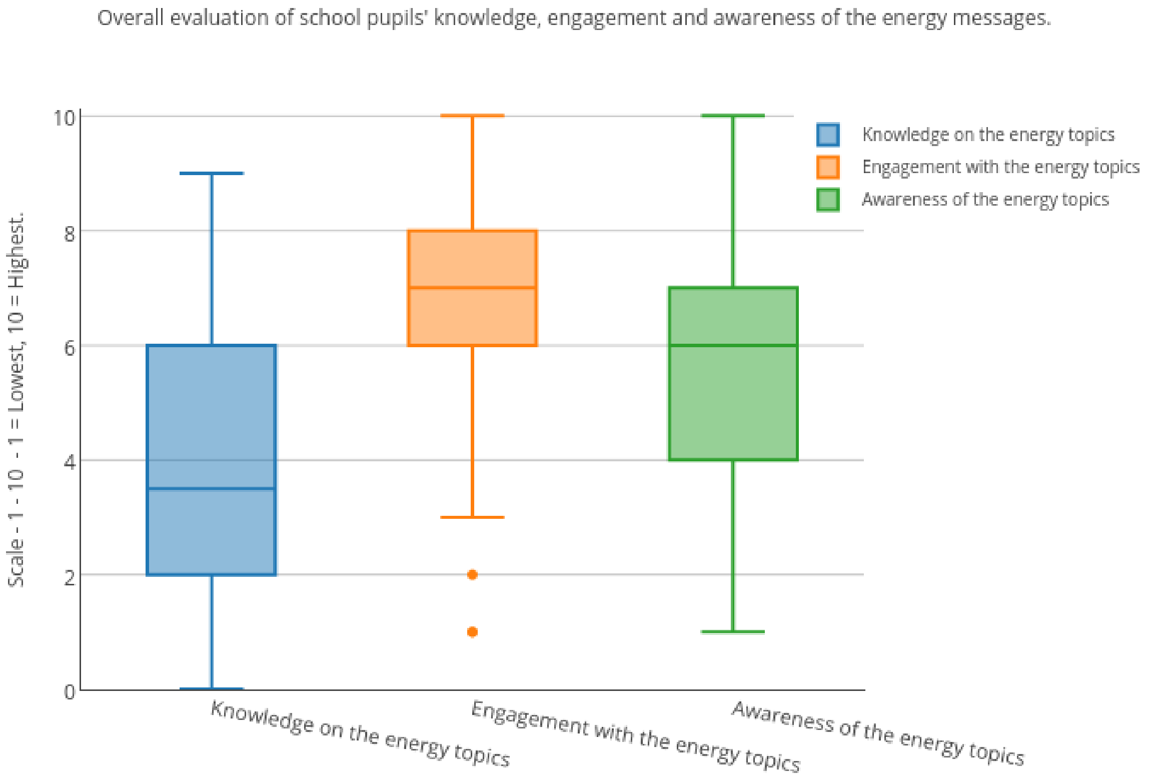


Figure 6.4: Overall evaluation of pupils' knowledge of, engagement with and awareness of the energy messages.

6-8 overall, apart from three outliers that provided a score below 3 (Figure 6.4). All the outliers were attributed to a single energy fact:

Fact 27/11/2014: *Did you know electric eels can generate an electrical charge of around 600 volts?* In analysing the individual scores for each fact, wind farms again scored high in terms of engagement with two of the top three scoring facts being about wind power (07/11/2014 and 18/11/2014). The lowest engagement was regarding the topics of battery storage (28/11/2014) and security of supply (10/11/2014). Finally, teachers rated the pupils' overall engagement higher than their awareness and knowledge.

6.6.3 Awareness:

In the analysis of pupils' awareness, we found similar results to knowledge, with the pupils having a greater awareness of wind farms (07/11/2014 and 25/11/2014) compared to the other topics. Likewise, we saw limited awareness of geothermal power (03/11/14), coal power generation (13/11/2014) and security of supply (10/11/2014).

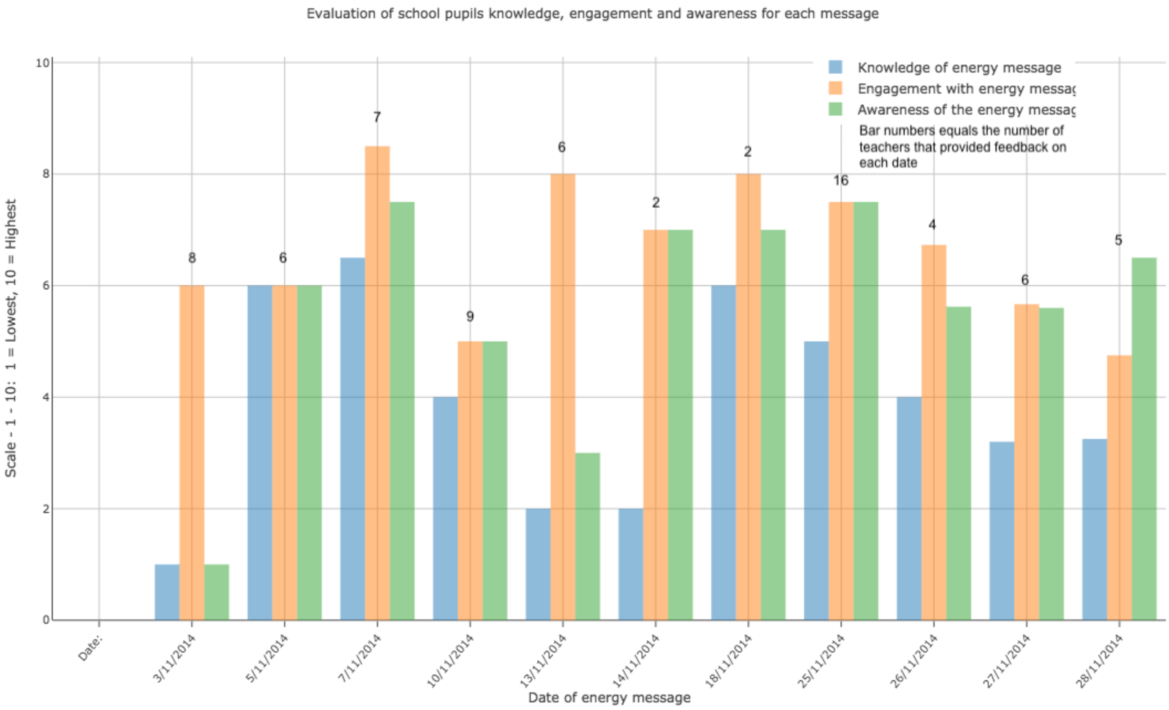


Figure 6.5: Evaluation of pupils' knowledge, engagement and awareness for each message.

6.6.4 Teachers' evaluation of the impact of the messages on pupils

In analysing the teachers' response to the catch-all questions, thematic analysis was undertaken. In taking this approach two core themes, impact and improvement, were generated, then for each theme a number of sub-themes were developed, e.g., stimulated discussion. The results of this analysis can be seen in Table 6.1 and Table 6.2, along with the co-occurrence between impact or improvement and each sub-theme. The higher the value, the more the topic was discussed in the response to the questions.

1. Impact	**Co-occurrence value (similarity value)**
1.1 - Application stimulated discussion	0.42
1.2 - School sustainability groups	0.19
1.3 - Application was engaging for the school pupils	0.19
1.4 - Application caused a change in perspective	0.16
1.5 - Facts were suitable	0.13

Table 6.1: Thematic analysis results for the core theme of impact.

2 - Improvement	**Co-occurrence value (similarity value)**
2.1 - Turning off lights and appliances had a large focus	0.43
2.2 - Facts were not suitable	0.15
2.3 - Application had a low level of engagement	0.14

Table 6.2: Thematic analysis results for the core theme of improvement.

6.6.4.1 Impact results

The first key result to highlight is that under the impact topic, a number of teachers felt that the application stimulated discussion (co-occurrence value = 0.42); example responses include:

Teacher 1: *“Great idea for generating discussion and ideas.”*

Teacher 2: *“Great facts and discussion as a result.”*

The next area of focus was that a number of teachers highlighted that sustainability groups were already running within their school (co-occurrence value = 0.19):

Teacher 3: *“There is a specific club (Carbon Footprint Crew- CFCs) who ensure energy is not wasted in the school.”*

Teacher 4: *“Our Green Action Team have started to make their own energy posters.”*

Continuing the analysis, when looking at the application’s ability to engage the pupils, it seemed that the results where somewhat conflicted. As under the theme impact (Table 6.1), a number of comments highlighted the application’s ability to stimulate engagement, with responses including:

Teacher 5: *“Pupils showed engagement and began a conversation about energy.”*

Teacher 6: *“Really interesting app, great way to engage the children.”*

However, under the theme improvement (Table 6.2), a number of teachers stated that the application generated a low level of engagement from the pupils. In reviewing these comments it was highlighted that a lack of imagery and video was the reasoning behind the low engagement:

Teacher 7: *“Could include short video clips or pictures as a starting point.”*

Teacher 8: *“Pictures for the younger children.”*

Finally, a number of teachers found that the application had an impact on the school pupils’ perceptions:

Teacher 9: *“Pupils are beginning to notice when energy is being wasted.”*

Teacher 10: *“All the class were happy to have the opportunity to correct me when I left the whiteboard on.”*

This is just the teachers’ view of the pupils’ actions and perceptions, so it cannot be equated to any direct evidence of a change in actions or behaviour taken by the pupils.

6.6.4.2 Improvement results

In the improvement theme, turning off lights and appliances had the largest co-occurrence value (0.43); example responses include:

Teacher 12: *"Children were all enthusiastic about what they use at home and parents commented on the knowledge they were sharing at home! Especially switching off lights!"*

Teacher 13: *"Noticing lights being left on, computers on standby."*

Secondly, as with the level of engagement with the application there was a conflict about the suitability of the facts. Teachers responded with positive feedback:

Teacher 14: *"Like the facts as a starter for lessons or form time discussion."*

Teacher 15: *"Excellent facts, prove you learn something new every day."*

However, on the other hand, a number of responses highlighted issues with the facts, as can be seen in Table 6.2 and responses like:

Teacher 16: *"More eco-school based facts would be useful."*

In the next section we discuss the results, make recommendations that can improve the teaching of energy sustainability, evaluate the success of the application, and present learnings that can be used in future educational ICT projects.

6.7 Discussion

Throughout this section we discuss the implications of the results.

6.7.1 School pupils' knowledge, engagement and awareness

The first area of discussion is the school pupils' knowledge, engagement and awareness of the big energy topics. In this section we highlight two areas of discussion: 1. increasing teaching on alternative energy generation, security of supply and storage, and 2. looking at how we can harness school pupils' high levels of engagement.

6.7.1.1 Increasing teaching on alternative energy generation, security of supply and storage

Our results showed that pupils had prior knowledge and awareness of renewable energy generation through wind power. It is great that student have this initial knowledge of wind power, but as society transitions towards a more sustainable energy mix, a wide range of renewable energy generation technologies will be required. It is important that alternative energy generation sources (e.g. biomass, geothermal, etc.) gain as much attention as wind farms, especially as our results showed pupils have less knowledge and awareness of these alternative energy generation technologies.

Pupils also had limited awareness of security of supply and low engagement with battery storage. Both these topics play a vital role in understanding how the world is going to help to meet the energy supply trilemma (E.ON 2017). It is this delicate balance between impact on the environment, economic cost of energy and security of supply that makes the topic of sustainable energy such a challenging one. Therefore, as with alternative renewable energy sources, students need a gradual introduction to these topics.

6.7.1.2 School pupils' engagement

Throughout the testing, teachers consistently gave a high rating to the pupils' level of engagement with the facts and the topic of energy sustainability. This is a great result, as it shows that pupils are willing to engage in the topic. However, it is important that while the students have this high level of engagement, it must be used to increase their knowledge and awareness, which the teachers consistently rated as lower than the school pupils' level of engagement. Providing expert knowledge to help students convert their high levels of engagement into more knowledge is one area where the application has succeeded, as will be highlighted through the next section.

6.7.2 Teachers' evaluation of the messages impact on school pupils

The second area of discussion was looking at the results from the teachers' evaluation on the impact of the messages. For this we had three core areas of discussion: 1. how the messages stimulated discussion, 2. the large focus on turning off lights and appliances and 3. the impact of current sustainability groups running at schools.

6.7.2.1 Stimulated discussion

In analysing the results of the two catch-all questions, the first aspect to note is that the application succeeded in stimulating discussion between the pupils and generated an environment for collaborative learning. The application helped develop Vygotsky et al.'s (2012) zone of proximal development by exposing the pupils to expert knowledge around geothermal power, coal power generation and security of supply — all topics they had limited awareness of. It also showed that the application is a useful tool to help teachers have up-to-date expert knowledge. As the results showed, much of pupils' knowledge, engagement and awareness was based on energy generated through wind farms and the sustainable action of turning off lights and appliances. As we move towards a more sustainable world, we will need to have a wide range of different energy generation sources and look beyond simple behaviour change such as turning off light to reduce our energy consumption. This up-to-date expert knowledge must be shared with teachers so that they can pass it on to their pupils. It is this success in digitalising EDF Energy's expert knowledge into a useful teaching resource for school teachers that is one of the major contributions of this chapter.

6.7.2.2 Turning off lights and appliances

Teachers' comments were focused on pupils needing to turn off lights and appliances, and it is good that students are noticing the electricity wasted in this way. However, as highlighted throughout this thesis, space heating has a much larger influence on domestic energy consumption and, in turn, on the environment. This highlights a mismatch between the teachers' knowledge and industry expert knowledge; since LED and other low-energy lighting has started to become widespread, turning off lights now has a limited impact on the environment. Therefore, in order to increase pupils' impact on reducing energy consumption, we need to focus their attention on space heating and water heating, and increase their understanding that lighting and appliances represent only a small percentage of total domestic energy consumption. In helping pupils understand the role space heating has on the environment, it would be a great opportunity to introduce some of the concepts around energy efficiency measures and retrofitting. It would also be beneficial to help students understand the principles behind the adaptive model of thermal comfort (Clear et al. 2014), which looks to promote the use of blankets, hot drinks, multiple layers of clothing and adjusting room ventilation to produce the required levels of comfort.

6.7.2.3 Sustainability groups

A surprising result was the number of teachers highlighting the sustainability groups and initiatives already taking place throughout their schools. The development of the application was mainly done in isolation with the EDF Energy's educational programme, The Pod. With hindsight, the application could have been improved through greater engagement with schools during the design and development phase of the project, as this would have allowed the application to take advantage of the existing sustainability groups and initiatives being run at the school. It is excellent news to hear that so many schools are employing a hands-on approach to sustainability. In future research we will look to leverage the capabilities of these groups to help promote, design and develop the application, a take a more user centred design approach to the problem (Norman & Draper 1986).

6.7.3 Evaluation of the application and future research

In this last section we discuss the limitations of the smartphone application and areas for future research.

6.7.3.1 Limited retention and feedback

In evaluating the application, the first area to discuss is that a majority of the teachers only used the application once and a limited number of teachers completed the feedback. Therefore, the application failed to take advantage of the spacing effect or help with the formation of habitual behaviours. In looking to find the main cause of this failure, we feel that more work is needed to integrate the smartphone application into the school timetable and help the teachers find a regular time in their teaching routine to use the application. A good idea would have been to ask teachers to link using the application to an existing habit or routine that they carry out each day, like completing the register. The application could also have taken greater advantage of the existing sustainability groups that have been set up at the school, as the teachers running these groups would be highly engaged and could be used to promote the application. When it comes to the teachers' feedback, only 15% of sessions resulted in teachers completing the feedback form, which would need to be improved in future research. To achieve this, there are two primary areas that should be changed to help increase the feedback rate:

1. Remove email from the feedback form — a number of teachers highlighted that they did not want to provide their email address as they were worried they would be sent spam or marketing

material.

2. Improve the user interface of the feedback button — the feedback button is only on the more detailed screen of the application, which means that teachers who only looked at the shortened version of the fact would not have seen the feedback form. Making the feedback button look more like a call-for-action may have improved the feedback rate.

6.7.3.2 Stimulating change through ICT

The application stimulated discussion around sustainability, and helped pupils notice when energy is being wasted around their school. This shows that a simple application that regularly reminds pupils how to lead a more sustainable lifestyle can start to generate a small change in their mindsets, and, more importantly, it can help them to understand why it is important to take sustainable actions. In moving forward, ICT as a tool to stimulate discussion around sustainability looks promising, especially when ICT is used to distribute expert knowledge. Finally, in the future it would be great to see how we can convert pupils into energy detectives. Pupils could collect data from around their school through crowdsourcing and then would become the energy police, learning what actions are sustainable, the balance between demand and environmental impact, and finding novel solutions to reduce the school's energy consumption.

6.7.3.3 Suitability of the facts

In developing the facts, the main aim was to keep them in line with key stage 2 and 3 of the National Curriculum. However, the teachers had mixed views regarding the suitability of the facts, with some teachers finding them at the right level for their pupils, while others struggled to link the facts to school-based energy savings or found the facts too complex for their pupils. Therefore, in future research it would be useful to add difficulty levels to the facts and then present three different levels on each day (e.g. low, medium and high) as this would allow teachers to tailor the fact to the ability of their students. It would also be beneficial in future research to include image and video content to support the facts, as teachers felt this was a missed opportunity.

6.8 Conclusion

This chapter has presented the implementation and trial of a novel application called Daily Energy Message. The application helped analyse pupils' levels of knowledge of, engagement with and awareness of energy sustainability topics. Our results highlighted that school pupils are knowledgeable about wind power and turning lights and appliances off, but have limited knowledge of alternative renewable sources of energy generation. The application was also shown to be successful in spreading up-to-date expert knowledge from EDF Energy's employee to teachers, which stimulated discussion. However, due to the lack of repetitive use by teachers, the application was not successful at forming habitual discussions about sustainability.

6.9 Appendix

Please find below the energy facts and the in detail content for each fact used within the Daily Energy Month Application.

1. Did you know that yesterdays rubbish could be turned into tomorrow's electricity?

   It said that by 2020 up to 3.5 per cent of Britain's electricity and half of the domestic gas demand could be generated from energy from waste plants. Find out more about the energy we use and how we produce our electricity with our Energy Presentation. Energy from waste is about taking waste and turning it into a usable form of energy. This can include electricity, heat and transport fuels (e.g. diesel). This can be done in a range of ways. Incineration is the most well known.

2. Did you know supermarket in Staffordshire is solely powered by its own food waste?

   The store at Cannock, Staffordshire, already sends all its food waste to the UK's largest anaerobic digestion plant. It is no longer supplied by the National Grid. The food waste that is sent to the waste centre creates enough power for 2,500 homes. Do you recycle your food waste at school and at home?

3. At the end of a TV programme there is often a sudden increase in the amount of electricity that's used in people's homes. Why do you think this could be?

   After some popular programmes up to 1.75 million kettles get switched on. Find out how much the electricity your household items use with our Greedy Guzzlers quick activity — you may be surprised! Want to learn more about the amount of food you waste? Take part in our whole school activity Lunchtime Crunchtime. The national grid have to ensure we have enough power for these surges. They instruct hydro electric plants to increase their output and also we get some electricity from France.

4. Did you know birds can sit on electricity cables without getting electrocuted? Why do you think this is?

   When a bird is perched on a single wire, its two feet are at the same electrical potential, so the electrons in the wires have no motivation to travel through the bird's body. No moving electrons means no electric current. The movement of electrons through a device like your TV is what gives it the energy to display images and produce sound. People working on electricity cables use insulating materials to protect themselves from getting electrocuted, such as industrial rubber gloves. An insulator is something which doesn't carry electric current very well.

5. In 2013 over 20% of the electricity generated in the UK came from nuclear power!

   What do you think are the pros and cons of Nuclear? Nuclear power is energy contained in atoms. This energy can be released as heat from a chain reaction in a radioactive element such as uranium. Want to know more about nuclear energy? Watch our short film featuring our friend Busta and Pong as they explore a nuclear power station. There are currently 9 nuclear power stations in the UK.

6. 18% of people in the world don't have access to electricity.

   Energy poverty is a lack of access to modern energy services. These services are defined as household access to electricity and clean cooking facilities (e.g. fuels and stoves that do not cause air pollution in houses). Use our Energy Presentation to look into this some more, what would a world be like without energy. Could you go for a day or week even without electricity? Think about how your day to day life would change.

7. Did you know electric eels can generate an electrical charge of up to 600 volts?

   The eels generate an enormous electrical charge to stun prey and put off any predators! Another animal that uses electricity is the electric catfish, it uses an electrical current as it swims to look out for anything that may get in its way or dangers that maybe lurking in the deep! You can find out all about electricity and its uses with our Electricity lesson plan.

8. Iceland generates 25% of it's electricity through heat

   Iceland is a pioneer in the use of geothermal energy for space heating. Geothermal energy is the heat from the Earth. It's clean and sustainable. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma. The first geothermal power plant was built in Iceland in 1969; today there are seven of them.

9. How long have electric cars been around? — answer is 180 years!

   These days there are thought to be over 10,000 electric vehicles in the UK, have you seen any charging points near you? Released in Japan in 1997, the Toyota Prius became the world's first mass-produced hybrid electric vehicle. To find out more about the pros and cons of electric vehicles - take a look at our Electric Vehicle Lesson Plans.

10. The coal that powers electricity was once a plant or a tree — Millions of years ago even before there were even any dinosaurs on earth.

    Coal contains energy that the plants absorbed from the sun millions of years ago. Burning coal releases this energy. It can then be used to heat water to generate steam, which is then used to drive a turbine to generate electricity. The main element of coal is carbon but it also contains hydrogen, oxygen, nitrogen and sulphur. Coal has been mined around the world through history but how much should we use in the UK? As a class why not run our Energy Debate quick activity or use our Energy Mix lesson plan?

11. The UK is the windiest countries in Europe, and we have over 30,000 wind turbines.

    Wind Turbines spin 70—80% of the time in the UK. The first offshore wind farm in the UK was a near-shore installation in Blyth harbour, north east England, which started operating in 2001. Could your school have a wind turbine? Have a look at our Will Wind Work lesson plans.

12. Recycling one aluminium can saves enough energy to run a TV for three hours - so get recycling!

    Save energy and recycle all of your aluminium products - for more tips take a look at our Energy Saving Ideas Quick Activity. Recycling aluminium uses only around 5% of the energy and emissions needed to make it from the raw material bauxite. It can be recycled again and again — so get into the habit today! People have been recycling aluminium for nearly 100 years and an incredible 75 per cent of the metal ever made is still in use today.

13. Did you know poo can be used as a source of energy? In countries around the world, poois used as a fuel for cooking and heating.

    How much do you know about biofuel? Why not look into this with your class and find out more. Generating power from poo produces a lot less carbon dioxide compared to when fossil fuels are used. At the moment scientists are studying panda poop to see if it can help us turn plants into fuel for greener cars of the future!

14. Did you know a flying wind turbine is set to take to the skies in America.

    Wind turbines are usually placed on the Earth's surface, but as winds are stronger at greater heights flying wind turbines are now being designed to make the most of this natural resource. Once study has observed that 'there is enough power in Earth's winds to be a primary source of near-zero-emission electric power. Create your own mini wind turbine with our How to make a windmill quick activity — think about how you could make it fly!

15. In 1928 the first electricity pylon was erected in Falkirk - it took another 5 years to put up the other 26,000.

    In Britain before the National Grid was built, electricity was very expensive and most people did not have access to electricity and even if they did they could not afford it. The first switch flicked by most homes was the light switch. Find out more with our 'How Does Electricity Get to Our Homes?' poster.

16. A school in Devon has decreased its energy bills from £1000 a day to £0.

    Why not run our fun Switch on to Switching Off activity at your school and see the difference you can make over a fortnight?

17. A flash of lightening can heat the air around it to temperatures five times hotter than the sun's surface — that's hot stuff! Each bolt can contain up to one billion volts of electricity.

    Can you name other weather types which can be used to produce electricity? E.g. wind and sunshine. Lightning is a huge electrical discharge that flows between clouds, from a cloud to air, or from a cloud to the ground. About 100 strikes of lightening hit the earth's surface each second.

18. It would take 500 million (500,000,000) AA batteries to provide the same amount of electricity as the average coal power station.

    Can you name different types of battery? Is there anything in your classroom that contains a battery? The most economical and environmentally friendly version of the AA battery is the NiMH rechargeable AA battery. Recharging a set of NiMH AA rechargeable costs only a small percentage of the price of alkaline AA batteries, and when you've used them, you don't have to pile your used batteries into a landfill, you simply recharge them. Every year, about 200 million AA batteries are sold in the UK alone! They are the most popular by far.

19. The international space station is powered by an acre of solar panels (equivalent to a football pitch).

    The International Space Station requires 75 to 90 kilowatts of power. Fifty-two computers control the systems on the ISS. It also uses eight miles of wire to connect the electrical power system.

20. A record high of 22% of the UK's electricity was generated by wind on the 17th August this year, enough to power 15,458,666 million homes.

    On that day wind was generating a greater proportion of the UK's electricity needs than coal (which was providing 13%), on the average day wind power usually provides enough electricity for 6 million homes. The UK's first commercial wind farm was built in Delabole, Cornwall in 1991. Wind power is now the UK's largest source of renewable energy generation.

CHAPTER 7

EXPLORING THE RELATIONSHIP BETWEEN HOUSEHOLDERS' PRO-ENVIRONMENTAL VALUES, IDENTITIES AND HEATING PATTERNS

"We buy things we don't need, to impress people we don't like" — Tyler Durden — Fight Club (Fincher 1999)

7.1 Introduction

As highlighted throughout Chapter 2, if the UK is to meet its CO_2 targets and move towards sustainable levels of energy consumption, space heating must be addressed. One promising technology that looks to reduce space heating demand is smart heating controls. However, as discussed in section 2.5.3, there is a lack of evidence related to the energy savings, cost effectiveness and usability of this technology.

The UK government (Department for Business Energy and Industrial Strategy 2016*c*) has proposed requirements for new heating systems such as independent time control and individual radiator controls, which mean that more householders will have greater control over their heating schedules and heating patterns. However, this does not necessarily mean these householders would choose sustainable heating patterns. Since space heating is already having a significant impact on the environment, and this is going to increase as householders require higher levels of comfort, more research must be done to understand the psychological driver of pro-environmental heating behaviours.

To achieve this, this chapter first evaluates the role a householder's pro-environmental values and self-identity can play in predicting self-reported pro-environmental and heating behaviours, objective programmed heating schedules, objective actual heating patterns and smart thermostat adoption. Secondly, since pro-environmental motives may not be the only relevant self-identity in this context, we also look at the role a householder's technology self-identity (e.g. seeing oneself as an early adopter of new technology) can play in predicting each of the above factors. A key contribution of the chapter is to explore sustainable heating behaviours from both self-reports and observations, and to identify any disparity between these.

The content of the chapter is an edited version of the author's Environment and Behavior journal paper that is currently under review.

7.2 Background

In the section we present the background literature for the research presented in this chapter.

7.2.1 Knowledge-action and value-action gaps

A consistent finding from the literature on pro-environmental behaviour is that increasing environmental knowledge does not necessarily lead to sustainable behaviours (Kollmuss & Agyeman 2002), contrary to the 'information deficit model' that continues to guide energy policy. For example, 73% in the UK say they are aware of environmental problems and 63% agree that if we continue on our current course we will soon experience a major environmental disaster (Department for Environment & Affairs 2008). However, there has still been a 7% rise in overall domestic energy consumption from 1970 to 2015 (Department for Business & Strategy 2016), rates of dwelling energy efficiency improvements are still low and desired heating setpoints continue to rise (Palmer et al. 2013). Part of this disparity between awareness and action is because some pro-environmental heating actions are not easily feasible for certain parts of the population, such as retrofitting for rented accommodation or reducing space heating for the elderly. Other factors include cultural norms and conventions around comfort, social dynamics and competing heating preference and requirements within the home (Shove 2003, Jackson 2005), as well as the level of individual's activity and local climate (Fountain et al. 1996, Clear et al. 2014). Furthermore, a number of energy-consuming behaviours are habitual interactions with technology, such as washing machine use, turning lights on and off and space heater use (Pierce et al. 2010, Huebner et al. 2013). While knowledge is often a poor predictor of sustainable heating behaviours, other work has found that values are not necessarily a consistent predictor either. Values define our preferences in terms of an individual's prioritisation of one thing before another because of a notion of betterness (Oreg & Katz-Gerro 2006) and are a central feature of the dominant theory of pro-environmental behaviour, the Value Belief Norm model (VBN) (Stern & Dietz 1999). The VBN posits that values and a pro-environmental worldview predict beliefs and moral obligations to act to protect the environment, and the model has been used to predict various behaviours including energy consumption (Poortinga et al. 2004) and the acceptability of energy policies (Steg et al. 2005). Stern's model incorporates the New Ecological Paradigm (NEP) or worldview (Dunlap et al. 2000), which links the ascent of the environmental movement to the growing acceptance of a more eco-centric outlook. However, while the NEP and similar measures of worldviews, attitudes or values may positively correlate with certain pro-environmental and energy saving behaviours, there remains a consistent value-action gap (Department for Environment & Affairs 2008, Flynn et al. 2009). This gap may be more evident for some behaviours than others; for example, pro-environmental values have been shown to predict domestic pro-environmental behaviours (e.g., energy saving) but not air travel behaviours (Alcock et al. 2017). The contradictory evidence in the literature highlights a need to explore the value-action gap in relation to sustainable heating behaviours in particular, which have to date received far less attention than other pro-environmental behaviours, and yet appear to be among the most intractable (Emmert et al. 2010).

7.2.2 Pro-environmental self-identity

Other research suggests pro-environmental self-identity is a better predictor of pro-environmental behaviours than many other psychological predictors, including values and knowledge (Sparks & Shepherd 1992, Cook et al. 2002, Whitmarsh & O'Neill 2010). Self-identity can be referred to as: *"how an individual sees him/herself, and can encompass all aspects of the self such as physical attributes, preferences, values, personal goals, habitual behaviour, personality traits and personal narratives." (Gatersleben et al. 2014, p. 4)*

Self-identity is the label that individuals use to describe themselves; it is a product of their social interactions, and it has an influence on subsequent behaviours (Cook et al. 2002). It can also extend over a wide range of pro-environmental behaviours, as establishing an identity can help demonstrate consistency across actions, including waste management, transport and buying behaviours (Gatersleben et al. 2014). This is one of the mechanisms through which 'behavioural spillover' (i.e. when changing one behaviour leads to additional behaviour change) is thought to work (Whitmarsh & O'Neill 2010). Indeed, self-identity has been found to be a stronger cross-situational motivator for pro-environmental behaviours than pro-environmental values. The concept of self-identity has also been applied to energy, and it has been shown that individuals with high pro-environmental self-identity were more likely to purchase green energy (Van der Werff et al. 2013) and to exhibit a set of domestic energy conservation behaviours (Whitmarsh & O'Neill 2010). However, little research has examined links between self-identity with heating patterns. This article expands on the literature by investigating this link.

7.2.3 Technology self-identity

In addition to understanding householders' pro-environmental self-identities, it is critical to explore alternative self-identities that are likely to affect heating behaviours. It has been suggested that technology splits the environmental discourse into two sides: technophilic, who suggest that technical solutions can help solve our environmental problems, and technosceptic, who suggest that we need to change our lifestyles and behaviours instead (Brand & Fischer 2012). Technology can play a key role in encouraging the uptake of energy efficiency measures in the domestic energy sector as shown in Chapter 4, and this may be particularly the case for technology enthusiasts who feel it fits with their image of a modern home. The Nest Learning Thermostat (Nest Labs 2011) is a good example: of this, as a modern, aesthetically pleasing device that can improve engagement due to its industrial and interactive design, it can also be used to save energy (Yang & Newman 2013). In addition, as the number of installed smart meters increases due to the UK's smart meter roll-out program, it is vital to understand how householders' views on and identification with technology influences their propensity to take pro-environmental actions or not. In previous research, the main focus has been on pro-environmental self-identity, e.g. Cook et al. (2002) and Gatersleben et al. (2014), and limited research has been done on alternative householder self-identities. This article expands the literature by investigating the role a householder's technology self-identity (e.g. seeing oneself as an early adopter of new technology) plays regarding space heating.

Our definition of technology self-identity is how likely an individual sees themselves as an early adopter of new technologies and the level of importance technology plays in defining one's identity.

7.2.4 Self-reported vs objective behaviours

Finally, in most studies reviewed here (Sparks & Shepherd 1992, Cook et al. 2002, Poortinga et al. 2004, Steg et al. 2005, Whitmarsh 2009, Van der Werff et al. 2013, Alcock et al. 2017), the researchers do not measure participants' actual (e.g., observed) objective behaviour, but rather rely on their self-reported behaviours. In a recent review conducted by Kormos & Gifford (2014), it was shown that there was a large positive effect size *(r = .46)* between self-reported and objective behaviours. While this effect size is large, the lack of absolute correspondence between the measures is of significant concern to both theory and intervention development. One reason for these misleading results is the influence of the social desirability bias (Whitmarsh 2009), the situation in which participants present themselves in the best possible light (Fisher 1993). The bias causes self-reporting participants to respond with the answer that they see as being "correct" or socially acceptable. The observed disparity between participants' self-reported and objective pro-environmental behaviours led to the inclusion of both sets of measures in the current research, representing an important contribution to heating behaviour research.

7.2.5 Research questions

Based on our review of the literature, we have formulated a number of key research questions that we seek to address:

1. To what extent do householders' pro-environmental values, pro-environmental self-identities and technology self-identities influence their:
    a) self-reported pro-environmental behaviours, including space heating behaviours?
    b) objective programmed heating schedules?
    c) objective actual heating patterns?
    d) adoption of smart thermostats?
2. Do householders who self-report undertaking sustainable heating behaviours actually undertake those behaviours?

7.3 Method

This section will outline the research design of the study.

7.3.1 Study overview

In this study we used a mixed-methodology approach by collecting both self-reported and objective behavioural data from questionnaires and smart thermostats. To collect objective data, we collected data from 110 smart thermostats in householders' properties and logged data between November 2015 and December 2016. In conjunction, to collect self-reported data we sent out 584 questionnaires with a response rate of 35.27%, resulting in total of 206 questionnaires collected.

The participants were recruited through EDF Energy, and all participants were employees of EDF Energy. The participants were contacted by EDF Energy asking them if they would like to take part in the study. The initial participants (584) were provided from a sample of employees who had agreed to undertake trials of new products and services on behalf of the energy company. In the group of 584, 200 had agreed to pay for and install a Netatmo smart thermostat at a cost of £199, which would allow the collection of heating data (putting them in the home improver stage of the power law of engagement for energy saving framework (Figure 4.3)). The participants were recruited through direct email, and were incentivised to respond by providing three randomly selected participants with a £100 Amazon voucher. Once participants agree to the trial they were asked to complete a questionnaire to collect self-reported data, and to also provide details to link them to their Netatmo smart thermostat to collect objective heating data. Participants were assigned to two condition groups based on if they had a Netatmo smart thermostat installed or not.

Ethical approval for the trial was secured from the University of Bristol, and all participants had to provide us direct consent to allow us to access, store and analyse their data for the study.

7.3.2 Participants

In the study we have two samples: participants who had smart thermostats installed (110) and participants who did not have smart thermostats installed (96).

1. **Smart thermostat sample** — Contains 110 employees from a major energy company who have had a Netatmo smart thermostat installed (see Figure 7.3). The participants have a skew towards males, with the sample containing 61.8% males and 37.3% females, with 0.909% preferring not to say.

2. **Non-smart thermostat sample** — Contains 96 employees from the same energy company, none of whom have a smart thermostat installed in their household. The participants in this sample are split 50% male and 49% female, with 1% preferring not to say. The average age ranges for both samples can be seen in Figure 7.1.

As Figure 7.1 shows, the smart thermostat sample had more participants in the older age ranges. However, the average age of each sample is 39 years old for the non-smart group and 41 years old for the smart thermostat sample, and there was not a significant difference between them: *t(206) = .053, p =*

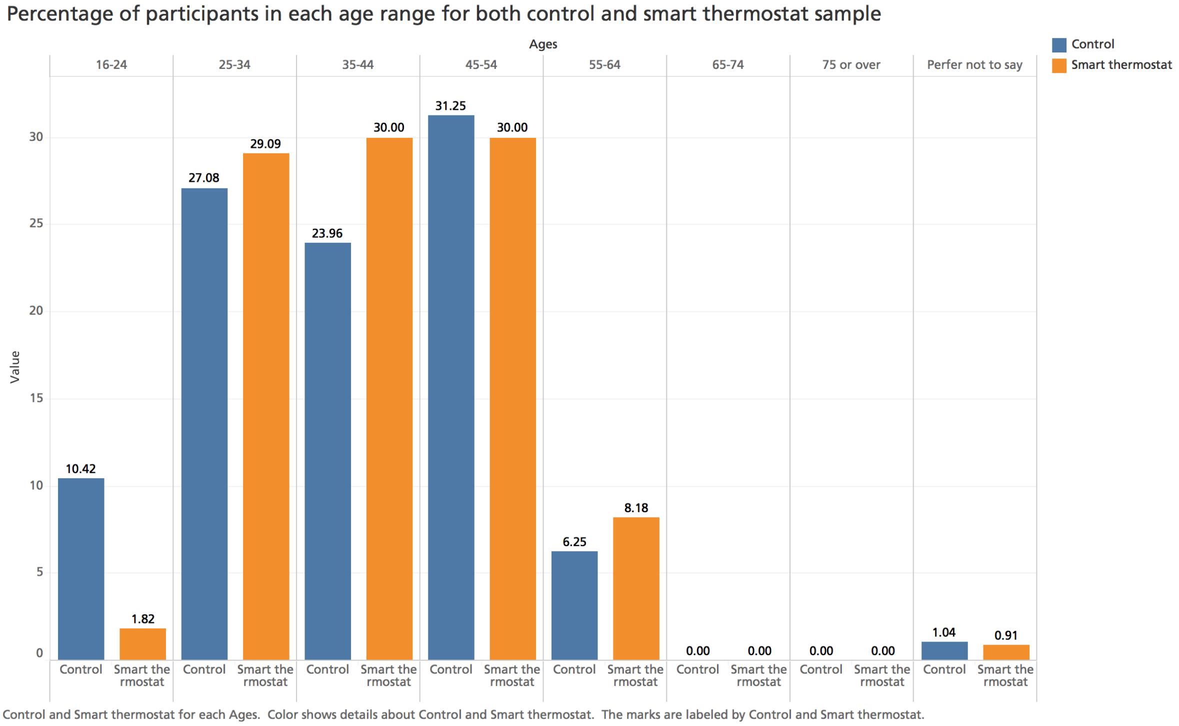


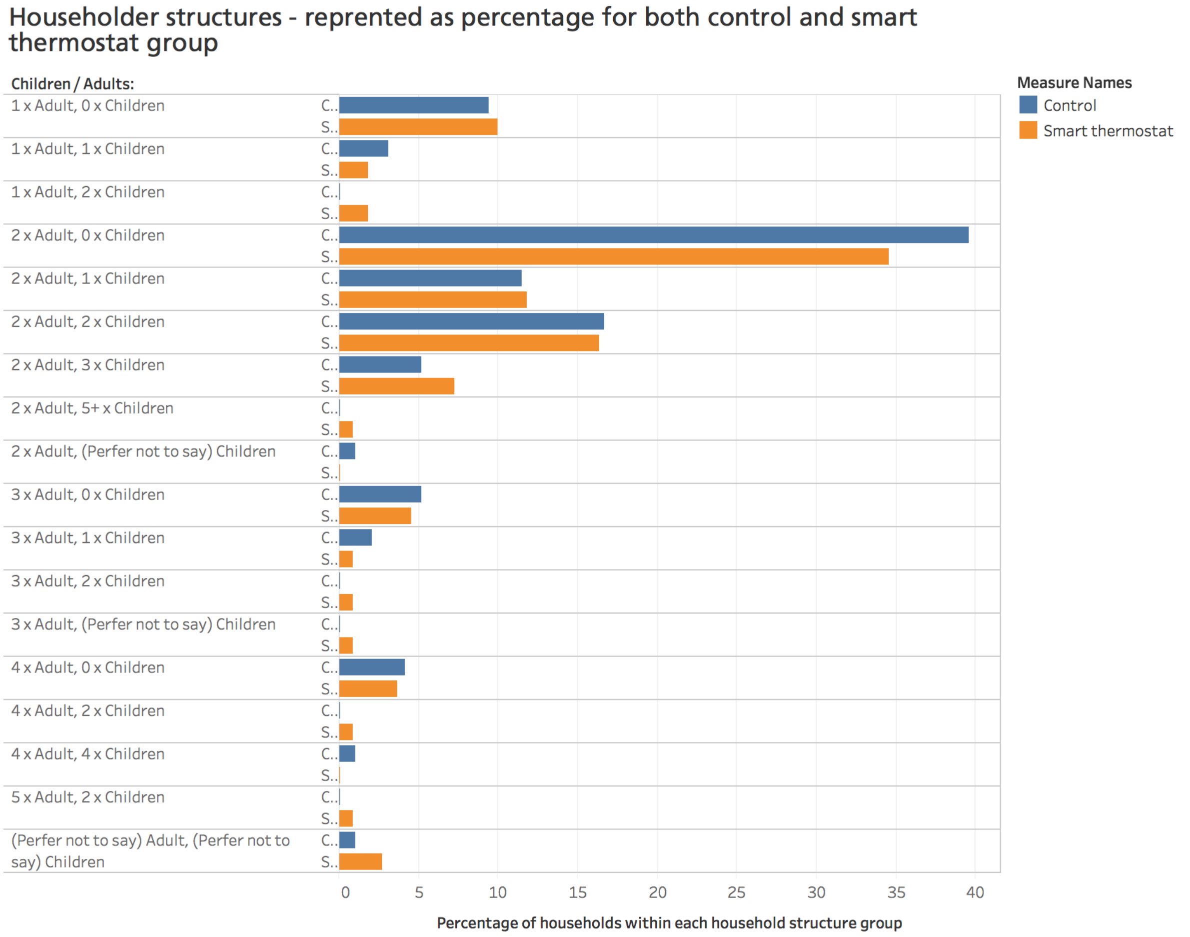
Figure 7.1: Percentage of participants in each age range for both smart thermostat and non-smart thermostat samples.

.958. Similarly, Figure 7.2 shows both non-smart and smart thermostat samples have a similar number of children and adults in their household structure.

It must be noted that the smart thermostat group paid for the purchase and installation of the Netatmo smart thermostat, therefore the sample has a bias towards those with higher incomes and home owners, as this group does not require permission to install the device in their home.

7.3.3 Netatmo smart thermostat

The Netatmo smart thermostat is an Internet-connected thermostat that logs household internal temperature, setpoint, boiler usage and heating schedules. In addition to the data collected from the Netatmo thermostat, data was also collected on external temperature from local weather stations. The Netatmo thermostat breaks down the householders' setpoints and schedules into *temporal zones* throughout the day. For example, day zone, night zone, eco (ecological) zone and personal zone, with the hours and setpoint of each zone being defined by the householder. This allows us to analyse each period of time ('zone') individually or collectively as an average. In addition, we also have the actual heating setpoint and hours of heating including the manual overrides the householder has made, and when the householder set the thermostat to away mode, frost guard (keep boiler activity to a minimum to avoid the water freezing) or turned it off. Finally, we have also processed the difference between the householder's programmed schedule and actual heating patterns to calculate how many hours the householders override



Smart thermostat and Control for each Children / Adults:. Color shows details about Smart thermostat and Control. The view is filtered on Children / Adults:, which keeps 18 of 43 members.

Figure 7.2: Household composition - represented as percentages for both control and smart thermostat groups.

their schedule, and if the householder increases or decreases the temperature. These data points provide us with a complete objective view of the householders' programmed heating schedule, actual heating patterns, and the interactions they have had with their thermostat.

7.3.4 Objective programmed heating schedules assumptions

Understanding what heating patterns are "sustainable" is a complex issue that can vary between householders (Pierce et al. 2010). Therefore, we outline the assumptions we have made during our analysis. To evaluate how sustainable a householder's heating schedule is, we have looked at four metrics:

1. maximum desired setpoint
2. average setpoint across all zones
3. hours of heating on eco setting

Figure 7.3: Netatmo Smart Thermostat.

4. scheduled heating scores:
   $$Scheduled\ heating\ score = \sum hours\ of\ scheduled\ heating\ per\ zone\ * scheduled\ heating\ setpoint\ per\ zone$$

In taking this approach we do not punish householders who work at home, as they will score poorly on two of the metrics, heating score and hours on eco setting, but if they are sustainable they will perform better on the other two metrics (maximum desired setpoint and average setpoint across all zones). In a similar manner, if the householders are away a lot and have scheduled a high setpoint for a short period, their scores will do well on two metrics, heating score and hours on eco setting, but will score poorly on two other metrics, average and maximum setpoints. In looking at these variables we get a complete view of the householder's objective desired heating schedule, including a number of the heating schedule edge cases (people working at home, people away a lot, etc.) that could cause inaccuracies in our results.

7.3.5 Objective actual heating patterns assumptions

In looking at householders' objective actual heating patterns (deviations from their programmed schedule) we have used three metrics:

1. average actual setpoint
2. average actual setpoint — removing householder's 'away', 'frost guard' and 'off' mode setpoints

3. actual heating score — which is calculated in the same manner as the scheduled heating score, but uses the actual heating setpoint and actual heating hours

In addition, to explore how householders are using their thermostat, we have taken into account the number of hours the householders manually override their thermostat, and whether the manual changes are, on average, an increase or a decrease in temperature. We made the assumption that away and frost guard reflect the house being unoccupied, as these settings are design to be used when you're leaving your property for a period of time.

In looking at these heating variables in combination with all the programmed heating schedule variables, we get a more complete view of householders' objective programmed heating schedules and objective actual heating patterns, but also the number of hours the householders override their heating system. This approach of taking both the programmed heating schedule and the householder's actual heating behaviours helps us to remove some of the bias towards certain living or working patterns. But it doesn't remove this bias completely.

7.3.6 Self-reported behaviours

In conjunction with the data collected from the householders' thermostats, householders completed a questionnaire measuring self-reported:

1. pro-environmental values
2. pro-environmental self-identities
3. technology self-identities
4. pro-environmental behaviours, including heating behaviours

7.3.6.1 Pro-environmental values

We used a shortened (six-item) version of the NEP Scale (Dunlap et al. 2000, Whitmarsh 2009). The NEP Scale has been used in a large number of studies (Poortinga et al. 2004, Steg et al. 2005, Attari 2010) and was found to be reliable *(Cronbach's alpha = .738)*. Responses were measured on a five-point Likert scale from: strongly disagree (1) to strongly agree (5). Example items include "plants and animals have as much right to exist as people" and "people have the right to modify the natural environment to suit their needs" (reverse-scored).

7.3.6.2 Pro-environmental self-identity and technology self-identity

Pro-environmental self-identity was measured with an adapted version of Whitmarsh & O'Neill's (2010) four-item measures, again using a five-point agreement scale. Example items include: "Saving energy is an important part of who I am" and "I think of myself as an energy-conscious person". In addition, we used two questions to measure technology self-identity, using the same response scale. An example item was: "I think of myself as an early adopter when it comes to technology". Both scales were reliable *(Cronbach's alphas = .839 and .830, respectively).*

7.3.6.3 Self-reported pro-environmental behaviors

We used a shortened (six-item) version of Whitmarsh & O'Neill's (2010) battery of general pro-environmental behaviours, and added eight new questions focused on space heating (these are behaviours that someone in the simple actions stage of the power law of engagement for energy saving would undertake (Figure 4.3). Responses were given on a four-point scale: never (1), occasionally (2), often (3), always (4) with a 'not applicable option'. Example items include: "Change your thermostat schedule to save energy" or "Recycle". Principal component analysis with oblique rotation (direct oblimin) was applied to reduce these 14 behaviours into behavioural sub-scales. The Kaiser-Meyer-Olkin (KMO) measure verified the sampling adequacy (KMO = .776). Four factors had eigenvalues over Kaiser's criterion of 1, and in combination explained 55.67% of the variance. The results can be found in the Table 7.1. Items were removed that reduced the scale reliability, leaving four factor groups highlighted next and in Table 7.1:

1. Factor 1 — Smart heating behaviours
2. Factor 2 — Simple sustainability behaviours
3. Factor 3 — Positive green behaviours
4. Factor 4 — Turn it off behaviours

(In Factor 2, "Turn your thermostat up" was removed to increase the reliability score of this factor). In looking at the four factors generated from the principle component analysis we can see that the groupings look logical from a behavioural point of view. This logical split of behaviours and the eigenvalues of each group being over Kaiser's criterion of 1 highlights that four factors are a suitable level of grouping for the behaviours.

Finally, we asked a number of demographic questions including gender, age, and householder composition. We also included measures of domestic insulation, renewable energy supply and renewable heating system to establish the role of more structural measures in adoption of regular pro-environmental behaviours (consistent with spillover effects (Whitmarsh & O'Neill 2010)).

7.3.7 Analysis techniques

All the data were analysed in SPSS, a software package for statistical analysis. For each of the regressions discussed below, we undertook an evaluation of the standardised residuals to check that the models were a good fit for the data. To assess the residuals, we used Field's (2013) three-point check for standardised residuals:

1. standardised residuals with an absolute value greater than 3.29 are cause for concern as these values are highly unlikely and are outliers;
2. if more than 1% of cases have standardised residuals with an absolute value greater than 2.58 then there is evidence that the level of error in our model is unacceptable; and
3. if more than 5% of cases have standardised residuals with an absolute value greater than 1.96, then again there is evidence that the level of error in our model is unacceptable.

All our regressions in this chapter successfully pass both points 2 and 3, and each outlier we found with a standardised residual higher than 3.29 is discussed in the relevant results section.

In our regression analyses we also undertook the Durbin-Watson test to detect the presence of autocorrelation, and all of our significant regressions presented in this chapter have values close to 2. This shows that the assumption that our errors are independent is likely to be met (Field 2013).

Finally, in each of our regressions we checked for multicollinearity by checking the Variance Inflation Factor (VIF) for each predictor to ensure it is below 10, and checking that the average VIF across all predictors is not substantially greater than 1. In addition, we also check that each predictor doesn't have a tolerance ($\frac{1}{VIF}$) below 0.2 (Field 2013). Thus, we ensured our predictors are not highly correlated, as this can result in small changes in our model leading to erratic coefficient estimates. All regressions presented in the chapter passed Field's tests for multicollinearity.

7.4 Results

This section presents the results of the study.

7.4.1 Self-reported pro-environmental behaviours

We used step-wise linear regression to assess whether householders' pro-environmental values, pro-environmental self-identities and technology self-identities influence their self-reported pro-environmental behaviours. The variables in each model were:

1. Model 1:
    a) NEP Score
    b) Pro-environmental self-identity
2. Model 2:
    a) Technology self-identity
3. Model 3:
    a) Installed insulation in their property

Table 7.1: Summary of exploratory factor analysis of behaviour statements using oblique rotation (direct oblimin)(N=153)

Principal Component factor analysis on 14 items with oblique rotations (direct oblimin) - Components				
Items	**1**	**2**	**3**	**4**
Discuss the installation of energy efficiency measures to improve the comfort of your home	**.847**			
Turn your thermostat down to save energy	**.630**			
Change your thermostat schedule to save energy	**.499**			.429
Turn your thermostat up		.809		
Close doors in rooms that you are heating		**-.548**		
Put on more clothes rather than turning the heating up	.385	**-.498**		
Recycle	.385	**-.443**		
Walk, cycle or take public transport for short journeys instead of driving for environ			**.714**	
Compost your kitchen waste			**.692**	
Avoid eating meat for environmental reasons			**.528**	
Buy environmentally-friendly products	.468		**.523**	
Turn off heating when not needed				**.776**
Turn off lights you're not using		-.418		**.716**
Use radiator valves or thermostats to turn off heating in unused rooms				**.645**
Eigenvalues	3.97	1.44	1.28	1.11
% of Variance	28.36	10.29	9.11	7.93
Cronbach's alpha of loading	.69	.52	.51	.64

   b) Installed a renewable energy system
   c) Has a renewable energy tariff

4. Model 4:
   a) Gender
   b) Age range
   c) Number of children
   d) Number of adults

The regression analysis for each behavioural factor can be found in Tables 7.2-7.5.

7.4.1.1 Pro-environmental self-identity

In all cases we find pro-environmental self-identity to be a significant predictor of pro-environmental behaviours:

1. Factor 1 — Smart heating behaviours — *($\beta = .455, p = .000$)*

Table 7.2: Linear regression to predict Factor 1 pro-environmental behaviours (smart heating behaviours) (N=181), with 95% confidence interval.

Linear regression analysis for Factor 1 (smart heating behaviours)						
Model		**B**	**Std. Error**	β	**t**	**Sig.**
1	(Constant)	-.325	1.296		-.251	.802
	NEP Score	.093	.051	.134	1.828	.070
	Pro-environmental self-identity	.405	.062	**.480**	6.567	**.000**
2	(Constant)	-1.995	1.434		-1.391	.166
	NEP Score	.105	.050	**.151**	2.090	**.038**
	Pro-environmental self-identity	.407	.061	**.483**	6.725	**.000**
	Technology self-identity	.209	.083	**.174**	2.525	**.013**
3	(Constant)	-3.205	1.662		-1.928	.056
	NEP Score	.118	.050	**.169**	2.361	**.020**
	Pro-environmental self-identity	.376	.062	**.446**	6.102	**.000**
	Technology self-identity	.231	.083	**.192**	2.797	**.006**
	Householder has installed insulation in their property	.544	.341	.110	1.595	.113
	Householder has installed a renewable energy system	1.456	.926	.108	1.572	.118
	Householder has a renewable energy tariff	.579	.360	.111	1.609	.110
4	(Constant)	-1.152	2.071		-.556	.579
	NEP Score	.093	.051	.133	1.800	.074
	Pro-environmental self-identity	.383	.063	**.455**	6.122	**.000**
	Technology self-identity	.204	.085	**.169**	2.398	**.018**
	Householder has installed insulation in their property	.752	.357	**.152**	2.109	**.037**
	Householder has installed a renewable energy system	1.520	.933	.113	1.630	.105
	Householder has a renewable energy tariff	.447	.368	.086	1.216	.226
	Gender	-.074	.371	-.015	-.200	.842
	Age Range	-.248	.180	-.104	-1.382	.169
	Number of children	-.233	.160	-.107	-1.460	.147
	Number of adults	.022	.248	.006	.090	.928

Note. R^2 *= .288 for step 1;* $\vec{\Delta}R^2$ *=.030 for step 2;* $\vec{\Delta}R^2$ *= .033 for step 3;* $\vec{\Delta}R^2$ *=.022 for step 4*

Table 7.3: Linear regression to predict Factor 2 pro-environmental behaviours (simple sustainability behaviours) (N=158), with 95% confidence interval.

Linear regression analysis for Factor 2 (simple sustainability behaviours)						
Model		**B**	**Std. Error**	β	**t**	**Sig.**
1	(Constant)	4.183	.983		4.254	.000
	NEP Score	.016	.037	.032	.436	.663
	Pro-environmental self-identity	.306	.049	**.465**	6.275	**.000**
2	(Constant)	4.061	1.112		3.653	.000
	NEP Score	.017	.038	.034	.458	.648
	Pro-environmental self-identity	.306	.049	**.465**	6.254	**.000**
	Technology self-identity	.016	.066	.017	.238	.813
3	(Constant)	3.050	1.315		2.319	.022
	NEP Score	.025	.038	.051	.665	.507
	Pro-environmental self-identity	.313	.051	**.476**	6.181	**.000**
	Technology self-identity	.029	.067	.032	.440	.661
	Householder has installed insulation in their property	-.065	.277	-.017	-.233	.816
	Householder has installed a renewable energy system	-.417	.764	-.040	-.547	.585
	Householder has a renewable energy tariff	.393	.288	.100	1.368	.173
4	(Constant)	3.959	1.612		2.456	.015
	NEP Score	.006	.039	.013	.166	.868
	Pro-environmental self-identity	.305	.051	**.464**	5.962	**.000**
	Technology self-identity	.023	.069	.024	.327	.744
	Householder has installed insulation in their property	.035	.291	.009	.120	.905
	Householder has installed a renewable energy system	-.175	.770	-.017	-.227	.820
	Householder has a renewable energy tariff	.309	.292	.079	1.060	.291
	Gender	.298	.297	.078	1.005	.316
	Age Range	-.027	.146	-.015	-.182	.856
	Number of children	-.204	.130	-.121	-1.564	.120
	Number of adults	-.077	.199	-.028	-.390	.697

Note. R^2 *= .227 for step 1;* $\vec{\Delta}R^2$ *=.0 for step 2;* $\vec{\Delta}R^2$ *= .012 for step 3;* $\vec{\Delta}R^2$ *=.026 for step 4*

Table 7.4: Linear regression to predict Factor 3 pro-environmental behaviours (positive green behaviours) (N=150), with 95% confidence interval.

Linear regression analysis for Factor 3 (positive green behaviours)						
Model		**B**	**Std. Error**	β	**t**	**Sig.**
1	(Constant)	-.338	1.304		-.259	.796
	NEP Score	.076	.047	.115	1.619	.108
	Pro-environmental self-identity	.443	.063	**.503**	7.064	**.000**
2	(Constant)	.794	1.436		.553	.581
	NEP Score	.066	.047	.101	1.419	.158
	Pro-environmental self-identity	.449	.062	**.510**	7.209	**.000**
	Technology self-identity	-.154	.085	-.126	-1.818	.071
3	(Constant)	-.423	1.716		-.246	.806
	NEP Score	.072	.048	.110	1.509	.133
	Pro-environmental self-identity	.466	.065	**.530**	7.140	**.000**
	Technology self-identity	-.143	.086	-.117	-1.656	.100
	Householder has installed insulation in their property	-.090	.358	-.018	-.251	.802
	Householder has installed a renewable energy system	-.660	.893	-.053	-.739	.461
	Householder has a renewable energy tariff	.474	.376	.089	1.260	.210
4	(Constant)	1.620	2.138		.758	.450
	NEP Score	.059	.049	.090	1.197	.233
	Pro-environmental self-identity	.466	.066	**.530**	7.078	**.000**
	Technology self-identity	-.162	.090	-.132	-1.797	.074
	Householder has installed insulation in their property	-.030	.372	-.006	-.081	.936
	Householder has installed a renewable energy system	-.612	.906	-.049	-.676	.500
	Householder has a renewable energy tariff	.453	.383	.085	1.183	.239
	Gender	-.201	.391	-.040	-.515	.608
	Age Range	-.053	.189	-.022	-.281	.779
	Number of children	-.218	.168	-.097	-1.299	.196
	Number of adults	-.367	.259	-.099	-1.414	.160

Note. R^2 *= .293 for step 1;* $\vec{\Delta}R^2$ *=.016 for step 2;* $\vec{\Delta}R^2$ *= .011 for step 3;* $\vec{\Delta}R^2$ *=.019 for step 4*

Table 7.5: Linear regression to predict Factor 4 pro-environmental behaviours (turn it off behaviours) (N=153), with 95% confidence interval.

Linear regression analysis for Factor 4 (turn it off behaviours)

Model		**B**	**Std. Error**	β	**t**	**Sig.**
1	(Constant)	6.367	1.056		6.030	.000
	NEP Score	.002	.040	.003	.041	.968
	Pro-environmental self-identity	.230	.052	**.352**	4.398	**.000**
2	(Constant)	4.801	1.197		4.010	.000
	NEP Score	.014	.040	.027	.341	.734
	Pro-environmental self-identity	.235	.051	**.360**	4.582	**.000**
	Technology self-identity	.185	.071	**.198**	2.610	**.010**
3	(Constant)	5.880	1.414		4.159	.000
	NEP Score	.004	.040	.008	.095	.924
	Pro-environmental self-identity	.237	.053	**.364**	4.483	**.000**
	Technology self-identity	.170	.072	**.181**	2.359	**.020**
	Householder has installed insulation in their property	-.110	.293	-.029	-.374	.709
	Householder has installed a renewable energy system	-.111	.802	-.011	-.139	.890
	Householder has a renewable energy tariff	-.441	.306	-.111	-1.443	.151
4	(Constant)	7.337	1.706		4.300	.000
	NEP Score	-.014	.041	-.028	-.341	.734
	Pro-environmental self-identity	.239	.054	**.366**	4.449	**.000**
	Technology self-identity	.145	.074	**.155**	1.977	**.050**
	Householder has installed insulation in their property	.061	.308	.016	.198	.843
	Householder has installed a renewable energy system	-.007	.809	-.001	-.009	.993
	Householder has a renewable energy tariff	-.560	.312	-.141	-1.797	.075
	Gender	.022	.317	.006	.071	.944
	Age Range	-.184	.157	-.099	-1.171	.243
	Number of children	-.226	.137	-.134	-1.651	.101
	Number of adults	.082	.211	.030	.388	.698

Note. $R^2 = .125$ *for step 1;* $\vec{\Delta}R^2 = .038$ *for step 2;* $\vec{\Delta}R^2 = .013$ *for step 3;* $\vec{\Delta}R^2 = .030$ *for step 4*

2. Factor 2 — Simple sustainability behaviours — *(β = .464, p = .000)*
3. Factor 3 — Positive green behaviours — *(β = .530, p = .000)*
4. Factor 4 — Turn it off behaviours — *(β = .366, p = .000)*

7.4.1.2 Technology self-identity

Technology self-identity was a significant predictor for both Factors 1 and 4 *(β = .169, p = .018, β = .155, p = .050, respectively)*, but not Factors 2 or 3. Factors 1 and 4 both include a number of pro-environmental behaviours related to interaction with technological devices (lighting or heating systems).

7.4.1.3 Investment and structural pro-environmental behaviours

The final significant predictor of Factor 1 behaviours was whether a householder had installed insulation in their property *(β = .152, p = 0.37)*. Factor 1 includes the behaviour "Discuss the installation of energy efficiency measures to improve the comfort of your home". Therefore, the result is expected. However, our other two structural and investment pro-environmental behaviours were not good predictors of any of our factors.

7.4.1.4 Demographic data

Household composition, gender and age were not significant predictors of pro-environmental behaviours.

7.4.1.5 NEP Score

We found NEP scores not to be a significant predictor of self-reported pro-environmental behaviours.

7.4.1.6 Evaluation comments

The Factor 2 regression analysis shown in Table 7.3 contained a single outlier with a standardised residual score of -3.346. This was due to this participant having a significantly low score on Factor 2 behaviours *(value = 3, μ = 9.34)*. The Factor 4 regression shown in Table 7.5 also contains a single outlier with a standardised residual score of -3.429. Similar to Factor 2, this was due to the participant scoring a significantly low score on Factor 4 behaviours *(value = 5, μ = 9.96)*. The outliers were included in the analysis as they represent less than 1% of cases in our sample, which Field's states is acceptable (Field 2013).

7.4.2 Objective programmed heating schedules

This section presents the results from analysing the householders objective programmed heating schedules in relation to their NEP score, pro-environmental self-identity, technology self-identity and the pro-environmental behaviours that we measured.

7.4.2.1 NEP Score, pro-environmental self-identity and technology self-identity

We found no significant influence of NEP or either identity measure on householders' maximum desired setpoint, average setpoint across all zones, hours of heating on eco setting or overall scheduled heating score (Table 7.6). This apparent disparity between identity predictors of self-reported and objective heating measures was investigated further: we first examined whether pro-environmental scales were predictors of our objective programmed heating schedule variables, and then also looked at a number of the individual's pro-environmental behaviours as predictors of objective heating behaviours.

Table 7.6: Objective programmed heating schedule - linear regression analysis summary.

Objective programmed heating schedule - Linear regression analysis summary						
	NEP Score		**Pro-environmental self-identity**		**Technology self-identity**	
Objective heat variable	β	**Sig.**	β	**Sig.**	β	**Sig.**
Maximum setpoint	.046	.664	.062	.558	-.062	.561
Average setpoint over all zones	-.038	.718	.104	.329	.028	.795
Hours on ECO setting	-.020	.853	-.044	.678	-.107	.313
Scheduled heating score	-.134	.205	.023	.829	.168	.111

7.4.2.2 Pro-environmental behaviours

We used linear regression analysis to see if our four pro-environmental behaviour Factors could be used to predict a householder's maximum setpoint, average setpoint across all zones, hours of heating on eco setting and scheduled heating score. Here, the only significant predictor was Factor 2 - simple sustainability behaviours - which had a negative correlation with a householder's average setpoint across all zones (β = -.350, p= .21). That is, householders who state that they often take Factor 2 pro-environmental behaviours (e.g., close doors in room they are heating) have a lower average setpoint across all zones.

We then examined the individual behaviour "change your thermostat schedule to save energy" to check whether it was a good predictor of householders' objective programmed heating schedules. Again, we found no significant correlation (maximum setpoint: β = .022, p = .839, average setpoint across all zones: β = -.103 , p = .339, hours of heating on eco setting: β = .073, p = .498 and schedule heating score: β = -.064, p = .554).

7.4.3 Objective actual heating pattens

This section presents the results from analysing the householders objective actual heating pattens in relation to their NEP score, pro-environmental self-identity, technology self-identity and the pro-environmental behaviours that we measured.

7.4.3.1 NEP Score, pro-environmental self-identity and technology self-identity

In a similar manner to the objective programmed heating schedules, we looked at the relationship between NEP Score, pro-environmental self-identity and technology self-identity on the one hand, and objective actual heating patterns on the other. We again found no significant relationship in any of these cases (Table 7.7). We explored the result in more detail by examining the relationship between self-reported behaviours and objective heating patterns.

Table 7.7: Objective actual heating - linear regression analysis summary.

Objective actual heating - Linear regression analysis summary						
	NEP Score		**Pro-enviromental self-identity**		**Technology self-identity**	
Objective actual heating variables	β	**Sig.**	β	**Sig.**	β	**Sig.**
Average actual setpoint	-.114	.283	-.021	.884	.062	.560
Average actual setpoint - removing away modes	-.157	.136	-.093	.379	.006	.956
Actual heating score	-.099	.349	.055	.604	.000	.999

7.4.3.2 Pro-environmental behaviours

We found only one self-reported behavior scale, Factor 4 (turn it off behaviours), had a negative correlation with the actual average setpoint when accounting for away modes *(β = -.261, p = .047)*. This factor includes “turn off heating when not needed”, which would reduce a householder’s overall actual average setpoint, when accounting for away modes.

Looking at the individual self-reported behaviour “Turn your thermostat down to save energy” in relation to how many hours householders have manually changed their thermostats’ setpoint, we found no significant findings for either decreasing *(β = -.107, p = .344)* or increasing *(β = .111, p = .300)* it. Next, considering the pro-environmental behaviour “Put on more clothes rather than turning the heating up”, we again found no significant relationship between householders who stated that they put on more clothes rather than turning the heating up and the number of hours the householders increased their thermostat manually *(β = .126, p = .242)*. Again, we also looked at the number of hours the householder manually decreased their thermostat, and surprisingly we found that householders who stated they put on more clothes rather than turning the heating up actually had a negative correlation with the number of hours the householder decreased their setpoint *(β = -.228, p = .042)*. Finally, we looked at the behaviour “Turn up your thermostat” in relation to the hours the householders manually increased and decreased their thermostat. We also found a negative correlation between how often the householders self-report turning up their thermostat and the amount of hours they increase their setpoint *(β = -.223, p = .35)*. In addition, we also found a positive correlation between how often householders self-report turning up their thermostat and the number of hours householders decreases their setpoint *(β = .254, p = .22)*.

7.4.4 Adoption of smart thermostats

Step-wise logistic regression analysis examined the predictors of smart thermostat adoption in five steps:

1. NEP score and pro-environmental self-identity
2. technology self-identity
3. our four pro-environmental behaviour factors
4. our financial and structural investment pro-environmental behaviours
5. demographic data

Next, we selected only the variables that had a significant influence on the dependent variable (smart thermostat sample vs non-smart thermostat sample), and re-ran the regression. The results of this logistic regression are presented in Table 7.8.

Table 7.8: Logistic regression analysis to predict if householders are in the smart thermostat group (only significant variables highlighted) (N=175), with 95% confidence interval.

Forced entry logistic regression analysis to predict if householders are in the smart thermostat group. [95% bootstrap confidence intervals based on 1000 samples]							
					95% C.I. for EXP(B)		
Model:		**B**	**Sig.**	**S.E**	**Lower**	**Odds Ratio Exp(B)**	**Upper**
	Constant	2.734	.015	1.123		15.398	
Step 1a	Pro-environmental self-identity	**-206**	**.004**	.072	.707	**.814**	.937
	Factor 4 - Turn it off behaviours	**-.209**	**.041**	.102	.665	**.812**	.991
	Factor 1 - Smart heating behaviours	**.364**	**.000**	.093	1.198	**1.439**	1.727
Note: R^2 = .089 (Hosmer & Lemeshow), .133 (Cox & Snell), .153 (Nagelkerke).							

The first point to note in Table 7.8 is that Factor 1 (smart heating behaviours) was the largest significant predictor of membership of the smart thermostat group (b = .364, Wald $X^2(1) = 15.191$, $p < .001$) with an odds ratio of Exp(B) = 1.439. That is, householders are more likely to have a smart thermostat if they:

1. discuss the installation of energy efficiency measures
2. turn their thermostat down to save energy
3. change their thermostat schedule to save energy

Next, both pro-environmental self-identity and Factor 4 (turn it off behaviours) have a significant *negative* effect on membership of the smart thermostat group (b = -.206, Wald $X^2(1) = 8.246$, p = .004; b = -.209, Wald $X^2(1) = 4.192$, p = .041, respectively).

7.5 Discussion

Throughout this section we discuss the implications of the results.

7.5.1 Self-reported pro-environmental behaviours

Our results show that pro-environmental self-identity is a significant predictor of self-reported pro-environmental behaviour. These results support similar findings in the academic literature (Cook et al. 2002), but extend them to pro-environmental space heating behaviours. Seeing oneself as a ‘green’ or energy-conscious person influences a broader range of pro-environmental behaviours than previously suggested, not only including more overtly identity-expressive actions like buying green products or recycling (Whitmarsh & O’Neill 2010) but also action conducted within one’s own home. In addition, we have shown the benefit of exploring alternative self-identities, as technology self-identity was also a significant predictor for a number of our pro-environmental behaviours including those involving lighting and heating technologies. Limited research has been undertaken on alternative self-identities, and the result highlights that it is not only pro-environmental self-identity that can have an effect on self-reported pro-environmental behaviours, but that technology self-identity can also have an influence. This highlights the need to further investigate how other self-identity factors could have an influence, as this would help build a clear view of predictors for self-reported pro-environmental behaviours. For example, future research could explore householders’ comfort, convenience, cleanliness or frugality self-identity, since these reflect salient motivation in relation to sustainable heating behaviours (Shove 2003, p.17).

Finally, in our results we found the NEP score was not a significant predictor of any pro-environmental behaviours. One reason for this could be that NEP reflects a more abstract view of the environment than does pro-environmental identity, which has previously been shown to be a more proximal influence on behaviour than values (Gatersleben et al. 2014).

We also found no evidence of behavioural spillover, since adopting structural sustainable energy behaviours (e.g., installing insulation) had no significant relationship with the habitual pro-environmental behaviours we examined. This lack of consistency across pro-environmental behaviours has been observed in previous studies and is indicative of the distinct predictors of these diverse behaviours (Whitmarsh & O’Neill 2010).

7.5.2 Objective programmed heating schedule and objective actual heating patterns

While identity predicted self-reported heating behaviours, we found householders’ pro-environmental NEP score, pro-environmental self-identity and technology self-identity do not have an influence on their objective programmed heating schedule or their objective actual heating patterns. This important finding highlights that there is a gap between psychological variables like values and identity and respective actions in terms of their objective programmed heating schedules and actual heating patterns. Similarly, there is a gap between self-reported and objective behaviour: householders’ self-reported undertaking of pro-environmental behaviours had limited predictive value when it came to objective programmed heating schedule and heating patterns. Indeed, some of the individual self-reported sustainable heating behaviours were actually negatively correlated with the respective observed heating actions. There may be several reasons for the disparity between worldview/identity and self reported and actual behaviours:

Firstly, our results provide further evidence of the value-action gap (Flynn et al. 2009) observed for travel and other behaviours (Alcock et al. 2017). In terms of heating, this may be due to even individuals with strong pro-environmental views and a high level of pro-environmental self-identity being unwilling to sacrifice certain levels of comfort. In other words, there are a range of factors that influence heating behaviours, not limited to views on environment or technology. Further work should explore these diverse motivations and identities, as noted above.

Secondly, our finding may reflect social desirability bias found previously for self-reported pro-environmental behaviours (Fisher 1993). Householders' responses would then reflect their ideal pro-environmental self rather than their objective actual self, leading to limited correlation between their self-reported and observed heating behaviours. In this context, it could be the case that householders are over-optimistic in their self-reported responses, so householders infer their pro-environmental self-identity from their *perceived* behaviours, rather than from their objective behaviours. Therefore, householders who see themselves as highly pro-environmental will have higher levels of self-reported pro-environmental behaviours as they *think* they do these behaviours but in reality do not. This is consistent with findings from recycling research (Corral-Verdugo 1997), and is consistent with self-perception theory (Bem 1967). If our findings are due to social desirability bias, this is a crucial area for future research. More studies should measure objective behaviours, and this is becoming simpler with new sensors and smart devices. If measuring objective behaviours is not possible, questionnaires should endeavour to use concrete response scales or ask participants to self-log each time they undertake a certain pro-environmental behaviour, as this will allow householders to be more specific and detailed with their responses. Indeed, a related explanation for our finding is that there may not have been sufficient equivalence between our self-reported and objective measures or biased or inaccurate memory recall, such that there is inevitable disparity between reporting that one 'sometimes' turns down the thermostat and actual thermostat use over an extended period of time.

A third possible explanation for our results is that householders' heating preferences happen within a social context of a family or other co-habitants, which could cause an individual's pro-environmental values and pro-environmental self-identity to be suppressed in favour of the social norm of the group or personal heating actions (e.g., turning down thermostat in one room could be undermined by decisions taken by other household members, such as turning on radiators elsewhere. This is especially true when it comes to levels of comfort, which is a subjective and personal factor (Clear et al. 2014). In future research, it is important to explore in more detail the social decision process behind both setting up a household heating schedule, and social decision process undertaken to allow a householder to manually override the heating schedule.

7.5.3 Adoption of smart thermostats

We did find a significant relationship between smart heating behaviours and adoption of a smart thermostat. Firstly, this could mean that householders with smart thermostats are more engaged in their heating. Secondly, it could highlight that smart thermostats are not meeting their automation promise, as householders are having to regularly change their schedules and turn down their thermostat to save energy, rather than the device undertaking these actions on their behalf. In the first case, it could highlight a secondary benefit of smart thermostats leading to increased engagement, helping to transfer householders to later stages of the power law of engagement for energy saving (Figure 4.3). But as it has been shown throughout this chapter, this engagement does not directly translate into more sustainable heating patterns. The second case highlights a need for further research on the behavioural factors behind householders' relationships with automated energy saving devices, as these devices should reduce the decision burden on householders and automate the energy saving, but this was not the case in our results.

We also found that pro-environmental self-identity had a negative effect on smart thermostat uptake, which is intriguing since we found it had positively predicted all four self-reported pro-environmental behaviour scales. This could highlight a more complex interrelationship between pro-environmental self-identity and pro-environmental behaviours than previously indicated; perhaps those with strong pro-environmental identity have a negative view of the environmental benefit of energy savings that could be achieved through a smart thermostat, consistent with a technosceptic environmentalist discourse (Brand & Fischer 2012).

Finally, that we found Factor 4 (turn it off behaviours) has a negative relationship with smart thermostat adoption is unsurprising given that all the pro-environmental behaviours in Factor 4 relate to manual interaction with technological devices. Therefore, it could be the case that individuals that show these types of behaviours like to have manual control over their heating and lighting, and the proposition of having a smart thermostat automating these behaviours could feel like a loss of control. In a similar manner, each of the behaviours in Factor 4 are curtailment behaviours that would save money. Therefore, householder income could be an underlying variable in our results, as householders who adopt "turn it off" behaviours perhaps do not have the disposable income to purchase a smart thermostat. On this final point, while we did not measure income, all our participants were employed, therefore our conclusions tend to favour the former explanation of householders not wanting to lose manual control.

7.5.4 Limitations of the study

The first limitation comes from the fact that we have only questioned a single individual from each household, rather than collecting data from all members of a household. In future studies we would like to expand our work to include the pro-environmental values, pro-environmental self-identity and technology self-identity of all householders within a household and explore social dynamics of heating behaviours.

The second limitation to our research is that we did not elicit property information (e.g., age, building type). Therefore, the householders could appear to heat a lot because their building is energy inefficient compared to the householders with an energy efficient house. In a similar manner, householders with a large building and an inadequately sized boiler will have longer average hours of heating to get their property to their desired setpoint. This is a limitation of the study, but as we measure both programmed and actual heating behaviours it still allows us to draw conclusions about the way in which householders are looking to heat their property and how they adapted their heating. In future research it would be advantageous to ask participants for permission to access their EPC to allow for additional data to be analysed.

7.6 Conclusion

With only 8% of heating and cooling demand worldwide being met by renewables, and three-quarters of global energy used for heating being powered by fossil fuels (Kristin et al. 2016), it is critical that we change our heating behaviours. In this chapter we wanted to explore the relationship between householders' values, identities and heating patterns. Critically, we found a dichotomy between self-reported behaviours and objective behaviours and discussed the possible reasons for this. This result should serve as a warning, building on that of Kormos & Gifford (2014), that in testing theories and proposing interventions we must look at objective behaviours rather than just self-reported behaviours, as self-reported behaviours can lead to misleading conclusions (Bleys et al. 2017).

7.7 Appendix

Please find below the questionnaire used for the research presented in this chapter.

1. Here are some statements about the relationship between people and the environment. For each statement, please indicate whether you strongly disagree, disagree, neither, agree or strongly agree with it:

    a) Saving energy is an important part of who I am

        i. Measure — Environmental self-identify
        ii. Direction — Positive

    b) Plants and animals have as much right to exist as people

        i. Measure — NEP
        ii. Direction — Positive

    c) People were meant to rule over the rest of nature

        i. Measure — NEP
        ii. Direction — Negative

    d) People are severely abusing the planet

    i. Measure — NEP
    ii. Direction — Positive
  e) I think of myself as the type of person who has the latest technology
    i. Measure — Technology self-identity
    ii. Direction — Positive
  f) The balance of nature is strong enough to cope with the impact of modern industrial nations
    i. Measure — NEP
    ii. Direction — Negative
  g) Being environmentally-friendly is an important part of my identity
    i. Measure — Environmental self-identify
    ii. Direction — Positive
  h) I think of myself as an early adopter when it comes to technology
    i. Measure — Technology self-identity
    ii. Direction — Positive
  i) The balance of nature is very delicate and easily upset
    i. Measure — NEP
    ii. Direction — Positive
  j) I think of myself as an energy-conscious person
    i. Measure — Environmental self-identify
    ii. Direction — Positive
  k) I think of myself as someone who is very concerned with environmental issues
    i. Measure — Environmental self-identify
    ii. Direction — Positive
  l) People have the right to modify the natural environment to suit their needs
    i. Measure — NEP
    ii. Direction — Negative

2. What two or three things could you do personally to reduce your overall energy consumption in the home? Please write what comes to mind first below ...

3. On a scale of 1 to 11, please indicate the environmental impact you think each of these energy-saving behaviors has, with 1 for no impact and 11 for major impact:

   a) Air dry laundry instead of using the tumble drier
   b) Close bedroom window at night instead of leaving them open

   c) Install Solar PV (Photovoltaic) panels
   d) Insulate water tank using a thermal jacket
   e) Switch TV off when not being watched
   f) Install condensing boiler
   g) Wear a thick jumper at home in winter
   h) Cook food with the microwave not the oven
   i) Install a mounted wind turbine at your home
   j) Use radiator valves to turn off heating in unused rooms

4. And now for some more actions. On a scale of 1 to 11, please indicate the environmental impact you think each of these energy-saving behaviors has, with 1 for no impact and 11 for major impact:
   a) Wash clothes at 40 degrees or less
   b) Install draught proofing in your home
   c) Turn thermostat down by 1 degree
   d) Install solid wall insulation in your home
   e) Turn off light when not in use
   f) Only fill kettle to the level required
   g) Defrost freezer regularly
   h) Install water efficient shower head
   i) Install cavity wall insulation in your home
   j) Put lids on saucepans when cooking
   k) Install loft insulation in your home

5. Please indicate how often you take each of the following actions: (always, often, occasionally and never)
   a) Use radiator valves or thermostats to turn off heating in unused rooms
   b) Turn your thermostat up
   c) Discuss the installation of energy efficiency measures to improve the comfort of your home
   d) Compost your kitchen waste
   e) Change your thermostat schedule to save energy
   f) Turn off heating when not needed
   g) Walk, cycle or take public transport for short journeys (i.e. trips of less than 3 miles) instead of driving for environmental reasons

   h) Close doors in rooms that you are heating
   i) Put on more clothes rather than turning the heating up
   j) Recycle
   k) Turn off lights you're not using Buy environmentally-friendly products
   l) Avoid eating meat for environmental reasons
   m) Turn your thermostat down to save energy

6. Have you installed insulation in your home since you have lived in your property?

7. Do you currently have a green or renewable energy tariff with your energy supplier?

8. Finally, some basic questions about you. Are you ...
   a) What age range are you in?
      i. 16-24
      ii. 25-34
      iii. 35-44
      iv. 45-54
      v. 55-64
      vi. 65-74
      vii. 75+
      viii. Prefer not to say
   b) And how many children usually live in your property?
      i. 0
      ii. 1
      iii. 2
      iv. 3 or more
   c) How many adults (including yourself) usually live in your property?
      i. 1
      ii. 2
      iii. 3
      iv. 4 or more

CHAPTER 8

DISCUSSION

"We all want progress. But progress means getting nearer to the place where you want to be. And if you have taken a wrong turning, then to go forward does not get you any nearer. If you are on the wrong road, progress means doing an about turn and walking back to the right road; and in that case the man who turns back soonest is the most progressive man. We have all seen this when doing arithmetic. When I have started a sum the wrong way, the sooner I admit this and go back and start over again, the faster I shall get on. There is nothing progressive about being pigheaded and refusing to admit a mistake. And I think if you look at the present state of the world, it is pretty plain that humanity has been making some big mistakes. We are on the wrong road. And if that is so, we must go back. Going back is the quickest way on." — Lewis (1952, p 20) — Mere Christianity

8.1 Introduction

This chapter synthesises the insights gained from the literature review in Chapter 2 with the results of the research undertaken in Chapters 3-7. There are four topics of discussion presented in this chapter:

1. Retrofitting and space heating must play a larger role in academic research, the offerings of energy companies' and governmental policy;
2. We should distinguish between investment in behaviour change and habitual behaviour change;
3. ICT has a significant role to play in reducing energy usage, but it is not the complete answer;
4. Householders' comfort and resignation with their property must be given more attention.

The final part of the chapter will then present areas of future research that can be developed by building on the work within this thesis.

8.2 Retrofitting and space heating must play a larger role in academic research, the offerings of energy companies and governmental policy

DiSalvo et al.'s (2010) paper on mapping the landscape of sustainability HCI showed how the sustainable HCI community was focusing on changing individual's habitual behaviours through persuasion. It was surprising to see that limited sustainable HCI research was focused on encouraging householders to install energy efficiency measures, and similarly little research looked at helping householders develop sustainable heating patterns. This finding promoted the literature review presented in Chapter 3. This chapter highlighted the disparity between researchers' time and effort, and the potential energy savings the interventions could generate. The disparity was caused by the focus on behaviour change, especially with regards to electrical appliances and lighting that have limited impact compared to space heating. The chapter concluded by defining the need for both the sustainable HCI and ICT4S communities to investigate the application of psychological techniques to encourage retrofitting, improve information provision for retrofitting, apply participatory sensing to energy efficiency measures and apply sustainable interaction design to householders' heating systems. This is not only an issue within academic research. A number of companies emphasise the breakdown of householder's energy consumption from electricity (Allcott 2011, Bidgely 2017, Engage 2017) rather than gas consumption required for space heating. Energy companies have also been focusing their attention on their customers' electricity consumption, especially, on electric disaggregation (Tweed 2015, EDF Energy 2017*a*) and the installation of electric micro-generation. It has only been with the popularity of smart heating controls that energy companies are increasing their focus on heating behaviours. Since the UK government removed the Green Deal financing mechanism, there has been limited progress in defining significant governmental policies that would help accelerate the installation of energy efficiency measures or substantially affect householders' space heating behaviours. The current implementation of ECO and the new recommendation on boiler standards expected to be set through the Heat in Buildings consultation (UK Government 2018) are the only programmes that are continuing at present. The focus on householders' electric consumption and limited attention to retrofitting and space heating causes a misalignment between researchers, industry and governments with regard to levels of effort and the levels of potential CO_2 savings. It would be wise to put the most effort, funding and resources into the improvements that can have the most significant CO_2 savings. As demonstrated in sections 2.1.2 and 2.1.3, space heating has the largest CO_2 impact in the domestic energy sector; it is also challenging to transition to renewables. Therefore, this should be the main focus for researchers, energy companies and governments.

This thesis has provided a number of key contributions to help researchers better engage with this topic. Firstly, the "power law of engagement for energy consumption" framework presented in Chapter 4 enables researchers to understand the stages householders go through in undertaking retrofitting, and it also provides a method for HCI and ICT4S researchers to understand how different ICT solutions or interventions can help at different stages in the process of retrofitting. Secondly, Chapter 5 directly states both the barriers and drivers faced by householders when they consider retrofitting. The barriers and drivers help researchers understand the challenges they must overcome when developing solutions and interventions. Thirdly, Chapter 7 showed that, when it comes to space heating, there is a complex dichotomy between psychological variables like values and identity, and respective space heating actions. This psychological complexity should provide HCI and ICT4S researchers new and interesting areas of research as it is vital that we understand this psychological complexity if we are to help householders move towards more sustainable heating patterns.

Finally, the UK government has limited vision on a transition towards a low-carbon heating system or an energy efficient housing stock, both of which need to change. The UK government needs to implement long-term strategies to help make a systemic change in the way householders are heating their property and increase the rate of uptake of energy efficiency measures. The strategy requires substantial long-term investment, and needs to overcome the householders' barriers that were highlighted in Chapter 5. It is also important to understand that part of the strategy needs to include helping householders understand the impact their space heating has on the environment. As shown in Chapter 7, there is a misalignment between householders' sustainability views and their objective heating behaviours.

8.3 Investment behaviour change and habitual behaviour change

To help increase the uptake of retrofitting, more research on methods to promote *"investment behaviour change"* is necessary, rather than just *"habitual behaviour change"*. We define investment behaviour change in the domestic energy sector as getting a householder to reallocate their financial investments or resources to improve the sustainability of their household. Investment behaviours require a large commitment from householders, but provide more sustainable energy and CO_2 savings, and provide these savings for a longer period of time. Once insulation is installed, it can last the lifetime of the property if well maintained. Investment behaviours are also transferable: if a householder moves out of their property and a new householder moves in, the new householder will still receive the environmental benefits of the insulation and reduced energy bills. Lastly and most importantly, as highlighted throughout this thesis, investment behaviours are the only method of achieving the high levels of CO_2 reductions required to keep our Earth within its ecological boundary. As investment behaviour change is a single action, at a single time and place (e.g., install solar panels, buy a smart heating control) we need to develop different methods and techniques to promote these type of actions compared to habitual behaviour change. The power law of engagement for energy saving framework presented in Chapter 4 provides an initial mapping of one method of developing an increase in investment behaviours, starting with investment behaviours on the simple-to-achieve scale that require low motivation, leading to investment behaviours on the hard-to-achieve scale, which require increased amounts of motivation. The academic community also needs to understand that as individuals move towards investment decisions that require larger commitments in terms of cost, time and disruption, we must explore and better understand the psychology and economics of purchasing higher priced items, like family holidays or cars, as shown in

Chapter 5.

8.4 ICT has a significant role to play, but it is not the complete answer

Although the research presented in this thesis has focussed on the role ICT can play in sustainability, two questions remain: how significant is ICT in this area, and do we sometimes rely too much on ICT being a solution to sustainability issues?

In Chapter 4, Figure 4.7 maps the different types of ICT that can be used at the different stages in the power law of engagement for energy saving, and Chapters 5-7 show how different methods of ICT have been applied to help increase the levels of retrofitting and help individuals develop sustainable heating patterns. ICT has played a significant role in each of these studies, and we have found ICT can have a significant impact on:

1. Householder and property insight — ICT provides a method of understanding householders' behaviours and habits in much greater detail than ever before. It enables us to learn more about the property the householder lives in, and the objective behaviours that householders undertake within their property. The insight has been driven by the increase in data collected from smart meters and smart heating controls. The change has been most prominent throughout my industrial work at EDF Energy. In the four years since I started at EDF Energy, meter readings have gone from an average of one or two per household per year, to a reading of electricity consumption every ten seconds and gas readings every 30 minutes thanks to smart meters. The heating setpoint, indoor temperature, outdoor temperature, heating schedule and boiler usage data is collected every ten minutes thanks to smart heating controls. This creates a total of 10,272 data points per customer per day. The increase in data has caused ICT to have a significant role within the domestic energy sector. With smart heating controls, you can tell if a householder has sustainable or unsustainable heating patterns, the hours they are most likely to heat their property, and find out if their property has a high or low leakage rate or if their boiler is functioning effectively. These insights provide a significantly richer picture that enables us to start to understand in more detail the complex social and personal factors that causes unsustainable heating patterns or limited uptake of energy efficiency measures. Without smart heating controls for the research carried out in Chapter 7, it would have been extremely challenging to find the dichotomy between self-reported heating behaviours and objective heating behaviours. Chapter 5 also showed that increased property insight can help us understand if householders are likely to be undertaking renovation, which would allow us to target them with energy efficiency measures that can be installed at the same time. Even better would be to provide householders with tailored preventative energy efficiency measures when they have a under-performing boilers, appliances or low levels of insulation. This can only be achieved through an increase in the use of ICT within the domestic energy sector.

2. Householder engagement — ICT can play a significant role in getting householders engaged in energy. However, the length of that engagement is extremely difficult to judge. For example,

as shown in section 2.5.3 there is an increase in the number of smart heating controls, which indicates householders are interested in monitoring and controlling their heating more efficiently, or alternatively, they just want to buy the latest gadget. Regardless of the reason, it is driving householders to become more engaged in their heating behaviours. This is emphasised in section 7.5.3 as our research showed a significant relationship between smart heating behaviours and smart thermostat adoption, which could have been driven by the ownership of the smart thermostat getting participants more interested in their heating behaviours. In trying to understand this relationship between energy and ICT, we feel that one reason ICT can increase householder engagement is that energy alone does not interest a large segment of the population. It has also been shown that 64% of male consumers are interested in technology that can completely automate the management of their electricity, and 41% also want to monitor and managed their usage through the latest personal electronics (Guthridge et al. 2011). As highlighted in the power law of engagement for energy saving framework, ICT can be used as a catalyst to get householders used to monitoring both their energy consumption and heating patterns, and provide a method for householders to learn about energy efficiency measures. Implementing low-cost technology solutions can also require little commitment by householders while also being significantly engaging to the householder, particularly so if the device is novel and aesthetically pleasing. Finally, Chapter 6 showed that ICT can play an even greater role in increasing engagement in energy topics among school pupils. This is important as this generation will have to live with our mistakes and it is vital that they understand sustainability. We must teach the younger generations using the channels they already use (smartphones, social media, messaging, Snapchat, etc.) as this will be the primary method of engaging them.

3. Householders' understanding of energy — In the research presented in this thesis, it has been shown that there is a level of misunderstanding when it comes to energy. Firstly, in Chapter 7 we showed a misalignment between householders' environmental worldviews and pro-environmental self-identity, and householders' actual objective heating schedules and objective heating patterns. ICT can play a significant role in helping householders see this misalignment. This can be achieved through presenting householders with more detailed insights as highlighted in point 1. For example, if householders with strong environmental views understood the large impact their space heating behaviours have on the environment, it should prompt them to make educated decisions to reduce their space heating demand, which would be in line with their values and identity. Secondly, when it comes to retrofitting there is a wide range of energy efficiency measures that simple net present value calculations show to be cost effective, but householders do not undertake the measures due to the barriers highlighted in Chapter 5. In the list of barriers, limited expert knowledge and poor communication were listed, both of which can be solved with improved ICT and providing householders with new methods of directly contacting installers, contractors or suppliers. Property insight can also be presented to the householders based on the data collected by ICT, giving them recommendations for energy efficiency measures. This would again help provide the householder

with a greater understanding of how their property consumes energy. Finally, Chapter 6 showed that students understood some key energy topics (turning lights off, wind farms), but lacked knowledge of others (alternative fuels, heating behaviours). Therefore, we feel that ICT can play a significant role in helping students to develop a more complete understanding of core energy topics through linking teachers with energy experts, as was shown with the Daily Energy Message smart phone application in Chapter 6.

Due to these three factors, we feel ICT has a significant role to play in both encouraging householders to install energy efficiency measures and helping householders to adopt more sustainable heating patterns. The role ICT plays in the domestic energy sector is only just beginning. The rollout of smart meters and the uptake of smart heating controls is going to radically change researchers' understanding of the domestic energy sector in terms of householder insight, property insight, householder engagement and householders' understanding of energy. It is key that researchers are provided with access to the data, as quite often access to this data can be limited. EDF Energy have been a great example of how providing researchers with access to the data can help push forward the academic literature, as the research presented in this thesis shows. The change in the levels of insight will also shift the way energy companies engage with householders and change the way installers, contractors and suppliers provide advice and recommendations for energy efficiency measures and retrofitting.

However, ICT is not the complete answer. There are a large number of social and individual householder dynamics surrounding both retrofitting and space heating behaviours that ICT will have a limited impact on. For example, a householder's financial situation, building regulation standards, a country's energy mix, home ownership, society's rapid levels of increased consumption, governmental policies and government incentives are beyond the scope of ICT to address. These factors contribute to the operating environment in which the householder makes their decision, as defined in the adapted FBM in Chapter 4 (Figure 4.4, Figure 4.5 and Figure 4.6). Modifying these factors require a significant social, economic and political shift that ICT can only have a limited impact on, in isolation. More work needs to focus on the role ICT can play in creating systemic change through applying pressure on governmental organisations to change environmental policy. In the quest to create systemic change through ICT, it is necessary to focus on how we can enable householders to learn about and demand policy change. This is especially necessary as householders become more empowered through their increased understanding of energy.

8.5 Householder's comfort and resignation must gain more attention

Chapter 7 demonstrated that householders' sustainability views do not necessarily relate to their objective heating schedules or heating patterns. Therefore, the factors that drive householders' heating patterns are greater than just environmental factors. In a similar manner, Chapter 5 (Table 5.1) showed different factors that drive householders to retrofit. One factor which plays a vital role in both householders heating patterns and retrofitting is comfort. Comfort is a core driver for retrofitting, but it also causes householders to have unsustainable heating patterns. However, comfort can quite often be seen as a second thought when it comes to presenting the benefits of energy efficiency measures and is rarely incorporated as a benefit in the initial cost of measures. On top of this, comfort gets little explanation in householders' heating or energy bills, and it is rare to link the increase in comfort with the increased impact on the environment and cost of heating. As we showed in section 2.5.2, householders' heating demand and comfort levels can vary, and this is influenced by different social and cultural norms that affect individual habits and attitudes towards heating. However, householders need a more detailed understanding that an increase in heating demand and comfort comes at a cost, both financially and to the environment. If householders want a higher level of comfort at a lower cost, the installation of energy efficiency measures is a method to achieve this. ICT can play a significant role in helping to engage householders to understand their current level of comfort. As highlighted in section 5.6, this is especially true of the adoption of smart heating controls.

Another factor that requires greater attention is householders' level of resignation with their current level of comfort within their property. This was a key barrier discussed in Chapter 5. If householders are resigned about their household's energy saving potential, they will have limited motivation to learn more and discover how to improve their comfort, which is one of the underpinning aspects of the power law of engagement for energy saving framework. This was built on Kaplan & Haenlein's (2010) research that showed behaviour change is not generated by telling people what to do, but instead encouraging them to learn about new behaviours. Householders need to feel that they are in control of developing their own sustainable heating behaviours and sustainable households. It must be a rewarding, learning and social process, and this cannot be achieved if householders are resigned about the current state of their property and levels of comfort. A method to reduce resignation and empower householders is to use ICT to provide tools that use sustainability through design (Blevis 2007) to encourage householders and society to change the design of their environment (sustainability in design), as highlighted in Chapter 3. The tools must provide householders with the knowledge, understanding and empowerment to improve their properties, leading to increased levels of comfort and reduced environmental impact. This poses a significant challenge, but it would be a worthwhile area of research for both the sustainable HCI and ICT4S communities.

8.6 Future research

In this final section we present a number of areas for future research that can be built on the findings within this thesis, but which have not been explored due to the time limitation of the EngD.

Firstly, Chapter 4 presents the power law of engagement for energy saving framework, which is a theoretical framework to help researchers and industry experts better understand the householder's decision-making process when installing energy efficiency measures. However, this framework was built using a grounded theory approach that uses insights from academic and industrial literature. Therefore, it would be advantageous to validate the framework with more quantitative data. The increase in householder and property information being achieved through ICT will help validate the framework. In validating the model, it is important to design methods of analysing householders to define which stage they are at within the framework and to understand how to define when a householder is likely to move from one stage to another. At the moment, the framework also mainly applies to householders who own their property, and it could be improved by expanding its application to householders who rent or live in social housing. Finally, the methodological approach taken to develop the power law of engagement for energy saving framework started with the householders' motivations and abilities. In the future, this same approach could be undertaken but starting with the property's physical characteristics. This would develop a household retrofitting framework of energy efficiency measures recommended based on helping householders improve comfort, financial savings or energy reductions, compared to level of investment required, disruption and the challenge of installation.

Secondly, when it comes to encouraging householders to install energy efficiency measures, we need to understand that these measures are expensive. This is especially true of big-ticket items such as solar PV, heat-pumps or converting gas to electric heating. Therefore, in future research we would like to investigate the psychology of selling and marketing high-priced items. Through this research it is vital to explore how products are currently sold at successful companies such as car manufacturers, technology hardware companies and holiday companies. Researchers should not be afraid to investigate methods used by commercial companies. As part of this research, it is vital to explore the role of product aesthetics, user experience and marketing, and find out how these factors influence users' desire for products and services. Once this is understood, these techniques and methods could be applied to energy efficiency measures to help them become desirable. In this area, Tesla has already started successfully to apply marketing and product aesthetics to solar panels (Tesla 2017) and electric vehicles.

Thirdly, as shown throughout this thesis, there has been a rapid increase in the amount of data that is being collected through smart meters and smart heating controls, which now enables for a much more data-driven approach to research. In future research it would be interesting to see how a data-driven approach can help identify and engage high-impact householders, those that exhibit very unsustainable heating patterns as shown in Chapter 7, or those within the disengaged stage of the power law of engagement for energy saving framework presented in Chapter 4. Targeting these householders will enable communications, tools and resources to be used more effectively, rather than taking a one-size fits all approach. A data-driven approach could also be used to help householders understand the energy savings generated from both habitual behaviours and investment behaviours. It could highlight the significance of turning down your thermostat by 1^{o}C compared to paying to get loft insulation installed, and the effect on the householder's level of comfort. Taking this type of data-driven approach is now available due to the rise in data that is being collected from households.

Fourthly, in Chapter 6 we showed how ICT can help stimulate discussion around energy sustainability and help spread up-to-date energy knowledge to teachers. As sustainability is a complex topic which can be hard to define (Chasin 2014), it is important that we expose school pupils more to the topic. In future work on this topic it is vital that we make discussing and debating sustainability issues a regular occurrence. In Chapter 6 we didn't quite manage to get the school pupils to habitually discuss sustainability, but this should be the goal moving forward. The more school pupils discuss sustainability the more informed they will be, which will help them make better environmental decisions. To achieve this it is also important to consider the ICT information channels that young people are using. With the rise of Instagram, Snapchat and Youtube the use of images, videos and multimedia has increase in importance. This was an area that the teachers felt could have been improved. In future work it would be great just to focus on images and video rather than text. In doing this it will help improve the engagement from the school pupils and provide a more compelling tool for the school teachers.

Finally, Chapter 7 demonstrated that technology self-identity had an influence on a householder's self-reported environmental behaviours. This leads to the question: what other self-identities influence householders' space heating behaviours? Two that would be beneficial to explore in the future are level-of-comfort self-identity and frugality self-identity. As highlighted throughout this thesis, both financial costs and levels of comfort play an important role in space heating behaviours and uptake of energy efficiency measures. In exploring this, it is important to measure both the householders' self-reported behaviours and their objective behaviours. As highlighted in Chapter 7, there can be a gap between psychological variables and respective actions. Finally, on top of exploring these two new self-identities, it is also important to look at the social context when households have multiple individuals with different self-identities. For example, do households conform to a single shared self-identity? Or does a single individual's self-identity dominate within a social context? Lastly and most importantly, how does this shared social self-identity affect the household's space heating behaviours? To achieve this, the methodology in Chapter 7 can be used again, but with a questionnaire that encompasses all members of the household rather than just the individuals who purchased the smart heating control. This would allow the perspective of each family member within the household to be taken into account.

CHAPTER 9

CONCLUSION

"One's ideas must be as broad as Nature if they are to interpret Nature." — Sherlock Holmes — A Study of Scarlet by Arthur Conan Doyle (Doyle 1887)

This final section presents an overview of the thesis's core contributions and provides a short, personal reflection about completing the research.

9.1 Contributions

In this thesis, the core contributions to knowledge in order of significance are:

1. **Contribution 1 — Chapter 7**

   Presented an in-depth evaluation of the role that householders' sustainability views have regarding their heating patterns. In the evaluation it was found that pro-environmental self-identity is a significant predictor of self-reported pro-environmental behaviours, including space heating behaviours. It also showed that technology self-identity is a significant predictor of light and heating pro-environmental behaviours. Finally, the evaluation highlighted a gap between psychological variables like values, identity and respective action when it comes to objective programmed heating schedules and actual heating patterns.

   Publication: Environment and Behavior (under review)

   (Main Author) Weeks, C., Ferguson, D., Preist, C., and Whitmarash, L. Exploring the relationship between householders' pro-environmental values, identities and heating patterns.

2. **Contribution 2 — Chapter 5**

   Highlighted a number of drivers and barriers to retrofitting that helped to extend the academic literature. The chapter also showed the role that ICT can play in promoting the drivers and reducing the barriers. The core drivers listed in descending order of impact: potential financial savings, increased comfort, subsidies, accurate information and broken products. The largest barriers were: initial cost, limited expert knowledge, time investment, resignation (in the current state of their property) and poor communication.

Publication: EnviroInfo2015 and ICT for Sustainability 2015

(Main Author) Weeks, C., Delalonde, C., and Preist, C. Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help? — 29th International Conference on Informatics for Environmental Protection (EnviroInfo 2015) and 3rd International Conference on ICT for Sustainability (ICT4S 2015)

3. **Contribution 3 — Chapter 3**

   Demonstrated that the research of the sustainable HCI and ICT4S communities focused too much on persuasive psychological techniques to change householders' habitual behaviours, especially behaviours dealing with electricity consumption. The case was made for investment and heating behaviours that can provide large energy and CO_2 savings.

   Publication: NordiCHI 2014 - Workshop 8: Is there a European strand of sustainable HCI?

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Sustainable HCI and Encouraging Retrofitting. — 8th Nordic Conference on Human-Computer Interaction

4. **Contribution 4 — Chapter 4**

   Presented a novel theoretical framework called the power law of engagement for energy saving that highlighted how disengaged householders might be converted into engaged retrofitting householders.

   Publication: ICT for Sustainability 2014 — Nominated for Best paper award

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. Power law of engagement: Transforming disengaged householders into retrofitting energy savers. — 2nd International Conference on ICT for Sustainability (ICT4S 2014)

5. **Contribution 5 — Chapter 6**

   Presented an ICT solution to help develop school pupils' knowledge of key energy sustainability topics by disseminating expert knowledge of EDF Energy's staff members to teachers. The research also presented that students have a significant knowledge and awareness of wind farms and the sustainable action of turning off lights, but limited knowledge and awareness of alternative forms of renewable energy generation.

   Publication: CHI2016 - Late-Breaking Work

   (Main Author) Weeks, C., Delalonde, C., and Preist, C. The use of Digital Technology to Evaluate School Pupils' Grasp of Energy Sustainability.

The five contributions highlighted above show that the thesis has helped move the academic literature forward, and could stimulate future research. Finally, the contributions should also help the academic community in our quest to better understand how we can stay within the ecological limits of our planet.

9.2 Personal reflections

At the beginning of this journey I always knew that the topic of energy and environmental sustainability was going to provide me with greater insight into one of the biggest challenges humanity will face over the next century. In the early stages of the EngD, I read and learned as much as possible about the topics, and I felt horror at the rapid devastation of the environment that was being caused by humans. It was frightening to see not only the scale of the destruction, but the rapid pace at which the destruction was increasing. However, as I started to apply my knowledge to the problem and started to speak, interact and collaborate with individuals from around the world, I began to see the potential for change. Individuals and groups had endless energy and passion for the topic and you could see that they were not only talking about change, but taking the necessary actions. As well as the efforts at the grassroots level, I also felt that there was a change in the tone of environmental sustainability: governments around the world were making changes. Progressive governments were challenging themselves to move to renewables as rapidly as possible, and some underdeveloped nations were deciding to skip the fossil fuel stage of development (although some governments are now going backwards). This change in governments' mentality, in combination with the rapid decrease in the cost of renewable technologies, encourages me to have faith in our ability to transform the energy sector. I do believe our transition to renewable sources of energy will be fast and more rapid than most, as I feel once the wheels of capitalism kick in renewables will be the only feasible financial option for companies and governments. Capitalism will make the transition happen significantly faster than expected and I believe we are already seeing the start of that journey. The transition will leave traditional dirty energy generators to change or die. However, do I see individuals significantly reducing their own levels of energy consumption and levels of comfort, whether it be space heating, air flights or dietary requirements? This is a tricky question. I feel individuals' personal views of the environment are changing, and among the younger generation the environment is gaining greater attention, but I still feel the required levels of change will not be achieved. This puts our environment in a risky situation, but humans are adaptable and resourceful; I am certain we will find a solution.

Personally I have found the process of completing an EngD incredibly rewarding. I have spent the last five years of my life dedicated to a subject that is extremely close to my heart, I have met amazing people from all over the world, visited new countries, and I hope I have helped to make a significant impact in our understanding of how we can move towards sustainable levels of consumption, especially within the domestic energy sector. I would like to note that the process of completing the EngD has been rewarding on multiple levels. From the academic side, I have written papers, presented at conferences and indulged in literature written by brilliant minds. From the industrial side, I have helped build a fantastic team at EDF Energy, run large projects that affect millions of customers, presented my research in front of whole auditoriums of people and learned the workings of a large company. Along this journey I have created so many memories, built relationships that I will have for life, and grown and learnt so much about myself. I would just like to end by thanking everyone who has supported or helped me along the way: without you, this would not have been achievable.

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