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**Uptake, use, and learning about new home technologies to
reduce energy system emissions: Policy implications from
different problem framings**

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I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

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Abstract

In the UK and beyond, new end-use technologies are widely expected to enable households to reduce energy system emissions as part of action on climate change. However, there are different ways to understand problems and solutions associated with this proposition. UK energy policy focusses on designing, identifying, and promoting the uptake of promising technologies, implicitly assuming that technologies' impact will follow their adoption in a predictable way, but alternative problem framings draw attention to how the meaning and use of technologies emerge as they become part of everyday life. For example, domestication theory highlight how technology impact emerges from households' learning during technology uptake and use.

This thesis draws on contrasting problem framings to provide policy-relevant insights into household engagement with two technologies expected to decrease energy system emissions in the UK. Two papers on residential demand response employ systematic review methodology to identify insights that may help to promote engagement with residential demand response and inform assumptions about how much flexibility it could provide the UK electricity system as part of decarbonisation. Meanwhile, two papers on smart hybrid heat pumps make use of process analysis informed by domestication theory to investigate users' learning about this novel lower carbon heating technology. One suggests ways to influence users' learning about smart hybrid heat pumps to support UK energy policy objectives, while the other develops conceptualisations of learning in domestication theory by proposing a framework of four learning processes. The thesis concludes by discussing opportunities and limitations for different problem framings to inform energy policy, and opportunities for further research into users' learning to support deeper emissions reductions.

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List of acronyms

BEIS	The Department for Business, Energy and Industrial Strategy
CCC	The Committee on Climate Change
CPP	Critical Peak Pricing
CPR	Critical Peak Rebate
DECC	The Department of Energy and Climate Change
DLC	Direct Load Control
DR	Demand Response
dTOU	Dynamic Time of Use pricing
EPRI	Electric Power Research Institute
HFC	Hydrofluorocarbon
IHD	In-Home Display
kWh	Kilowatt hour
LPG	Liquid Petroleum Gas
Ofgem	Office of Gas and Electricity Markets
PCT	Programmable Communicating Thermostat
REA	Rapid Evidence Assessment
RHI	Renewable Heat Incentive
RTP	Real Time Pricing
SCOT	Social Construction of Technology
SHHP	Smart Hybrid Heat Pumps
sTOU	Static Time of Use pricing
STS	Science and Technology Studies
TOU-CPP	Time of Use – Critical Peak Pricing
TRVs	Thermostatic Radiator Valves
UK	United Kingdom
VPP	Variable Peak Pricing

Motivation and Overview

Mitigating the worst effects of climate change requires urgent action to reduce global greenhouse gas emissions. In 2019, the UK government committed to achieve net zero emissions by 2050, accounting for energy system and other emissions occurring within the UK. Broadly speaking, the UK's strategy to reduce energy system emissions involves increasing low carbon electricity generation, increasing efficiency, and increasing electrification of energy end uses. These changes imply a greater role for electricity, and new strategies to increase electricity system flexibility to balance increasingly variable electricity supply with growing electricity demand.

Developing lower carbon electricity generation has so far contributed the majority of emissions reductions in the UK. However, households are also expected to make important contributions to decreasing UK energy system emissions by adopting new end-use technologies such as electric vehicles and lower carbon forms of heating. There is also growing interest in the potential for residential users to provide electricity system flexibility by changing the timing of electricity demand via smart automated appliances and/or time varying pricing (demand response). However, the uptake of technologies such as lower carbon heating and home insulation are badly lagging, and progress to achieve targeted emissions reductions is already behind schedule.

Overall, then, this thesis aims *to provide insights relevant to policy to increase UK households' contribution to reduce energy system emissions through the adoption and use of new technologies*. However, it also engages with current debates around *problem framings* – ways of conceptualising problems and actions to address them – by recognising that the deployment of new end-use technologies can be understood in more than one way. UK energy policy typically focusses on designing, identifying, and promoting the uptake of promising technologies, implicitly assuming that technology impact will follow in a predictable way. By contrast, alternative problem framings conceptualise technology and society as co-constructed, implying that ways of life may continue to change and that technology impacts cannot be fully predicted. This suggests that policy to reduce emissions could usefully attend to processes that emerge during the use of new technologies as well as economic and other influences on technology uptake.

The four papers making up the body of this thesis adopt two distinct problem framings, and identify policy relevant insights related to two different technologies: residential demand response and smart hybrid heat pumps (SHHP), an innovative lower carbon heating

technology. Papers 1 and 2 are concerned with the uptake and use of residential demand response, and reflect aspects of dominant problem framings, including through their use of concepts and of systematic review methodology – an approach involved in evidence-based policy paradigms. Papers 3 and 4, which are primarily concerned with the use of SHHP, take an alternative approach. They make use of domestication theory and the methodological approach of process analysis to analyse how users construct meanings and uses of SHHP in processes of learning that unfold over time. In this way the thesis contributes insights relevant to policy on residential demand response and smart hybrid heat pumps, and contributes to the problem framings debate by discussing opportunities and challenges for insights from different problem framings.

Chapter One of this thesis provides further background on UK policy and the current debate surrounding dominant and alternative problem framings. It also provides background on the conceptual and methodological approaches adopted by the four papers making up the body of this thesis; Figure 2 in Section 3 of Chapter 1 provides an overview of the research questions addressed by each paper and the problem framings they adopt.

Chapters Two to Five consist of the four papers of the thesis. In Chapter Two, Paper 1 addresses the question:

Are modelling studies realistic about how much demand response we can really expect from residential consumers?

This paper presents findings from a systematic review of primarily quantitative evidence on consumer engagement with residential demand response drawn from international trial and programme evaluations. It then compares these empirical findings with assumptions made by studies modelling the potential for residential demand response to increase electricity system flexibility in support of emissions reductions. The findings suggest that modelling studies should pay closer attention to empirical evidence on user engagement to inform modelling assumptions. Modelling studies often assumed much higher levels of user engagement than those identified in the reviewed literature and included flexible use of loads such as electric vehicles, for which little empirical evidence was identified at the time of the review. Furthermore, both empirical and modelling studies gave little consideration to how engagement with demand response might vary at different moments in time, despite this having potentially important implications for the provision of electricity system flexibility. These findings can also contribute to inform policy assessments of the potential for residential demand response.

Paper 2, presented in Chapter Three, was based on work originally conducted for the UK department of Business, Energy and Industrial Strategy (BEIS). It builds on the findings of Paper 1 by addressing the question:

What are the key factors affecting residential user engagement with demand response?

This paper presents the findings of an additional systematic review of primarily qualitative evidence on user engagement with residential demand response, drawn from international trials, programmes, surveys and focus groups. Review findings were organised around concepts, such as consumer motivations and barriers, which were specified by BEIS and reflect dominant problem framings. However, the review identified literature drawing on a range of problem framings. It identifies that user engagement with residential demand response may be influenced by factors such as: familiarity and trust in demand response and associated technologies; perceptions of risk and control; complexity or effort; and users' characteristics and existing routines. These findings contribute to research on residential demand response by highlighting that user engagement may be influenced by factors other than time varying pricing and enabling technologies, supporting the findings of other work. They contribute to the overall thesis aim by suggesting ways to promote user engagement with residential demand response, for example by focussing on more predictable forms of demand response around which users may be able to construct new routines, and implementing automation and similar technologies in ways that do not increase complexity or reduce trust or perceived control.

Papers 3 and 4 drew on interviews and observations with households and installers involved in the FREEDOM Project, an industry-led trial of SHHP. This followed a chance meeting with one of the industry partners and a mutual interest in working together: I was interested in smart hybrid heat pumps because of the policy importance of residential heat decarbonisation in the UK, while my work on demand response was relevant to some aspects of smart control tested as part of the trial.

Paper 3, presented in Chapter Four of this thesis, addresses the question:

What were the outcomes and processes of user learning about smart hybrid heat pumps in the context of the FREEDOM project trial? And what are the implications for UK heat decarbonisation policy?

Drawing on interviews and observations with users and installers involved in UK technology trial, the paper identifies a number of policy-relevant outcomes of users' learning about SHHP. For example, interviewees often learned that heat pumps are technically incapable of providing those functions which were provided by the boiler as part of the hybrid system; this challenges the expectation that experience of hybrid systems might increase UK households' willingness to accept full heat pumps if these are rolled out in the future (CCC 2018, 2019c). Meanwhile, some interviewees developed unintended routines of using SHHP, including bypassing the intended operation of smart controls, which might reduce the expected efficiency benefits on offer from SHHP. By analysing how this learning emerged, Paper 3 also suggests opportunities to influence users' learning in support of policy objectives. For example, using non-technical language to explain the functioning of SHHP may help to avoid users' constructing misconceptions about their functionality, while ensuring the presence of material elements such as thermostatic radiator valves on bedroom radiators may help to avoid unintended and less efficient ways of using SHHP while promoting the construction of positive meanings by helping to avoid discomfort. This analysis builds upon previous work applying domestication theory to illuminate policy-relevant insights (Hargreaves, Wilson, and Hauxwell-Baldwin 2017; Judson et al. 2015), and contributes to calls for energy policy and related research to draw upon a wider range of problem framings (see, for example, Spurling et al., 2013; Foulds and Christensen, 2016; Labanca and Bertoldi, 2018; Jensen et al., 2019; Royston and Foulds, 2019).

Paper 4, presented in Chapter Five, builds on the analysis in Paper 3 by addressing the question:

Taking domestication theory as a starting point, how can processes of user learning about a new end-use energy technology be conceptualised?

This paper makes a conceptual contribution to domestication theory, responding to calls for the processes and dynamics of learning within domestication to be more fully conceptualised (Juntunen 2014). It takes the established concepts of cognitive, symbolic and practical learning as a starting point, applying process analysis to analyse *how* these emerge. Through this abductive approach it proposes a framework of four interlinked learning processes, each emerging from interactions between elements related to new technologies and elements related to users' daily lives. This framework contributes to illuminate the emergence of cognitive, symbolic and practical learning, and also interactions with ongoing trajectories of domestication at the household and societal levels. In particular, the analysis suggests how

learning about more energy efficient and smart automated technologies might contribute to the emergence of trajectories of increasing demand for services such as comfort and convenience. This analysis has the potential to contribute to inform policy by providing a generic framework to understand how users' cognitive, symbolic and practical learning about new technologies might be influenced in support of policy objectives. Understanding interactions between household and societal domestication trajectories may also suggest ways to avoid increases in demand for energy services alongside the adoption of new technologies.

Finally, Chapter Six discusses policy implications of dominant and alternative problem framings by reflecting on Papers 1 – 4, and suggests opportunities for further work. The discussion suggests this could usefully include working with policy professionals to explore how the framework of learning processes proposed in Paper 4 might help to inform policy action related to users' learning about new technologies. It could also engage directly with households or grassroots community energy groups to explore whether understanding processes of users' learning might help to challenge the emergence of increasing demand for energy services alongside the adoption of more efficient and automated technologies, with the potential for deeper emissions reductions.

A note on section numbering: section numbers are written in Arabic numerals and begin again at Section 1 in each of the six chapters.

Chapter One: Overall Introduction

1. UK policy strategies to decarbonise residential energy use and the expected role of smart hybrid heat pumps and demand response

This section provides background and context to the four papers presented in Chapters 2 – 5. It briefly reviews UK policy approaches to involving households in decarbonisation, focussing on residential demand response and decarbonising home heating, and introduces selected aspects of the two technologies studied in the papers: demand response and hybrid heat pumps. As well as providing background and context to the papers, the review of policy approaches helps to illustrate how UK policy may favour certain problem framings – an idea which will be reviewed in greater detail in Section 2 of this chapter and returned to in the overall discussion of the thesis (Chapter Six).

1.1 Overview of current UK decarbonisation policy ambitions and organisations involved in policy making

The UK Government committed to reduce greenhouse gas emissions by 80% of 1990 levels by 2050 as part of the 2008 Climate Change Act (CCC 2008); in 2019, this was updated to net zero (CCC 2019a). The net zero target includes electricity and fuels used within the UK, in addition to emissions from UK-based activities such as agriculture and the accidental release of hydrofluorocarbon (HFC) refrigerant gases; however, it does not include emissions embedded in the production of imported goods and services consumed in the UK. Overall, UK decarbonisation strategy emphasises using energy more efficiently by decreasing the quantity of energy required to provide a certain level of energy services; increasing generation of lower carbon electricity; and increasing electrification of final energy demands, for example heating and transport, to make use of this electricity (HM Government 2011, 2017a, 2020). Electricity is therefore expected to be an increasingly important energy carrier, but other types of energy carriers including lower carbon fuels may also play important roles. Since this thesis aims to generate insights relevant to UK policy, it similarly focusses on how households might contribute to reduce emissions from the UK *energy* system. However, it should be noted that ignoring embedded emissions in imported goods and services limits understanding of households' potential contribution to address climate change.

Almost full emissions reductions are required in all sectors to achieve net zero. Households are expected to play an important role in reducing energy system emissions, for example by adopting new end-use technologies such as electric vehicles and low carbon heating systems

(CCC 2019a). Deploying low carbon heating systems may be particularly challenging. At present, the majority of home heating in the UK is provided by central heating systems fuelled by individual boilers burning natural gas (fossil methane) distributed via national infrastructure ('mains gas') (Hanmer et al. 2019; Hanmer and Abram 2017). The transition to low carbon heating systems therefore requires both central planning and investment in infrastructure, and changes in technologies in almost all households. While the UK has so far achieved mandatory emissions reductions legislated under the Climate Change Act (2008), this has resulted almost entirely from decreasing the carbon intensity of UK grid electricity (CCC 2016a; Staffell 2017). In 2019, renewable sources contributed around 35% of total electricity generation; by contrast, renewable heat accounted for only around 8% of total UK heat demand (including industrial heat). In the same year around 15% UK's total greenhouse gas emissions originated with the use of natural gas for residential cooking, space and water heating (BEIS 2021a). The UK is now off track to meet interim targets towards both net zero and the less ambitious prior goal (CCC 2019b, 2020b), and progress in deploying lower carbon heating systems has been particularly slow (CCC 2019a; Rosenow et al. 2020).

Heat decarbonisation also poses particular challenges. Unlike power system decarbonisation, decarbonising home heating will require considerable public engagement (CCC 2019a). It is not yet clear which technologies or combinations of technologies may be technically and economically optimal (CCC 2020a), and households in different geographical areas may be offered different low carbon heating options (CCC 2019a) or asked to install different technologies at successive points in time (CCC 2018, 2019c). Some alternative technologies also have characteristics which differ from the gas boiler systems familiar to most UK users; for example, heat pumps operate more efficiently when they are run more continuously, including overnight, which is currently unusual in the UK (see, for example, Hanmer et al. 2019; Judson *et al.*, 2015; CCC, 2020a). These issues, and particularly their relevance to hybrid heat pumps, are discussed in more detail below, but overall it is clear that home heat decarbonisation requires households' active engagement with new technologies.

Households' use of new technologies may also contribute to support wider energy system change. Increasing electrification of transport, heating and other end uses is also expected to require around a doubling of current total electricity demand, which must all be supplied by low carbon sources (compared to around 50% today) (CCC 2019a). These changes will increase both peak electricity demand and the share of inflexible generation, with implications for the balance of electricity supply and demand. Electricity systems require supply and demand to be balanced within tight limits in real time, and this has traditionally been achieved by planning

sufficient generation and network capacity to meet peak demand, plus contingency reserves, and dispatching flexible fossil fuel generation to follow electricity demand profiles (Strbac 2008). However, this strategy is challenged by increasing penetrations of inflexible low carbon generation, while increasing electrification may magnify the problem by increasing both total electricity demand and demand variability. In contrast to the typical approach of supply following demand, demand response describes changing electricity demand in response to grid conditions: for example, decreasing demand at times of network congestion resulting from high levels of electric heating, or increasing demand to make use of high wind generation. By changing the times at which they use electricity, households may therefore be able to provide part of the additional flexibility required to decarbonise the UK energy system (CCC 2019a; HM Government 2017b; National Infrastructure Commission 2016).

Technologies and policy approaches related to demand response and decarbonising home heating are reviewed in more detail below. However, before reviewing UK policy approaches to decarbonising home heating and residential demand response, it is helpful to introduce the main organisations involved. The Climate Change Act (2008) established the Committee on Climate Change (CCC) as a statutory committee with responsibility to recommend emissions reductions levels and steps to meet them through a series of interim carbon budgets (CCC 2008; Priestly 2019). The UK Government is legally bound to consider these recommendations when setting carbon budgets, which become legally binding once they are presented to and accepted by Parliament. The first five carbon budgets as well as the updated net zero target and emissions level of the sixth carbon budget have been legislated following the advice of the CCC (BEIS 2021c; Priestly 2019). The CCC also provides annual feedback to Parliament on progress to meet the budgets and other advice as specified by the Climate Change Act (2008) or requested by the responsible Minister (CCC 2008). The government department presently responsible for formulating policy to reduce direct emissions from electricity and fuel use in homes is Business, Energy and Industrial Strategy (BEIS). This role was previously held by the Department of Energy and Climate Change (DECC), which was merged with Business, Innovation and Skills (BIS) in 2017. The CCC's analysis has previously informed heat decarbonisation strategy (DECC 2012), and is informing further strategy development (BEIS 2018). This overview refers to documents produced by the CCC, DECC and BEIS, as well as the UK Government, and the National Infrastructure Commission which is a separate commission advising government on major UK infrastructures. It covers the period from 2008, when the Climate Change Act was passed, up to the legislation of the Sixth Carbon Budget in 2021 (the first of the carbon budgets to target net zero emissions).

1.2 Policy approaches and technologies with particular relevance to this thesis

UK policy approaches to decarbonise residential heating have emphasised increasing thermal efficiency of buildings and replacing gas boilers with low carbon alternatives. Increasing electrification of heating, alongside some district heating in urban areas with dense heat demand, have been included in policy scenarios since 2008, but the discussion about other technologies has changed over time.

Bioenergy was initially envisaged as an important potential contributor to decarbonise home heating (CCC 2008), but following concerns about sustainable sourcing of larger quantities of biomass¹, in 2010 bioenergy's expected role in heat was restricted to high temperature industrial heat which can less easily be provided by other sources (CCC 2010). Some years later, concerns were raised about the electricity system impacts of widespread heating electrification via heat pumps (DECC 2013b). Heat pumps are a technology that can make use of renewable electricity at efficiencies of greater than 100% to produce low-temperature heat suitable for heating homes. This is achieved by collecting ambient heat energy from the environment (typically the air or soil, but also water or shallow geothermal) and using electrical energy to drive refrigeration cycles that increase the temperature of this energy (The Energy Saving Trust 2010). However, peak heat demand in the UK is considerably higher than peak electricity demand, so that widespread replacement of gas boilers with heat pumps would require a large expansion of electricity generation and network capacity despite heat pumps' high efficiency. Furthermore, heat demand is highly variable over time, which implies that a considerable share of additional electricity infrastructure would be in use for a small proportion of time.

Hybrid heat pumps, the technology which is the subject of the third and fourth papers of this thesis, entered policy debates in response to these concerns (DECC 2013b). They combine electrically driven heat pumps with gas boilers, which could reduce the electricity system impact of heat electrification by allowing most heat to be provided by electricity while gas supplies peak heat demand. Existing gas infrastructures can provide long-term energy storage and the greater variability in gas demand implied by the use of hybrids can be accommodated by gas networks (FREEDOM Project Final Report 2018; CCC 2018).

Because heat pumps can make very efficient use of grid electricity, which is also decreasing in carbon intensity, hybrid heat pumps utilising natural gas boilers could decrease emissions

¹ Biomass describes solid fuels derived from recently living plants, such as wood, which can be burnt to produce heat and/or electricity.

compared to the use of gas boilers alone (CCC 2018; Turvey et al. 2018). However, deeper decarbonisation with hybrid heat pumps would require lower carbon gas as well as electricity. The idea of hydrogen² as an option to decarbonise residential heating entered the policy discourse in 2013, at the same time as hybrid heat pumps (DECC 2013b). Hydrogen had previously been discussed as a potential contributor to decarbonising industrial heat and forms of transport, for example long distance freight transport, which would be more difficult to convert to battery electric vehicles because of the capacity and weight of batteries required (CCC 2008, 2010; HM Government 2011). If it is produced by the electrolysis of water using renewable electricity, or from steam reformation of methane alongside effective capture and storage of the carbon dioxide which is also produced, hydrogen could offer a lower carbon form of gas for heating homes. However, there are a number of uncertainties surrounding the development of low carbon hydrogen (CCC 2018, 2020a; Lowes, Woodman, and Speirs 2020; Staffell 2017). The CCC have recommended that 10 million hybrid systems should be installed by 2035 based on the reasoning that this would keep open the option to either switch to full electric heat pumps or to decarbonise gas, delaying the need to decide between alternative technologies (CCC 2018, 2019c). At present, the main policy approach to encourage uptake of lower carbon home heating systems is the Renewable Heat Incentive (RHI), which provides a subsidy payment per unit of renewable heat generated for seven years after installation (DECC 2013a). Hybrid heat pumps are eligible for the RHI provided that the heat generated by the heat pump component is metered (Ofgem 2018).

In comparison to technological change, including increased energy efficiency, UK policy discourses include relatively little discussion of measures to decrease absolute demand for heat and other energy services. The CCC have discussed the possibility that households could reduce indoor temperatures by one degree centigrade (CCC 2008, 2010, 2015); however, technologies, in the form of various “smart” heating controls, are also starting to be seen as a route to achieving heat demand reduction, for example through heating schedule automation (CCC 2016b; HM Government 2011). The CCC have also recommended policies to encourage shifts away from the consumption of meat and dairy (CCC 2020a), but this recommendation was not implemented in the legislation of the sixth carbon budget: instead the UK government

² Hydrogen as an energy carrier could be produced by steam reformation of methane (i.e. natural gas), accompanied by capture and storage or utilisation of the carbon dioxide gas that is simultaneously produced or by using renewable electricity to electrolyse water, producing hydrogen and oxygen gas. Hydrogen may be easier to store than electricity, particularly over longer time periods. However, neither the production of hydrogen through electrolysis nor carbon capture and storage has been widely developed, and concerns have been raised around the life cycle emissions associated with producing hydrogen through methane reformation (Lowes et al. 2020).

focussed on technological change, “whilst maintaining people’s freedom of choice, including on their diet” (BEIS 2021c).

Interestingly, while demand reduction has received little attention, residential demand response has been actively discussed as a potential new source of electricity system flexibility. Residential demand response is the subject of the first and second papers of this thesis. In the UK to date demand response has been mostly developed with industrial and commercial consumers. However, residential demand response could offer a substantial new source of demand-side flexibility (Gils 2014) and has been developed more extensively in other countries (National Infrastructure Commission 2016).

Interestingly, although increasing electrification of heating could pose a challenge for energy system decarbonisation by increasing electricity demand, it might also increase the potential resource for demand response. Flexible operation of home heating systems may be possible if houses are well insulated, and the potential flexibility of hybrid heat pumps has been particularly highlighted (CCC 2019a). The combination of an electrically driven heat pump and gas boiler could allow the heat pump to be flexibly operated by switching to gas in response to electricity system needs as well as at times of peak heat demand; this might be mediated by direct load control or automation in response to time varying pricing (Turvey et al. 2018).

Overall, then, policy approaches for households’ contribution to energy system decarbonisation tend to emphasise technological change alongside financial incentives for the uptake of these technologies, or in the case of residential demand response, for continuing participation. The following section discusses how such approaches relate to different *problem framings*.

2. Dominant and alternative problem framings in energy policy and related research

It is widely expected that households will contribute to address climate change through adopting new technologies that reduce energy system emissions. However, there is currently a debate around the dominance of certain *problem framings* in energy policy and related research, and the extent to which dominant or alternative problem framings might support emission decreases sufficient to address climate change (see, for example, Spurling *et al.*, 2013; Sorrell, 2015; Darby and Fawcett, 2018; Eyre *et al.*, 2018; Shove, 2018; Jensen *et al.*, 2019). The term *problem framing* is used by, for example, Spurling *et al.* (2013), Jensen *et al.* (2019) and Royston and Foulds (2019) to describe the way in which problems are conceptualised. It highlights that the same problem may be understood in different ways,

suggesting possible targets for action and by extension excluding others (Foulds and Christensen 2016; Spurling et al. 2013). Problem framings also influence ideas about which problems are relevant (Royston and Foulds 2019), creating a mental space for thinking about what changes are possible in pursuit of a certain goal, and how they can be effected (Jensen et al. 2019).

Diverse problem framings may be applied to address the overall thesis aim: *to provide insights relevant to policy to increase UK households' contribution to reduce energy system emissions through the adoption and use of new technologies*. As part of addressing the overall thesis aim, the papers within this thesis draw upon two different problem framings, one of which remains close to dominant problem framings and one of which represents an alternative approach. By reflecting on the opportunities and limitations for these two approaches to address the overall thesis aim, the thesis discussion in Chapter Six contributes to the debate about how different problem framings may support action to address climate change.

Since this thesis considers how different problem framings can illuminate user interactions with new technologies, it is worth elaborating on how the term technology is used here. The term 'technology' is often used to refer to physical objects supporting certain functionalities: cars, gas boilers, electricity meters and so on. However, within Science and Technology Studies (STS) the term 'technology' refers not only to such physical objects, or 'artefacts', but also the diverse ways in which they are connected with diverse elements within wider society. This definition emphasises that the functionalities or impacts of technologies emerge from relationships between artefacts and wider society rather than directly from the artefacts themselves (Geels 2002).

Considering the two technologies studied within this thesis, smart hybrid heat pumps (SHHP) are often understood as 'technologies' in the sense of technological artefacts. However, as the empirical analyses in Papers 3 and 4 (Chapters Four and Five) of this thesis will illustrate, the uptake, use, and potential impacts of SHHP are both influenced by and may ultimately influence meanings and routines within households and social norms in wider society. Conversely, residential demand response is often thought of as an activity or practice, reflecting the fact that it can involve people actively changing the timing of electricity-using activities within the home. However, residential demand response always also involves technological artefacts of some kind: from smart controls mediating automated responses through to electricity meters communicating the requirements of the electricity system through time varying pricing. Within this thesis, therefore, both SHHP and residential demand

response are conceptualised as technologies following the understanding of technology within STS. This is also consistent with the dictionary definition of technology as ‘the practical application of knowledge’ (Merriam Webster n.d.).

The remainder of this section provides conceptual background for the discussion in Chapter Six, as well as for the papers themselves. It begins by reviewing debates about the role of different problem framings in energy policy and related research. It then outlines the two conceptual approaches adopted by the papers making up the body of this thesis and considers how they represent dominant and alternative problem framings.

2.1 Dominant and alternative problem framings in energy policy and related research

The review in Section 2.1 indicates that policy strategies to reduce emissions from home energy use are often based on technological change, with the underlying assumption that changing technologies in the home will change households’ contribution to energy system emissions. This approach draws upon insights from engineering and economics, which are applied to design new technologies, identify those technologies which appear most promising from a techno-economic perspective (for example, through optimisation modelling) and promote their uptake (for example, through subsidy schemes such as the Renewable Heat Incentive). Insights from social psychology and behavioural economics may also be applied to promote technology uptake by influencing individual consumer choice between technological alternatives (such as gas boilers or heat pumps), as well as between behaviours (such as using cars or public transport) (Evans, McMeekin, and Southerton 2012; Labanca and Bertoldi 2018; Shove 2010; Spurling et al. 2013).

Techno-economic framings also predominate in energy related *research*. When they are included, perspectives from the social sciences and humanities are typically introduced late in the research process as a means to increase acceptance of new technologies and promote their ‘correct’ use, rather than as part of defining relevant problems and the questions to be addressed (Jensen et al. 2019; Royston and Foulds 2019). This is important, because alternative framings can offer relevant insights beyond those provided by the dominant techno-economic framings.

One important criticism of dominant techno-economic problem framings is the implicit assumption of technological determinism: in other words, that technologies themselves create predictable impacts (see, for example, Shove, 2010; Foulds and Christensen, 2016). This arises because dominant problem framings conceptually abstract technological change from wider

society (Labanca and Bertoldi 2018; Shove 2018). In other words, the narrow focus on technological change means dominant techno-economic problem framings do not offer any framework to understand the complex and reciprocal relationships between changes in technological artefacts and changes in wider society. As noted by Shove (2018), this abstraction is necessary to make engineering calculations of the relative efficiency of different technologies – and the design and uptake of more efficient technologies can be a useful part of enabling households to contribute to reduce energy system emissions (Labanca and Bertoldi 2018). Nonetheless, this narrow focus is problematic because it fails to illuminate ways in which technology and society *do* interact, and the implications of these interactions for addressing climate change. For example, studies drawing on alternative conceptual frameworks have highlighted that the uptake of new technologies may be resisted, that new technologies may be used in unintended ways (see, for example, Sørensen, 2006, 2013), and that households' demand for services such as comfort, cleanliness and convenience may increase alongside the introduction of new technologies (Shove 2003). Each of these phenomena can reduce the ability of new technologies to deliver the emissions reductions that might be predicted when applying purely techno-economic problem framings. Indeed, concerns have been raised about the potential for insights from dominant problem framings to transform consumption adequately to address climate change (see, for example, Sorrell, 2015; Darby and Fawcett, 2018; Shove, 2018).

As well as drawing attention to these issues, alternative problem framings can suggest new opportunities for policy making. These can include suggestions to increase the impact of technology projects, but can also suggest entirely new ways to understand and govern energy use (Jensen et al. 2019; Royston and Foulds 2019). For example, the concept of *rebound effects* describes the observation that energy savings from increases in technological efficiency are often lower than that suggested by engineering calculations alone (Sorrell and Dimitropoulos 2008). A purely technical problem framing may not anticipate this effect. Therefore, the concept of rebound effects may help to draw policy attention to this unintended outcome of changing technology (Marsden 2019) and avoid overestimation of the impact of increasing energy efficiency (Chitnis and Sorrell 2015; Druckman et al. 2011). Rebound effects have typically been identified through an economic problem framing, and this also suggests possibilities for action to address rebound effects. For example, economy-wide carbon pricing could divert financial savings from increasing energy efficiency towards lower-carbon categories of consumption (Druckman et al. 2011; Vivanco, Kemp, and Voet 2016). However, an economic problem framing suggests that increases in consumption logically *should* result

from the financial savings associated with increasing energy efficiency, implying that rebound effects might be reduced but cannot be avoided entirely.

Alternative problem framings consider rebound effects as emerging through processes involved in technology uptake and use (see, for example, Evans, McMeekin and Southerton, 2012; Jensen *et al.*, 2018). By illuminating different parts of the problem, this framing could suggest different possibilities for action. For example, Shove (2018) suggests that dominant ways of thinking about more efficient technologies act to reproduce current levels of energy service demand³, and proposes that efficiency could be increased *without* increasing demand if ideas about ‘normal’ and desirable levels of service can be challenged at the same time as technological efficiency is increased. Meanwhile, the problem framing of sufficiency starts by asking what level of energy services is ‘enough’ rather than how technological change can meet demand for services most efficiently (Darby and Fawcett 2018). This perspective also recognises the possibility of rebound effects, but suggests an entirely different point of entry to address the issue.

It can be noted that the actions suggested by these alternative problem framings are less clearly defined than those suggested by an economic problem framing (also see, for example, Shove, 2010; Hampton and Adams, 2018). However, proponents of alternative problem framings argue that issues of increasing energy demand and resource use associated with mainstream framings of energy efficiency show alternative problem framings deserve greater attention (see, for example, Darby and Fawcett, 2018; Shove, 2018). Chapter Six will return to discuss the opportunities and limitations for insights from different problem framings to address the overall thesis aim, including through discussion of the insights offered by the four papers forming the body of this thesis. Papers 1 and 2 reflect aspects of dominant problem framings, while Papers 3 and 4 draw on an alternative problem framing, which provides an opportunity to reflect on the opportunities and limitations of these problem framings to address the overall thesis aim. The following sub-section introduces the conceptual approaches adopted by these four papers.

³ The concept of energy services is often used to highlight that energy is not used for its own sake, but rather to deliver some desired end state to its users. The concept also draws attention to the difference between energy services provided when commercial energy is converted by end-use devices – for example, heat provided by a boiler or movement provided by a car – from associated desired states, such as thermal comfort or mobility, that might be provided in alternative ways – such as wearing additional clothing or riding a bike (Fell 2017). Changing demand for energy services might therefore involve shifting to alternative ways to provide desired end states as well as decreasing absolute demand.

2.2 Conceptual approaches adopted by the four papers of this thesis

The papers making up the body of this thesis adopt two distinct approaches to address the overall thesis aim. This sub-section describes ways in which the concepts used within Papers 1 and 2 remain close to problem framings currently prevalent in UK energy policy. It then introduces domestication theory, the conceptual framework informing the analysis within Papers 3 and 4, and explains ways in which this represents an alternative problem framing.

2.2.1 Papers 1 and 2: Reflecting concepts from dominant problem framings

Papers 1 and 2 take the form of systematic literature reviews to answer policy relevant questions. As Section 3 of this Chapter will explain in more detail, systematic review methodology includes steps to reduce bias when identifying and synthesising findings relevant to the defined research question. As such, neither Paper 1 nor 2 adopted any explicit theoretical perspective a priori; rather, they aimed to reflect the literature that was identified by following the formal steps of the review. Nonetheless, both papers reflect elements of dominant problem framings in terms of the language and concepts used, including “consumers”, “behaviour change”, “factors”, “motivations” and “barriers”. This language can carry certain assumptions because of its use in problem framings such as economics (see, for example, Shove, 2010). Within Papers 1 and 2, these terms were not necessarily intended to carry the meaning implied by their theoretical associations; for example, ‘consumers’ was intended to mean the converse of electricity producers rather than rational economic actors; ‘behaviour change’ was used to refer simply to what people do, without any assumption that this results from individual choice; and ‘factors’ is intended to mean things that can have influence, without the associations of abstraction and lack of interdependence which this term can carry, for example from its use in regression models.

The use of these terms does partly reflect the predominant language in the reviewed literature, while the concepts of “motivations” and “barriers” were specified by the UK Department of Business, Energy and Industrial Strategy (BEIS), which was the client for the work on which Paper 2 was based (see BEIS, 2017). Papers 1 and 2 were primarily addressed to audiences engaged in modelling electricity systems, and energy policy and related research. Using language and concepts already familiar to these audiences may help address the overall aim of this thesis by helping to communicate with these audiences – including the findings that contribute to challenge assumptions within dominant problem framings (for example, Paper 1 challenges assumptions about the extent to which pricing or automation technologies might influence engagement in residential demand response, while Paper 2 indicates how engagement may be influenced by broader social arrangements, rather than technologies or

individual behaviours). On the other hand, the use of language and concepts drawn from dominant problem framings may limit the extent to which dominant assumptions can be challenged (Shove 2010). The opportunities and limitations of using language and concepts drawn from dominant problem framings are discussed further in Chapter Six.

2.2.2 Papers 3 and 4: Domestication theory as an alternative problem framing to understand technology uptake and use

Papers 3 and 4 are informed by domestication theory. Similarly to dominant problem framings, this conceptual framework also focuses on technological change; however, it explains this as occurring through mutual changes in technologies, their users, and wider society, rather than maintaining a narrow focus on change in technological artefacts in isolation. Domestication theory therefore contributes to address the overall thesis aim by helping to illuminate and identify opportunities to influence aspects of the problem that are less commonly considered in policy discourses. Importantly, domestication theory provides a framework to study how technologies are used, as well as their uptake, and how technology impact emerges from interactions between technologies and users rather than being inherent in technologies themselves. In this way, it counters assumptions of technological determinism by highlighting the emergent and in principle unpredictable nature of technology impact. It can also help to identify opportunities to influence technology impacts; however, understanding these impacts as emergent also suggests that the outcomes of any attempts to influence them should also be considered as inherently unpredictable. Other conceptual frameworks can also help to illuminate complex interactions between technological artefacts and society, but domestication theory was identified as the most appropriate theoretical approach because it focusses on the uptake and use of new technologies within particular households. This can be contrasted with, for example, theories of social practice, which do not specifically focus on new technologies (Ingram, Shove, and Watson 2007), and frameworks associated with sustainability transitions, which often focus on new technologies but over societal scales (Schot et al. 2016).

Chapter Six will further discuss opportunities and challenges for insights from domestication theory and other alternative problem framings to contribute to address the overall thesis aim. Meanwhile, this sub-section provides a detailed review of domestication theory, introducing its initial development within media studies and explaining how and why it was developed within Science and Technology Studies (STS). It then explains which conceptual features make the STS version of domestication theory appropriate to inform the analyses in Papers 3 and 4.

Domestication theory arose during a period of interest in use and users and rejection of technological determinism across multiple disciplines (Oudshoorn and Pinch 2003; Silverstone 2006; Sørensen 1994). It was originally developed within cultural and media studies, but was later taken up and developed by scholars in Science and Technology Studies (STS), so that work on domestication proceeded in two different although not incompatible streams (Sørensen 2006).

Within media studies, domestication theory was developed to examine the effects of new information and communication technologies such as television, personal computers, and the internet in the home and everyday life. It adopted the metaphor of users 'taming' 'wild' technologies as they make them part of everyday life (Haddon 2006). This was seen as requiring users to make technologies compatible with their household's 'moral economy', a concept that describes the idea that meanings as well as commodities are exchanged between the household and wider society, and that households cultivate an idea of how they should be organised (Silverstone 2006); for example, to avoid waste, and to encourage children to spend time in nature have been identified as aspects of certain households' moral economies influencing the domestication of certain energy technologies (Nyborg 2015; Winther and Bell 2018). Domestication therefore requires *negotiation* between technologies and users, as users seek to make technologies work; and between individuals within households, who may have different needs and interests relating to the technology. A key insight is that such negotiations result in the co-construction of technologies and users: technologies' use and meaning may be changed by users, while users' routines and identities may be changed by using technologies (Silverstone 2006; Sørensen 1996, 2006).

In the initial conceptualisation of domestication, Silverstone and colleagues identified four phases through which the process occurs. *Appropriation* referred to purchase or gaining ownership of technologies; *objectification* referred to artefacts being given a physical space and put on display; *incorporation* referred to their use becoming part of daily routines; while *conversion* described how use of a technology can become part of individuals' and households' communication of status and identity to the outside world (Oudshoorn and Pinch 2003). The domestication phases were originally conceived as occurring in sequence, although it was later considered that aspects of each phase can occur at different points in time throughout the domestication process. In addition, the definitions of some phases were expanded: appropriation was expanded to include *commodification*, or the ways in which market research, design, advertising and public policy act to 'package' technologies with meaning; *objectification* came to refer to location within social and cultural spaces as well as physical

space; while *conversion* was broadened to include more general discourse and discussion, sharing frustration as well as pride, and potentially including resistance and refusal (Silverstone 2006).

The domestication framework attracted STS scholars because it offered conceptual resources to study the social and cultural processes involved in technologies' *use*. Broadly speaking, STS is concerned with understanding the development and impacts of science and technology through understanding their relationship with culture and society. Earlier work in the field focussed largely on technology design and innovation, but work towards understanding use and users had begun in the Social Construction of Technology (SCOT) and the concept of technology script (Sørensen 1996). Work on the Social Construction of Technology (SCOT) had effectively countered the idea of technological determinism – the assumption that technologies have predictable impacts which are inherent in the technologies themselves – by demonstrating how the same technology can be given different meanings by different groups of users. This empirical observation was conceptualised as technologies' interpretive flexibility. However, SCOT did not provide a framework to understand the ways technologies may influence the meanings and uses their users construct. Meanwhile, technology script conceptualises interactions between designers and users, by describing how designers' ideas about users, and how technologies will, or should be used, become embodied in technological artefacts through design processes. Thus, in contrast to SCOT, the concept of script explains how technologies' design can influence their use. The active role of users is also made visible through the observations that users must 'read' or 'decode' scripts in order to put technologies to use and give them meaning, and that users may follow technology scripts (subscription), alter them (de-script) or take actions to oppose the technology (anti-programme) (Akrich 1992; Akrich and Latour 1992). Nonetheless, as processes underlying the reading of script and outcomes such as anti-programme are not developed, it can be argued that design and designers are still given greater attention (Sørensen 1994). By contrast, in media and cultural studies use and users had always been the starting point for analysis.

Domestication theory was therefore seen as offering useful resources to develop conceptualisations of use and users within STS. This also drew on related ideas from within STS. For example, existing work on Actor Network Theory contributed the idea that technologies enter networks of human and non-human actors between which competencies, actions and responsibilities are delegated, while insights from domestication theory suggested that such networks also include users' existing routines and circulating cultural meanings (Sørensen 1994). Sørensen (1996) also drew upon the STS tradition of studying learning to

develop the idea of domestication as a type of social learning. Concepts such as learning-by-doing, learning-by-using and learning-by-interacting had become established in technology studies and evolutionary economics to describe how producers learn to use tools of production more efficiently, users of technologies can develop new practices, and learning can be facilitated by exchanging information between these different groups. Again, the emphasis is placed on design and innovation - perhaps because learning-by-using first arose as a concept to explain improvements in production efficiencies in the absence of technological change. Scholars in technology transfer had also identified the principle that users must learn about technologies to put them to use within new contexts, without exploring the processes underlying this learning (Sørensen 1996).

Considering the four domestication phases (appropriation, objectification, incorporation and conversion) in terms of social learning led Sørensen (1996) to identify three *dimensions* that users accomplish during domestication. In the *practical* dimension, domestication involves developing patterns of use: following the idea of co-construction, this might involve both departure from the intended use of the technology, and changes in users' routines. The *symbolic* dimension involves constructing meaning, both for the technology and in terms of users' identity as users of the technology. While Silverstone and colleagues had focussed on meaning, identity, and use, Sørensen added a *cognitive* dimension, involving learning about the artefact or the appropriation of new knowledge (Sørensen 1996; Sørensen, Aune, and Hatling 2000). However, this did not indicate a shift towards individual psychology as a principle element in domestication (Sørensen 1996). On the contrary, STS scholars conceptualised how collective domestication processes may give rise to emergent societal trajectories, including the development of infrastructures, institutions, and social norms, which influence further processes of domestication; for example, social norms, such as the idea that cars must be used to transport children to different activities as part of 'good' parenting, can discipline users to domesticate a technology they may otherwise resist (Sørensen 2006). The conceptualisation of a reciprocal relationship between micro and macro level domestication processes advanced the recognition within media studies, that micro level domestication processes are influenced by users' access to economic, social and cultural resources (Silverstone 2006).

The analysis in Papers 3 and 4 draws upon the branch of domestication theory developed in STS rather than media and cultural studies. Firstly, this is because the three domestication *dimensions* (cognitive, symbolic and practical) offer a more parsimonious analytical framework than the domestication *phases* (appropriation, objectification, incorporation and conversion).

Secondly, the STS version offers conceptual tools to consider how domestication processes within households can have emergent effects on societal level structures such as infrastructures and social norms. This provides a framework to identify insights relevant to energy policy at the national level from analyses of domestication processes within particular households. Finally, the focus on learning draws attention to the potential for evolution in technologies' meaning and use at both household and societal levels, and can also suggest possibilities for policy to influence change (Sørensen 1996, 2006).

Chapter Six discusses opportunities and challenges for insights from alternative problem framings, such as domestication theory, or dominant problem framings such as those reflected in Papers 1 and 2, to address the overall thesis aim. The following section describes the research design and methodology for the thesis and introduces systematic review and process analysis as appropriate methodologies to support analysis within the two problem framings adopted by Papers 1 and 2, and Papers 3 and 4.

3. Research design and methodology

This section gives details of the methodologies, and methods for data collection and analysis, applied by the four papers presented in this thesis. Pragmatism is adopted as the overall methodological approach. This fits the overall thesis aim, of *providing insights to inform policy making*, because it suggests that research methods should be chosen according to their usefulness to address research goals by answering particular questions or producing particular kinds of knowledge (Morgan 2014; Pratt 2016). However, researchers' choice of methods and methodological approaches does not always follow neatly from their adoption of certain research paradigms or conceptual frameworks (Denzin 2010). Instead, methodological approaches can contribute to the construction of problem framings in a similar way to conceptual frameworks. Participation in research communities can influence researchers' decisions about which research methods are appropriate, including through researchers' training and their expectations about how their work will be received by different audiences (Denzin 2010; Morgan 2014; Van De Ven and Poole 2005). Furthermore, the assumptions underlying dominant methodologies might ultimately begin to influence the ways in which researchers conceive of the social world (Abbott 1988; Denzin 2010).

This section therefore provides background to the overall discussion in Chapter Six, as well as the papers making up the body of this thesis, in a similar way to the preceding review of conceptual approaches adopted in this thesis. It reviews two methodological approaches, systematic review and process analysis, and explains why they were selected as appropriate

approaches to address the research questions within Papers 1 and 2 and Papers 3 and 4 respectively. It also outlines how the data for each paper were collected and analysed; further details can be found in the methods sections and appendices (where applicable) of the papers presented in Chapters 2 – 5. The overall thesis discussion in Chapter Six will reflect on the opportunities and limitations of these methodologies in the context of informing UK policy to increase UK households' contribution to reduce energy system emissions.

3.1 Papers 1 and 2: Systematic review

Systematic review was the methodological approach adopted by Papers 1 and 2. As described in Section 1.4, these papers adopted problem framings currently dominant in energy policy making and related research. This sub-section explains how systematic review forms part of evidence-based policy and practice and introduces rapid evidence assessment as a constrained form of systematic review intended to generate useful research findings within policy-relevant timeframes. It then explains why it was appropriate to answer the research questions posed in Papers 1 and 2 and describes how it was applied.

3.1.1 Systematic review and rapid evidence assessment as part of evidence-based policy and practice

Systematic review involves reviewing literature to answer a defined research question, by following defined and transparent criteria for searching for and selecting available literature and extracting and synthesising findings. An important aim is to provide summaries of evidence that avoid bias, which might otherwise result from, for example, the selection and inclusion of certain studies rather than others (Petticrew and Roberts 2006). The methodology was particularly developed in medical sciences to synthesise evidence about treatment effectiveness, but the concern to base policy and practice on the best available evidence has led to the adoption of systematic review methodology in other areas, including energy policy (Sorrell 2007; Speirs, Gross, and Heptonstall 2015). There are a number of important differences compared to medical sciences. For example, the most interesting questions in energy policy often do not relate to the effectiveness of particular interventions on defined populations, may not be amenable to experimental or quasi-experimental approaches, and answering them may require qualitative data or multiple data and study types (Sorrell 2007). Furthermore, medical systematic reviews often take the form of a meta-analysis, where statistical analysis is performed on the pooled results of multiple studies. This is possible because trials of medical treatments often follow similar protocols and generate quantitative findings (Petticrew and Roberts 2006); by contrast, even when research questions related to energy policy can be answered using quantitative data, relevant studies may involve such

diverse contexts, research designs and methodologies that quantitative meta-analysis is not possible (Petticrew and Roberts 2006; Sorrell 2007). Nonetheless, all systematic reviews aim to search for and select studies, and extract and synthesise data using methods that reduce bias; are transparent, so that any limitations and possible biases are visible to research users; and are reproducible (Petticrew and Roberts 2006; Sorrell 2007; Speirs et al. 2015).

Papers 1 and 2 employ rapid evidence assessment: a constrained form of systematic review designed to deliver many of the benefits of a full systematic review within shorter time frames. Full systematic reviews may take up to 12 months, while rapid evidence assessments can be completed in 2 – 6 months, enabling more timely input into policy making (Speirs et al. 2015). This is achieved by limiting the scope of the review, for example by constraining the literature search to a limited number of languages, databases, and/or periods of time. Rapid evidence assessment remains a form of systematic review as it makes use of clearly defined and published steps to search for, select and synthesise findings; the review process therefore remains transparent and reproducible, and reduces bias that may appear as the result of researchers (intentionally or unintentionally) cherry-picking results (ibid.).

The following sub-section describes how rapid evidence assessment was applied in Papers 1 and 2 and explains why systematic review was appropriate to address the research questions posed in these papers. It ends by commenting on forms of bias that may be represented in Papers 1 and 2 despite the use of systematic review methodology.

3.1.2 Applying rapid evidence assessment in Papers 1 and 2

Informed by policy interest in residential demand response (National Infrastructure Commission 2016) and techno-economic modelling of the potential for residential demand response to contribute to energy system decarbonisation, Papers 1 addresses the research question:

Are modelling studies realistic about how much demand response we can really expect from residential consumers?

To answer this question, Paper 1 reports findings from a rapid evidence assessment of international trials, surveys and programmes of residential demand response, including quantitative findings on the percentage of targeted households enrolled in trials and programmes; the percentage change in demand according to the reference value; and persistence of enrolment and response across multiple years. It then compares these findings with assumptions made by studies modelling the potential for residential demand response to

provide various electricity system services in support of reducing emissions. Details of the approach to the review are summarised in Box 1 and presented in Appendix A of Paper 1 (located at the end of this thesis) in greater detail.

Data extraction and synthesis for Paper 1 was guided by pre-defined categories derived from the research question. These included level of enrolment in demand response trials or programmes as a percentage of the target population; level of response as a percentage of the reference load; and qualitative or quantitative evidence on the persistence of enrolment or response over time (for example, qualitative descriptions or quantitative results reported across multiple years). While Paper 1 reviews primarily quantitative evidence, meta-analysis was not appropriate due to heterogeneity in study designs and contexts. Instead, Paper 1 presents graphical summaries of key results of reviewed studies, highlighting the diversity of reported results. It also reviews qualitative explanations of why such variation may occur.

Systematic review methodology is appropriate to address this question for several reasons. Firstly, because the research question can be seen as critical of modelling study assumptions, it is important that systematic review offers a transparent approach that can avoid real or perceived biases such as cherry-picking results that show particularly high or low levels of engagement with demand response. Systematic review was also useful as an approach to collect and synthesise findings from a large number of studies including both academic and grey literatures. Grey literature was an important source of data for both papers: a large amount of data on residential demand response is contained in industry reports rather than academic studies, and these included some types of information which were less represented in the academic literature. Notably, industry evaluations of programme performance across multiple years were an important source of data to evaluate persistence of enrolment and response over time. Finally, systematic review was selected as an appropriate methodology because of its existing application in informing energy policy (Sorrell 2007; Speirs et al. 2015). This is relevant as Paper 1 is addressed primarily to producers and users of energy system modelling studies, and modelling forms an important input to UK energy policy (Strachan and Li 2021).

ACADEMIC LITERATURE SEARCH STRATEGY

Database: ScienceDirect

Dates: 1990 – 2014

Search term: (pilot OR trial OR test) AND (“demand response”) AND (residential OR “mass market” OR domestic) AND electricity

Results were filtered for journals on the topics of energy or electricity.

Initial results: 683

GREY LITERATURE SEARCH STRATEGY

Databases: An initial search was performed in Google. This search identified a number of other potential sources, which were searched separately: the websites of consultancies Navigant, Vaasa Ett, and Brattle Group; the website of the UK energy regulator, Ofgem; the website of EPRI (The US Electric Power Research Institute); smartgrid.gov (a website of the US Department of Energy); and ec.europa (the website of the European Commission).

Dates: The search was performed in 2014. No start data was applied to the results (with the exception of the separate search in EPRI, when the search was limited to 2009 – 2014 due to the very large number of potential results).

Search term: (pilot OR trial OR test OR programme OR program) AND (“demand response” OR “demand side response” OR “direct load control”) AND (residential OR domestic) AND electricity

Initial number of results: The top 100 search results in Google were reviewed initially.

Further details of search strategy: Many of the top 100 results consisted of sites of demand response vendors or utility news sites that referred to examples of DR trials or programmes without including their empirical findings. When this was the case, limited further searches were made in Google to seek to identify a source that presented the findings of these trials or programmes (for example, within a consultancy report or regulatory filing). Such further searches were restricted to examples of DR trials or programmes where a higher probability of publicly reported results was expected: trials or programmes already referred to in the academic literature; undertaken in response to regulation; and undertaken in connection with, or analysed by public sector bodies or consultancies involved in demand response research or analysis. These searches included (where known) the name of the trial/programme, the utility or other organiser of the trial/programme, and the search terms ‘results’ OR ‘findings’ OR ‘evaluation’ OR ‘impact’. The top 10 results for each search were reviewed.

INCLUSION AND EXCLUSION CRITERIA

Inclusion criteria: including quantitative or qualitative empirical evidence on engagement by residential consumers with demand response, including in the form of existing reviews or meta-analyses, provided these included details of the trial or programme. References were followed in review articles when the review itself did not identify all of the information sought by this study.

Exclusion criteria: only considering demand response in other sectors, such as industrial or commercial customers; not presenting raw data on recorded real-life engagement of residential consumers with demand response (for example, studies modelling DR potential or presenting econometric analyses without raw data).

FINAL SEARCH RESULTS INCLUDING ACADEMIC AND GREY LITERATURE: 122

Box 1: Rapid Evidence Assessment search strategy for Paper 1

Paper 2 builds on Paper 1 by addressing the research question:

What are the key factors affecting residential user engagement with demand response?

This question builds on the findings of Paper 1 by investigating the factors underlying user engagement with demand response as quantified through measures of enrolment, response and persistence. Paper 2 posits that better understanding the factors underlying user engagement could enable policy makers to more accurately predict demand response potential, by using observable user characteristics as a proxy for their engagement, and to influence demand response performance by influencing factors associated with it. Thus, Paper 2 addresses an audience of policy makers and researchers involved in policy-related research; in fact, it was based on work originally undertaken on a consultancy basis for the UK Department of Business, Energy and Industrial Strategy (BEIS 2017). In this case, rapid evidence assessment was selected as an appropriate methodology firstly because it was specified by BEIS for the consultancy work on which the paper is based; this reflects the use of systematic review in general and rapid evidence assessment in particular as part of evidence-based energy policy (Sorrell 2007; Speirs et al. 2015). Furthermore, qualitative data on engagement with residential demand response has been generated by studies applying multiple and sometimes contested theoretical frameworks. This made systematic review useful to avoid real or perceived biases such as preferring findings drawn from certain theoretical frameworks. Details of the search strategy are summarised in Box 2 and are presented in Section 3 of Paper 2 (Chapter Three of this thesis) in greater detail.

Data analysis for Paper 2 was structured around the broad categories of motivations, barriers, and enablers to residential consumer engagement with demand response, which were initially derived from the requirements of BEIS. Thematic analysis of the identified academic and grey literature was then used to inductively identify more specific categories of influences on consumer engagement falling under each of these three broad categories. Narrative synthesis was adopted to synthesise these findings, as this approach can enable heterogeneous qualitative findings – for example, based on studies employing different theoretical frameworks – to be synthesised descriptively (Petticrew and Roberts 2006).

ACADEMIC LITERATURE SEARCH STRATEGY

Database: ScienceDirect

Dates: 1990 – 2016

Search term: (pilot OR trial OR programme OR program OR survey OR "focus group") AND TAK("demand response" OR "demand side response" OR "direct load control" OR "time varying price*" OR "dynamic price*" OR "real time price*" OR "time-of-use") AND (residential OR domestic OR "SME" OR commercial OR business) AND electricity.

Note that "TAK" limits the search to title, abstract and keywords.

Initial number of results: 960

GREY LITERATURE SEARCH STRATEGY

The grey literature search focused on those sources identified as most useful in the review for Paper 1. It also included the IEA Demand Side Management Energy Efficiency Technology Collaboration Program on the suggestion of BEIS.

<i>Grey literature source:</i>	<i>Search strategy:</i>	<i>Initial results:</i>
EC Europa inventory of European Smart Grid Projects	Initially reviewed all projects identified as Demonstration and Deployment (rather than Research and Development) AND identified as belonging to the category "Smart Customer and Smart Home".	117
US Department of Energy Smart Grid Investment Grant Consumer Behaviour Studies	Initially reviewed all Consumer Behaviour Study Program Reports.	14
US Electric Power Research Institute (EPRI)	Searched the term 'demand response' within two research programmes identified by EPRI: 1) "Energy Efficiency and Demand Response" 2) "Understanding Electric Utility Customers"	1) 59 2) 56
IEA Demand Side Management Energy Efficiency Technology Collaboration Program	Initially reviewed all completed tasks and associated publications.	50

INCLUSION CRITERIA

Including qualitative or quantitative empirical evidence on factors influencing residential consumer engagement with DR, from Europe, North America, Australia, New Zealand, and Japan.

Including both evaluations and analyses of trials and programmes, and consumer surveys and focus groups conducted independently of trials or programmes.

FINAL SEARCH RESULTS INCLUDING ACADEMIC AND GREY LITERATURE: 55

Box 2: Rapid Evidence Assessment search strategy for Paper 2

While systematic review methodology is intended to reduce researcher bias, Papers 1 and 2 do include certain limitations and biases. Both papers only include studies published in English. In addition, neither attempted a fully comprehensive review covering every relevant study. However, there is some evidence that the findings of reviews which cover only the most relevant databases do not differ from the findings of comprehensive systematic reviews; and constrained systematic reviews such as rapid evidence assessment may be more useful to inform developing policy debates, because they can be produced more rapidly than comprehensive systematic reviews (Speirs et al. 2015). Furthermore, systematic review methodology specifies the publication of a detailed search strategy, which ensures that these limitations are transparent to research users. Less visible limitations and biases in both papers relate to assumptions underlying systematic review methodology; and, in Paper 2, to the approach to synthesise findings informed by different problem framings. These are considered in the overall thesis discussion presented in Chapter Six.

3.2 Papers 3 and 4: Process analysis

The analysis in Papers 3 and 4 is informed by the conceptual framework of domestication theory, which takes a constructivist perspective less often represented in energy policy and related research. This requires a different methodological approach to the one used in Papers 1 and 2. This sub-section introduces the methodological approach of process analysis, which was applied in Papers 3 and 4, and explains why it is suitable to support analyses of domestication processes. Papers 3 and 4 are based on two stages of a process analysis of the same empirical data, namely repeat interviews with households participating in a trial of smart hybrid heat pumps (SHHP), interviews with the installers responsible for helping them to set up and understand how to use the SHHP system, and in some cases observations of this stage of installation. This sub-section first introduces process analysis as a methodological approach. It goes on to describe different aspects of data collection and management. Finally, it explains how the research questions addressed in Papers 3 and 4 emerged inductively through initial interview analysis, and how process analysis was applied to answer each of these questions.

3.2.1 Process analysis as a methodological approach to study domestication

Process analysis describes an approach to explain how and why phenomena result from the temporal progression of activities, events, and the interactions between them (Langley et al. 2013). Here 'events' describes occurrences of interest *at specific points in time*, which can occur and interact across multiple levels of analysis. The emphasis on interactions and progression over time make process analysis very suitable to study processes of domestication, which involve interactions between technologies, users, and wider society that progress over

time (see Section 2.2.2). Both Papers 3 and 4 consider how processes of domestication unfold. Process analysis can also support theoretical development through abductive approaches, which take existing conceptual frameworks as a starting point and develop them through inductive empirical analysis (Van De Ven and Poole 2005); in Paper 4, the approach of process analysis supported the abductive development of domestication theory. This sub-section gives an overview of the methodological approach of process analysis, and section 3.2.3 explains how it was applied to answer the research questions posed in Papers 3 and 4.

The approach of process analysis is often contrasted with variance research, which explains phenomena as the result of independent variables acting on dependent variables. An important difference between the two approaches is the way in which they deal with time. Temporal progression is a central element of explanations in process research. By contrast, variance approaches may effectively ignore or black box time. They explain how changes in the value of dependent variables result from the effect of pre-defined independent variables that each take a single value and act continuously across the period of analysis. In this way, time is conceptualised as merely the “medium” in which variables act upon each other (Van De Ven and Poole 2005). Variance approaches can include aspects of time by including variables such as ‘fast’ or ‘slow’, ‘stable’ or ‘dynamic’, or by performing a series of variance analyses covering successive time periods (Langley et al. 2013). Similarly, variance approaches may include processes as a causal logic that links change in dependent and independent variables, or by assigning a value to specific processes so that they act as independent variables. However, these ways to include time and processes in variance approaches involve considerable simplification. Reducing processes to a causal logic means the mechanism of change is not articulated, making it difficult to test empirically, while operationalising time or processes as variables requires reduction to a single measurable value. Thus, variance approaches offer relatively limited conceptual resources to explain how and why change occurs (Van De Ven and Poole 2005).

A particular feature of process analysis is its focus on *interactions* (Abbott 2007). This enables process approaches to support analysis of how actions and interactions cause entities to evolve by changing their attributes; by contrast, variance analysis emphasises changes in the value of pre-defined variables and cannot easily identify new variables if these emerge. Considering interactions also allows process approaches to explain how attributes’ causal meanings may change because of changes in what went before (path dependence), and to explain recursive relationships between micro and macro levels of analysis (Abbott 1988, 2007). By contrast, although context may be operationalised as an independent variable,

variance approaches do not support analysis of causality from micro to macro levels so cannot consider how micro level changes might change context over time (Abbott 1988). This feature of process analysis makes it a particularly helpful approach to study domestication. The domestication concept is based on the idea of interactions between users and technologies, as well as wider society. Furthermore, the concepts of household and societal domestication trajectories highlight that the interactions involved in domestication extend backwards and forwards in time and interact across multiple levels, from individual households to wider society (see Section 3.2.2).

Process analysis therefore describes an overall approach, within which a range of methods can be employed. In general, these involve gathering and temporally sequencing longitudinal data, then following strategies to detect patterns in sequences and progressions of events, activities, and interactions. Techniques to analyse patterns in the data are often qualitative (Langley et al. 2013), but may be quantitative, for example involving formal coding of data prior to quantitative analysis (Abbott 1992; Langley 1999; Van De Ven and Poole 2005). Different techniques have different applications, advantages and disadvantages, notably trade-offs between more accurately representing empirical data and providing more abstract, parsimonious and potentially generalisable accounts (Langley 1999); however, developing theoretical ideas always involves a degree of induction and inspiration, and as this cannot emerge directly from any analytical strategy it is hard to programme systematically (Langley 1999; Langley et al. 2013). Less formal strategies for structuring data include dividing the period of analysis into temporal periods that are recognisably different from one another (Langley 1999), and structuring analysis around pre-defined outcomes (Pettigrew 1997). It is important to emphasise that, because processes are ongoing and social life is inherently open ended, the “outcomes” visible at the time the research is conducted are not final end points but only an analytical tool (Langley et al. 2013; Pettigrew 1997).

To summarise, process analysis is appropriate to analyse domestication processes because it supports the analysis of interactions that unfold over time, as well as reciprocal relationships between micro and macro levels of analysis. Similarly, longitudinal data collection and inductive analysis are appropriate to study domestication processes, as these unfold over time in ways which, in principle, cannot be predicted in advance. The following sub-section describes how these principles informed methods of data collection for Papers 3 and 4, and the initial inductive analysis from which the research questions addressed in Papers 3 and 4 emerged. Section 3.2.3 then describes how process analysis was applied as part of Papers 3 and 4.

3.2.2 Data collection for Papers 3 and 4

This sub-section presents details related to data collection for Papers 3 and 4. This includes gaining access to conduct the fieldwork as part of an industry-led technology trial; data collection; data management; ethical considerations; and sampling issues. Section 3.2.3 then describes the approach to data analysis for Papers 3 and 4.

Gaining access to conduct fieldwork as part of the FREEDOM Project trial

Early in my PhD I attended an Energy Systems Catapult workshop on energy systems flexibility where I met an industry partner involved in an upcoming trial of smart hybrid heat pumps (SHHPs). The FREEDOM project trial would be the first trial of SHHPs in the UK, as well as the largest globally (Carter, Lancaster, and Chanda 2017; Sun et al. 2019). The main phase of the trial ran from 2017 – 2018. It trialled hybrid systems comprising air source heat pumps and gas boilers which were installed in 75 homes in Bridgend, South Wales (Turvey et al. 2018). Funded by the UK energy regulator, Ofgem, this project was led by distribution network operator Western Power Distribution, gas distribution network Wales & West Utilities, and smart energy technology company PassivSystems (Turvey et al. 2018). Project partners Imperial College London provided energy systems modelling as part of the project (see, for example, Imperial College, 2018); City University conducted research on the design of the smart control user interface (Stumpf 2019; Stumpf et al. 2018); while consultancy Delta-ee supported surveys and focus groups to assess user experiences and perceptions of the SHHP system, as well as further modelling (Turvey et al. 2018).

I was interested in smart hybrid heat pumps because of the policy importance of residential heat decarbonisation in the UK, and because my work on user engagement with demand response was relevant to the trial, which included hybrid heat pumps' ability to provide demand response through fuel switching between electricity and gas. Following this chance meeting I learned more about the trial and was able to negotiate access to conduct interviews and observations with trial participants and installers.

Data collection

Data collection and analysis followed an inductive approach to reflect the potential for emergent outcomes to emerge during the domestication process, as well as the potential for interesting but unanticipated findings and themes to emerge during primary research. Recognising that technology use can change and evolve over time, I conducted data collection near the beginning and end of the trial period. Figure 1 provides an overview of primary data

collection for Papers 3 and 4. Interviews during or after the final stage of installation (“handover”), when installers taught users about the system and helped them to set up controls, related to existing routines involving heating as well as the ways in which users became involved in the trial and their experiences of installation. These initial user interviews were conducted in the period October – November 2017. Follow-up user interviews were conducted in March – April 2018, so that the period of analysis covered the winter heating season of 2017 – 2018, which included a period of particularly cold weather.

In total I conducted 27 user interviews, involving 20 different household members and with an average length of 60 minutes; six observations of handover; and two installer interviews. All interviews were semi-structured: using topic guides covering the themes I wished to investigate, but open enough to allow other themes of interest to emerge during interviews. I supported this by following threads of conversation started by my interviewees and actively probing to encourage them to elaborate on topics covered by the interview guide, but also topics that they raised spontaneously. For example, one of the findings reported in Paper 3 is that learning about heat pumps as part of a hybrid system can lead users to construct the (technically incorrect) cognitive understanding that heat pumps are unable to provide hot water, or space heating at lower outdoor temperatures: functions performed by the boiler as part of the hybrid system. This finding is highly relevant to the overall thesis aim, as the Committee on Climate Change assumed that experience of a hybrid system might increase users’ acceptance of full heat pumps if these were rolled out in the future (CCC 2018, 2019c), but was not anticipated by the topic guides, which focused on practical and symbolic rather than cognitive aspects of users’ learning. Follow-up questions helped to identify how interviewees may have constructed this misconception, informing policy recommendations with the aim of avoiding it. Topic guides were also refined through reflection during each round of interviews.

Topic guides for initial and follow-up user interviews can be found in Appendices I and J. Broadly, I set out to investigate how characteristics of SHHP and trialists’ existing practices influenced SHHPs’ uptake and use. More specifically, during the initial user interviews I was interested in how SHHP uptake and use were influenced by users’ experiences of automation and direct load control; the integration of a novel heating technology (heat pumps) with one that was already familiar to users (gas boilers); and users’ interactions with installers and with their wider social networks. The development of the topic guides for the initial user interviews was thus informed by domestication theory; my previous work on users’ engagement with

demand response, which had identified perceived control, transparency, and trust as important influences on users' engagement with residential demand response and

1) Open coding using NVivo to identify analytical themes and findings on learning outcomes and processes

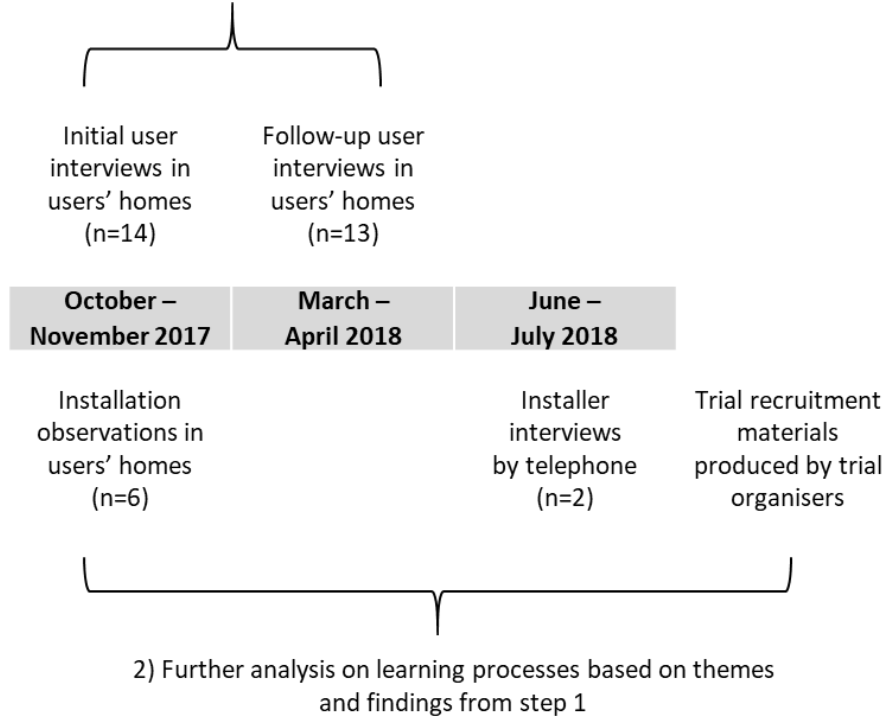


Figure 1: Timeline and strategy for data collection and analysis for Papers 3 and 4

particularly automation and direct load control; and wider reading on user experiences of heat pumps (including, for example, The Energy Saving Trust, 2010, 2013; Roy and Caird, 2013; Owen, Mitchell and Gouldson, 2014; Bell *et al.*, 2015; ETI, 2015; Judson *et al.*, 2015; Moore, Haines and Lilley, 2015; Gram-Hanssen *et al.*, 2016).

Follow-up interviews were related to users' routines involving heating; understandings and meanings of SHHP and use of their controls; and what led to these arising during the trial. Topic guides for follow-up user interviews were informed by domestication theory, and preliminary analysis of initial user interviews. For example, I probed interviewees about topics they raised in the initial interviews, such as practices connected to the use of heat or expectations, understandings and meanings associated with SHHP, if they did not refer to these spontaneously. Furthermore, the format of the topic guide for follow-up user interviews was informed by reflection on initial user interviews. The main part of the topic guide for follow-up user interviews consists of a matrix, rather than list, of topics and questions. This

design was informed by the observation that during initial user interviews conversations about different aspects of the trial and of SHHP were often highly interconnected, making a structured list of questions less useful than a matrix that could be used at a glance to track themes mentioned during the interview while supporting planned probing questions and coverage of all planned topics.

Both initial and follow-up user interviews took place in users' homes. Some interviewees invited me to see particular elements of the smart hybrid heat pump technology or its controls. During follow-up user interviews, I also asked interviewees to show and tell me about the main features they used in the app-based controls that formed part of the SHHP system. This allowed me to observe how easy it was for different interviewees to interact with the controls (for example, due to their general familiarity with mobile apps, as well as more specific issues such as forgetting passwords), and invite users to tell me about whether and how they used and interpreted different parts of the app as part of understanding and using the SHHP system. Furthermore, it allowed me to check the settings of temperatures and timings towards the end of the trial, in order to compare these with initial control settings set during handover, and with interviewees' initial expectations of how temperature settings would or would not change as they used the SHHP system.

Data on installers' interactions with users was also collected at two time points. Semi-structured interviews were conducted with the two lead installers responsible for carrying out handovers after trial completion, in order to inquire into the full range of interactions between installers and users over the course of the trial. Topic guides for installer interviews can be found in Appendix K. These were designed to gain additional insights into how installers may have influenced users' learning about SHHP. They covered the ways in which installers engaged with users over the course of the trial, their perceptions of how users had interacted with the trial technology, and their ideas about how the SHHP system should or could be used. This enabled me to investigate user-installer interactions from the installer perspective, including how installers understood and approached users as part of their role in the trial, to complement users' accounts of their interactions with installers. In addition, I was present to observe handovers alongside six initial user interviews. This allowed me to directly observe user-installer interactions at a key moment. I was able to compare notes from my observations with installers' remembered accounts, including observations of users after the handover was complete and installers had left. As well as supplementing data from installer interviews, these observations informed some questions included in the installer interview topic guide.

Data management

Interviews were audio-recorded and fully transcribed by myself, while hand-written notes were taken during installation observations which were then typed up. Recordings were transferred to a password protected computer following the interview.

Interview data were anonymised by assigning pseudonyms to all interviewees; these pseudonyms have been used to identify interviewees within this thesis. In addition, anonymisation numbers assigned to each household as part of the FREEDOM Project trial were recorded alongside these pseudonyms. This allowed information gathered by the trial organisers to be associated with interviewed households – notably, enabling me to identify that three out of the 14 households I interviewed experienced known technical issues during the trial (in which the remote control of the smart hybrid systems did not function as intended). Access to this information helped to prepare me for conducting follow-up interviews with these households, and informed the sampling for Paper 4 (in which these households were excluded to enable a deeper level of analysis with the remaining households; see also Section 3 of Paper 4, within Chapter Five of this thesis).

Ethical approval and other ethical considerations

Before the start of data collection (on October 2nd 2017), ethical approval was granted by the University of Sussex Social Sciences & Arts Cross-Schools Research Ethics Committee. Information sheets and Consent forms for households and installers can be found in Appendices F - H. All interviewed households were informed and consented to participate in the FREEDOM Project trial as a whole, including different forms of data collection by researchers involved in the trial. As such, the consent form below relates only to participation in and audio-recording of the interviews I conducted within the context of the trial. This was requested by trial partners who wished to avoid overburdening trial participants with research contact. Installers were additionally asked for consent to use direct quotations from the interview. This reflected the possibility that installers may have professional concerns regarding information shared as part of the interview, together with the fact that only a small number of installers were involved in the trial, which could make it easier to guess the identity of interviewees.

In addition to the formal ethical review process, ethical considerations were raised because the nature of the initial and follow-up user interviews involved talking with people about a range of aspects of everyday life within the private sphere of their homes. In some instances

my interviewees explicitly asked me to confirm that I would not write about a certain topic they had just spoken about, and more generally when working with interview data I was always mindful of whether certain parts of the conversation became more personal or private (for example, topics related to health issues or certain family matters). Consequently, I have avoided writing about such topics, particularly as they were not central to my analysis.

Sampling

Interviews and observations used convenience sampling because my access was mediated by trial partners. The FREEDOM Project trial was funded by the UK energy regulator, Ofgem, through the Network Innovation Allowance, and partners from Ofgem were concerned to protect trial participants from being overburdened with research contact during the trial (which included various other interviews, focus groups and surveys alongside those described here). I negotiated permission to conduct two interviews with 14 households. My access to specific households was mediated by the installers, who asked households if they would be willing to be interviewed and then passed their contact details on to me. Installers also invited me to conduct handover observations. Finally, my sampling of interviewees was mediated within the households themselves: interviews included any adult members of the household who was available and willing to take part. Table 1 lists the pseudonyms assigned to all interviewees and summarises the composition and circumstances of interviewees' households.

This sampling strategy inevitably introduces certain limitations to this research. For example, self-selection by interviewees may mean that interviews were conducted with households and household members who volunteered to participate because they were more enthusiastic about or engaged with the technology. This may be supported by the observation that one household refused a second interview after feeling dissatisfied with their experiences during the trial; in three other households, while both adult household members participated in the initial interview only one was willing or available to participate in the follow-up interview. Indeed, participants in the trial may have been more interested in new technologies in general. On the other hand, some of my interviewees described themselves as not being particularly 'technical', and may also have participated in interviews because they were more often at home and were willing to help; while some households who experienced technical issues during the trial did agree to participate in follow-up interviews. Furthermore, my interviewees described replacing an old or broken gas boiler as a frequent motivation to participate in the trial. Nonetheless, expanding the sample to include households who decided not to participate in the trial could further illuminate processes involved in SHHP uptake, while encouraging a

higher proportion of household members to participate in interviews could help to reveal how different needs were negotiated within households – particularly if household members who were less engaged with or enthusiastic about SHHP sometimes chose not to participate in interviews themselves, and delegated this to their partner or another household member.

The trial context may also have influenced research findings. Use interviews indicate that users' learning about SHHP may have been influenced by expectations about what types of operation might be expected during a trial (in contrast to 'normal' patterns of operation) and feelings of gratitude for receiving new heating equipment for free. This is discussed further in Paper 3, where it forms part of the research analysis.

Interviewee(s) (all names are pseudonyms)	Household members and selected circumstances
Lucy	Working couple with a baby. Lucy works for a utility company.
Kim and Tom	Working couple with three children. Tom works as a heating engineer.
Mike	Working couple. Mike works as a handyman and has knowledge of heat pumps, while his wife works in healthcare.
Richard and Sophie	Working couple with a child at university. Richard teaches engineering at college while Sophie works for the local council.
Alan and Carol	Retired couple with adult children. Alan worked as a carpenter.
Anne and Cai	Retired couple with adult children. Cai worked as an electricity system engineer.
Jim and Rachel	Couple with adult children, one living at home. Jim works in the electricity sector while Rachel is often at home.
Ruth and Harry	Working couple. Ruth works for the local council while Harry is a toolmaker.
Clive	Couple with adult children, two living at home.
Hayley	Couple with three young children. Hayley is a home-maker, her husband works as a carpenter.
Nick	Single man who works in a factory producing petrol engines.
Laura	Working couple with two children. Laura is a primary school teacher.
Debbie and Phil	Retired couple with adult children (declined follow-up interview).
Paul	Working couple with children. Paul works in the electricity sector.

Table 1: Interviewees' households and their circumstances

3.2.3 Data analysis in Papers 3 and 4

This sub-section first describes the initial inductive analysis from which the research questions addressed in Papers 3 and 4 emerged. It then introduces the research question and detailed analytical approach followed for each of these two papers.

Initial inductive analysis

The research questions addressed in Papers 3 and 4 emerged from initial inductive coding of both initial and follow-up user interviews, performed using NVivo. Inductive coding involves allowing themes to emerge from the data under analysis, rather than applying pre-defined concepts to the analysis of the data. This approach was adopted to allow unexpected findings to emerge during the analysis, and this supported the conceptual contribution made in Paper 4.

Coding of the initial user interviews was completed, and early findings were used to inform topic guides for follow-up user interviews. Preliminary coding themes were identified separately for a sample of follow-up user interviews. Coding themes for initial and follow-up user interviews were then compared and used to generate higher-level themes, which were used to structure a new, merged NVivo file to complete coding for the remaining follow-up user interviews. This synthesis involved a level of abstraction, and generated the first ideas for the conceptual contribution made in Paper 4. The final coding structure for both initial and follow-up user interviews can be found in the Appendix to Papers 3 and 4 (located at the end of this thesis).

Initial inductive coding suggested two research questions, each concerned with users' learning, but addressing different audiences.

Research question and approach to analysis for Paper 3

Paper 3 addresses an audience of policy makers and researchers engaged in policy-related research. It addresses the research question,

What were the outcomes and processes of user learning about smart hybrid heat pumps in the context of the FREEDOM project trial? And what are the implications for UK heat decarbonisation policy?

This question was defined by identifying certain outcomes of users' learning about SHHP with particular relevance to UK heat decarbonisation policy, including the Committee on Climate Change's recommended the roll out of 10 million SHHP by 2035, which followed the FREEDOM

Project trial. By addressing this question, Paper 3 aims to identify recommendations for UK heat decarbonisation policy, while also highlighting the value of alternative perspectives approaches such as domestication theory to inform energy policy making. Considering how new technologies are used, as well as their uptake, is one distinctive feature of domestication theory.

To address these two research aims, process analysis for Paper 3 was structured around outcomes of users' cognitive, symbolic and practical learning during SHHP use, which were identified as relevant for UK heat decarbonisation policy. Here, practical learning included the use of heat in the home as well as use of SHHP controls. Cognitive learning included understandings about how SHHP work and the functions they provide. Symbolic learning included meanings about SHHP, and about the trial itself. Understandings were differentiated from meanings by considering whether interviewees explained why they held a certain view; for example, not drying laundry on radiators because it reduces efficiency would be categorised as an understanding, but seeing hot radiators as a sign of an effective heating system would be categorised as a meaning. The analysis discusses the policy relevance of these learning outcomes to address the paper's two aims.

Process analysis can be applied to seek explanations of why and how identified outcomes emerged (Pettigrew 1997). In this case, further analysis guided by the concepts of cognitive, symbolic and practical learning sought to identify processes of user learning leading to the policy-relevant outcomes already identified. This drew primarily on interviewees' accounts during initial and follow-up user interviews, while trial recruitment materials, installation observations and installer interviews were analysed to provide additional insights into how users' learning occurred. This analysis of *how* the identified learning outcomes emerged was used to inform policy recommendations seeking to influence users' learning in support of policy objectives. These focused on how policy might be able to affect various influences on users' learning about SHHP, while also recognising that users' learning in principle cannot be fully predicted.

Research question and approach to analysis for Paper 4

Paper 4 differs from Papers 1 – 3: it makes a *conceptual* contribution, by proposing a framework that develops conceptualisations of users' learning in domestication theory. As such, it addresses an audience of researchers within Science and Technology Studies and other fields who might be interested in this conceptual development. Chapter Six discusses how this conceptual contribution may be useful to inform policy related to the overall thesis aim.

Paper 4 addresses the research question:

Taking domestication theory as a starting point, how can processes of user learning about a new end-use energy technology be conceptualised?

This question was defined following the emergence of coding themes (experiencing, making sense, responding) which appeared to describe aspects of users' learning not yet fully conceptualised in domestication theory. By addressing this research question, Paper 4 develops conceptualisations of *how* and *why* learning processes within domestication arise, and lead to the types of emergent outcomes (cognitive, symbolic and practical learning) which the theory already describes.

Developing theory through process analysis often involves abduction: taking existing theory as the starting point for analysis and using empirical analysis to further specify this theory (Langley et al. 2013; Van De Ven and Poole 2005). Since process analysis usually involves detailed analysis of a small number of cases, generating theory involves identifying the broad type of phenomenon which these specific cases exemplify, and deriving more abstract explanations that are more broadly applicable. Theoretical ideas and explanations can be tested by comparing either across cases, or between different time points within the same case (Langley et al. 2013).

The analysis for Paper 4 was based on a sub-set of ten cases, representing the ten interviewed households who agreed to repeat interviews, and who did not experience connectivity issues with the external control of SHHP as part of the trial. It followed an abductive approach as the concepts of cognitive, symbolic, and practical learning derived from domestication theory (see, for example Sørensen, 2006) formed the theoretical starting point for analysis. Similarly to the analysis for Paper 3, the outcomes of these three forms of learning were used to structure process analysis. However, in line with the aim to identify more generalisable findings, the analysis was expanded to include both uptake and use and to include all cognitive understandings or symbolic meanings about SHHP, users' identities, or routines of using heat or SHHP controls, rather than selecting outcomes with relevance to policy. The more in-depth analysis required to address the aim of this paper was also supported by further structuring the data for analysis. The period of analysis was divided into three temporal periods (uptake/installation, early use, and later use); this enabled replication of theoretical ideas at multiple points in time (although this replication could be taken further if the trial had lasted for more than one heating season). Further details on this approach to analysis are provided in Sections 3 and 4 of Paper 4 (Chapter Five of this thesis). Data from both initial and follow-up

user interviews was temporally sequenced into an analytical chronology summarising learning in each of the ten household cases, drawing on the learning outcomes, influences on learning identified through empirical analysis, and initial ideas on theory based on initial inductive interview analysis and the analysis for Paper 3. By increasing simplification and structuring of data, strategies such as devising visual representations can help to move process analyses towards a greater degree of abstraction as part of the development of theoretical ideas (Langley 1999). As part of the analysis for Paper 4, theoretical ideas collected in the analytical chronologies were further developed through iteratively constructing visual representations of processes occurring in different temporal phases and amongst different groups of households. Final synthetic visualisations were also included within Paper 4, as a way to communicate findings about processes and their dynamics (Langley et al. 2013).

3.3 Overview of research design and methodology across papers

To summarise, Papers 1 and 2 apply systematic review methodology to address questions about consumer engagement with residential demand response. Paper 1 reviews quantitative evidence on users' enrolment, response and persistence in demand response trials and programmes, while Paper 2 reviews qualitative evidence on factors that might explain these different levels of engagement. The two papers present different sets of data but address similar audiences, namely policy makers and researchers working with problem framings close to current policy making practices. In doing this they adopt the perspective of evidence-based policy and practice. Papers 3 and 4 apply process analysis methodology to address questions about users' learning about smart hybrid heat pumps, based on interviews and observations with users and installers over the course of a technology trial. The focus on learning and use, as well as uptake, represents a departure from the problem framings typically adopted in energy policy and related research, and requires a different methodological approach. Process analysis offers an appropriate approach to study users' learning as conceptualised by domestication theory: it can support the study of how technologies and users interact in ways that evolve over time, and of how micro level processes may have emergent influences on macro level processes as well as being influenced by them. Papers 3 and 4 present two stages of a process analysis of the same primary data, addressing two different audiences. Paper 3 addresses policy makers and researchers working with problem framings close to current policy making practices, by focussing on outcomes of user learning with direct relevance to UK heat decarbonisation policy, and identifying processes of learning specific to smart hybrid heat pumps. Paper 4, meanwhile, makes a conceptual contribution by considering a wider range of learning outcomes and proposing a more generic set of learning processes.

Figure 2 provides an overview of how the four papers forming the body of this thesis adopt different problem framings, address different research questions, and apply different conceptual and methodological approaches to address the overall thesis aim.

The next section outlines the publication status, authorship, and contribution of authors for each of the four papers making up the body of this thesis. Chapters 2 – 5 then present the papers themselves.

Research aim: <i>to provide insights relevant to policy to increase UK households' contribution to reduce energy system emissions through the adoption and use of new technologies</i>			
Problem framing 1		Problem framing 2	
Conceptual framework: Concepts reflecting dominant problem framings		Conceptual framework: domestication theory	
RQ1: Are modelling studies realistic about how much demand response we can really expect from residential consumers?	RQ2: What are the key factors affecting residential user engagement with demand response?	RQ3: What were the outcomes and processes of user learning about smart hybrid heat pumps in the context of the FREEDOM project trial? And what are the implications for UK heat decarbonisation policy?	RQ4: Taking domestication theory as a starting point, how can processes of user learning about a new end-use energy technology be conceptualised?
Methodological approach: Systematic review relating to the evidence-based policy paradigm		Methodological approach: Process analysis	
Data 1: primarily quantitative data from first systematic review (122 studies in final sample)	Data 2: primarily qualitative data from second systematic review (55 studies in final sample)	Data 3: Repeat interviews with users participating in the FREEDOM Project trial of smart hybrid heat pumps (n=27), installer interviews (n=2), installation observations (n=6)	
Audience 1: Policy professionals and researchers involved in policy-related research			Audience 2: Researchers interested in the conceptual development of domestication theory

Figure 2: Overview of how the four papers forming the body of this thesis adopt different problem framings, address different research questions, and apply different conceptual and methodological approaches to address the overall thesis aim. Research questions (RQ) 1 – 4 are the research questions addressed in each of the four papers making up the body of the thesis.

4. Overview of papers: publication status and contributions of authors

No.	Title	Authors	Publication Status	Contribution of authors
1	On demand: Can demand response live up to expectations in managing electricity systems?	Bryony Parrish Rob Gross Phil Heptonstall	Published 2019 (Energy Research & Social Science 51:107-18)	This paper was based on a report for the HubNet research consortium. BP developed the search approach, conducted the final search and extracted data with supervision from PH and RG. BP conducted the analysis and wrote the report with supervision from PH and RG and the final report was edited by PH. The journal paper was drafted by BP with supervision from PH and RG, then edited by RG. BP, PH and RG further edited the text to produce the final version. BP, PH and RG made changes in response to reviewer comments.
2	A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response	Bryony Parrish Phil Heptonstall Rob Gross Benjamin K. Sovacool	Published 2020 (Energy Policy 138:111221)	This paper was based on a report produced for BEIS by BP, PH and RG. BP developed the search approach, conducted the final search and extracted data with supervision from PH. BP conducted the thematic analysis and wrote the original draft with supervision from PH and RG, and the draft was edited by RG. BKS created the first paper draft based on this report. BP focused and re-drafted this text, added the analysis in the discussion section, and drafted the conclusions, with supervision from PH and RG. BP, PH and BKS further edited the text to produce the final version. BP made changes in response to reviewer comments.
3	Consumers or users? The impact of user learning about smart hybrid heat pumps on policy trajectories for heat decarbonisation	Bryony Parrish Sabine Hielscher Timothy J. Foxon	Published 2021 (Energy Policy 148:112006)	BP organised, planned, conducted, transcribed and analysed interviews and observations with supervision from SH and TJF. BP drafted and edited the paper, and made changes in response to reviewer comments, with supervision and feedback from SH and TJF.
4	Conceptualising processes of user learning in domestication theory	Bryony Parrish	Working Paper intended for submission to SPRU working paper series	This paper was based on the same empirical data as Paper 3. BP conducted process analysis, drafted and edited the paper with supervision and feedback from SH and TJF.

Chapter Two: On demand: Can demand response live up to expectations in managing electricity systems?

Abstract

Residential demand response (meaning changes to electricity use at specific times) has been proposed as an important part of the low carbon energy system transition. Modelling studies suggest benefits may include deferral of distribution network reinforcement, reduced curtailment of wind generation, and avoided investment in reserve generation. To accurately assess the contribution of demand response such studies must be supported by realistic assumptions on consumer participation. A systematic review of international evidence on trials, surveys and programmes of residential demand response suggests that it is important that these assumptions about demand response are not overly optimistic. Customer participation in trials and existing programmes is often 10% or less of the target population, while responses of consumers in existing schemes have varied considerably for a complex set of reasons. Relatively little evidence was identified for engagement with more dynamic forms of demand response, making its wider applicability uncertain. The evidence suggests that the high levels of demand response modelled in some future energy system scenarios may be more than a little optimistic. There is good evidence on the potential of some of the least 'smart' options, such as static peak pricing and load control, which are well established and proven. More research and greater empirical evidence is needed to establish the potential role of more innovative and dynamic forms of demand response.

Keywords: Demand response; decarbonization; modelling assumptions; residential consumers.

1. Introduction

Many scenarios that explore how to decarbonise future energy systems envisage an increasing role for demand response (DR), sometimes also referred to as demand side response (CCC 2015). Demand response involves achieving changes in electricity demand at different times – for example, shifting demand from peak to off-peak demand periods. This may be achieved through price signals, automation of appliances, direct control of particular loads, information, or some combination thereof, see for example Braithwait, Hansen, and Hilbrink (2014); Cappers et al. (2012); Wiekens, van Grootel, and Steinmeijer (2014). Demand response is not a new concept, but in most countries it plays a limited role and electricity supply and demand are balanced mainly by ensuring that generation, reserves, and network capacity are sufficient to meet demand (Strbac 2008). Many future scenarios envisage large scale electrification of heat and transport, which account for very significant fractions of total energy consumption internationally. Electric heating and transport will create new challenges and opportunities through increases in total and peak electricity demand, as well as the challenges associated with managing electricity systems which include much higher penetrations of wind, solar and nuclear generation (Pudjianto et al. 2013; Strbac 2008).

System modelling studies indicate that demand side flexibility can significantly reduce the need for network upgrades, peaking plant and ancillary services (Imperial College and NERA 2015). For this reason the value of demand flexibility is gaining prominence in policy reports (National Infrastructure Commission 2016; Ofgem 2017). In Europe, the majority of theoretical potential for demand response lies with residential consumers (Gils 2014). Whilst the potential role of energy storage including batteries and their possible contribution to electricity system management is likely to be important in the future, their current role in the domestic context is limited. This paper is therefore focused on the international evidence on domestic consumer participation in DR trials, programmes and surveys, and considers this with reference to the role of consumer demand response in modelling studies.

Modelling studies that explore the *value of* demand response should not be conflated with analysis of the *potential for* flexibility from the demand side. The value might be assessed through a system modelling study whilst the potential might be evaluated through a customer survey or engineering evaluation of particular types of automation or load. Nevertheless the two topics are clearly linked, because it is important that the potential for DR is not overestimated in models because of unrealistic assumptions about consumer engagement. For this reason this paper investigates the empirical evidence on the level of demand response

achieved in a wide selection of international trials and programmes, incorporates relevant data from surveys on consumer attitudes to DR and asks: are modelling studies realistic about how much demand response we can really expect from residential consumers?

The remainder of the paper is structured as follows: Section 2 describes the approach; Section 3 reviews key concepts in the DR literature; Section 4 presents our principal findings on consumer engagement with DR; Section 5 presents judgements about DR made in a sample of modelling studies; Section 6 discusses the findings from Sections 4 and 5, and Section 7 concludes.

2. Methodology

The evidence on which this paper is based was drawn from the results of a rapid evidence assessment (REA), a constrained form of systematic review of academic and grey literature (Sorrell 2007; Speirs et al. 2015). A wide ranging review of the international literature on demand response trials, programmes and surveys was undertaken and the findings categorised. Systematic searches of academic and grey literature sources sought to identify a comprehensive (though not exhaustive) selection of reports detailing consumer enrolment and participation in DR, consumer response rates and whether consumers remained enrolled and engaged through time (see below for more details). Details of the approach to the review are presented in Appendix A. Specific search terms were also used to identify a sample of modelling studies that made assumptions about the nature and level of demand response. Sixteen papers were selected from the review results and their characteristics are summarised in Table 4. Appendix B presents the trials, surveys and programmes revealed through the evidence assessment.

3. Characterising demand response

Assuming demand response is voluntary rather than imposed through regulation, it must achieve consumer engagement in order to be realised. Analysts and modellers may expect consumers to respond predictably to price signals, accept home automation, and engage in largely planned and predictable household activities that facilitate a response (Abi Ghanem and Mander 2014). However, consumer participation in demand response may not follow these expectations. For example, Kim and Shcherbakova (2011) suggest that consumers have limited knowledge of the potential benefits of DR, and that electricity is typically a routine and passive purchase that is not altered unless consumers are actively dissatisfied.

These factors may lead to consumers not taking up DR opportunities, either by not enrolling in schemes or by enrolling but only offering limited responses, or to ‘response fatigue’ where consumers stop responding or withdraw from programmes. The U.S. Electric Power Research Institute (EPRI) divide consumer engagement into three categories: *participation* – the decision to enrol in a DR programme; *response* or performance⁴ – the amount of load shifting that is provided by participants; and *persistence* – the decision to remain enrolled in the programme through time (EPRI 2012b). Section 4 of this paper summarises the evidence from trials and programmes under each of these categories, together with the factors that influence consumer participation and response.

Different forms of demand response are commonly classified according to whether time varying pricing is used to promote changes in electricity use, known as price based demand response, or consumers are rewarded for estimated changes in demand compared to a baseline level, known as incentive based demand response. A more limited number of schemes aim to use information to change demand, with no economic incentive at all. Types of demand response also vary by the timing, duration, frequency and predictability of demand response and by whether response occurs as a result of manual behaviour change, automation, or direct load control⁵. It is important to distinguish between *static* and *dynamic* interventions – that is those that might change continuously rather than according to a predetermined schedule, and between occasional events (demand peaks which occur a few times per year) and more frequent, usually diurnal, load shifting.

The classifications and the specific types of demand response discussed in this paper are outlined in Fig. 1 and Table 1.

Sections 4 and 5 of this paper consider the relationship between participation, response and persistence and each of these categories of DR, as well as the types of load shifted and other relevant factors, in both real world programmes and trials and in models.

⁴ EPRI use the term ‘performance’ but this paper generally uses the term ‘response’.

⁵ This is the use of signals from an external actor to control consumer appliances, an early example of which is the UK’s radio teleswitch system, which uses a radio signal to control overnight storage heating and facilitate response to time of use tariffs such as ‘Economy 7’ (ENA 2016). DLC also has a long history in the US where it typically attracts incentive payments (Cappers et al. 2012).

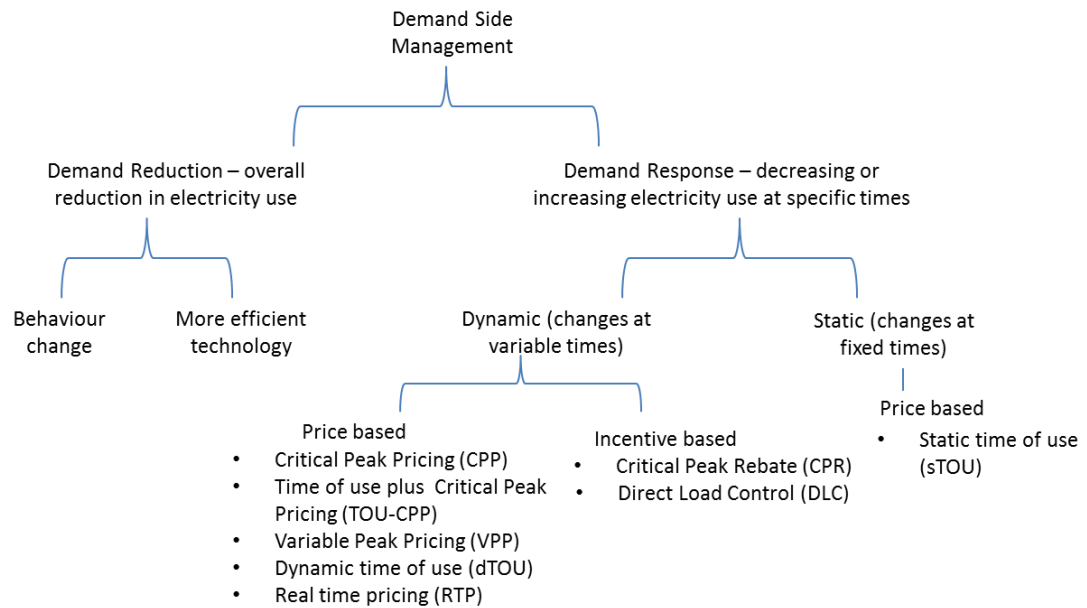


Fig. 1 Classifications of demand reduction and demand response (authors' own)

4. Evidence on residential consumer engagement with demand response

The evidence review revealed 83 residential demand response schemes, of which 19 were established programmes and 64 were trials. The review also includes 11 studies based on surveys, focus groups or interviews that offer complementary insights. The evidence base is drawn from 18 countries, including the US, Canada, Australia, New Zealand, the UAE, and several countries in Europe. 63% of the evidence is from North America and 30% from Europe. In what follows we report findings primarily on a per trial/programme basis, discussing participation, response and persistence rates. Evidence from trials and programmes is reported on a findings per-scheme basis and reports of trials and programmes are referred to as 'studies'. Additional insights from surveys and focus groups are also included as appropriate and where quantitative findings are available these are also referred to as studies⁶. The high level view we provide gives a preliminary indication of the evidence base available on customer engagement with DR. Additional research could apportion findings on a per capita basis, distinguish further between trials and programmes, and provide additional geographical or historical detail. Further details of the review findings are provided in Appendices B to E.

⁶ The studies are identified firstly by naming the utility or other organiser, or the location of the study where this is more appropriate. The name of the study follows in speech marks and is the name given to the study by the organisers where known, otherwise it is a description of the trial. As well as being referenced throughout the text, Appendix B includes a summary of trials reviewed, with references, in alphabetical order.

Price based schemes	Description
sTOU (static time-of-use)	Prices vary by time of day between fixed price levels and over fixed periods. These may vary by season.
CPP (critical peak pricing)	Prices increase by a known amount during specified system operating or market conditions. This applies during a narrowly defined period and is usually applied only during a limited number of days in the year.
TOU-CPP (time of use plus critical peak pricing)	Critical peak pricing overlaid onto time of use pricing. TOU-CPP therefore has two pricing components – daily time of use pricing, and occasional critical peak pricing applied during critical system events (Fig. 4 refers to these as TOU-CPP-D and TOU-CPP-CE respectively)
VPP (variable peak pricing)	Similar to time of use, but the peak period price varies daily based on system and/or market conditions rather than being fixed.
dTOU (dynamic time of use)	Prices vary between fixed price levels, but the timing of different prices is not fixed.
RTP (real time pricing)	Price can differ on a daily basis and change each hour of the day (or more frequently) based on system or market conditions.
Incentive based schemes	Description
CPR (critical peak rebate)	Similar to CPP, but customers are provided with an incentive for reducing usage during critical hours below a baseline level of consumption.
DLC (direct load control)	Customers are provided with an incentive for allowing an external party to directly change the electricity consumption of certain appliances. Customers can usually override control although they may lose some incentive. DLC may also be combined with time varying pricing.

Table 1 Types of pricing and other economic incentives discussed in this paper (authors' own)

We first present high level findings on participation, response and persistence, sections 4.1-4.3. Later sections discuss explanatory factors and the load types used for DR.

4.1 Participation – recruitment rates for DR trials and programmes

Of the 94 studies identified in the review only 28 reported on recruitment levels. As Fig 2 shows, reported recruitment rates vary widely from 2% to 98% of the target population. Some of this variation can be explained by whether customers were solicited for voluntary participation (opt-in) or were placed onto the trial or programme by default (opt-out); and the type of opt-in strategy used. Perhaps unsurprisingly, high recruitment rates were reported by studies utilising opt-out recruitment. Opt-out recruitment may be a way to increase participation in demand response, but as we explain below, the evidence reviewed suggests

that in aggregate, customers participating in schemes recruiting through opt-out recruitment exhibit lower average responses than participants who opt-in to demand response schemes.

Reported opt-in recruitment rates varied widely, but just over half of the studies identified secured participation from 10% or less of the target population (Allcott 2011; CL&P 2009; ConEd 2012; DTE Energy 2014; EPRI 2013, 2014; Eto et al. 2012; GDS Associates 2013; George and Bode 2008; Kofod 2007; Phillips, Owen, and Ward 2013; Sullivan, Bode, and Mangasarian 2009; VTT 2004). In some cases active engagement may be lower than the percentage enrolment numbers suggests: for example, one study suggests that around 40% of

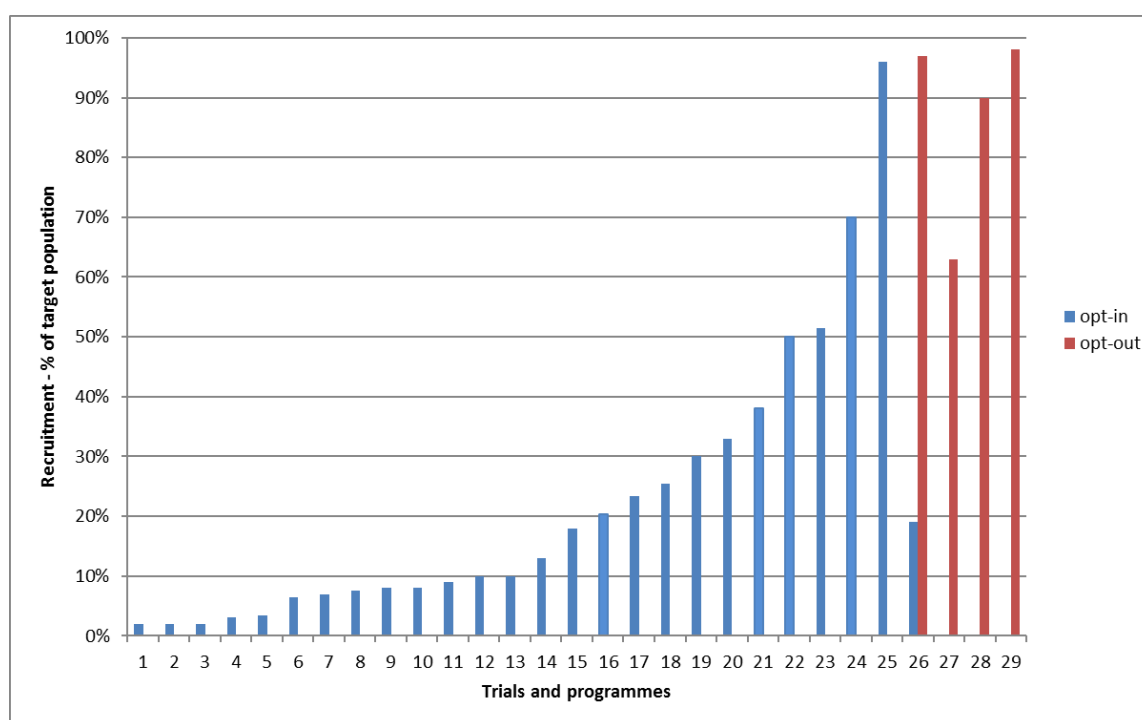


Fig. 2 Reported recruitment using opt-in and opt-out recruitment strategies⁷

⁷ **Note to Fig. 2**

1: SCE "Summer Discount Plan"; 2: DTE "Smartcurrents"; 3: EDF "Tempo"; 4: CL&P "Plan-it wise pilot"; 5: First Energy "Consumer Behavior Study"; 6: SMUD "Residential summer solutions"; 7: ConEd "CoolNYC"; 8: PG&E "smart rate"; 9: PG&E "smart AC"; 10: UK "CLNR"; 11: Marblehead Municipal "energysense"; 12: ComEd "Energy smart pricing plan"; 13: Denmark "DR by Domestic Customers using Direct Electric Heating"; 14: UK "Economy 7" and "Economy 10"; 15: PG&E "DR contingency reserves trial" (direct phone call); 16: California "SPP"; 17: BGE "Smart Energy Pricing Pilot"; 18: Ontario "smart price pilot"; 19: Ireland "CBT"; 20: SCE "DR contingency reserves trial"; 21: PG&E "DR contingency reserves trial" (door to door); 22: Norway "EFFLOCOM trial"; 23: Green Mountain Power "eEnergy Vermont"; 24: Netherlands "Your Energy Moment"; 25: Laredo "Customer Choice and Control trial"; 26: "SmartPricing Options" SMUD; 27: Newmarket Hydro "TOU Pricing Pilot"; 28: Ontario "TOU regulated price plan"; 29: ComEd "CAP". See Appendix B for full list of references.

UK residential consumers enrolled in time of use tariffs such as Economy 7 and Economy 10 may be unaware of the tariff structure and fail to shift loads, probably as a result of having inherited the tariff from previous occupants (Ipsos MORI 2012). Fig. 2 provides an overview of findings revealed in the evidence review, showing the variation in recruitment rates by opt-in and opt-out recruitment for 28 trials and programmes comprising 29 reported recruitment levels.

Expanding on Fig. 2, Fig. 3 presents recruitment rates according to demand response type, for both opt-in and opt-out recruitment. The SMUD "SmartPricing Options" and Green Mountain Power "eEnergy Vermont" studies represent particularly interesting examples because they included multiple demand response types within the respective programmes. Therefore, to facilitate easier comparison between response types within these two studies, in Fig 3 recruitment levels for these trials are labelled 'A' for SMUD "SmartPricing Options" and 'B' for Green Mountain Power "eEnergy Vermont". Note that some studies which are shown in Fig. 2 are not included in Fig. 3 because the study included multiple types of demand response but only an overall recruitment rate could be identified.

Opt-out recruitment rates are consistently high across the range of demand response types for which results were identified. For opt-in recruitment there is considerable variation in recruitment rates within each type of demand response, and no obvious pattern in rates of recruitment across different types of demand response. However, within single trials (Green Mountain Power "eEnergy Vermont" and SMUD "SmartPricing Options") rates of recruitment to different types of demand response are very similar for opt-in as well as opt-out recruitment. This suggests that the context and strategy for recruitment may be more important determinants of recruitment rates than characteristics of different types of demand response.

Higher opt-in recruitment rates may result from more expert recruiters (US DOE 2014), more resources devoted to face-to-face marketing such as door-to-door recruitment, local meetings or workshops (Eto et al. 2012; Hartway, Price, and Woo 1999; Sullivan et al. 2009; US DOE 2014), and the involvement of trusted organisations (Phillips et al. 2013). Schemes with a more local nature have features that may encourage higher participation, such as facilitating the use of known and trusted local parties to support recruitment (SE2 2015), and creating a sense of community in local or regional projects (Kobus and Klaassen 2014; S3C Consortium 2014).

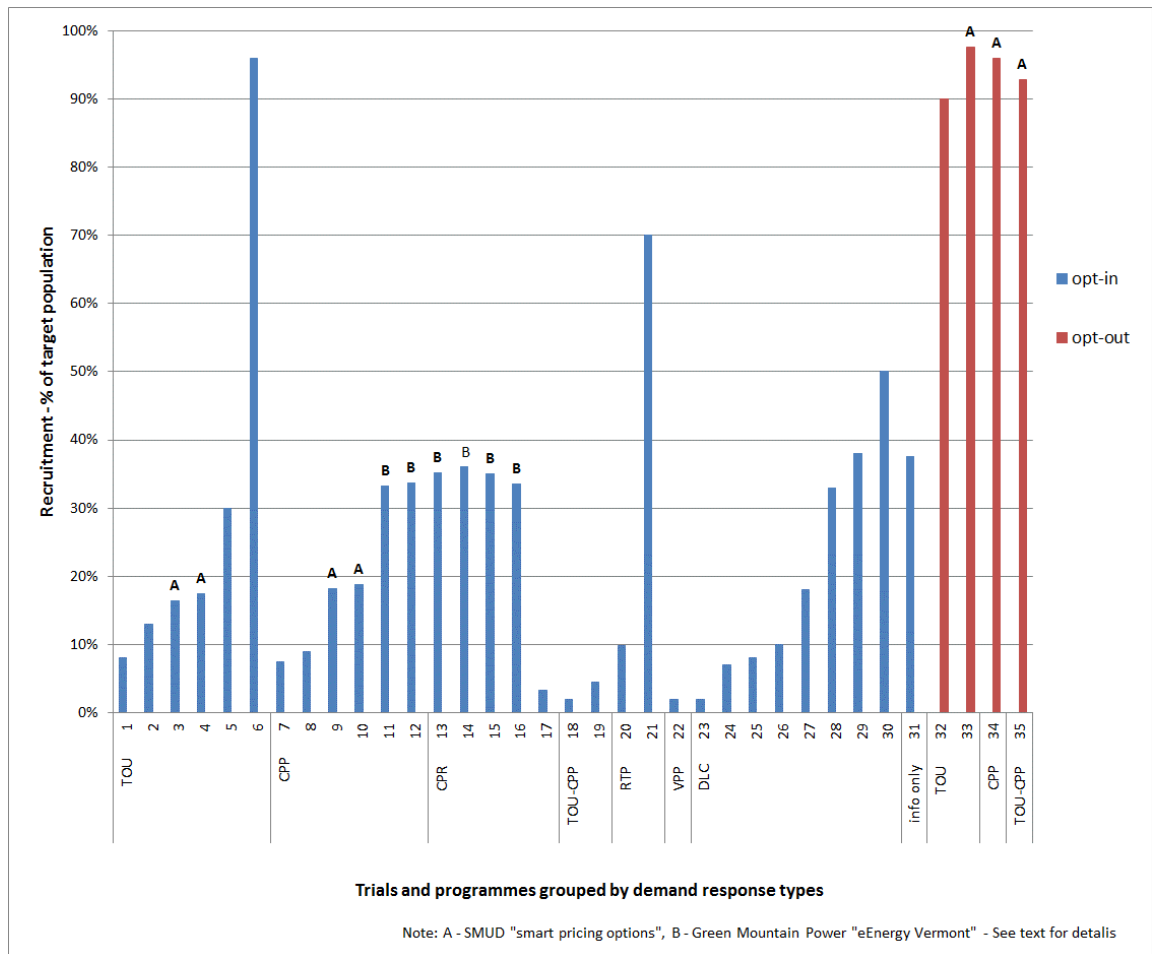


Fig. 3 Reported recruitment by type of demand response⁸

⁸ Note to Fig. 3

1: UK "CLNR"; 2: UK "Economy 7" and "Economy 10"; 3: SMUD "SmartPricing Options" (TOU); 4: SMUD "SmartPricing Options" (TOU+IHD); 5: Ireland "CBT"; 6: Laredo "Customer Choice and Control trial"; 7: PG&E "smart AC"; 8: Marblehead Municipal "energysense"; 9: SMUD "SmartPricing Options" (CPP+IHD); 10: SMUD "SmartPricing Options" (CPP); 11: Green Mountain Power "eEnergy Vermont" (CPP); 12: Green Mountain Power "eEnergy Vermont" (CPP+IHD); 13: Green Mountain Power "eEnergy Vermont" (CPR+IHD); 14: Green Mountain Power "eEnergy Vermont" (CPR); 15: Green Mountain Power "eEnergy Vermont" (CPR, later offered CPP); 16: Green Mountain Power "eEnergy Vermont" (CPR, later offered CPP, + IHD); 17: First Energy "Consumer Behavior Study"; 18: DTE "Smartcurrents"; 19: SMUD "Residential summer solutions" (TOU-CPP); 20: ComEd "Energy smart pricing plan"; 21: Netherlands "Your Energy Moment"; 22: EDF "Tempo"; 23: SCE "Summer Discount Plan"; 24: ConEd "CoolNYC"; 25: PG&E "smart AC"; 26: Denmark "DR by Domestic Customers using Direct Electric Heating"; 27: PG&E "DR contingency reserves trial" (direct phone call); 28: SCE "DR contingency reserves trial"; 29: PG&E "DR contingency reserves trial" (door to door); 30: Norway "EFFLOCOM trial"; 31: Green Mountain Power "eEnergy Vermont" (information only); 32: Ontario "TOU regulated price plan"; 33: SMUD "SmartPricing Options" (TOU); 34: SMUD "SmartPricing Options" (CPP); 35: SMUD "SmartPricing Options" (TOU-CPP) (Potter et al. 2014). See Appendix B for full list of references.

4.2 Response

The review revealed 52 studies providing information on response, drawn from 40 trials and 12 programmes. For the most part, the evidence found in the review is focused on response in the form of demand reductions but one study of dynamic pricing reported demand increasing with high wind output. Levels of response vary widely from over 80% reduction in reference load to practically zero. This subsection focuses on the extent to which the *intended* effects of DR are delivered by consumers. Some of the studies examined also reported unintended effects, for example, critical peak pricing resulting in daily load shifting as well as a response during critical peak events; ‘snap back’ of load after the end of a peak, or a second peak that is higher than the first. Studies also reported both increases and decreases in overall electricity use.

Fig. 4 summarises the evidence base on how consumers respond to different forms of demand response, grouped by the basic treatment type (that is, different structures of time varying pricing, direct load control, or information only). The figure aggregates the number of studies for each type of intervention and the range of findings on response levels across studies. Due to the volume of data, individual studies are not identified in the figure, although the number of studies from which data are drawn for each category of intervention are shown next to each range bar. The figure also represents something of a simplification in that studies report using a range of metrics – for example some consider peak power, others energy during peak periods and some do not specify (see note to Fig. 4).

Relatively little evidence was identified for consumer engagement with more dynamic forms of response (dynamic time-of-use and real time pricing). As a result there is more uncertainty about these forms of intervention, in terms of how widely applicable the response ranges may be in different contexts and how significantly they are affected by factors such as automation, price, appliance type and climate.

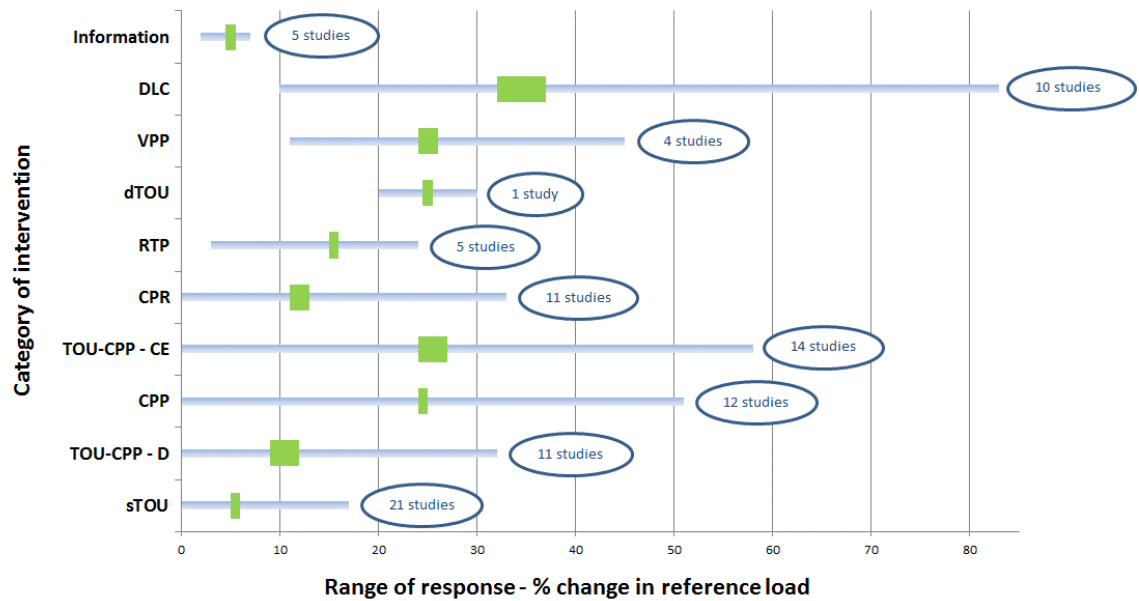


Fig. 4 Summary of reported responses, grouped by treatment type⁹

4.3 Persistence

The extent to which enrolment and response persist over time is an important question for planning the contribution residential DR could make to electricity systems (Potter, George, and Jiminez 2014). It is possible that either response or enrolment may change over time as, for example, demand response participants learn to respond more effectively (Williamson and Shishido 2012), or become fatigued and stop responding or leave the trial or programme (Kim and Shcherbakova 2011). Table 2 summarises changes in enrolment and response for the 10 trials and 10 programmes that reported these across two or more years. Taken together, these do not suggest a clear trend for enrolment or response to change over time. It could be assumed that certain types of demand response are linked to higher or lower levels of

⁹ Note to Fig. 4.

Fig. 4 presents reported change in reference load and includes studies reporting change in peak energy or power, the most common metrics for response identified in the review. Some reported responses as a percentage change without being clear whether this referred to power or energy. Results presented in units other than percentage change in peak energy or power are summarised in Table C1 in Appendix C. Energy and power are not equivalent and Fig. 4 seeks only to report the range of findings on response reported in the literature. In almost all cases response refers to the percentage *reduction* in the reference load, but one dynamic time of use (dTOU) study reports a 30% *increase* in demand at low price periods, simulating increased use of wind generation, as well as 20% reduction in demand during high price periods. If a study reported more than one result, for example if it included different types of demand response or average responses for different times of year, every reported result was included. In some cases direct load control was combined with time-varying pricing, and reported responses are included under both sections. Acronyms as per Table 1. See Appendix B for full list of references.

persistence; for example, consumers might find it more difficult to respond to more dynamic pricing such as real time pricing or variable peak pricing and as a result persistence may be lower for such forms of demand response. To assess this, Table 3 presents changes in enrolment and response by demand response type wherever this was reported. Again, these results do not suggest a clear trend for changes in enrolment or response according to demand response type.

	Enrolment over time			Response over time		
	increase	decrease	stable	increase	decrease	stable
Trials	1	1	4	2	3	5
Programmes	6	1	1	1	3	6

Table 2 Persistence of enrolment and response in trials and programmes across two or more years

		Enrolment over time			Response over time		
		increase	decrease	stable	increase	decrease	stable
Trials by DR type	TOU					1	3
	CPP						2
	TOU-CPP	1		1	2	1	3
	CPR						
	VPP	1			1		
	RTP						
	DLC		1			1	1
	Information only						1
Programmes by DR type	TOU	1					1
	CPP	1				1	
	TOU-CPP						
	CPR	1					2
	VPP						1
	RTP	1					1
	DLC	2	1	1	1	2	1
	Information only						

Table 3 Persistence of enrolment and response in trials and programmes by type of demand response across two or more years¹⁰

Appendix D presents the findings for each of these studies, and whether response/enrolment levels were 'stable' (defined as changing 10% or less across the reported period, or a description that response/enrolment were stable), increased, or decreased. Summarising changes over the whole time period reviewed does not indicate the size of changes within this period but these are partly presented in Appendix D. Differences between the trials and

¹⁰ A number of trials included more than one type of demand response, and are counted in more than one cell of table 3. Two trials did not report on enrolment over 2 or more years by demand response type, and so these results are omitted from Table 3.

programmes summarised in Table 2 contribute to changes in enrolment and response and mean the results are not fully comparable. Recruitment efforts may decrease as a result of regulatory uncertainty surrounding a programme, for example (S. S. George, Bode, and Hartmann 2011), while reported response could be influenced by changes in strategies for triggering demand response and/or changes in temperature or other factors influencing baseline demand, for example (S. George, Perry, and Malaspina 2011; Rocky Mountain Institute 2006). Enrolment increases in programmes reflects ongoing active recruitment, particularly for new programmes: for example, the Ameren Illinois "Power Smart Pricing" programme saw participant numbers increase from 500 in 2007 to over 13,000 in 2013 (CNT Energy 2008; Elevate Energy 2014).

4.4 Factors affecting engagement with Demand Response

The evidence reviewed reveals significant variation in participation and average reported responses. Understanding the reasons behind this will clearly be important to assessing the contribution demand response could make to electricity system flexibility. A number of factors were identified in the literature that may affect response rates, and these are described below.

4.4.1 Automation technology & real time information

In general, if participants have access to additional information (for example, in-home displays indicating current price levels) or automation technology, average responses are greater than those for pricing alone. Trials that tested automation and information alongside pricing reported responses that were on average 2.5% higher with additional information, and 15% higher with automation technologies, compared to responses with neither technology. Responses with both additional information and automation were on average 13% higher compared to responses to pricing only. The impact of automation and information on responses varies between trials – the range for automation is -4.7% to 31.9% and for information is -1.1% to 6.8% (Appendix E).

4.4.2 Appliance ownership and climate

Larger responses would be expected where baseline electrical demand is higher, and this was generally found to be the case. Customers with air conditioning or electric heating generally showed larger responses than customers without these typically larger electrical loads, while responses were larger during periods of higher summer temperatures (and by implication, greater air conditioning use). Seasonal variations in overall response present a more complex picture, with responses being lower in winter for studies based in Canada but higher in winter for studies based in Sweden and New Zealand. Some Canadian participants reported finding it

harder to respond in winter than summer (IBM Global Business Services and eMeter Strategic Consulting 2007). These differences seem likely to relate to whether participants feel able to use their appliances flexibly rather than the total electricity demand at a certain time. Fig. 5 presents reported response levels for trials and programmes comparing these load and seasonal factors.

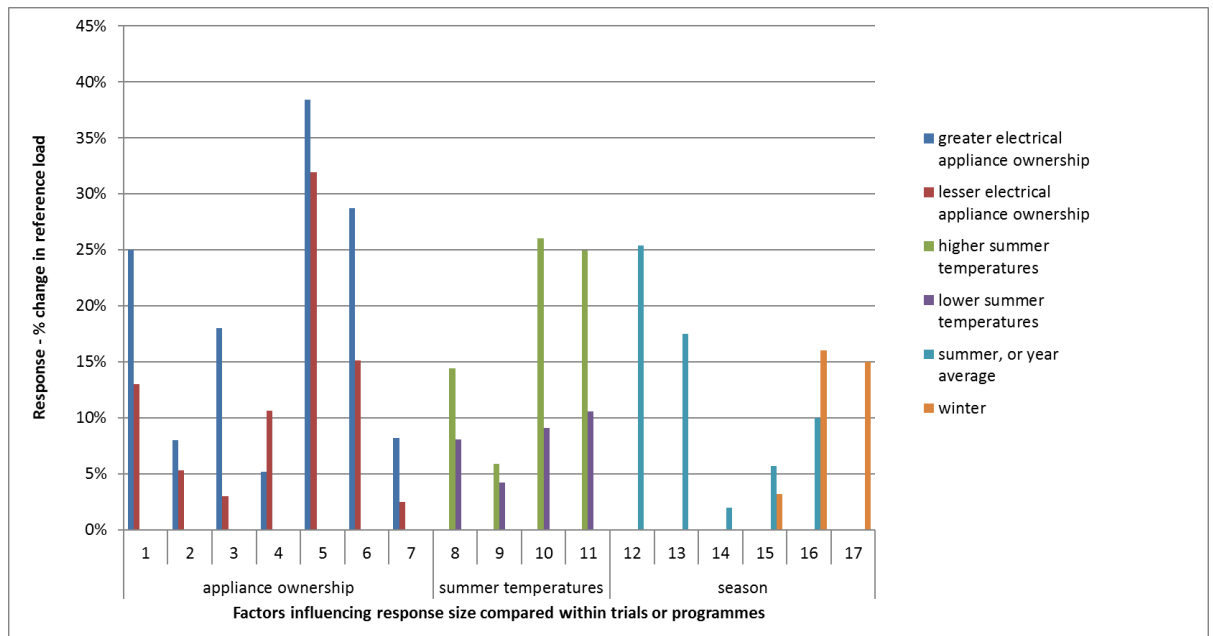


Fig. 5 The influence of appliance ownership, summer temperatures and season on reported response levels¹¹

4.4.3 Opt-in vs opt-out

In general, customers enrolled through opt-out recruitment appear to be less responsive on average than customers who opt-in and volunteer to participate. Fig. 6 presents reported responses for three studies that directly compared average response associated with opt-in and opt-out recruitment. In each case the average response of customers who opted in was higher. Other studies included opt-out recruitment only. The ComEd “CAP” trial identified no significant response overall. However, six other studies that tested opt-out recruitment did report an overall response (Braithwait, Hansen, and Armstrong 2012; Faruqui et al. 2013; A Faruqui and Sergici 2009; Navigant 2008; Wolak 2006, 2010).

¹¹ Note to Fig. 5

1: Powercents DC, CPP; 2: Powercents DC, CPR; 3: Powercents DC, RTP; 4: Xcel "energy pilot", TOU; 5: Xcel "energy pilot", CPP; 6: Xcel "energy pilot", CPP-TOU, peak; 7: Xcel "energy pilot", CPP-TOU, daily; 8: California SPP, CPP; 9: California SPP, TOU; 10: DTE "smart currents" TOU-CPP + PCT, daily; 11: DTE "smart currents" TOU-CPP + IHD + PCT, daily; 12: Ontario "smart price pilot", CPP; 13: Ontario/Hydro Ottawa "smart price pilot", CPR; 14: Ontario/Hydro Ottawa "smart price pilot", TOU; 15: Ontario "TOU regulated price plan"; 16: Sweden "Sala Heby Energi Elnät AB"; 17: Mercury Energy "TOU trial". See Appendix B for full list of references.

Because opt-in and opt-out recruitment is likely to influence enrolment as well as response, it may be particularly helpful to consider studies that consider the aggregate change in demand, accounting for the number of consumers enrolled as well as the average percentage response by those consumers. Analysis of the ComEd “CAP” trial identified a sub-group of ‘event responders’, representing around 10% of total participants, who exhibited load reductions in line with customers opting-in to similar pricing in other studies. This analysis suggests that opt-in and opt-out recruitment may give rise to similar aggregate responses overall (EPRI 2011). Further analysis of the SMUD “smart pricing options study” identified three sub-categories within the opt-out recruitment group: those who would likely have opted-in, those who opted-out, and “complacents” who would likely not have opted-in, but did not opt-out. While around 20% of “complacents” exhibited no measurable response, a larger group of “complacents” exhibited a small response, and another group exhibited a substantial response. Unlike (EPRI 2011), this suggests that opt-out recruitment increased the proportion of responding customers compared to opt-in recruitment. Extrapolating the results to all SMUD’s residential customers suggests opt-out recruitment could reduce peak demand by 5.7% in aggregate compared to 3.3% in aggregate for opt-in recruitment (Cappers et al. 2016). Another study comparing responses to critical peak pricing implemented through opt-in and opt-out recruitment found that although opt-in recruitment led to lower enrolment than opt-out recruitment, it actually resulted in higher aggregate responses (Ida and Wang 2014).

Taken together this evidence suggests that although opt-out recruitment can lead to higher participation, average responses across enrolled customers are likely to be lower than for equivalent opt-in groups. The results reveal no clear trend in aggregate response with opt-out compared to opt-in recruitment and suggest that in different circumstances this may be similar to, larger, or smaller than aggregate response with opt-in recruitment.

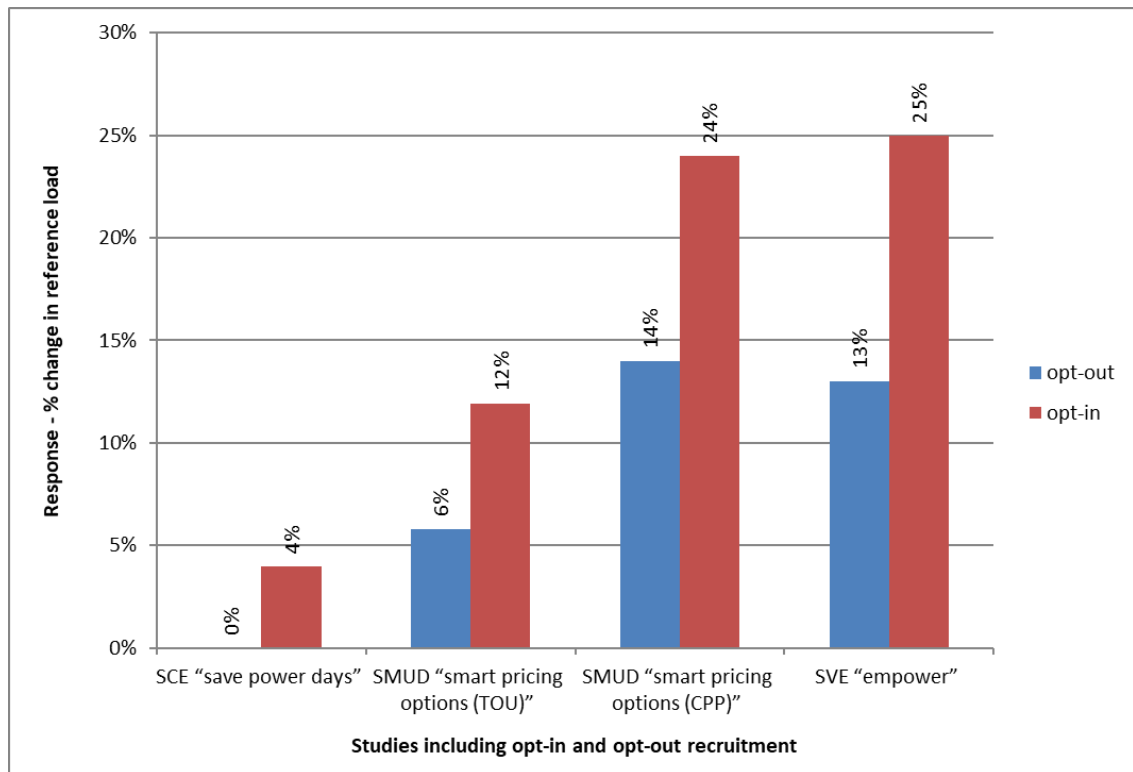


Fig. 6 The impact of opt-in and opt-out recruitment on reported responses See Appendix B for full list of references.

4.4.4 Price ratio

It may be assumed that greater financial differentiation between peak and off-peak periods when DR is or is not required should result in greater responses by consumers, but the evidence reviewed presents a more complicated picture. Five studies tested different peak to off-peak price ratios. Two of these (BC Hydro and GPU trials) identified greater responses where price ratio was higher (Chi-Keung, Horowitz, and Sulyma 2013; A Faruqui and Sergici 2009). However, the other three (Ireland "CBT", Mercury Energy "TOU trial" Danish "DLC trial") reported that different price or rebate levels made no difference to the level of response (CER 2011; Kofod 2007; Thorsnes, Williams, and Lawson 2012).

Some analyses compared the impact of price ratio across different studies. (Faruqui and Sergici 2013) found that 37% percent of the variation in average response for 34 studies can be explained by the combination of price ratio and enabling technologies such as automation or information through in-home displays. (Newsham and Bowker 2010) analyse critical peak pricing and time-of-use pricing separately, since these forms of demand response typically differ in price level, frequency, and the presence of event notifications for CPP. These authors conclude that when CPP and TOU tariffs are analysed separately there is no clear trend for higher price ratios to result in larger reported responses. However, (Faruqui and Sergici 2013)

find that both price ratio and enabling technologies have a strong relationship with demand reduction for TOU pricing, although for CPP enabling technology has a greater impact than price.

4.4.5 Level of commitment by organisers

It is possible that the level of commitment to demand response by trial and programme organisers could influence their level of effort to engage with customers, and hence the levels of enrolment and persistence that they achieve. Whilst it is not straightforward to identify levels of motivation in many of the studies identified in the review, some do suggest higher or lower levels of commitment by the organiser. For example, at the time of the ComEd "Energy smart pricing plan" trial, ComEd was prohibited by law from offering new electricity tariffs so in order to conduct the trial, they partnered with a local non-governmental organisation (Allcott 2011). This suggests a relatively high level of motivation by ComEd to explore or pursue demand response. Conversely, some organisers pursue demand response because they are required to do so by regulation, for example (Navigant 2014a), and in these circumstances it is not clear how enthusiastic the organisers are.

There were also a range of intentions for conducting the studies identified in the review. There are examples, such as (S. George, Bode, and Schellenberg 2011), of studies reporting the performance of established programmes; pilot studies undertaken to evaluate demand response options the organiser is considering rolling out in the near future, such as (Williamson and Shishido 2012); and proof-of-concept trials for more novel forms of demand response, such as (Eto et al. 2012). It may be more straightforward to identify study intentions than organiser commitment to demand response. However, it does not necessarily appear to be the case that studies not intended to explore real-life implementation of demand response are associated with less effort to engage consumers. If studies are carried out on relatively small scales it is possible this may actually enable more intensive recruitment strategies such as face-to-face recruitment, as in (Eto et al. 2012), for example.

5. Demand response in modelling studies

This section summarises the assumptions made in a sample of 16 modelling studies revealed through the evidence review. It includes participation and response rates, forms of demand response, and types of electrical loads involved. Only participation and response are discussed here because none of the studies discuss persistence. It is important to be clear that the objective is not to show that the models are 'wrong', since many models seek to explore potentials and prospects rather than to represent findings from trials or programmes. Rather

Study	Assumed demand response type	Assumed participation (% of target population)	Assumed electrical loads participating in demand response
(Aunedi et al. 2013)	Automation	100%, 75%, 50% and 25%	Refrigerators
(Boait, Ardestani, and Snape 2013)	Real time pricing	70%	Heat pumps and electric vehicles
(Dallinger and Wietschel 2012)	Not specified	100%	Electric vehicles
(Dupont et al. 2014)	Automation	100%	Washing machines, dishwashers, tumble dryers, electric vehicles.
(Falsafi, Zakariazadeh, and Jadid 2014)	Not specified	Not specified	Not specified
(Finn, O'Connell, and Fitzpatrick 2013)	Not specified	Not specified	Dishwashers
(Fitzgerald, Foley, and McKeogh 2012)	Automation	6% ^A	Electric water heating (immersion heaters).
(Hamidi et al. 2008)	Static time-of-use PLUS dynamic pricing or automation for wind supply following	16% (static time of use), 15% (wind following).	Cold and wet appliances, water and space heating.
(Le, Jhi-Young, and Ilic 2009)	Real time pricing	Not specified	Not specified
(Pourmousavi, Patrick, and Nehrir 2014)	Direct load control PLUS static time-of-use pricing	100% ^B	Electric water heating
(Pudjianto et al. 2013)	Not specified	Not specified	Heat pumps with thermal storage, and electric vehicles.
(Roscoe and Ault 2010)	Automation PLUS real time pricing	100%	Various appliances
(Stanojevic et al. 2013)	Automation	100% ^C	Dishwashers, washing machines, tumble driers.
(Taneja, Lutz, and Culler 2013)	Not specified	20%	Refrigeration (prototype using phase change materials to increase thermal storage)
(Wang et al. 2012)	Automation	Not specified	Heat pumps
(Westermann and John 2007)	Not specified	Not specified	Not specified

Table 4 Assumptions made by modelling studies featuring residential demand response.¹²

¹² **Notes to Table 4**

A: model 100,000 electric water heaters. Assuming every household has one electric water heater, 100,000 water heaters represents around 6% of households identified in the 2011 census.

B: The authors do not state 100% participation, but explain: 'There are approx. 1.36 million EWHs in this region... This data has been scaled for use with the 1,000 EWHs in our study' (p. 772).

the purpose is to provide a fact base on what aspects of consumer participation are explicit in modelling studies and which are not. Table 4 summarises the principal assumptions found in the review of modelling studies.

5.1 Participation

Around a third of the modelling studies reviewed assume a very high level of consumer participation in demand response, with four studies explicitly specifying that 100% of the modelled load can be shifted (although for one study this is specified for all white good cycles and implied for electric vehicle charging) (Aunedi et al. 2013; Boait et al. 2013; Dallinger and Wietschel 2012; Dupont et al. 2014). (Roscoe and Ault 2010) model 75% of consumers shifting wet and cold appliances at a lower price threshold, but 100% during critical peak periods. (Stanojevic et al. 2013) assume that 80% of consumers have a smart dishwasher, and 100% have some form of smart washing machine (25% of these having a washer-drier). (Boait et al. 2013, p.690) assume “a suitable control system...in about 70% of electrically heated homes”.

Whilst other modelling studies do not clearly specify the percentage of load participating, they do appear to suggest that it is relatively high. For example, (Pudjianto et al. 2013) discuss the additional load that would result from full penetration of electric vehicles and heat pumps, appearing to show all additional load is re-distributed according to the optimisation process. (Finn et al. 2013) review statistics on total appliance ownership by households, and then model the impact of load shifting by these, but it is not clear whether the modelling covers total appliance ownership. (Falsafi et al. 2014) state that although response to price is voluntary, it is assumed that customers will respond, although it is not clear whether this means 100% of customers in the modelled system will participate in DR, or 100% of customers who choose to participate will actually respond. (Le et al. 2009 p.4) state that “loads are assumed to be responsive with respect to price”. (Wang et al. 2012 p.4) state that their model represents “a large population” of heat pumps, but do not state the total number of consumers these represent.

Lower participation levels are modelled by (Aunedi et al. 2013), who model 100%, 75%, 50% and 25% participation by UK residential refrigeration, and (Taneja et al. 2013), who model participation of 0-100% of commercial and residential refrigeration, and quote benefits assuming 20% participation. (Hamidi et al. 2008) assume 16% of households participate in TOU shifting, and 15% of total domestic loads participate in supply following (although if less than 100% of load is assumed to be flexible, this would represent more than 15% of households).

C: Assumes 80% of consumers have smart dishwasher, 75% have smart washing machine, and 25% have smart washer-drier, referring to ownership rates for standard appliances.

Similarly, (Westermann and John 2007) assume '0.1p.u.' (per unit) of load is flexible, but as the type of load is not declared it is not possible to know what percentage of the population this represents. (Fitzgerald et al. 2012) model 100,000 aggregate water heaters in the electricity system of the Republic of Ireland, which, if every household has one electric water heater, represents around 6% of the households identified in the 2011 census.

5.2 Response

Overall, while the studies reviewed generally take care to establish the technical basis for load shifting (for example, identifying every journey made by light vehicles in the UK, or modelling fridge duty cycles), they do not obviously consider the extent to which consumers might actually engage with the interventions modelled. One exception is the modelling study by (Stanojevic et al. 2013) , which takes its assumptions about participation and acceptable load shifting times from a survey of European customers (Mert, Suschek-Berger, and Tritthart 2008). In some cases the possible range of consumer preferences is acknowledged, but is not incorporated into the model: (Pourmousavi et al. 2014) suggest that consumers should have the option of overriding control, but do not model the impacts of this; (Falsafi et al. 2014) note that customer response is voluntary, but assume that customers always respond; (Wang et al. 2012) note that customers may be unwilling to hand over control of their thermostats, but assume that the economic incentive will be sufficient for them to do so. (Dallinger and Wietschel 2012) note that electricity price differentials may be insufficient for consumers to shift load, but assume they will shift load even when the economic incentive to do so is low.

5.3 Factors affecting engagement with Demand Response

5.3.1 Forms of DR represented in models and the role of automation or DLC

Three modelling studies reviewed, (Boait et al. 2013), (Le et al. 2009) and (Roscoe and Ault 2010), specifically include real time pricing. Others suggest that price or economic incentives would be used to control loads, but without specifying the price or incentive structure (Dallinger and Wietschel 2012; Falsafi et al. 2014; Finn et al. 2013). (Hamidi et al. 2008) model two components of DR, namely peak shifting in response to TOU pricing, and wind supply-following which the authors suggest could be dispatched by direct communication, autonomous response or price signals. In (Pudjianto et al. 2013) the load is shifted according to an optimisation algorithm, but it is not specified how this is communicated to customers.

The majority of the modelling studies reviewed include some form of automation. In (Fitzgerald et al. 2012), (Pourmousavi et al. 2014) and (Wang et al. 2012), this takes the form of changing temperature set points on programmable communicating thermostats (PCTs) for

space or water heating. (Stanojevic et al. 2013), (Taneja et al. 2013), (Roscoe and Ault 2010) and (Aunedi et al. 2013) model smart appliances that can either be controlled externally or respond autonomously to system conditions. Others are less specific, with (Dupont et al. 2014) describing load shifting as being ‘centrally optimised’ rather than price based, suggesting the use of direct load control, whilst (Westermann and John 2007) suggest the use of direct load control but do not specify which loads are controlled, and (Boait et al. 2013) suggest that automation would be used to facilitate consumer response to real time pricing.

Where automation/real time pricing is not specified it nonetheless seems likely to be required in order to achieve the dynamic responses described. Of the models reviewed, only (Hamidi et al. 2008) and (Pourmousavi et al. 2014) modelled the impact of simple TOU shifting, although (Finn et al. 2013) and (Dupont et al. 2014) noted that their optimisations tended to shift demand to periods of low load. This could indicate that a less dynamic response could achieve at least some of the modelled benefits, although (Dupont et al. 2014) note that the variability of optimum demand shifting increases with increasing variable renewable electricity, and (Hamidi et al. 2008) and (Pourmousavi et al. 2014) find that, alone, TOU shifting achieves lower benefits than dynamic shifting.

5.3.2 The types of loads shifted

The majority of modelling studies reviewed focus on the potential benefits from shifting a particular type of load. These included appliances types which consumers currently have little experience of, such as electric vehicles (Boait et al. 2013; Dallinger and Wietschel 2012; Dupont et al. 2014; Pudjianto et al. 2013), and heat pumps (Boait et al. 2013; Pudjianto et al. 2013; Wang et al. 2012). Wet goods are modelled by (Dupont et al. 2014; Finn et al. 2013; Hamidi et al. 2008; Roscoe and Ault 2010; Stanojevic et al. 2013), cold goods by (Aunedi et al. 2013; Hamidi et al. 2008; Roscoe and Ault 2010; Taneja et al. 2013). Conventional electric water or space heating and conventional air conditioning are also modelled. (Boait et al. 2013) include manual shifting of appliances usually considered to be inflexible, whilst some studies, such as (Falsafi et al. 2014) and (Westermann and John 2007) do not specify the type of load modelled.

6. Discussion: comparing modelling assumptions and empirical evidence

6.1 Participation, response and persistence: real world vs models

The evidence reviewed suggests that some modelling studies make highly optimistic assumptions about residential consumer engagement with demand response. For example, participation rates are assumed to be between 70 and 100% for five out of the eight modelling

studies which state their assumed participation, yet in real-world trials and programmes just over half of those studies that reported opt-in recruitment rates achieved overall recruitment of 10% or less of the target population. While opt-out recruitment can achieve enrolment rates of close to 100%, the percentage response across enrolled participants is likely to be considerably lower than for opt-in recruitment. More importantly in terms of electricity system management, the findings of this review revealed no clear trend for opt-out recruitment to increase aggregate response.

As we have suggested above, the intent, motivation, organisation and commitment of the range of actors involved in trials can vary significantly, and this can have very material implications for the level of demand response actually achieved. Similarly, the intent and objective of modelling studies will affect the results of such analyses. For example, at one extreme models may be used to explore the upper bounds of what is theoretically possible as opposed to assessing what outcomes are most likely based on observed levels of engagement and response in trials. This highlights the need to carefully assess the degree of alignment (or otherwise) in the motivations behind trials and modelling studies, and what that may mean for the validity of the assumptions underpinning modelling results.

The modelling studies reviewed tend not to explicitly state the level of response assumed. However, many make clear assumptions about the type of demand response. Eight of these include some form of automation, and three assume real time pricing or a similar dynamic price signal. There is reasonable evidence to support the assumption that some form of automation/DLC is accepted by at least some consumers, although the majority of evidence reviewed relates to direct load control of air conditioning during critical peak periods in North America. However, there is less evidence identified by the review to support the assumption that consumers would engage with more dynamic pricing, because most of the evidence comes from trials and programmes which offer static time of use or peak tariffs. Modelling studies acknowledge that voluntary responses may not always take place (Falsafi et al. 2014), that consumers may be unwilling to hand over control (Wang et al. 2012), or that price differentials may be too low to result in behaviour change (Dallinger and Wietschel 2012), but there is a clear disconnect between studies that assume consumers will respond to dynamic signals and the evidence base examined for this paper.

Simply put, models tend to assume a high level of participation and response to dynamic price signals. Yet the evidence suggests that participation and response rates are at best highly varied and at worst quite low, and that there is very little experience with dynamic pricing.

However this does not mean that demand response cannot provide many of the benefits discussed in modelling studies. Static load shifting between peak/off-peak periods could generate savings in wholesale electricity prices (Frontier Economics 2014), and continue to be valuable in a future system with higher penetrations of wind generation (Grünewald, McKenna, and Thomson 2014). It could offer greater benefits to consumers with electric vehicles or electric heating (Ward and Darcy 2014). The relative simplicity of static time of use pricing may make it a good option to introduce demand response to consumers (Steel 2014), while because it is more predictable, response levels for static load shifting may be modelled more accurately than for other forms of demand response.

The majority of the modelling studies specify the electrical loads involved in demand response, but there is considerable disconnect between the loads modelled and the empirical evidence. It seems unlikely that alternative electrical loads with different demand patterns will offer strong proxies for the loads of which there is as yet little empirical experience.

Five of the modelling studies reviewed featured wet appliances (washing machines, driers and dishwashers), and smart wet goods were specifically featured by five empirical studies and were commonly cited by trial or programme survey respondents as a load that was shifted in response to price. Other survey respondents generally stated that shifting wet loads would be acceptable, as long as routines were not disrupted and noise did not cause a disturbance at night, although some had additional concerns, and some may have overstated how they would actually behave - a concern particularly emphasised by (Mert et al. 2008).

Heat pumps were featured by three of the modelling studies, and heating and cooling were the most common loads targeted by empirical studies identified. Whilst heat pumps are technologically different from other heating technologies (and not yet widespread), it is possible that technical differences have been captured by the modelling studies and that consumer acceptance of shifting existing heating or cooling is analogous to acceptance of shifting heat pumps. The majority of empirical studies were based in North America, but examples were also found in Europe and elsewhere. The acceptability of shifting these loads may depend on factors such as the level of insulation, availability of alternative heat sources, or climatic conditions, but if these conditions are met the evidence suggest that it may be possible to shift these loads. However, some survey participants felt that these loads should be available on demand (Mert et al. 2008) and were already at the minimum levels for comfort (Bouly de Lesdain et al. 2014).

Whilst wet appliances, together with heating and cooling are reasonably well represented in the evidence, of the other main loads featured by the modelling studies reviewed, electric vehicles do not feature in any of the trials or programmes included in our review, and barely featured in surveys either. Furthermore, it does not seem that other loads can be easily considered analogous to electric vehicles, since the energy services provided are quite different.

Finally, three of the modelling studies assume flexible operation of refrigeration (Aunedi et al. 2013; Hamidi et al. 2008; Roscoe and Ault 2010). This featured in only two of the demand response studies reviewed, namely Spain “ADDRESS project” (Abi Ghanem 2014) and DTE “smartcurrents” (DTE Energy 2014). Surveys report mixed results on the acceptability of smart refrigeration, with some consumers stating it would be very acceptable, and others stating concerns about food quality and safety, which may persist despite assurances (Mert et al. 2008).

6.2 Evidence gaps and uncertainties

6.2.1 Response variability

Much of the evidence is concerned with *average* rates of participation and response. However it is also possible for response to vary relative to the average, through consumers changing a pattern of behaviour – for example if a substantial fraction of consumers overrode automated controls at the same time. This potential for response variability might influence the benefits that could be achieved from demand response. Variability in reported responses was not a factor that was explicitly investigated in the review, but certain studies reporting variable responses were identified. The UK “CLNR” trial of static time-of-use pricing found that although peak demand was reduced on average, this was not the case during the annual system peak (Bulkeley et al. 2015). Including automation as part of demand response will not necessarily avoid different patterns of behaviour leading to response variability, due to the potential for override and low use of automation. Participant override of direct load control may vary considerably, for example from 9–39% in the SDG&E “Smart Thermostat Pilot” (KEMA 2006) and from 21–31% in the ConEd Cool NYC programme (ConEd 2012). If demand response is to displace alternative forms of flexibility then it appears likely to be necessary that any variability in response is understood and can be predicted with sufficient accuracy, otherwise uncertainty, risk and costs may increase (O’Connell et al. 2014; Ward and Darcy 2014; Ward and Phillips 2014).

6.2.2 *Recruitment costs*

Aside from the limitations of evidence on consumer engagement, there appears to be a lack of evidence on the costs of implementing demand response (Owen, Darcy, and Ward 2013). Expected technology costs are reviewed by (Bradley, Leach, and Torriti 2013), but not the cost of engaging consumers, which can be significant (SE2 2015). Such costs could include changing billing systems and the additional marketing required to recruit customers onto demand response tariffs (Owen et al. 2013). If some forms of demand response can be relied on at certain times but not others the costs of any back-up management should also be considered when assessing the contribution demand response could make to electricity system management.

7. Conclusions

Residential demand response could offer various benefits as part of a low carbon energy system transition. By systematically reviewing evidence on residential consumer enrolment, response and persistence with international demand response trials and programmes this paper comments on assumptions made by studies modelling the potential of residential demand response.

Much of the evidence identified related to more traditional forms of demand response that aim to reduce peak demand and less evidence was identified for consumer engagement with dynamic forms of demand response and emerging new electrical loads such as electric vehicle charging. While understandable, this does at least raise questions around the extent to which consumers will engage with more dynamic demand response in the future.

Reported opt-in recruitment rates varied widely across the evidence reviewed, but just over half of the studies identified reported recruitment of 10% or less of the target population. Perhaps unsurprisingly, high recruitment rates were reported by studies utilising opt-out recruitment. However, across the enrolled population, average responses tend to be lower where participants are recruited on an opt-out basis, while the absolute size of response may be similar across both opt-in and opt-out recruitment.

Average response levels vary between different types of demand response, but also show considerable variation within types. Varying average response levels are influenced by the presence of automation technology and real time information; baseline electrical demand linked to appliance ownership and season; and the ratio between peak and off peak electricity pricing or comparable incentives. However, it is not clear that these factors are able to explain

all the variation in average response across different studies. In addition, some studies suggest that response levels may vary between different demand response events within a single trial or programme. Variability in response levels could make it more difficult to assess the potential contribution of demand response to electricity systems, and mean that demand response is unable to entirely displace other forms of electricity system management. Response levels at different times may be harder to predict for more dynamic forms of demand response.

Persistence in enrolment or response could change if demand response participants learn to respond better, or become fatigued and stop responding or leave trials or programmes. However, the evidence reviewed did not suggest a trend towards either outcome.

Overall, there is considerable evidence that at least some residential consumers are willing to participate in at least certain forms of demand response. However, any plans to increase residential demand response to provide greater flexibility in a decarbonising energy system should take careful account of the range of issues identified in the available evidence, including likely consumer engagement and the motivations of all actors involved. The evidence appears at present to be complex and somewhat mixed, and suggests that the high levels of demand response modelled in some future energy system scenarios may be more than a little optimistic. There is good evidence on the potential of some of the least 'smart' options, such as static peak pricing and load control, which are well established and proven. They may be able to offer many of the benefits sought in modelling studies. However, more research and greater empirical evidence is needed to establish clear guidelines for modelling of the potential role of more innovative and dynamic forms of demand response.

Chapter Three: A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response

Abstract

Demand response is increasingly attracting policy attention. It involves changing electricity demand at different times based on grid conditions, which could help to integrate variable renewable generation and new electric loads associated with decarbonisation. Residential consumers could offer a substantial new source of demand-side flexibility. However, while there is considerable evidence that at least some residential users engage with at least some forms of demand response, there is also considerable variation in user engagement. Better understanding this variation could help to predict demand response potential, and to engage and protect consumers participating in demand response. Based on a systematic review of international demand response trials, programmes and surveys, we identify motivations for participation, and barriers and enablers to engagement including familiarity and trust, perceived risk and control, complexity and effort, and consumer characteristics and routines. We then discuss how these factors relate to the features of different demand response products and services. While the complexity of the evidence makes it difficult to draw unequivocal conclusions, the findings of this review could contribute to guide early efforts to deploy residential demand response more widely.

Keywords: demand response; demand-side management; flexibility; residential; consumer engagement

1. Introduction

Demand response is increasingly attracting policy attention as a resource to increase the flexibility of electricity systems (COWI 2016; Grünewald and Diakonova 2018; National Infrastructure Commission 2016; Srivastava, Van Passel, and Laes 2018) as well as reduce the carbon intensity of electricity supply (Smith and Brown 2015; Vine 2008). Electricity systems require supply and demand to be balanced within tight limits in real time, which has traditionally been achieved mainly by sizing generation, reserves, and transmission and distribution network capacity to meet predicted demand (Strbac 2008). This will become more challenging if electric heating and transport increase peak electricity demand, and electricity systems include much higher penetrations of less flexible generation (Kroposki 2017; Pudjianto et al. 2013; Strbac 2008).

Demand response describes flexible electricity demand that can be increased or decreased at specific times, for example to make use of high wind generation or reduce demand peaks. This may help to integrate variable renewable generation and new electric loads cost effectively. Recent inputs to policy making have reinforced the message that enhancing system flexibility is a key factor in minimising the costs of integrating variable renewable sources of electricity (Aurora 2018; Vivid Economics and Imperial College London 2019). While commercial and industrial consumers currently contribute more to demand response in many countries, including the UK (National Infrastructure Commission 2016), residential consumers theoretically represent a large additional source of flexibility (Gils 2014) with potentially considerable value in decarbonised energy systems (OVO Energy and Imperial College London 2018).

Accessing demand side flexibility could require residential electricity consumers to engage with demand response programmes. EPRI (2012) characterise engagement with demand response as participation (being enrolled in demand response), performance (responding in the desired way) and persistence of effects over time, elements summarized in Fig. 1. Assessments of demand response *potential* reveal that it offers greater flexibility over shorter time frames, and indicate which types of demand response or electrical loads offer greatest potential for integrating variable renewables (Cappers et al. 2012; Müller and Möst 2018). The *performance* of demand response trials and programmes considering enrolment, response and persistence was reviewed by Parrish, Gross and Heptonstall (2019) in order to compare the results with assumptions included in studies modelling residential demand response. There is considerable

evidence that at least some residential users engage with at least some forms of demand response. However, there is also considerable variation in user engagement across different demand response programmes and trials, and across different users within the same trials or programmes (Carmichael et al. 2014; EPRI 2011; Parrish et al. 2019). This paper therefore builds on previous work through a systematic review of demand response trials, programmes and surveys that addresses the question: what are the key factors affecting residential user engagement with demand response?

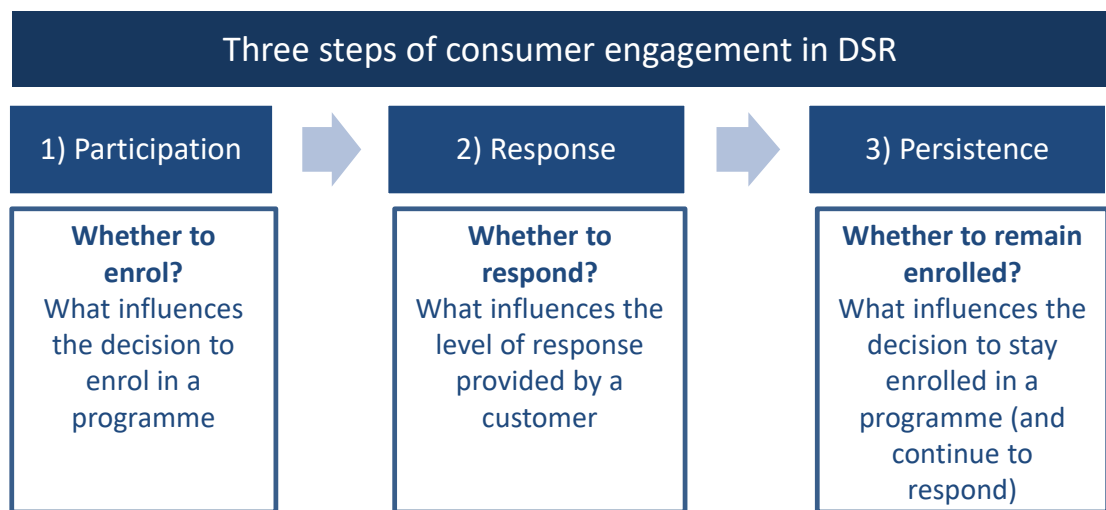


Fig. 1: Stages of consumer engagement in Demand Response (EPRI 2012b)

Better understanding the factors that affect residential user engagement with demand response is relevant to policy for several reasons. It could allow demand response potential to be more accurately predicted (US DOE 2016), or reduce marketing costs by target marketing to users who are likely to offer the greatest performance (EPRI 2012b). It could help to increase user engagement with demand response (US DOE 2014), and also to protect users by better informing them of whether they are likely to benefit from different demand response products and services (Steel 2014). To better understand residential user engagement with demand response, this paper presents the findings of the systematic review under the themes of consumer motivations, barriers and enablers, and user routines and characteristics. It goes on to discuss how these findings relate to the characteristics of different demand response products and services, and suggests policy implications for delivering residential demand response.

The remainder of the paper is structured as follows: Section 2 reviews key concepts in demand response, including a range of demand response products and services, to provide the background for the findings and discussion; Section 3 describes the research design, a systematic review; Section 4 presents our thematic findings; Section 5 discusses the implications of these findings for user engagement with different forms of demand response; Section 6 concludes and suggests policy implications.

2. Background

This section provides an introduction to the principles of demand response and a range of demand response products and services. This provides background for less familiar readers, and the main characteristics that differentiate different types of demand response form part of the discussion in Section 5.

The premise for flexible electricity demand by residential consumers is the idea that consumers use electricity to provide energy services, and that electricity use and the provision of energy services can sometimes be temporally separated. This suggests two categories of theoretically flexible loads. The first category comprises loads with thermal inertia: space and water heating, air conditioning and refrigeration. Because it takes time for temperature to rise or fall, it may be possible to change the timing of electricity demand while maintaining energy service provision. This can be enhanced by increasing thermal insulation or including additional thermal storage, such as hot water tanks, chilled water or ice storage. The second category comprises loads where electricity demand and demand for energy services are separated in time. This category includes the so-called ‘wet’ goods or appliances: washing machines, dishwashers and tumble dryers. This perspective suggests that other energy services, such as lighting, cooking and entertainment, will be less flexible because their involvement in demand response implies users changing their demand for these energy services.

Demand response typically relies on economic incentives to encourage consumers to shift demand. These can take the form of time varying pricing or rebates for changes in demand compared to a predicted baseline level; consequently, demand response is commonly classified as either price based or incentive based. However, some schemes do not include any economic incentive and aim to change demand based on information provision alone. Demand response may involve technologies to provide additional information to participants, for example on current pricing levels, and may rely on manual behaviour change or be facilitated by appliance automation or direct load control. Finally, types of demand response vary by the timing of demand response signals, which may vary daily or target occasional events a few

times per year. They may also be classified as *static* or *dynamic* according to whether or not pricing or other signals follow a predetermined schedule.

The classifications and the main types of demand response discussed in this paper are outlined in Fig. 2 and Table 1

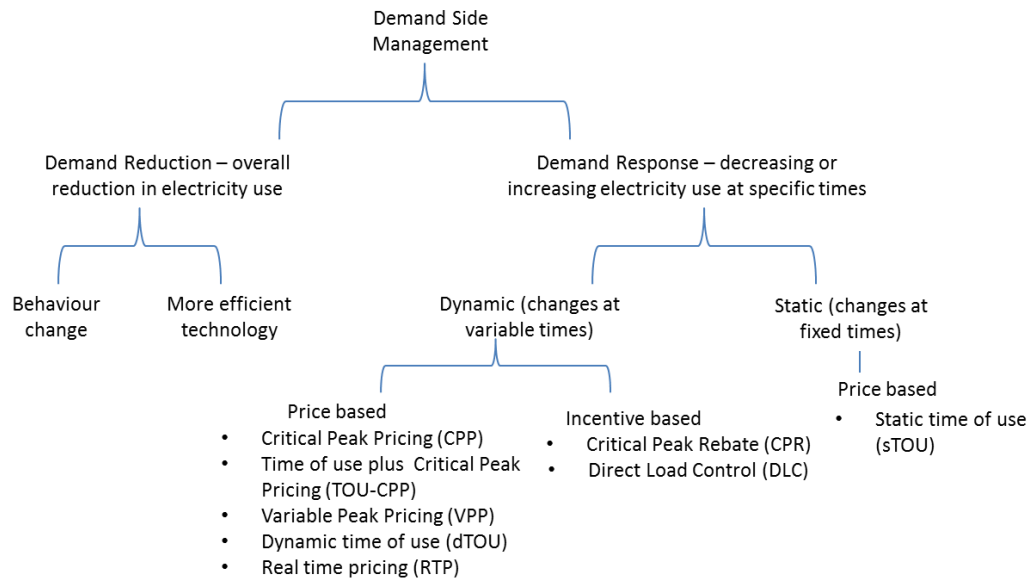


Fig. 2: Classifications of demand reduction and demand response (Parrish et al. 2019).

More specialised demand response products and services were also found in the demand response literature. In *local supply following*, different demand response products and services aim to shift demand to increase the use of renewable electricity generated locally (Carmichael et al. 2014; EcoGrid EU 2016; Kobus et al. 2015; Lebosse 2016; Swinson, Hamer, and Humphries 2015). *Peer-to-peer trading* aims to increase the use of embedded generation such as rooftop PV by directly trading surplus generation with other users locally (Moreno 2013; Wiekens et al. 2014). More specialised forms of automation include *smart appliances* such as washing machines, dishwashers, and tumble driers that automatically run at the optimum time, within the time slot set by users, to support more dynamic forms of demand response (Belmans et al. 2014; Chassin and Kiesling 2008; Kobus et al. 2015; Wiekens et al. 2014). *Smart charging for electric vehicles* varies from simple timers to delay charging until night time (Farhar et al. 2016; Friis and Haunstrup Christensen 2016), to more sophisticated technology to autonomously monitor low voltage distribution networks and dynamically curtail charging during times of high network load (EA Technology and Southern Electric Power Distribution 2016). Battery storage could facilitate demand response by storing surplus renewable generation, supplying electricity to users during peak times to reduce peak demand, and direct

control of battery charge and discharge could help to manage distribution network constraints (Western Power Distribution 2016).

Price based schemes	Description
sTOU (static time-of-use)	Prices vary by time of day between fixed price levels and over fixed periods. These may vary by season.
CPP (critical peak pricing)	Prices increase by a known amount during specified system operating or market conditions. This applies during a narrowly defined period and is usually applied only during a limited number of days in the year.
TOU-CPP (time of use plus critical peak pricing)	Critical peak pricing overlaid onto time of use pricing. TOU-CPP therefore has two pricing components – daily time of use pricing, and occasional critical peak pricing applied during critical system events.
VPP (variable peak pricing)	Similar to time of use, but the peak period price varies daily based on system and/or market conditions rather than being fixed.
dTOU (dynamic time of use)	Prices vary between fixed price levels, but the timing of different prices is not fixed.
RTP (real time pricing)	Price can differ on a daily basis and change each hour of the day (or more frequently) based on system or market conditions.
Incentive based schemes	Description
CPR (critical peak rebate)	Similar to CPP, but customers are provided with an incentive for reducing usage during critical hours below a baseline level of consumption.
DLC (direct load control)	Customers are provided with an incentive for allowing an external party to directly change the electricity consumption of certain appliances. Customers can usually override control although they may lose some incentive. DLC may also be combined with time varying pricing.

Table 1: Types of pricing and other economic incentives discussed in this paper (Parrish et al. 2019)

3. Research design and approach: A systematic review

The methodology used to identify the body of evidence discussed in this paper draws from previous methodological contributions offered by (Sorrell 2007; Speirs et al. 2015). This approach can be termed a systematic review. Systematic reviews of the literature, inclusive of academic literature and the “grey” or policy literature, aim to identify a comprehensive (though not exhaustive) selection of reports detailing factors influencing residential user engagement with different forms of demand response.

The authors began their review by searching the academic literature for studies on DR published between 1990 and 2016, using ScienceDirect. The authors searched for the terms (pilot OR trial OR programme OR program OR survey OR "focus group") AND TAK¹³("demand response" OR "demand side response" OR "direct load control" OR "time varying pric*" OR "dynamic pric*" OR "real time pric*" OR "time-of-use") AND (residential OR domestic OR "SME" OR commercial OR business) AND electricity. A resulting corpus of 960 initial results was collected. Few results on small or medium businesses were identified, and only findings on residential demand response are presented in this paper.

Grey literature source	Search strategy	Number of results
EC Europa inventory of European Smart Grid Projects	Initially reviewed all projects identified as Demonstration and Deployment (rather than Research and Development) AND identified as belonging to the category "Smart Customer and Smart Home".	117
US Department of Energy Smart Grid Investment Grant Consumer Behaviour Studies	Initially reviewed all Consumer Behaviour Study Program Reports.	14
US Electric Power Research Institute (EPRI)	Searched the term 'demand response' within two research programmes identified by EPRI: 1) "Energy Efficiency and Demand Response" 2) "Understanding Electric Utility Customers"	1) 59 2) 56
IEA Demand Side Management Energy Efficiency Technology Collaboration Program	Initially reviewed all completed tasks and associated publications.	50

Table 2: Grey literature search strategy

Because much literature on demand response consists of policy reports rather than peer-reviewed literature, the authors complemented their academic search with that of the grey literature. Grey literature searches were focussed on sources that were identified through rapid evidence assessment and yielded the most useful information for Parrish, Gross and Heptonstall, (2019) and BEIS (2017). Table 2 gives details of these searches, which resulted in an additional corpus of 296 studies. To filter this data, we relied on a screening process.

¹³ "TAK" restricts the search for these terms to the title, abstract and keywords.

Documents were excluded first based on their title/abstracts, and further excluded based on the full text where necessary, if they did not meet the following inclusion criteria:

- Geographical: Europe, North America, Australia and New Zealand, also Japan
- Sector: residential
- Evidence type: including some form of empirical evidence rather than theory alone
- Access: publications in English, available for free (or where the project team have journal database access)
- Any type of time varying pricing aiming to change electricity use at specific times, with or without additional information or automation (static time-of-use, dynamic time-of-use, critical peak pricing, variable peak pricing, real time pricing)
- Direct load control or automation (e.g. via smart appliances) aiming to change electricity use at specific times
- Rebates aiming to change electricity use at specific times (critical peak rebate)
- Information (alone) aiming to change electricity use at specific times
- Include all of the above acting over specific local areas
- Include all of the above using battery storage, PV etc. to facilitate demand response

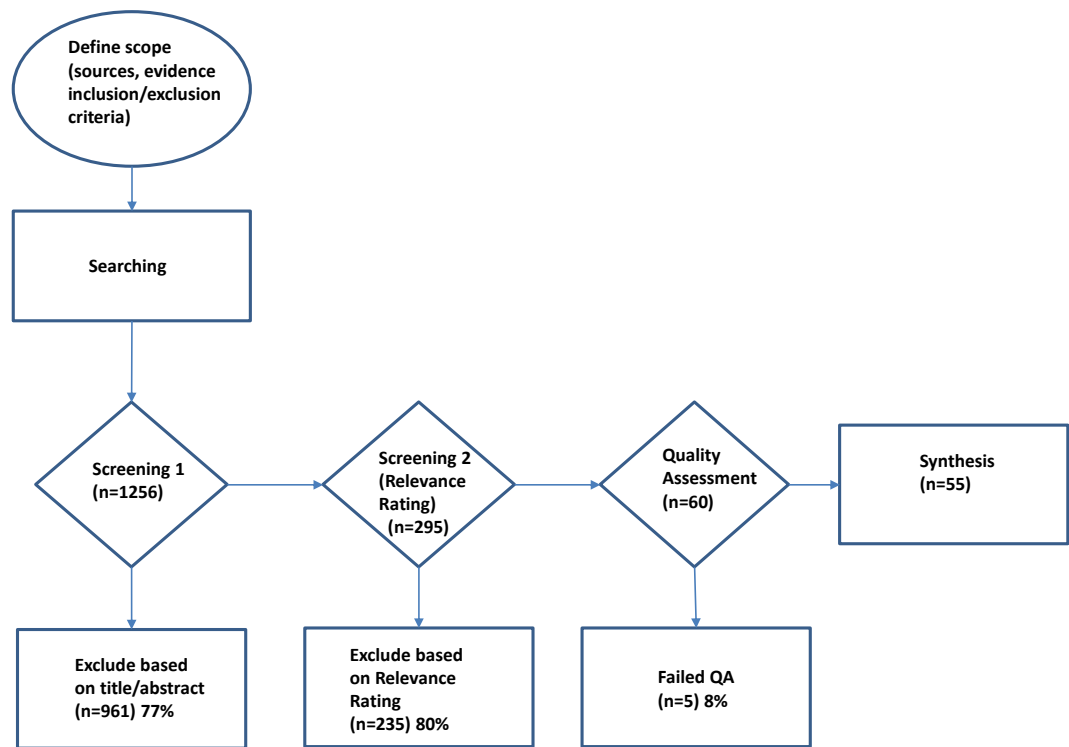


Fig. 3: Systematic Review Process Flowchart

This screening process, represented in Fig. 3, identified a total of 55 studies across the academic and grey literature. These covered a range of geographic locations, evidence types (trials, programmes, and stand-alone surveys) and forms of demand response. The distribution of evidence across these categories is summarised in Table 3. Trials and surveys represent the majority of the evidence base.

In this classification ‘programmes’ indicates residential demand response that has been implemented with the intention of providing services to a real electricity system, while ‘trials’ indicates the implementation of interventions such as time varying pricing, enabling technologies, and information provision for research purposes. ‘Surveys’ refers to surveys, focus groups or interviews that were conducted with people not taking part in a trial or programme of demand response (although such methods can also be used as part of research on consumer engagement with trials and programmes). A limitation of such stand-alone surveys, focus groups and interviews is that they capture data from consumers who may have no direct experience of demand response. On the other hand, many trials and programmes involve a self-selected group of participants because they recruit on an opt-in basis (voluntary recruitment). Therefore, while trials and programmes can provide evidence on consumers’

actual behaviour when enrolled in demand response, surveys, focus groups and interviews can offer some insight into the attitudes of the general population. This review therefore includes findings from both categories of evidence.

Following our screening of the literature, the full body of evidence across the academic and grey literature was reviewed to identify findings on factors affecting residential user engagement with demand response. The impact of different forms of time varying pricing; information provision; and/or enabling technologies including automation, direct load control and in-home feedback on electricity price and/or use, were reviewed quantitatively in Parrish, Gross and Heptonstall (2019). To build on this work we focussed on identifying qualitative motivations, barriers or enablers for consumer engagement with residential demand response. Because the literature we reviewed was diverse in terms of the form of residential demand response examined, the study context and design, and the perspectives that informed its analysis, we have not attempted to quantify the frequency of specific findings, but instead we have categorised findings inductively across studies to allow themes to emerge.

The next three sections thematically present the factors influencing user engagement with demand response identified from the evidence base represented in Table 3. The first section discusses residential consumer motivations to enrol in demand response, and, to a lesser extent, to change demand patterns following enrolment. The next section discusses the themes that could be considered as enablers or barriers that are associated with an increase or decrease in residential consumer enrolment and/or response: familiarity and trust; perceived risk and perceived control; and complexity and effort. The final section discusses the influence of user characteristics and user routines.

Location	Evidence type	No. studies (mean participant number)	No. studies by demand response products and services						
			sTOU	CPP	CPR	dTOU/RTP	In-home display	Direct load control	Automation
UK	Trial	7 (505)	4	0	0	1	3	2	2
	Programme	0	0	0	0	0	0	0	0
	Survey	2 (1017)	2	0	1	1	0	1	2
Europe	Trial	9 (923)	4	1	0	5	1	1	2
	Programme	1 (no data)	1	0	0	0	0	0	0
	Survey	4 (666)	1	0	0	2	0	2	3
North America	Trial	18 (7823)	11	10	3	3	8	0	7
	Programme	2 (no data)	0	0	0	0	0	2	0
	Survey	6 (1599)	2	1	0	0	0	1	1
Australia & NZ	Trial	3 (142)	2	2	0	0	0	1	1
	Programme	1 (no data)	0	0	0	0	0	1	0
	Survey	1 (53)	1	0	0	0	1	1	0
Totals			28	14	4	12	13	13	19
Reviews, meta-analysis and policy-analyses		5 studies							

Table 3: Categorisation of literature search results. Note that numbers do not sum across rows because a single trial, programme or survey may have included more than one type of intervention.

4. Results: motivations, barriers and enablers for residential demand response

This section presents the detailed findings of our systematic literature review to address the question: what are the key factors affecting residential user engagement with demand response? The first section describes residential consumer *motivations* for engagement with demand response. The second section describes themes emerging from the literature reviewed that could be considered as *enablers* or *barriers* for engagement with demand response: familiarity and trust; perceived risk and perceived control; and complexity and effort. The final section summarises findings on how *user characteristics* and *user routines* might influence engagement with demand response. These summary themes are carried forwards to inform the discussion in Section 5.

4.1 Results: Consumer motivations for demand response

This section considers why residential users might chose to enrol in demand response, and why they might choose to respond following enrolment.

The review identified a wide range of motivations for residential consumers to participate in demand response. Financial and environmental benefits were the most common motivations identified, and of these, financial benefits were typically given the highest importance (AECOM 2011; Allcott 2011; Carmichael et al. 2014; Dütschke and Paetz 2013; Torstensson and Wallin 2014; US DOE 2016). More specifically, some users state that bill reductions are more appealing than rewards or other financial incentives (Buchanan et al. 2016), although there may be little difference in actual enrolment rates for critical peak pricing and critical peak rebates (US DOE 2016).

Only two trials reported environmental and other social benefits as more important, (Bradley, Coke, and Leach 2016; EcoGrid EU 2016), although other studies found both were important, or did not compare them (Hall, Jeanneret, and Rai 2016; Lebosse 2016; Shipman, Gillott, and Naghiyev 2013; Western Power Distribution 2016). However, the potential environmental benefits of participating in demand response may not be obvious to users, for example, because total electricity use will not necessarily decrease as a result (Hall et al. 2016).

A wide range of other motivations for enrolment were identified. Expected household-level benefits included free or reduced cost technology (Bird 2015; Bradley et al. 2016), increased control over energy use and bills including through access to additional information (AECOM 2011; Hall et al. 2016; Western Power Distribution 2016), and thinking participation in demand response might be fun or interesting (Dütschke and Paetz 2013; Strengers 2010). More social motivations included pride discussing participation with neighbours or being encouraged by

children to be more environmentally friendly (Western Power Distribution 2016), or helping to increase electricity system reliability (Bird 2015; Lebosse 2016). If demand response has a local focus this can act as an additional motivation (Carmichael et al. 2014; EcoGrid EU 2016; Lebosse 2016).

There is some evidence that after enrolling users continue to weigh up the potential financial savings against effort, time, convenience and comfort when deciding whether to change their electricity use (Bartusch et al. 2011; Bradley et al. 2016; EcoGrid EU 2016; Friis and Haunstrup Christensen 2016). Participants might also enjoy the challenge of responding to dynamic pricing and treat it like a game or project (Carmichael et al. 2014).

4.2 Results: Enablers and Barriers facing Demand Response

Our systematic review identified not only consumer motivations, but also a collection of enablers and barriers facing demand response. We have placed these into the categories of familiarity and trust, perceived risk and perceived control, and complexity and effort.

4.2.1 Familiarity and trust

Mistrust can arise before or after enrolment, and is often linked either to technology or technical issues or to a lack of clarity around what demand response involves and who it benefits. Concerns around privacy and autonomy connected to direct load control, and consumers' ideas of why energy companies pursue demand response can contribute to mistrust (AECOM 2011; Bartusch et al. 2011; Lopes et al. 2016; Wiekens et al. 2014).

Unfamiliarity can be linked with mistrust, for example unfamiliarity with the concept of demand response can contribute to mistrust of energy company motivations (AECOM 2011). However, familiarity can have either positive or negative effects. Hall et al. (2016) linked the higher stated acceptance of time-of use tariffs to their availability in a local area, but found that awareness of public concerns about smart meter deployment caused users to be concerned about this enabling technology.

Trust may be promoted by measures that enhance transparency around demand response in general and, where relevant, direct load control in particular. Such measures include providing information on demand response from independent sources (Hall et al. 2016), communicating how different parties such as users and energy companies benefit from demand response (Buchanan et al. 2016; Lebosse 2016), and notifying users of any direct load control actions taken (Lopes et al. 2016). More generally, recruitment can be supported by the involvement of trusted actors (Bird 2015; Western Power Distribution 2016) including neighbours (EA Technology and Southern Electric Power Distribution 2016).

Trust may be eroded following enrolment in demand response, and may then be hard to rebuild (Wiekens et al. 2014). Loss of trust may arise from installation delays (Western Power Distribution 2016), technical issues (Wiekens et al. 2014), or opacity of dynamic pricing or automation schedules (Carmichael et al. 2014; Wiekens et al. 2014). In addition, engagement with forms of demand response that involve community action, such as peer-to-peer trading, may be impacted if users do not trust the behaviour of other community members (Wiekens et al. 2014).

Similarly to at the enrolment stage, trust after enrolment may be promoted by increasing transparency and addressing technical issues. Engagement may be promoted by honesty and accountability about delays and technical issues (EcoGrid EU 2016; Western Power Distribution 2016), as well as addressing customer's questions and issues, anticipating common issues and preventing them before they escalate, and setting realistic expectations about participation, performance of technology, and potential bill savings (US DOE 2016).

4.2.2 Perceived risk and perceived control

Perceived risk may be associated with different features of time varying pricing or rebates for demand response. Technologies that enable responses to time varying pricing may help to address the financial risk of time varying pricing, but can themselves be perceived as risky due to loss of control.

Higher price levels and less predictable pricing may increase perceived risk associated with time varying pricing. For example, perceived risk or complexity can deter some consumers from enrolling in real-time pricing (Allcott 2011), while participants in one trial of dynamic time-of-use pricing said they would be more likely to sign up again if price changes were more predictable (Carmichael et al. 2014). Some users prefer smaller high:low price ratios or a cap on price (Dütschke and Paetz 2013), and others prefer time-of-use pricing to critical peak pricing perhaps due to the much higher price ratios associated with the latter (Buryk et al. 2015).

Unlike time varying pricing, rebates that incentivise demand reduction carry no financial risk for participants, but we found mixed evidence on how this could influence enrolment. Users may state a preference for financial rebates rather than time varying pricing due to the absence of risk associated with the former (Bradley, Coke and Leach, 2016), and the use of rewards rather than financial penalties may facilitate recruitment (Lebosse 2016). However, a series of trials in the US found little difference in actual enrolment rates for critical peak pricing and critical peak rebates (US DOE 2016). These trials did identify that critical peak rebates

resulted in smaller and less consistent responses, but higher retention rates compared to critical peak pricing. Both effects were suggested to arise from the financial risk attached to critical peak pricing (US DOE 2016).

Automation can enable responses to time varying pricing, and has been associated with higher stated acceptance of dynamic time-of-use pricing (Fell et al. 2015). On the other hand, users might be concerned about loss of control associated with automation or direct load control (Hall et al. 2016; Lopes et al. 2016). Enrolment could be encouraged by features of direct load control or automation that increase users' perceptions of control. Such approaches include providing choice about how and when automation takes place; specific agreements on allowed control including limited duration; adequate notification of control; and the option to override (Buchanan et al. 2016; Hall et al. 2016; Lopes et al. 2016). Users may also prefer automation over direct load control because it is perceived as allowing them to retain greater control (US DOE 2016; Wiekens et al. 2014). However, some users may accept direct load control without override: the appliance standards set for air conditioners in New South Wales do not allow users to override the external control of their air conditioning, but attrition from the programme has been low, and reported satisfaction high (Swinson et al. 2015).

Concerns about direct load control or automation may increase or decrease following experience of these interventions. In a series of trials in the US, pre-trial market research indicated that users strongly preferred to programme thermostats themselves as they were reluctant to allow direct load control. However, experiences during the trial suggested that most users relaxed these concerns after gaining familiarity with the programmable thermostats and allowed direct load control by their utility (US DOE 2016). Similarly to at enrolment, user engagement while experiencing automation or direct load control can be influenced by features that affect users' perceived control. In one trial participants given more control options felt more positive about direct load control of their heating, although they did not override control any more frequently than other groups (EcoGrid EU 2016). Meanwhile, participant enthusiasm for smart appliances fell over the course of another trial, in part due to a perceived loss of control associated with a lack of feedback on the start and end times of automated smart appliances (Belmans et al. 2014).

4.2.3 Complexity and effort

The level of complexity and effort associated with demand response can affect consumer engagement before and after enrolment. This may be linked to the predictability of pricing schedules, and the effort of responding can be reduced by enabling technologies, but the evidence on neither of these factors is straightforward.

Considering demand shifting in general terms, some users expect changing demand patterns would be difficult or undesirable due to inconvenience and impact on daily routines (Bradley et al. 2016; Buryk et al. 2015; Lopes et al. 2016). However, others expect changing demand patterns to be easy (Buryk et al. 2015; Fell et al. 2015; Lopes et al. 2016). Some studies have highlighted the importance of how the effort consumers expect compares to the benefits they anticipate from participation (Allcott 2011; Lopes et al. 2016).

The complexity and effort involved in responding to time varying pricing may be linked to less predictable pricing schedules. For example, two trials of real time pricing reported very limited manual demand shifting because users found it difficult to change their use of appliances in line with continually changing price signals (Belmans et al. 2014; Friis and Haunstrup Christensen 2016). Similarly, some users report finding it harder to change demand on specific days rather than following a daily pattern (Lebosse 2016). Even routine responses to static time-of-use pricing may be perceived as too much effort by some users (Farhar et al. 2016). However, the evidence on this is mixed: in one trial of dynamic time-of-use pricing, 79% of respondents in the post-trial survey said they did not find the tariff too complex, 60% agreed it was easy to take advantage of low rates, and 50% agreed it was easy to avoid high rates (Carmichael et al. 2014).

Automation or direct load control can reduce the complexity and/or effort involved in responding to time varying pricing (Belmans et al. 2014; Farhar et al. 2016; Friis and Haunstrup Christensen 2016; Wiekens et al. 2014). These enabling technologies may be linked with perceived ease of use (Fell et al. 2015), and some users who are away from home during the day may choose them to increase response (Lebosse 2016). However, making use of automation or accessing additional information provided by enabling technologies can itself be perceived as excessively complex or difficult (AECOM 2011; Belmans et al. 2014; Carmichael et al. 2014; Farhar et al. 2016). Similarly, the requirement to install new technologies can act as a barrier to recruitment (AECOM 2011). This may be due to technology cost (Belmans et al. 2014), space requirements (Bird 2015), and the disruption associated with installations (Bird 2015; Hall et al. 2016). Technology installation can be a critical part of users' experience of demand response (Bird 2015).

4.3 Results: User routines and characteristics

The previous results sections discussed the role of user motivations, and barriers and enabling factors in the uptake and level of demand response. Many of the studies reviewed also

explored links between levels of engagement with demand response and various consumer characteristics, and/or the interaction between demand response and user routines.

4.3.1 User characteristics

Identifying more flexible groups of users could be helpful to better assess demand response potential, and inform users of whether they are likely to benefit from participating in demand response. Studies reviewed identified a number of approaches that could potentially be used to indicate higher or lower flexibility by users or households, which can be broadly categorised as socio-demographics; access to technology including the ability to make use of the range of available technologies; and the presence of dependents in households and time spent at home.

Some studies considered how user engagement varies with socio-demographic characteristics such as income and household size. Response was higher by households with higher income in the California SPP trial (Faruqui and George 2005), and by homeowners in the UK CLNR trial (Bird 2015). Evidence related to household size and composition is somewhat mixed. Smaller households gave larger average responses in the California SPP and UK EDRP (AECOM 2011), but the opposite effect was identified by Thorsnes, Williams and Lawson (2012) and in the UK LCL trial (Carmichael et al. 2014). Overall, the UK LCL trial found only weak correlations between household characteristics and demand response (Carmichael et al. 2014). The CLNR trial suggested socio-demographic groups may not be most appropriate way to identify more flexible customer segments, who could instead be identified by "socio-technical" groups (e.g. households with more appliances) or "flexibility capital" (e.g. shift workers) (Bird 2015).

Access to broadband and the specifications of existing appliances may restrict enrolment in some types of demand response (Bird 2015; Lebosse 2016; Western Power Distribution 2016). Flexibility may be increased by access to and ability to use enabling technologies such as appliance timers (Carmichael et al. 2014), better insulated buildings and access to and/or knowledge of alternative technologies such as fireplaces for heating (Carmichael et al. 2014; Lebosse 2016) or ways to keep cool without air conditioning (Strengers 2010). Conversely, response may be inhibited by lack of awareness or difficulty using enabling technologies (Carmichael et al. 2014; Western Power Distribution 2016), misunderstanding the ways in which they are being asked to change their electricity demand patterns (Lebosse 2016; Shipman et al. 2013), and incorrectly estimating the energy used by different appliances and the impact of changing the times that they are used (Wiekens et al. 2014).

Several studies identified time outside the home as a barrier to shifting demand, and spending more time in the home, or flexible working hours, as an enabler of response (Bradley et al. 2016; Carmichael et al. 2014; Dütschke and Paetz 2013; EcoGrid EU 2016; Friis and Haunstrup Christensen 2016; Lebosse 2016; Strengers 2010; Thorsnes et al. 2012; Torriti 2013). The UK CLNR found that households without dependents were more likely to respond to time-of-use pricing (Bird 2015). Similarly, Friis and Haunstrup Christensen (2016) reported that families with small children tended to find shifting wet goods more stressful, although some reported finding it easy because they were already used to a high degree of planning. Overall this suggests that the presence of children or other dependents could make demand shifting more difficult.

4.3.2 User routines

Some studies explored how the match or mismatch between the requirements of demand response and existing user routines influenced flexibility. While some patterns can be identified, there is heterogeneity in the extent to which users can be flexible in their routines and activities in the home.

At the appliance level, ‘non-time critical’ wet goods (washing machines, dishwashers and tumble driers) are often the appliances most involved in manual demand shifting (Carmichael et al. 2014; Lebosse 2016; Wiekens et al. 2014). More generally, the UK LCL trial found that the appliances participants identified as most flexible were those for which they had the least fixed routines (Carmichael et al. 2014). However, some users have various concerns about shifting the use of wet goods, including: noise, safety, and concerns about smells and creases developing when laundry is left in washing machines or tumble driers (Belmans et al. 2014; Carmichael et al. 2014; Friis and Haunstrup Christensen 2016; Lebosse 2016); convenience (Carmichael et al. 2014; EcoGrid EU 2016); unwillingness to lose quality time in the home (Bartusch et al. 2011; Friis and Haunstrup Christensen 2016); and fixed roles for certain household members (Carmichael et al. 2014). Similarly, comfort and convenience could influence users to override direct load control of water heating (Belmans et al. 2014) or space heating or cooling.

Demand shifting could be enabled if it can involve behaviours that are less disruptive to existing routines. Dishwashers may provide greater flexibility than other wet goods because users more frequently programme them in the evening (Belmans et al. 2014). Users may be more prepared to run dishwashers than washing machines overnight because it is less disruptive to existing family routines to unload clean dishes in the kitchen in the morning than to hang laundry (Friis and Haunstrup Christensen 2016). Similarly, night-time charging of

electric vehicles can become part of the routine of locking up for the night (Friis and Haunstrup Christensen 2016). In other cases, direct load control was implemented in a way that simply had little impact on participants, for example relatively short duration curtailments of heating, taking differing insulation levels into account (Lebosse 2016).

On the other hand, some groups of users are apparently willing and able to be more flexible in their routines in order to respond. For example, some users left the house to avoid electricity use at certain times (Carmichael et al. 2014; Strengers 2010), changed which household member used appliances (Carmichael et al. 2014), or created a fun family occasion out of using less electricity (Strengers 2010; Western Power Distribution 2016). One study reported consumers who treated responding to dynamic pricing as a game or a motivator to complete household chores (Carmichael et al. 2014). Some studies report users changing the use of appliances typically considered inflexible, such as cooking and lighting (Carmichael et al. 2014; Lebosse 2016). Different demand response participants may simply experience different levels of disruption to their daily lives and routines (Bradley et al. 2016).

5. Discussion: Implications for residential demand response

The previous sections report findings on factors influencing user engagement with demand response. They identify motivations, barriers and enablers for residential user engagement with demand response, as well as ways in which users' routines and characteristics may influence engagement. This section discusses the implications of these findings for delivering demand response, by relating them to user engagement with different demand response types and approaches to rolling out demand response. It ends with suggestions for further work.

5.1 Features of demand response

There is a wide variety of residential demand response types, as indicated in Section 2. However, in general residential demand response types vary according to whether they involve *time varying pricing*, *rebates*, or a *payment* for accepting direct load control; the *spread between high and low pricing*; the *predictability* of pricing or other schedules; and whether *enabling technologies* such as automation or direct load control are involved. This sub-section discusses how the various factors influencing user engagement described in Section 4 relate to these generic features of demand response, considering financial incentives, pricing and other schedules, and enabling technologies.

Financial incentives: This review identified a range of different motivations for enrolment, but the most common related to financial and environmental benefits. Financial benefits were most often found to have the highest importance in studies that assessed the relative

importance of these two types of motivations. Some studies reported that users continue to consider the potential for financial savings as well as the impact on their daily lives when deciding whether to change electricity demand patterns following enrolment. This suggests that adequate financial incentives may be necessary to attract participants to residential demand response programmes. This could involve sufficiently large rebates, price spreads, or payments for direct load control. However, some studies indicate that high peak prices could increase perceptions of risk and discourage enrolment. Rebates carry no financial risk, but there is mixed evidence on whether they encourage higher recruitment than the equivalent dynamic pricing.

Pricing and other schedules: Some residential users engage with more dynamic or unpredictable forms of time varying pricing, but in general, less predictable pricing schedules may increase perceptions of risk, increase the complexity and effort associated with response, and create mistrust. The studies reviewed indicate that trust may be supported by transparent pricing, while enabling technologies may reduce perceived risk and complexity/effort. However, other studies indicate that the impact of demand response on users' routines also influences complexity and effort, and that direct load control is likely to be more acceptable if it has lower impacts on comfort and convenience. This suggests that enabling technologies may be less able to reduce complexity and effort if they produce responses that conflict with user routines.

Conversely, more predictable pricing could enable the formation of new routines supporting response. The review revealed heterogeneity in both users' routines and their degree of flexibility. However, the evidence reviewed suggests that at least some users find demand response easier if their responses can become routine, and that this may be favoured by more predictable forms of time varying pricing. Overall the findings of this review suggest that less dynamic and more predictable forms of demand response may increase residential user engagement. The literature indicates that an exception may be cases where demand response is automated and involves changes to demand, such as short duration curtailment of heating, that do not impact on user routines and activities in the home.

Enabling technologies: Technologies such as automation or direct load control are designed to reduce the complexity and effort of demand response by facilitating demand shifting without the need for manual behaviour change. Our review found evidence that direct load control and automation can reduce perceived complexity, effort, and risk associated with residential demand response, but can also themselves introduce a series of barriers to engagement with

demand response. Firstly, installing and/or using some enabling technologies can itself be complex and/or difficult for some consumers. Secondly, although enabling technologies could reduce the risk of paying more by facilitating responses to higher prices, consumers may perceive a risk of losing control because of these technologies, although automation may be seen as offering greater user control than direct load control. Finally, expectations or experiences of enabling technologies may be linked to a loss of trust. Concerns about loss of autonomy and control may reduce trust at enrolment, while technical issues and opaque scheduling of automation or direct load control may reduce trust over time.

5.2 Approaches to delivering demand response

There are clearly trade-offs in the influence of different features of demand response on user engagement. Different approaches to delivering demand response can also influence engagement, and could help to address these trade-offs.

For example, while automation and direct load control can support engagement with residential demand response, these technologies may also introduce barriers to engagement. The ways in which automation and direct load control are delivered can reduce these barriers. For example, the reviewed literature suggests that perceptions of risk associated with direct load control may be reduced by delivering it in a way that increases perceived control, such as limiting possible direct load control actions, notifying users about control actions and providing more options for users to shape control including the ability to override.

More generally, the review revealed trust as an important factor in residential user engagement with demand response. Trust can also be influenced by how demand response is delivered. The literature reviewed indicates that trust during recruitment could be encouraged by providing transparent information on how different parties benefit from demand response, and/or by involving trusted actors in recruitment. After enrolment, trust could be encouraged by follow up engagement including setting realistic expectations about demand response, communicating effectively when customers have questions or problems, dealing with issues before they escalate and clear communication and accountability about issues that do arise.

Understanding variation in user engagement with demand response could help to protect users by informing them of whether they are likely to benefit or lose out from participating in residential demand response. However, this review did not identify clear links between different user segments and levels of engagement, which suggests that advice to consumers may need to take the form of more general information allowing more informed decisions about their participation. In particular, socio-demographic data is not always useful in

predicting the potential for demand response. Metrics such as household size and income perhaps indirectly indicate factors such as the number of appliances owned, and it seems likely that such links and the ways in which they influence flexibility vary between different contexts. More informed participation in demand response could be supported by approaches such as calculator tools that allow users to better assess whether they might pay more or less on different forms of time varying pricing, or bill guarantees to allow users to try time varying pricing for a limited period without the risk of paying more (US DOE 2016). The reviewed literature indicates that availability and knowledge of enabling and alternative technologies, time spent at home, and the presence of dependents appear to be better able to explain differing levels of flexibility. This suggests that it may also be possible to increase demand flexibility by providing support to use enabling technologies, or alternative ways to achieve energy services.

A number of studies reviewed indicated that experience of demand response, either personally or also through its local reputation, can have positive or negative impacts on consumer engagement. One study also suggested that users' trust can be hard to rebuild once it has been eroded. The findings of this review could contribute to guide early efforts to deploy residential demand response more widely with the aim of avoiding early negative experiences that could hinder further engagement.

5.3 Suggestions for further work

The complexity of findings in terms of details of demand response design and implementation, context, and user heterogeneity make it difficult to draw unequivocal conclusions about the impact of these individual dimensions on user engagement. Better understanding which groups of users are more likely to engage with residential demand response could have benefits including more accurate assessment of demand response potential, and protecting users by better informing them of whether they are likely to benefit from different demand response products and services.

The findings of this review indicate that user engagement with demand response can change with experience. While there are long standing examples of residential demand response, many of the studies reviewed were conducted over relatively short time frames. The timing of a study or its emphasis on certain themes may also have influenced the findings of the studies reviewed. For example, if the organisers of demand response trials or programmes recruit participants by emphasising the financial benefits on offer to them, this may contribute to consumers placing greater importance on financial rather than, for example, environmental

motivations for participation. Similarly, the technology involved in demand response may also change over time. Ongoing evaluations of early efforts to increase deployment would therefore be valuable.

6. Conclusions and policy implications

Demand response is increasingly attracting policy attention as a resource that could increase the flexibility of electricity systems and support energy system decarbonisation. There is evidence that at least some residential users engage with at least some forms of demand response, but considerable variation in user engagement could impact on demand response as resource to manage electricity systems (Carmichael et al. 2014; EPRI 2011; Parrish et al. 2019). To contribute to understanding this variation, this paper identifies factors affecting residential consumer engagement with demand response.

The paper is based on the findings of a systematic review of academic and grey literature. This review identified a final sample of 55 relevant studies, covering a range of geographic locations, evidence types (trials, programmes, surveys or focus groups) and forms of demand response. From this review, a number of general features that could influence residential user engagement with demand response emerged. These features, and the possible policy implications for residential demand response, are summarised in the remainder of this section.

First, our study identifies a range of factors that influence residential user engagement with demand response. These include:

- **Financial and other motivations for enrolment and response:** Financial and environmental benefits were the most commonly identified motivations for enrolment, and where these were compared, financial benefits were generally found to have the highest importance. Over time users may continue to weigh financial benefits against the effort of responding.
- **Familiarity and trust:** Users may mistrust the perceived motivations of demand response organisers, and this can be exacerbated by unfamiliarity with demand response and the ways in which it can create cost savings. However, greater familiarity with demand response could have positive or negative effects on engagement, depending on experiences and reputation in the specific context. More specifically, concerns around privacy and autonomy associated with direct load control may reduce enrolment, while technical issues and opaque dynamic pricing or automation schedules may erode trust over time.

- **Perceived risk and perceived control:** Enrolment may be discouraged by perceived risk and encouraged by perceived control by users. Direct load control, high price levels and less predictable pricing schedules may be associated with perceptions of risk and/or reduced control. The perceived risk of dynamic pricing may be reduced by some form of enabling technology, and users may see automation as allowing greater control than direct load control. Experience could decrease concerns about direct load control, but concerns may also increase if users experience technical issues. The risk of higher electricity bills may encourage response but reduce enrolment over time.
- **Complexity and effort:** Users may weigh expected complexity and effort against expected benefits from demand response when deciding whether to enrol. Responses may be limited if more dynamic pricing increases the difficulty of changing demand patterns, but different users consider different levels of complexity and effort to be acceptable. Enabling technologies in the form of automation or direct load control may reduce the complexity and effort associated with responding.
- **Interaction with user routines and activities:** Demand response could be facilitated if it is less disruptive to existing routines. However, different groups of users appear to experience different levels of disruption or be more or less willing or able to change their routines in order to respond.
- **User characteristics:** Evidence on the usefulness of socio-demographic data such as income and household size to predict flexibility is mixed. Potentially more flexible users may include those spending more time at home; households without dependents; and users with knowledge of and access to enabling technologies and/or alternative ways to obtain energy services.

The complexity of findings in terms of details of demand response design and implementation, context, and user heterogeneity make it difficult to draw unequivocal conclusions about these individual dimensions. Nonetheless, the findings of this review indicate how different features and approaches may influence engagement with residential demand response, and could contribute to guide early efforts to deploy residential demand response more widely.

Policies to encourage user engagement with residential demand response could be informed by relating factors that influence user engagement to the characteristics of different demand response products and services and approaches to deliver these. There are a wide variety of residential demand response products and services, but in general they vary according to three

dimensions. Firstly, *financial incentives* may involve time varying pricing, rebates, or a payment for accepting direct load control, and the spread between high and low pricing may also vary. Secondly, pricing or other schedules may vary in terms of their *predictability*. Thirdly, *enabling technologies* such as automation or direct load control may or may not be involved. Table 4 summarises how these generic features interact with the factors influencing residential consumer engagement with demand response identified by this review. Overall, our findings suggest that sufficiently high financial incentives and more predictable forms of demand response would tend to support residential user engagement. Enabling technologies may also support engagement if they are implemented in ways that do not reduce trust and perceived control.

In addition to these generic features, the ways in which demand response is delivered can also influence consumer engagement. Our research suggests that trust could be encouraged by providing transparent information on how different parties benefit from demand response, involving trusted actors in recruitment, and setting realistic expectations. Communicating effectively when customers have questions or problems, dealing with issues before they escalate, and clear communication and accountability about issues that do arise can help to maintain trust. If direct load control is implemented, users may perceive greater control if they are notified of which control actions take place. It may be possible to increase demand flexibility by providing support to use enabling technologies, or alternative ways to achieve energy services. Finally, although we did not identify clear findings on which consumer segments could benefit from demand response, general information, bill calculator tools or bill guarantees could help to inform and protect consumers.

Ultimately, the evidence suggests residential user engagement with demand response is complex. Financial motivations appear to be important in enrolment, but user engagement is also influenced by factors including familiarity and trust, perceived risk and perceived control, and complexity and effort. These can relate to characteristics of demand response products and services such as direct load control, other automation technologies, and more or less predictable pricing schedules. Furthermore, while demand response may be facilitated if it is less disruptive to existing routines, different users experience demand response differently, and user engagement can also depend on the details of how demand response is delivered. Further research could offer greater insight into this complexity but the findings of this review offer guidance to maximise potential and avoid risks associated with residential demand response's initial deployment.

	Motivations	Familiarity and trust	Perceived risk and control	Complexity and effort	User routines and characteristics
Financial incentives	Financial incentives may need to be large enough to attract participants		High peak prices could increase perceptions of risk, but there is mixed evidence on whether (risk-free) rebates increase enrolment		
Predictability		Some residential users engage with more dynamic or unpredictable forms of time varying pricing, but in general, less predictable pricing schedules may increase perceptions of risk, increase the complexity and effort associated with response, and create mistrust.			More predictable pricing could enable the formation of new routines that support response.
Enabling technologies		Technical issues, or opaque scheduling of automation or direct load control may reduce trust over time.	Enabling technologies may reduce perceived risk and complexity/effort, but less so if responses conflict with user routines. Perceived control may be increased by: automation rather than direct load control; limiting or allowing users to alter direct load control		

Table 4: How factors influencing residential user engagement relate to generic features of demand response (Authors' own)

Chapter Four: Consumers or users? The impact of user learning about smart hybrid heat pumps on policy trajectories for heat decarbonisation

Abstract

Decarbonisation policies often emphasise the uptake of new end-use technologies, seeing people as consumers of technologies with predictable impacts. In the UK, smart hybrid heat pumps (SHHP) have attracted policy interest as a technology potentially offering multiple benefits for home heat decarbonisation. This paper draws on domestication theory, a perspective that frames people as *users* who actively learn about technologies, to analyse interviews and observations with installers and users involved in the first UK trial of SHHP. This perspective reveals that that users' learning about SHHPs may erode part of the energy savings they offer and have implications for future technology uptake, including the trajectories of heat decarbonisation currently envisaged by policy makers. However, it also reveals opportunities for policy making to influence user learning, including paying closer attention to material elements such as radiator controls and space to air laundry alongside improved information provision. This could be supported by engaging with users as their learning emerges over time. Overall, the paper highlights the policy relevance of technology use as well as uptake and adds to calls for energy policy to think beyond information provision and economic incentives to engage with households, implying a less deterministic approach to policy making.

Keywords: heat decarbonisation; smart hybrid heat pumps; domestication; users; energy policy

1. Introduction

New end-use technologies are expected to play important roles in reducing carbon emissions, making them common targets of energy policy (e.g. IEA, 2010; HM Government, 2011). Heat decarbonisation is currently an important energy policy topic in many regions (BEIS 2018; CCC 2019c; IEA 2019). In the UK, smart hybrid heat pumps (SHHP) are an innovative end-use technology that has recently attracted policy attention, with the Committee on Climate Change recommending that around 10 million could be installed between 2020 and 2035 (CCC 2018, 2019c). The UK department of Business, Energy and Industrial Strategy (2018) have also expressed interest in hybrid systems and the Environmental Audit Committee are now consulting on the potential role of hybrids and other forms of heat pumps (UK Parliament 2020b).

Hybrid heat pumps combine electric heat pumps with a gas boiler, a combination which offers significant technical potential for decarbonising domestic heating. The possibility of switching between electricity and gas for heating could overcome technical challenges associated with the large-scale deployment of stand-alone heat pumps, such as the need to greatly increase electricity generation and network capacity (CCC 2018). Hybrid heat pumps can operate with existing radiators instead of requiring larger heat emitters to be installed; are designed to provide heating profiles similar to those UK users are familiar with; and could also offer demand response services to the electricity system (Turvey et al. 2018).

Policies aiming to reduce emissions through new end-use technologies often involve identifying promising technologies and then promoting their uptake, drawing on insights from engineering and economics (Evans et al. 2012; Labanca and Bertoldi 2018; Shove 2010; Spurling et al. 2013). However, this narrow view of how emissions reductions can be achieved may limit policy effectiveness (Jensen et al. 2019; Royston and Foulds 2019). One limitation of focussing only on the technical potential and uptake of new end-use technologies is that it overlooks the role of *use* in determining technology impacts (Sørensen 2006) including emissions reduction (Sørensen 2013).

Domestication is one alternative theoretical perspective that considers both the uptake and use of new technologies. It emphasises that users play active roles in constructing how technologies are used and the symbolic meanings attached to them, and that this contributes to trajectories of technological development on a societal scale (Sørensen 2006). By drawing attention to people's roles as users as well as consumers of technology, domestication theory can also suggest opportunities to improve policy making (Sørensen 2013).

This paper applies concepts from domestication theory to analyse findings from a regulator funded and industry led trial of SHHP (Turvey et al. 2018) which informed the Committee on Climate Change's recommendation to roll out hybrid heat pumps at scale as part of a trajectory of domestic heat decarbonisation (CCC 2018, 2019c). Because domestication theory conceptualises users' construction of use and meaning as resulting from different types of learning about new technologies, this paper addresses the questions: What were the outcomes and processes of user learning about smart hybrid heat pumps in the context of the FREEDOM project trial? And what are the implications for UK heat decarbonisation policy?

The analysis identifies ways in which users' learning challenges policy expectations about future trajectories of technology deployment. It also identifies ways in which policy might influence users' learning. In doing so, it adds to arguments that energy policy would benefit from looking beyond dominant ideas of predictable technology impact, and of information provision and economic incentives as ways to engage with households as technology consumers (Jensen et al. 2019; Labanca and Bertoldi 2018; Royston and Foulds 2019; Sørensen 2013).

The remainder of the paper is structured as follows: Section 2 outlines the FREEDOM project trial and recent developments in UK heat decarbonisation policy, before introducing domestication theory as a conceptual framework to understand user engagement with new technologies. Section 3 describes the methodology. Sections 4 – 6 present findings and discuss the policy relevance of *what* users learned about SHHP; the policy recommendations suggested by *how* users learned about SHHP; and broader policy implications of considering user learning. Finally, Section 7 summarises conclusions and policy implications.

2. Background

2.1 UK heat decarbonisation policy and the FREEDOM project

Decarbonising domestic heating is an important next step for reducing UK carbon emissions. Around 85% of UK households use natural gas for heating (BEIS 2018). For the UK to meet its commitment to net zero emissions, home heating must switch almost fully to low carbon sources by 2050, but progress to date has been too slow (CCC 2019a). Alongside insulation retrofit, policy makers have seen heat pumps as a key technology to decarbonise home heating, with lesser roles for bioenergy, combined heat and power and district heating in particular circumstances (CCC 2010; HM Government 2011). Policy makers began to consider the potential of hydrogen gas grids and hybrid heat pumps more recently (BEIS 2018; DECC 2013b). Switching to full electric heating provided by heat pumps or developing hydrogen gas

for heating would each pose significant challenges. The UK government and parliamentary committees are consulting on pathways to decarbonise heating (BEIS 2018; UK Parliament 2020a), and on the potential of electric, gas, and hybrid heat pumps as part of this (UK Parliament 2020b).

Hybrid heat pumps combine an electrically driven heat pump with a gas boiler, allowing strategic switching between gas and electricity use for heating. The Committee on Climate Change (2018, 2019) have recommended rolling out hybrid heat pumps at scale to on-gas homes, suggesting around 10 million could be installed between 2020 and 2035. This recommendation was informed by analysis of the FREEDOM Project trial: the first trial of SHHPs in the UK, as well as the largest globally (Carter et al. 2017; Sun et al. 2019). It trialled hybrid systems comprising air source heat pumps and gas boilers which were installed, free of charge, in 75 homes in South Wales (Turvey et al. 2018). Analysis of the trial data, including modelling at UK system level (Imperial College 2018), suggests that hybrid heat pumps could reduce system costs compared to full electrification: reducing the need for new electricity generation and network capacity, and enabling demand response via fuel switching between electricity and gas and the storage inherent in the gas network. At the household level, they also allow the use of relatively small heat pumps, and can operate effectively without upgrading building thermal insulation or systems of heat distribution, reducing capital costs and disruption in the near term. Smart controls developed for the trial automatically minimised running costs. They allowed users to set their desired heating profile using a smart phone app and wall mounted thermostat, while automating the timing of heat pump and gas boiler operation in response to users' settings, the time taken for individual homes to heat and cool, and different forms of demand response tested over the course of the trial, including varying gas and electricity pricing and direct control of heat pumps (Turvey et al. 2018).

Expectations about the benefits of SHHP rest in part on expectations about their users. Smart controls are key to achieving the technical benefits on offer because they mediate fuel switching between electricity and gas; achieving these technical benefits therefore implies that uptake of SHHP and use of the smart controls proceeds as expected. Furthermore, the CCC (2018) identify hybrid heat pumps as a "low regret" option that can reduce carbon emissions in the near term while maintaining the possibility of either full electrification, or development of a hydrogen gas grid in the future. This is based in part on the expectation that hybrid heat pumps would increase public familiarity with heat pumps in a way that supports any later transition to full heat pumps if this is desirable (CCC 2018).

The analysis in this paper refers to two documents produced by the Committee on Climate Change (CCC) as these were also informed by analysis of the FREEDOM project trial (CCC 2018, 2019c). The CCC have an advisory role (CCC 2008), with Business, Energy and Industrial strategy (BEIS) and formerly the Department of Energy and Climate Change (DECC) having primary responsibility for policy implementation. However, the CCC's analysis has previously informed heat decarbonisation strategy (DECC 2012), and is informing further strategy development (BEIS 2018).

The consumer appeal and acceptability of the trial technology were assessed during the trial via a focus group and series of participant surveys (Turvey et al. 2018). Other work has focussed on the design of smart control user interfaces (Stumpf et al. 2018) and on identifying households' current preferred heating patterns and their implications for policy (Hanmer et al. 2019). This paper contributes to knowledge of UK households' engagement with SHHP by taking a broader look at the ways in which they are used as part of everyday lives. To do this it draws on domestication theory, which the following sub-section introduces in greater detail.

2.2 Domestication theory as a framework for understanding user engagement with new technologies

Energy policy often focuses on deploying new end-use technologies to decarbonise energy services such as home heating. Insights from theoretical perspectives such as economics, behavioural economics and social psychology can inform interventions to promote technology uptake, and are used to support policy making more often than other social science perspectives (Evans et al. 2012; Jensen et al. 2019; Labanca and Bertoldi 2018; Royston and Foulds 2019; Shove 2010; Spurling et al. 2013). Studies drawing on such perspectives include Hafner *et al.* (2019) who, drawing on concepts from environmental psychology, found that UK homeowners' stated intention to purchase and install heat pumps was increased by framing heat pump choice as a social norm. Michelsen and Madlener (2013) combined concepts from social psychology and diffusion of innovations to survey German homeowners who had installed a renewable heating system with funding from a government grant. They found that most households installed solar thermal heating to supplement a boiler, because they saw this technology as more compatible with their existing routines. Heat pumps were installed more rarely, by households motivated by multiple factors including energy prices and environmental protection as well as comfort and convenience. Policy implications include the suggestion that policies to promote uptake of renewable heating systems should address these multiple motivations – for example, combining financial incentives such as grants with information

campaigns or technology demonstrations to communicate non-economic aspects of renewable heating systems (Michelsen and Madlener 2013).

However, technologies' impact is determined by their *use*, as well as uptake (Sørensen 2006, 2013). Perspectives that focus only on technology uptake overlook the importance of technology use. Domestication theory offers one alternative theoretical perspective that considers both uptake and use of new technologies. It highlights how users can shape new technologies as they integrate them into their daily routines, a process conceptualised as resulting from three types of learning by users (Oudshoorn and Pinch 2003; Sørensen 2006):

- Cognitive learning involves constructing *understanding* of the technology
- Practical learning involves developing patterns and ways to *use* the technology
- Symbolic learning involves constructing the *meaning* of the technology

Thus, users may change the meaning and/or use of the technology, decide not to use the technology, or even take action to oppose it (Oudshoorn and Pinch 2003; Sørensen 2006). As the meanings and use of technologies evolve across society, they can give rise to social norms and large-scale physical infrastructures, shaping opportunities for future technology development (Sørensen 2006). While drawing attention to the importance of these processes, domestication theory can also suggest fresh opportunities for policy making (Sørensen 2013).

Domestication theory has previously been applied to examine user engagement with new energy and smart home technologies (Hargreaves et al. 2017; Nyborg 2015; Ryghaug and Toftaker 2014; Winther and Bell 2018), including heat pumps (Judson et al. 2015; Juntunen 2014) and direct control of appliances to provide demand response (Aune 2002). A range of policy recommendations have been derived from this work: from designing home energy technologies that help users to incorporate new renewable technologies in their homes over time (Juntunen 2014), to supporting peer-to-peer learning and hands on demonstrations to help users incorporate new technologies into their daily lives (Judson et al. 2015; Ryghaug and Toftaker 2014).

Other perspectives can also consider both the uptake and use of new technologies. Social practice theories conceptualise the performance of everyday life activities as drawing upon socially recognised patterns of normality, which combine elements of meanings, materials and competences. The result is often that practices are reproduced and remain stable, but change can occur, for example if elements are combined in new ways. The introduction of new technologies can be conceptualised as a change in one element of social practices, which may

contribute to practice change (Shove, Pantzar, and Watson 2012). Social practice theories have some similarities to domestication theory, but domestication theory focuses specifically on the uptake and use of new technologies within particular households (Nyborg 2015; Ryghaug and Toftaker 2014), while social practice theories do not focus on technology specifically, and have emphasised how practices are constructed at a societal level (Ingram, Shove, and Watson 2007). Work on sustainability transitions considers how technologies and society co-evolve as technologies diffuse from 'niches' to become embedded in 'regimes'. This can include changes in institutions, supply chains and infrastructure as well as social norms and user practices (Markard, Raven, and Truffer 2012). Users can play various roles in transitions, and indeed domestication theory has informed insights into some of these, but again the focus is on transition processes at societal scales (Schot et al. 2016). As well as offering analytical frameworks, alternative approaches can suggest different ways of engaging users with new technologies. Experimentation, in the form of involving users in co-creation, could improve the design of new technologies, including by consideration of how users' routines influence their sustainability impact (Liedtke et al. 2015). Experimentation has also been applied to invite households to explore ways to make their routines less resource-intensive *without* changing technologies (Vadovics and Goggins 2019). However, this approach was outside the scope of the present study, which was based on an existing trial of adoption of a new technology, and so we judged that domestication theory was the most appropriate framework for analysis of user responses.

This paper draws on insights on user learning during the use of a new technology, smart hybrid heat pumps, to identify policy implications for the UK. Overall, the analytical framework offered by domestication theory is well suited to address the research questions of this paper. By taking UK heat decarbonisation policy as the starting point for analysis, the paper also highlights the policy relevance of considering technology use, as well as uptake (Judson et al. 2015; Nyborg 2015; Sørensen 2013), and adds to calls for energy policy to look beyond information provision and economic incentives as ways to engage with households (Jensen et al. 2019; Labanca and Bertoldi 2018; Royston and Foulds 2019; Sørensen 2013). The approach to link the analysis with policy is described in Section 3.

3. Methodology

This paper reports findings from interviews and observations with users and installers involved in the FREEDOM Project trial. Participants in the FREEDOM Project included 35 private and 40 social housing households (Turvey et al. 2018). This study involved 14 private households

participating in the trial. Convenience sampling was necessary because access to these households was mediated by different parties involved in organizing the trial. Table 1 summarises the composition of the households interviewed, and indicates that many interviewees had occupations relating in some way to energy or technology.

The timeline for data collection is indicated in Figure 1. Interviews and observations were conducted with participant households near the beginning and end of the trial. *Initial user interviews* related to existing routines involving heating as well as the ways in which users became involved in the trial and their experiences of installation. In six cases, it was also possible to observe the final stage of the installation process where the trial equipment and controls were explained to and set up with the users (*installation observations*). *Follow-up user interviews* related to users' routines involving heating; understandings and meanings of SHHP and use of their controls; and what led to these arising during the trial. Both initial and follow-up user interviews took place in users' homes and included any adult members of the household who wished to take part; these included 20 interviewees overall with an average interview length of 60 minutes. Following the trial, *installer interviews* were conducted with the two lead installers responsible for setting up trial controls with the users. These included the ways in which installers engaged with users over the course of the trial and their perceptions of how users had interacted with the trial technology.

All interviews were semi-structured. Topic guides were informed by domestication theory but were designed to be open enough to allow the emergence of ideas that might not be covered by this approach. The topic guide for the initial user interview was additionally informed by previous work on user interaction with heat pumps in the UK and Europe (for example The Energy Saving Trust, 2010; Roy and Caird, 2013; Juntunen, 2014; Judson *et al.*, 2015; Gram-Hanssen *et al.*, 2016), and the findings of a systematic literature review on residential user engagement with demand response (Parrish *et al.* 2020). Reflection during each round of interviews was used to refine the topic guides, while initial analysis of earlier rounds of interviews were used to inform the development of later topic guides.

Figure 1 also indicates the papers' analytical strategy. Both initial and follow-up user interviews were analysed inductively using NVivo. This initial inductive coding identified a number of themes relating to user learning 'outcomes' (what users learned) with relevance for current UK policy on SHHP. This generated the analytical basis of the paper. Further analysis of user interviews considered how the identified learning outcomes varied across different participant households and the 'processes' of user learning that led to them. Analysis of installer

interviews, installation observations and a selection of trial recruitment materials added further insights into how users learned. Analysis of learning processes was organised around the three types of learning conceptualised by domestication theory: cognitive, practical, and symbolic (see Section 2.1). Practical learning included the use of heat in the home as well as use of SHHP controls. Cognitive learning included understandings about how SHHP work and the functions they provide. Symbolic learning included meanings about SHHP, and about the trial itself. Understandings were differentiated from meanings by considering whether interviewees explained why they held a certain view; for example, not drying laundry on radiators *because* it reduces efficiency would be categorised as an understanding, but seeing hot radiators *as a sign of* an effective heating system would be categorised as a meaning.

Interviewee(s) (all names are pseudonyms)	Household members and selected circumstances
Lucy	Working couple with a baby. Lucy works for a utility company.
Kim and Tom	Working couple with three children. Tom works as a heating engineer.
Mike	Working couple. Mike works as a handyman and has knowledge of heat pumps, while his wife works in healthcare.
Richard and Sophie	Working couple with a child at university. Richard teaches engineering at college while Sophie works for the local council.
Alan and Carol	Retired couple with adult children. Alan worked as a carpenter.
Anne and Cai	Retired couple with adult children. Cai worked as an electricity system engineer.
Jim and Rachel	Couple with adult children, one living at home. Jim works in the electricity sector while Rachel is often at home.
Ruth and Harry	Working couple. Ruth works for the local council while Harry is a toolmaker.
Clive	Couple with adult children, two living at home.
Hayley	Couple with three young children. Hayley is a home-maker, her husband works as a carpenter.
Nick	Single man who works in a factory producing petrol engines.
Laura	Working couple with two children. Laura is a primary school teacher.
Debbie and Phil	Retired couple with adult children (declined follow-up interview).
Paul	Working couple with children. Paul works in the electricity sector.

Table 1: Interviewees' households and their circumstances

1) Open coding using NVivo to identify analytical themes and findings on learning outcomes and processes

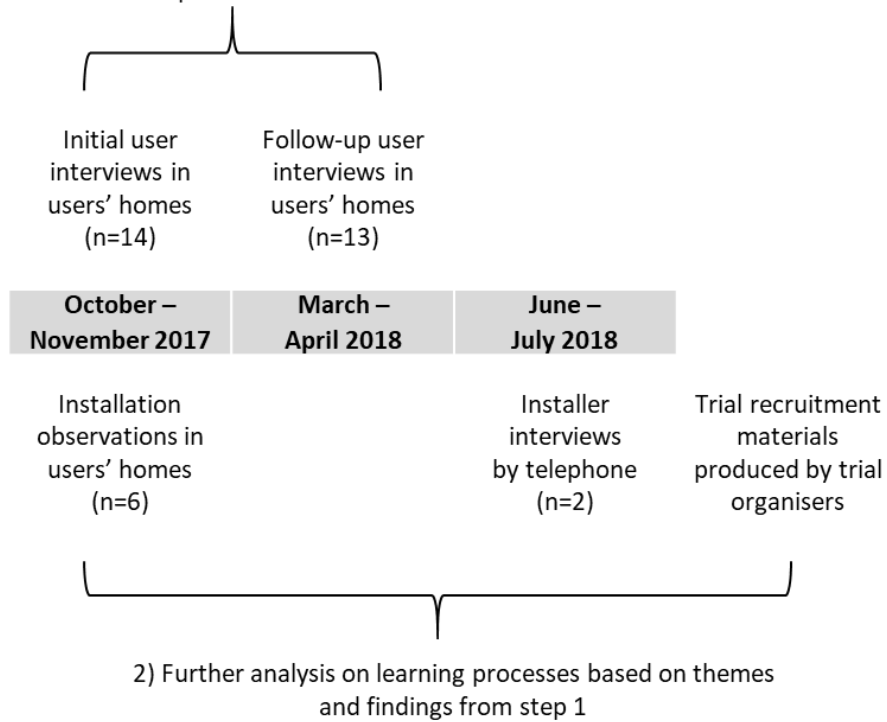


Figure 1: Timeline and strategy for data collection and analysis

4. What users learned about smart hybrid heat pumps

This section presents findings on outcomes of user learning and discusses their relevance for UK heat decarbonisation policy. Learning *outcomes* refers to the ways in which the technology was understood, used, and the meanings users associated with it that emerged from their cognitive, practical, and symbolic learning over the course of the trial. By taking UK heat decarbonisation policy as a starting point for analysis, this section aims to demonstrate the policy value of considering technology use, as well as uptake, when implementing lower carbon energy technologies within people's homes. Section 5 will then present findings on the *processes* involved in cognitive, practical, and symbolic learning before Section 6 discusses the policy implications for influencing user learning.

4.1 Learning about heat pumps as part of a hybrid system

The Committee on Climate Change identify hybrid heat pump deployment as a 'low regret' policy option, based partly on the expectation that experiencing hybrids would increase public familiarity with heat pumps in a way that supports any later transition to full heat pumps if this is desirable (CCC 2018). However, many interviewees ended the trial believing that heat pumps are inadequate as a sole heating technology:

"I don't understand. Technology wise, how could you not have the boiler? Because the heat pump doesn't do the work of the boiler." (*Sophie, follow-up user interview*)

This may be because users have learned about heat pumps as one component of a hybrid system, in which the gas boiler provides hot water and space heating at lower outdoor temperatures. Some users (wrongly) understand that heat pumps are unable to provide these energy services:

"I don't think the heat pump allows us to have hot water - it, um, it solely does the heating, you know? With the boiler doing the hot water. So I don't think we could - I thought it was put to me that you couldn't simply have [a heat pump]." (*Paul, initial user interview*)

"I was under the impression once the temperature got down to about five degrees, they virtually get to a point they can't do anything then" (*Jim, initial user interview*)

This clearly challenges the Committee on Climate Change's expectation that experiencing hybrid systems would increase public acceptance of full heat pump deployment in the future. The processes behind these learning outcomes are examined in Section 5.1. "Constructing understanding of smart hybrid heat pumps".

4.2 Learning to use smart hybrid heat pumps

It is widely recognised that introducing more efficient end-use technologies may lead to new patterns of use that off-set part of the expected energy savings (often known as direct rebound effects; see for example, Sorrell, Dimitropoulos and Sommerville, 2009). Considering how energy is used as part of everyday life can offer a fuller explanation of why new end-use technologies fail to achieve their expected impacts (Jensen et al. 2018), and suggest opportunities for policy to influence these outcomes.

Interview analysis indicated two patterns of use that could reduce the efficiency benefits offered by SHHPs. Some interviewees indicated that the (technically less efficient) practice of drying laundry on radiators might be reinforced or intensified as a result of the more constant heating provided by SHHPs:

R: "I use the radiators more, because obviously the heating is on a lot more isn't it?... jeans, you know, I don't tend to put them in the dryer because they tend to shrink a bit and that, but I can wash them and the following morning the jeans are dry."

Interviewer: "Just by being on the radiators?"

R: "Just by being on the radiators."

J: "Because the heating is on all the time!" (*Rachel and Jim, follow-up user interview*).

In addition, one interviewee described learning to effectively circumvent the intended operation of the smart controls in order to avoid night-time heating, which had kept himself and his wife awake:

"The only way I could get it to sort of work to an extent was to set it on the controls to away, so we'd have to tell it we're on holidays." (*Mike, follow-up user interview*)

Because smart controls are central to achieving the expected technical benefits of hybrid heat pumps (Turvey et al. 2018), changes in use that by-pass the operation of these controls could prevent these benefits from being realised.

The processes that influenced these learning outcomes are explored in more detail in Section 5.2, "Constructing the use of smart hybrid heat pumps".

4.3 Learning about smart controls

The FREEDOM project trial concluded that users generally accepted smart controls (Turvey et al. 2018), which bodes well for the prospect of achieving the technical benefits on offer from SHHPs. However, analysis of users' learning about smart controls during the trial suggests this conclusion deserves further attention.

Interview findings suggest that users were often positive about the idea of smart control in abstract, but many appeared to be unaware of the full range of smart controls tested in the trial. When discussing smart control, interviewees commonly identified a sub-set of the controls tested: the ability of the thermostat to learn how long it takes to heat their home; fuel switching to reduce gas use; and the option to control their heating remotely. Time of use pricing (one form of demand response tested during the trial) was mentioned by a minority of interviewees: those with work experience in the electricity sector that led them to speculate about the possibility of demand response, and those who were told about it at a focus group:

“I didn’t realise that their aim is to, um, alter the air source and the gas, and they want to... they want to run that, so that when the gas is cheaper, they'll use more gas, and when the electric is cheaper, they'll use more electric. Well, none of us in that [focus] group knew that, because we hadn't had any information about that.” (*Alan, follow-up user interview*)

In addition, some interviewees who experienced changing heating profiles felt uncertain about whether this represented ‘normal’ operation or was connected to the trial in some way:

“We've assumed that it's because of the trial they are trying different profiles of heating - if it's not that, it would alter things dramatically.” (*Jim, follow-up user interview*)

Some experiences described by interviewees may indeed have been due to technical issues arising during the trial (Turvey et al. 2018). In addition, some forms of direct control to provide response and reserve services (Turvey et al. 2018) may have been too brief to be noticeable (Eto et al. 2012; Lebosse 2016). Nonetheless, interview findings suggest that users’ apparent acceptance of smart controls might be better characterised as users not questioning automation of their heating that they were not fully aware of. Users often have a bias towards greater trust of automation with lower levels of experience (Hoff and Bashir 2015), but over time, a lack of transparency can influence the meaning that users construct about smart automation and demand response – including the development of mistrust (Carmichael et al. 2014; Wiekens et al. 2014). Altogether this suggests that users’ awareness and acceptance of smart controls requires more specific attention at an early stage, for example in any follow-up trials (Turvey et al. 2018).

The processes that influenced these learning outcomes are explored in more detail in Section 5.1 and 5.3, “Constructing understanding of smart hybrid heat pumps” and “Constructing the meaning of smart hybrid heat pumps”.

By focussing on learning outcomes, this section has supported the argument that technology use and user learning are relevant to energy policy. Section 5 now turns to present findings on *how* users learned about SHHPs during the trial, before Section 6 discusses opportunities for policy to influence users' learning.

5. How users learned about smart hybrid heat pumps

This section examines how users constructed understandings, uses, and meanings of SHHPs during the FREEDOM project trial. This analysis informs the policy implications identified in Section 6, which suggest how user learning might be influenced to support the envisaged role of SHHPs in UK domestic heat decarbonisation.

5.1 *Constructing understanding of smart hybrid heat pumps*

Cognitive learning involves users constructing *understanding* of the technology. Households' knowledge and awareness are seen as central to the uptake of new heating technologies (BEIS 2018; CCC 2018, 2019c), and information provision is a common policy intervention. However, interview findings suggest a number of ways in which users' cognitive learning about SHHPs may differ from a simple process of receiving expert knowledge. Paying attention to these can suggest ways to improve information provision.

Firstly, users may only be receptive to information they feel is relevant: some interviewees said they wanted installers to "just fit it up there" (Nick) or said they "don't need to understand how it works" (Harry). Perhaps because of this, installer interviews indicate that installers may limit the information they provide to users who seem less interested in technical details, instead focussing on practical issues around using the technology. Experts' desire to avoid over-burdening users with information may explain interviewees' lack of knowledge about the full range of smart controls tested as part of the trial (see Section 4.3). Installation observations indicated installers did not (routinely) provide users with information about time varying pricing or direct control of heat pumps; similarly, trial leaflets did not mention either of these forms of demand response, but did describe the features of smart controls most often mentioned by interviewees: the option for users to control their heating remotely, and the ability of the smart controls to learn how long it takes for homes to heat, detect outdoor temperatures, and switch between electricity and gas use to minimise running costs. Meanwhile, paying less attention to information with less relevance may have contributed to the misconception that heat pumps are ineffective at lower outdoor temperatures (see Section 4.1). Trial participants were given leaflets stating that heat pumps "can get heat from the air

even when the outside temperature is as low as -15°C , but user interviews revealed no indication that this contributed to cognitive learning about heat pumps' technical capabilities.

Another reason for this misconception appears to be the design of hybrid heat pumps, and the way users understand installers' explanations of this. Combining heat pumps with gas boilers is central to the technical benefits on offer from hybrids, but it effectively prevents users from experiencing and evaluating heat pumps' performance as a sole heating technology. After being asked about his statement that a heat pump "doesn't put out enough heat", Harry remarked on this clearly: "if you went down and turned the gas off now, then we'd soon find out, I suppose" (follow-up user interview). Beyond this, users' understanding of heat pumps' capabilities may be influenced by the way they understand the technical language used to communicate with them:

"When the system was explained to us, they said for it to work adequately, it had to be above... seven degrees outside... They led me to believe that the heat pump wouldn't be as efficient once they drop below that temperature." (*Debbie, initial user interview*)

Here Debbie uses the terms "adequate" and "efficient" interchangeably. Heat pumps *are* less efficient at lower outdoor temperatures (i.e. they use more electrical energy per unit of heat supplied), but this does not mean they cannot provide heat. Many other interviewees apparently conflated efficiency and effectiveness when talking about home heating. Thus, users' understanding of technical language may contribute to the misconceptions about heat pumps' technical capabilities described in Section 4.1. Section 6.1 discusses opportunities to influence users' cognitive learning, which could potentially avoid the construction of such misconceptions.

5.2 Constructing the use of smart hybrid heat pumps

Practical learning involves users developing patterns and ways to *use* the technology.

Understanding these processes can help to explain why rebound effects and other unintended uses of technologies arise (Jensen et al. 2018), and suggest opportunities for policy to influence these outcomes.

Interview findings indicate that the characteristics of heating provided by SHHPs can lead to practical learning in the form of changing use of heat or controls. Heating patterns during the trial differed from the two-peak morning and evening heating which most interviewees had been used to; unlike gas boilers, heat pumps operate more efficiently when they run more constantly, and heat pump electricity demand peaked at 04:00am and 14:30pm (Turvey et al. 2018).

Many interviewees appreciated more constant heating during the daytime because it aligned with the ways they already used heat at home, for example to provide comfort and care; similarly, Gram-Hanssen *et al.*, (2016) identified that more continuous heating by heat pumps fits with users' desires for greater thermal comfort. More constant daytime heating may also align with the use of radiators to dry laundry, contributing to the intensification of this routine described in Section 4.2. Similarly, Judson *et al.*, (2015) found that heating from heat pumps fits well with the routine of drying laundry on radiators. No interviewees reported that they had *started* to dry laundry on radiators following the introduction of the new technology, however. User interviews suggest this may be due to existing understandings about heating efficiency and condensation, but access to alternative ways to dry laundry such as tumble driers or airers may also be important. Where hybrid heat pumps replaced boilers with hot water tanks, households sometimes lost space used to dry or air laundry, and some interviewees suggested this exacerbated their use of radiators for these purposes.

Unlike changing appreciations of daytime heating, users typically preferred to maintain cooler temperatures while they slept. Some users, such as those already using thermostatic radiator valves (TRVs) to avoid heating their bedroom, never experienced night-time heating. However, many interviewees experienced uncomfortably warm night-time temperatures and/or troublesome noises from the heating system at some point during the trial.

Such experiences often prompted practical learning in the form of changing use of controls, such as turning down TRVs on bedroom radiators, or turning down night-time heat settings in the app-based controls. While the intention of these responses is to avoid discomfort, they can also be influenced by users' understandings about how to heat efficiently or how to use controls, which they already held or which they developed during the trial. For example, Alan explained that he used TRVs to avoid the effects of night-time heating, because to change the 'sleep' temperature settings in the app would mean:

“You're defeating what you're trying to do then, aren't you? You're warming up from nearly zero, up to where you want it. So it's back to the old system, then, before they put this in.” (Alan, *follow-up user interview*)

Alan's response to discomfort allowed him to avoid warmer temperatures in his bedroom, but maintained the efficiency benefits of night-time heating in other rooms. This solution was informed by Alan's pre-existing access to and understanding of how to use TRVs, but also his newly constructed understanding that continuous heating is more efficient. This indicates that cognitive learning can also influence practical learning about the new technology.

Changes in the use of controls typically allowed users to avoid discomfort, but as Jim's example illustrates, this was not always the case:

"We've actually woken up with it being so hot in the bedroom - the radiator's turned down on the frost setting in our bedroom - well, it seems a bit counter-productive opening the window when you've got the heating on, so we don't tend to open that. Whereas, perhaps, we would have had the window open if the heating hadn't been on, if it was too warm." (*Jim, follow-up user interview*).

If users are unable to resolve discomfort this can lead to practical learning that is less in line with the most efficient use of the technology. Mike's practical learning, described in Section 4.2, resulted in him effectively bypassing the operation of the smart controls, and was the culmination of several attempts to avoid night-time heating operation after himself and his wife were repeatedly kept awake. It could be possible to modify smart controls to offer users options to restrict night-time heating, but as this would reduce efficiency, it is interesting to consider alternative approaches to avoid discomfort for users.

Most interviewees either did not experience discomfort with the hybrid system or were able to easily resolve issues by changing how they used the heating controls installed in their homes, drawing on their pre-existing understandings about heating their homes and new understandings they constructed as part of the trial. However, Section 6.1 discusses opportunities to avoid discomfort for the remaining users, and to reduce intensification of drying laundry on radiators.

5.3 Constructing the meaning of smart hybrid heat pumps

Symbolic learning involves users constructing the *meaning* of the technology; meaning can influence future technology uptake when shared socially (Sørensen 2013). Interview findings suggest that meaning is constructed during both uptake and use of SHHPs. Information provision can influence this learning at both stages, but is not the only factor at play.

At uptake, users' meanings about SHHPs appear to be largely informed by trial recruitment messages, since these are similar to commonly stated motivations to take part in the trial such as expecting to save money on heating bills and wanting to help the environment. In addition, many interviewees associated smart controls with ideas of increased comfort and convenience; for some users, these meanings seemed to also be influenced by pre-existing ideas about smart control, automation, or technological progress generally.

During use, additional symbolic learning can occur as users gain experience of SHHPs. "Just

getting used to the system” meant Hayley moved from finding the idea of smart control “a bit scary” (initial user interview) to seeing the SHHP as “like an old system... it doesn’t worry me at all [now]” (follow-up user interview). When experiences align with existing routines, this may contribute to the construction of more positive meanings. For example, some users who never experienced or easily resolved discomfort from night-time heating developed positive meanings about the warmer temperatures they experienced on rising during the night or early morning. Anne (follow-up user interview) took this as a sign “it’s keeping the house really well warm” while Sophie (follow-up user interview) said the continuous warm temperatures were “probably my favourite thing about it”. By contrast, users may develop negative meanings if they experienced discomfort that they are unable to easily resolve. Jim ultimately found night-time heating “a bit too unbearable” (follow-up user interview); similarly, before Mike learned how to avoid automated night-time heating, he explained that “literally there was no way to shut the thing off, so it did get a little bit annoying” (follow-up user interview).

The ‘FREEDOM Project Final Report’ (2018) suggests that providing information on cost and efficiency will lead users to accept unfamiliar patterns of heating. Laura’s symbolic learning demonstrates this can be the case: she contacted the trial organiser after hearing noises from the heating system during the night, and started to see night-time heating more positively after being told it would reduce her heating costs:

“It’s not hot at night-time. It’s hot, warmer than people would... yeah. It does go off, but it doesn’t drop as much as people would think. But that’s fine, because I know why.” (Laura, *follow-up user interview*)

However, for Laura the cost of heating with LPG was a major ongoing concern; her husband, who Laura felt “just [doesn’t] want to listen to the reasons why” (follow-up user interview) remained unhappy about night-time heating. Previous research has found that financial incentives are important to users at the point of uptake, with other concerns becoming more important once heat pumps are in use (Winther and Wilhite 2015).

Interestingly, interviewees’ symbolic learning also appeared to be mediated by the meanings they attached to participating in a trial. Even when they were seen as problems, many users perceived unexpected patterns of heating as something to be expected:

C: “It is an experiment after all... Because we’ve had a few problems with it, haven’t we?”

A: “Yeah. Like I said, when it's warming up before it should, and coming on in the middle of the night.” (*Alan and Carol – follow-up user interview*)

Many interviewees interpreted issues they experienced as trial “teething problems” (Anne and Cai; Clive; Jim and Rachel; Lucy; Ruth and Harry follow-up user interviews); others apparently wanted to cooperate with what they perceived as the trial’s objectives, or were grateful for receiving free heating equipment: as Clive commented, “You got it [SHHP] for free, don’t moan!”.

Overall, user interviews suggested symbolic learning can occur at the point of uptake and through differing experiences of the patterns of heating provided by SHHPs during use. During use, symbolic learning may only sometimes be influenced by information provision and cognitive learning. Given the importance of smart controls, the influence of the trial context on symbolic learning about heating patterns that might be linked to their operation (see Section 4.3) deserves further attention.

Section 6.1 discusses possible opportunities to influence users’ symbolic learning about SHHP.

6. Policy implications of considering user learning

This section first discusses implications for heat decarbonisation policy, directly related to users’ learning about SHHPs during the FREEDOM Project trial. Section 6.2 then discusses some broader implications of considering user learning in energy policy.

6.1 Policy implications of users’ learning about smart hybrid heat pumps

Section 4 identified a number of learning *outcomes* with relevance for UK heat decarbonisation policy, given that user learning about new technologies can occur at a societal scale with lasting implications for technological development (Sørensen 2006). For example, users’ learning that heat pumps are inadequate as a sole heating technology challenges the expectation that rolling out hybrids would facilitate any later to switch to full heat pumps (if this is desirable) by increasing users’ familiarity with heat pump technology. Meanwhile, certain ways in which users learn to use heat and use controls could reduce the technical benefits hybrid heat pumps are expected to deliver.

The remainder of this sub-section is based on the analysis of learning *processes* in Section 5. It discusses approaches that might influence users’ learning to promote certain outcomes about the meaning and use of SHHPs. Following the structure of Section 5, it begins by discussing information provision and cognitive learning, before moving on to discuss practical and symbolic learning. Table 2 provides a summary overview of what interviewees learned about

smart hybrid heat pumps, how this learning was constructed, and the policy implications of both.

Firstly, the analysis in Section 5.1 identifies that users select which information they pay attention to. This suggests that *better tailoring information to households' needs* could make information provision more effective by not overwhelming users with information they are likely to ignore, but also presenting relevant information in a way that speaks to their own needs and interests. Secondly, it suggests that *communicating information in a way that makes sense to users* might be enabled by paying attention to how they construct understandings from the information they receive. For example, talking about energy *cost* rather than efficiency might help users to understand that heat pumps use a higher proportion of electrical energy relative to ambient heat energy at lower outdoor temperatures – and thus cost more to run at these temperatures – but avoid the misconception that heat pumps are *ineffective* at lower outdoor temperatures, which some interviewees constructed from their understanding of the term 'efficiency'. Similarly, Judson *et al.*, (2015) suggest that it is easier for households to understand energy use expressed as cost rather than more technical measures such as kWh.

What did users learn about smart hybrid heat pumps? (see Section 4)	How was learning constructed? (see Section 5)	Policy implications of what and how users learned (see Sections 4 and 6)
Heat pumps cannot provide adequate heating and hot water without a gas boiler (C) .	Learning about heat pumps as part of a hybrid system where familiar gas boilers provided some services (C) . Ignoring written information and misunderstanding technical language used by installers (understanding 'efficient' to mean 'effective') (C) .	<i>What:</i> challenges expectation that experience of hybrids increases acceptance of full heat pumps (C) . <i>How:</i> Verbal information about <i>expense</i> rather than <i>efficiency</i> may help to avoid this misconception (C) .
Pre-existing routines of drying laundry on radiators reinforced or intensified (P) .	Routine aligned with more constant heating provided by SHHP. Some users also lost drying space (if the SHHP replaced a boiler with hot water tank) (P) .	<i>What:</i> decreased system efficiency and reduced energy savings. Expected benefits of fuel switching, mediated by smart controls, may not be realised (P) . Negative meanings associated with unresolved discomfort may impact further technology uptake (S) .
Unintended use of control interface, circumventing operation of smart controls (P) .	Followed repeatedly being kept awake by heating system operation, and failure of intended use of controls to resolve this (P) . Discomfort was usually resolved by changing use of controls such as TRVs but, if not, frustration and annoyance can result (P, S) .	<i>How:</i> material changes (e.g. provision of TRVs, spaces to dry laundry where not available) and effective information on how and why to use them, may influence laundry drying; use of controls; and help to avoid discomfort (C, P, S) . Some users may benefit from follow-up contact to help address issues not predicted during installation (C, P, S) .
Low awareness of demand response tested during the trial (C) . Attributing unexpected patterns of heating to trial context (S) .	Installers avoid over-burdening users with information (C) . 'Trial' taken to mean technology unproven or in development – 'teething problems' should be expected (S) .	<i>What:</i> awareness of smart controls should be given more attention to promote transparency and avoid mistrust (C, S) . <i>How:</i> effective information provision may increase understanding of demand response (C) . Cognitive understandings about cost and efficiency are not sufficient for all users to accept discomfort (S) .

Table 2: Summary of what and how users learned about smart hybrid heat pumps in the context of the FREEDOM Project trial, and implications for policy.
C, P, and S indicate points related to cognitive, practical, and symbolic learning. Section 6.1 provides more detail on ways in which the three types of learning may be linked.

Interview findings indicate that *practical* learning can also be influenced by users' pre-existing or newly constructed understandings about efficient heating and how to use controls. This suggests that effective information provision about, for example, the efficiency losses of drying laundry on radiators might help to avoid the intensification of this routine. On the other hand, interview findings suggest the limitations of information provision and cognitive learning. Understanding how to use heating controls did not always allow users to avoid discomfort; similarly, it seems questionable whether knowledge of the efficiency penalty would prevent the use of radiators to dry laundry if no alternatives are available. Therefore, supporting *complementary material changes* in the home could go further to influence practical learning about SHHPs. These might include ensuring access to alternative ways to dry laundry and ensuring thermostatic radiator valves (TRVs) are installed in bedrooms to help more users avoid uncomfortable night-time heating. However, practical solutions may not always be so obvious: some interviewees were uncomfortably warm despite turning down bedroom TRVs, or were kept awake by noise rather than higher temperatures. Installers used technical surveys to plan SHHP installation. Extending these to consider how the distinct features of the new technology might play out in different houses and households could provide an early opportunity to identify possible issues and make tailored suggestions or even implement changes.

Material changes such as these could also influence symbolic learning (the construction of meaning). Interview findings reveal that whether users initially experience discomfort, and how easily they can use controls to avoid it, can make the difference between developing positive or negative meanings (effectiveness or frustration) for the same technology characteristic, namely night-time heating. Information provision and cognitive learning could support the use of new and existing controls. For some users, cognitive learning about cost or efficiency benefits can also play a direct role in construction of meaning – however, for other users experiences of discomfort may be more important. Effectively attending to symbolic learning might be even more important in a wider roll out of SHHP, because interview findings suggest that the meanings attached to participating in a trial made interviewees more tolerant of unexpected heating patterns.

Finally, because this analysis reveals that practical and symbolic learning continue with experience of the technology, it suggests that more effective policy would support ongoing guidance that can be *tailored based on households' unfolding experiences* over time. During interviews, installers reported that many users contacted them to seek help as the trial

progressed, but user interviews revealed this was not always the case. A follow-up telephone call from installers could help to address issues or questions that arise after technology installation (Turvey et al. 2018). This could also provide an opportunity for installers to support households' learning based on their unfolding experiences with SHHPs, through providing further, tailored information, and/or support with any material changes that could help to integrate hybrid heat pumps into daily routines.

This discussion suggests that installers are in many ways well placed to support users' learning. Installers communicate with users face-to-face, and it may be easier to tailor verbal, rather than written, information to households' needs (Isaksson 2014). User and installer interviews suggest that, similarly to the findings of Owen, Mitchell and Gouldson (2014), installers already attempt to tailor the information they provide to users; that relationships with local installers may encourage users' trust in the advice they receive; and that at least some users already contact installers for help with emerging issues. Furthermore, installers already conduct pre-installation technical surveys. Gram-Hanssen *et al.*, (2016) and Hargreaves, Wilson and Hauxwell-Baldwin (2017) suggest that improved communication between installers and users could be achieved through expanding existing installer certification schemes. This could also include training on material changes that could support practical and symbolic learning, such as the installation of TRVs in bedrooms. However, asking installers to take on this role is likely to present challenges as well as opportunities. Installer interviews suggest that although installers attempt to tailor information provision, they find it hard to assess users' understanding, and rely on leaving behind written manuals that few users read. Furthermore, some installers may feel that explaining the operation of new heating technologies and helping users to control them is too difficult (Owen and Mitchell 2015) or simply not their responsibility (Gram-Hanssen et al. 2016). Any policy based on user learning should therefore consider whether installers, or other actors, such as users' peers (Judson et al. 2015), have the necessary skills and opportunities to influence different types of learning.

6.2 Broader policy implications of considering user learning

Beyond the recommendations outlined above, this analysis helps draw attention to a number of broader policy implications associated with considering user learning. Firstly, the analysis presented in this paper suggests that when policy advice is based on technology trials, consideration should be given to how the trial context may have influenced findings about users (see also Winther and Bell, 2018). More generally, it adds to calls for energy policy to think beyond information provision and economic incentives as ways to engage with

households and end users (Jensen et al. 2019; Labanca and Bertoldi 2018; Royston and Foulds 2019), and highlights that it is relevant for policy to consider new technologies' *use*, as well as uptake (Judson et al. 2015; Nyborg 2015; Sørensen 2013). Because households and users are heterogeneous, and user learning continues over time, considering learning implies identifying opportunities to flexibly respond to and influence learning as it emerges. This is quite different to the 'fit and forget' approach to new end-use technologies implied by a focus on technology uptake, and implies a less deterministic approach to policy making (Jensen et al. 2019; Sørensen 2013).

Because this paper took current policy expectations as a starting point for analysis, it focused on 'unwanted' (Isaksson 2014) user learning that might pose a risk to fully achieving the expected benefits of SHHP. However, user learning can also represent an opportunity to create changes in routines or technologies that improve sustainable outcomes (see, for example, Hyysalo, Juntunen and Freeman, 2013; Vadovics and Goggins, 2019). Drawing attention to user learning also invites reflection on the role that learning itself can play in reducing domestic carbon emissions.

7. Conclusion and Policy Implications

New end-use technologies are expected to play an important role in reducing carbon emissions. In the UK, the Committee on Climate Change has recommended the large-scale roll out of smart hybrid heat pumps (SHHP), based on expectations that uptake of this innovative heating technology could contribute to pathways of decarbonisation for domestic heating. Hybrid heat pumps potentially offer several advantages compared to full heat pumps, such as requiring less additional generation and network capacity and providing greater electricity system flexibility. Alongside decarbonisation of the gas grid they offer a pathway to greatly reduce carbon emissions from home heating, but they are also seen as providing option value by facilitating any later transition to full heat pumps if this is desirable.

While energy policy often focuses on technology *uptake*, this paper focusses on the policy relevance of understanding SHHPs' *use*. It applies concepts from domestication theory – which explains users' engagement with new technologies in terms of learning – to analyse interviews and observations with 14 households and two installers participating in the trial of SHHPs which informed the advice of the Committee on Climate Change.

Analysing users' learning about how SHHPs work, how to use them and what symbolic meaning they carry identified a number of policy-relevant findings. Over time and on a societal

scale, such learning could impact upon the heat decarbonisation pathways envisaged by the Committee on Climate Change; however, analysing learning processes can also suggest opportunities for policy to influence users' learning.

Learning about how hybrid heat pumps work:

- The Committee on Climate Change expect that experiencing a hybrid system would increase UK households' familiarity with and acceptance of full heat pumps, in a scenario where it is desirable to roll these out in the future. However, this expectation is challenged because users' learning about hybrid heat pumps may lead them to (wrongly) understand that heat pumps are unsuitable as a sole heating technology.
- Users could be supported to understand the functioning of the new technology by providing information that is tailored to their needs and communicated in a way that makes sense to them. For example, information that heat pumps operate less efficiently at lower outdoor temperatures can be understood to mean they do not provide effective heating; communicating in terms of 'higher cost' rather than 'lower efficiency' might be more easily understood, and avoid this misconception.

Learning about how to use smart hybrid heat pumps:

- Smart controls that mediate fuel switching between electricity and gas are essential to realise the expected technical benefits of SHHPs. However, if users experience discomfort it is possible for them to effectively bypass the operation of smart controls via unintended use of the user interface. In addition, energy savings could be reduced if users intensify the routine of drying laundry on radiators because it aligns with the more constant heating provided by SHHPs.
- More effective information provision can help users to develop more efficient ways to use SHHPs. Perhaps more importantly, material changes in the home such as installing thermostatic radiator valves or creating spaces to dry clothes, could help to integrate SHHPs into households' existing routines – reducing rebound effects and avoiding discomfort.

Learning about the meaning of smart hybrid heat pumps:

- The trial concluded that users accepted smart control, but this apparent acceptance may have been influenced by the trial context, meaning this conclusion deserves further attention.

- Helping users to avoid discomfort via effective information and appropriate material changes could also encourage users to develop more positive meanings about the technology. If users experience discomfort or other concerns, providing information on, for example, cost benefits is unlikely to be sufficient for all users to develop positive meanings about the smart hybrid heat pump system.

This analysis also indicates that learning proceeds over time, so that engaging with users after a period of use could allow any inputs to be better tailored to individual households' experiences. Installers may be well placed to provide this kind of support, but there are challenges as well as opportunities in asking them to take on this role, and other approaches to influence users' learning could be explored.

More broadly, this analysis adds to arguments that rather than focussing solely on technology uptake, information provision, and economic incentives, policy aiming to reduce carbon emissions from domestic energy use should consider technology *use*, and the ways in which users learn about technologies as they become part of their daily lives. It suggests achieving this may require flexibility: to respond to heterogeneity between different users, and to user learning that emerges over time. Altogether this implies a less deterministic approach to policy making. While this paper has discussed recognising and avoiding user learning that could represent a risk to achieving policy objectives, users' learning can also represent an opportunity to reduce emissions from home energy use, for example by changing routines. Better understanding how and why users learn about new technologies could contribute to reduce emissions from home energy use in both ways.

Chapter Five: Conceptualising processes of user learning in domestication theory

Abstract

The idea that users learn about new technologies in order to make them work within their daily lives is an important concept in domestication theory. It offers a way to conceptualise how technologies and users become co-constructed, and how this extends in path dependent trajectories at both the societal and household level. Studies of users' learning can also offer insights for policy seeking to reduce emissions through the deployment of new technologies in the home. Nonetheless, processes of *how* users learn about new technologies have remained under conceptualised, which also limits opportunities to inform policy. This paper contributes to address this by applying process analysis to study users' learning about a novel heating technology, smart hybrid heat pumps, which is designed to reduce emissions from home heating. Starting from the concepts that cognitive, practical and symbolic learning emerge from interactions between technologies, users' lives and wider society, the analysis abductively develops a framework of four learning processes. The process of *receiving* information emerges from interactions between information that is available to users and information that is important to users. *Experiencing* emerges from interactions between technology characteristics and users' routines and material arrangements. *Interpreting* emerges from interactions between information received and experiences with understandings and meanings users already hold. Finally, *responding* involves interactions between understandings and meanings constructed through the process of interpreting and users' strategies, actions and resources. The analysis illustrates how these four interlinked processes give rise to cognitive, symbolic and practical learning. It also suggests how these processes may be involved in ongoing trajectories at the household and societal level. In particular, it proposes that learning as part of the domestication of more energy efficient and automated technologies may draw upon and act to reinforce socially circulating meanings about how technologies 'should' perform, contributing to trajectories of escalating demand for comfort and convenience. Understanding how users learn may help to identify new opportunities for policy making and implementation.

Keywords: domestication theory; users; social learning; smart hybrid heat pumps.

1. Introduction

New energy end use technologies, including energy efficient technologies and, increasingly, smart automated technologies, are expected to play an important role in addressing climate change by reducing emissions from residential energy use (e.g. IEA, 2020; BEIS, 2021). The analytical framework of domestication theory offers important insights into the potential impacts of such new end use technologies. It challenges technological determinism – the assumption that technology impact is inherent within technological artefacts – by highlighting that users do not passively consume technologies, but actively construct their meaning and use. Users' routines and identities may also change through processes of domestication, or users may reject a technology or even take action to oppose it. These insights can inform strategies and actions in support decarbonisation, for example, drawing attention to the risk that new smart home technologies might be rejected or not deliver anticipated energy savings (Hargreaves et al. 2017), suggesting how households' uptake of microgeneration technologies or electric vehicles might be increased (Juntunen 2014; Ryghaug and Toftaker 2014), or suggesting how installers might also encourage changes to routines and material arrangements to promote greater emissions reductions from using smart hybrid heat pumps (Parrish, Hielscher, and Foxon 2021).

Domestication processes can be conceptualised in terms of *learning* about new technologies. Users learn about what new technologies are for and how they work, and learn when they construct symbolic meanings of technologies and routines of using them in their daily lives. Designers also learn, including about users' wants and needs, policy makers learn about societal needs and demands in order to respond to and attempt to shape them, and so on. While end-users remain the focus of the framework, the concept of learning thus supports analysis of domestication as a multi-sited process that connects micro level processes within homes, workplaces, or similar settings, with macro level elements such as physical infrastructures and social norms. Learning also highlights the path-dependence of domestication on both levels (Sørensen 2006).

However, certain aspects of learning within domestication remain under conceptualised. Emphasis has been placed on *what* happens: that users learn actively and that the meanings and uses of technologies may change as a result; and *why* this happens: because users seek to make new technologies 'work', practically and symbolically, within their own lives and contexts. However, a general conceptualisation of *how* learning unfolds has not been

developed. Insights into how users learn about new technologies could suggest ways to influence these processes, with the aim of reducing carbon emissions.

This paper contributes to the conceptualisation of users' learning within domestication theory by addressing the question: Taking domestication theory as a starting point, how can processes of user learning about a new end-use energy technology be conceptualised? This question is addressed through analysing user learning about smart hybrid heat pumps (SHHP), an innovative energy efficient and smart automated technology that could contribute to decarbonise home heating (CCC 2018, 2019c). The FREEDOM Project trial (Turvey et al. 2018) involved installing smart hybrid heat pumps in 75 homes in south Wales (UK), and this paper presents findings of a process analysis (Langley 1999; Pettigrew 1997) based on repeat interviews and observations with members of ten of these households. Starting from the theoretical basis that learning involves understandings, meanings, and uses, which emerge from negotiations between technologies and users, the process analysis traces learning over time and identifies four interlinked learning processes, each emerging from interactions between different aspects of new technologies and users' daily lives. In addition, the analysis illustrates how these four interlinked processes give rise to cognitive, symbolic and practical learning. It also suggests how these processes may be involved in ongoing trajectories at the household and societal level.

Section 2 provides further background on existing conceptualisations of learning in domestication theory, while Section 3 gives details of the methodology. Section 4 provides background on the trial, outlines empirical evidence to illustrate the four learning processes, and discusses how they might explain the emergence of similar patterns of learning about SHHP across interviewed households. Section 5 discusses how the proposed learning processes contribute to conceptualisations of learning within domestication theory and concludes the paper.

2. Conceptualisations of learning in domestication theory

2.1 Domestication processes as learning processes

The concept of domestication describes processes that occur as users seek to make technologies 'work' within their lives and contexts (Sørensen, 1996, p.10); the name expresses the idea of 'taming' 'wild technologies' so that they become meaningful, useful and familiar (Sørensen, 2006, p.46). The domestication framework originated in media and cultural studies, which highlighted that 'working' implies the creation of both routines of use and meanings

associated with the technology, and defined four phases through which these processes occur (Oudshoorn and Pinch 2003):

- Appropriation describes acquiring technology
- Objectification describes physically placing and displaying a technological artefact
- Incorporation describes using technologies as part of the routines of daily life
- Conversion describes how technologies are used as part of symbolic communication outside of the household

Domestication theory was developed within the STS community, building upon the theory of the Social Construction of Technology (SCOT), which challenged technological determinism by highlighting technologies' interpretive flexibility. This development drew upon concepts of technology script to conceptualise how the materiality of artefacts may influence their meaning and use, which had been under-conceptualised in SCOT (Sørensen 1996); it also included conceptualising domestication processes as processes of *social learning* (Sørensen 1996). The notion of learning offers a way to conceptualise technology-user interactions without returning to technological determinism and investigate how technologies and users may be co-constructed (ibid.). The concept of learning also highlights that domestication processes proceed over time and interact across multiple sites, including individual households and wider society (Sørensen 2006); this is useful as the four domestication phases were often associated with analyses within single sites, typically households, giving the appearance of defined end points (Haddon 2006).

Sørensen, Aune and Hatling (2000) drew on the four domestication phases to identify three more generic 'dimensions' of domestication. The cognitive dimension involves learning about artefacts and appropriating knowledge; the practical dimension involves users' construction of patterns of use; and the symbolic dimension involves the construction of meanings associated with technology and their relationship with users' identities (ibid.). These dimensions similarly lend themselves to studying domestication at multiple sites, and may be applied to a range of technologies (the four domestication phases originally being developed to study domestication of media and ICTs). To emphasise the concept of learning, in this study I simply refer to them as cognitive learning, symbolic learning, and practical learning.

2.2 Current conceptualisations of learning within domestication theory

This sub-section reviews current conceptualisations of learning in domestication theory by taking the position that all domestication processes involve users' learning; in other words, it includes work conducted within media studies as well as the STS tradition, which may use the language of domestication phases rather than learning. These two branches of domestication theory may be considered as compatible although there are some differences in how they have been applied (Sørensen 2006). This review suggests that learning in domestication theory has primarily been conceptualised in terms of *what* kinds of learning occur; *why*; and various ways in which learning is influenced. It also suggests how conceptualisations of learning might be developed further.

Sørensen, Aune and Hatling (2000) concisely identified *what* kinds of learning occur in domestication, as described in Section 2.1 above. Meanwhile, endeavouring to make new technologies work as part of users' lives is identified as the central reason *why* users learn about new technologies. Sørensen, Aune and Hatling (2000) highlight that users do not learn about new technologies in order to develop technically or scientifically 'correct' understandings, at least for their own sake; instead, users learn as part of efforts to make new technologies "function and make sense" within households (p.240). Similarly, (Sørensen, 1996, p.10) explains that "domestication is necessary both to make artefacts work and to make sense. Both action and meaning are important". Thus, the idea that users learn to make technologies work applies to both practical and symbolic aspects of domestication: both routines of use and meanings. As part of this, users respond to the needs and interests of themselves and others, for example members of their household or wider social network (Bakardjieva 2006; Sørensen 1994, 2006).

The concepts of technology script and de-scripton elaborate on why active learning is required for users to make technologies work within their daily lives. Technology script describes how designers' ideas about users and about how technologies will or should be used become embodied within features of technological artefacts. This concept is accompanied by the observation that users must read and translate this script (de-scripton) to put technology to use, and that various challenges may be involved in making artefacts designed for ideal users work in users' particular contexts (Akrich 1992; Sørensen 1996). Thus, technologies do not necessarily work automatically when they are introduced into users' particular contexts; instead, this can require active learning by users.

Technology script is therefore one influence on learning in domestication, although the relative influence of script and of users' interpretation in any particular instance of domestication is an empirical question (Sørensen 2006). Another important influence is negotiations between household members with different needs and interests (Nyborg 2015) as well as by commitments to and roles in social networks outside the home (Bakardjieva 2006; Sørensen 2006). Learning may also be influenced by users' access to different types of resources used as part of domestication. Learning may be influenced by individuals' competences, skills or interest in technologies (Sørensen 1996). At the household level, access to economic resources can influence technology acquisition and use (Bakardjieva 2006) and existing material arrangements may also influence the adoption of new technologies by making it relatively easy or difficult to incorporate them in the home (Juntunen 2014). At the societal level, infrastructures and the availability of technological alternatives may influence the domestication of technologies such as cars (Sørensen 1994, 2006). Socially circulating meanings can also influence domestication processes within the home. The cultural circulation of diverse meanings associated with using a technology may support similarly diverse patterns of use or non-use, but domestication may also be disciplined by social norms and expectations so that non-use requires considerable effort (Sørensen 2006). In this way, social norms and discourses can be conceptualised as another form of script relating to the 'proper' use of technology (Bakardjieva, 2006, p.74).

Influences on learning in domestication may change over time. For example, needs and interests may change throughout users' life course, including with the arrival or growth of children or retiring from work (Bakardjieva 2006; Haddon 2006; Juntunen 2014). Users' past experiences and prior domestications can suggest strategies and actions for practical learning (Sørensen 1994), and influence technology uptake and symbolic learning (Haddon 2006) for example by increasing users' trust in a technology type (Juntunen 2014). Material arrangements in the home which enable and constrain the uptake of new technologies may also be the outcome of prior domestication processes (Juntunen 2014).

Past domestications also contribute to societal influences on learning within domestication. Advertising and authoritative or expert voices can contribute to socially circulating meanings relating to technologies and their correct uses (Bakardjieva 2006); however, via market research and designers' ideas about users, prior collective domestication processes at the household level can influence both marketing and design (Silverstone 2006). Social norms and other socially circulating meanings, large scale physical infrastructures, and the availability of

technological alternatives also emerge from collective processes of domestication within households – as well as influencing them. Domestication theory thus “bridges, a priori, the micro social and the macro social” (Silverstone, 2006, p.233) and conceptualises a recursive relationship between the two levels (Sørensen 2006).

The concept of learning is useful to understand how domestication processes follow path-dependent trajectories. Processes of domestications within households or other sites, and collective societal domestications each influence the “possibilities of learning new ways of doing and thinking” about technology (Sørensen, 2006, p. 56). When referring to the history of previous domestications within the household, and of collective domestications at the societal level, this paper uses the terms *household domestication trajectories* and *societal domestication trajectories*, respectively.

To summarise, current conceptualisations of learning in domestication theory therefore include *what* type of learning occurs (practical, symbolic and cognitive) and *why* this learning occurs (users’ efforts to make technologies work within their lives and contexts). It identifies various *influences* on users’ learning, including negotiations with technology script and the needs and interests of others inside and outside the household, and access to diverse resources at the individual, household and societal level. Furthermore, it identifies that there is a reciprocal and recursive relationship between learning at household and societal levels, and that learning is influenced by histories, or trajectories, of domestication at both household and societal scales. The following sub-section reviews how such conceptualisations have generated insights for reducing emissions from domestic energy use and suggests opportunities for further conceptual development.

2.3 Insights for reducing emissions and opportunities for conceptual development

Analyses based on domestication theory can offer useful insights into the potential for new end-use technologies to reduce emissions from activities in the home. Highlighting users’ learning can challenge narratives that take technological impacts as a given, and point out that technology impact is not always predictable (see, for example, Hargreaves, Wilson and Hauxwell-Baldwin, 2017). Relatedly, analyses have identified a need for caution or even regulation of claims of energy or cost savings from smart home technologies (Aune 2002; Hargreaves et al. 2017), and for policy makers to become more aware of the range of influences on learning about new technologies beyond cost savings and information provision (Aune 2002; Judson et al. 2015; Nyborg 2015; Parrish et al. 2021).

Insights into learning influences have generated recommendations such as training installers to support more energy efficient use of new technologies (Hargreaves et al. 2017; Parrish et al. 2021), enabling peer-to-peer learning to help users more effectively integrate heat pump technologies into their daily lives (Judson et al. 2015), and changing technology design with the aim of improving the integration of smart home technologies and their energy saving potential (Hargreaves et al. 2017). Ryghaug and Toftaker (2014)'s finding that users construct symbolic meanings of electric vehicles through use leads them to suggest that greater possibilities to experience or test drive EVs could increase their uptake, while Aune (2002) identifies a need for information and support to be tailored to different groups of users, and suggests that new technologies must work in accordance with users' objectives if they are to be trusted and accepted. Meanwhile, Juntunen (2014) draws on conceptualisations of path dependence to suggest that design principles of flexibility and interoperability should be adopted to help users incorporate new renewable technologies in their homes over time.

These insights and recommendations relate, firstly, to identifying that users *do* learn, and cautioning policy makers to recognise that technology impact is not always predictable and emerges from a wide set of influences; secondly, to promoting uptake and acceptance of new end-use technologies that may contribute to reduce carbon emissions from activities at home; and thirdly, to influencing technologies' use. Each of these has value. Highlighting the limitations of technological determinism is arguably particularly important in the context of technologies intended to reduce emissions, as a rather specific impact may be expected and desired. Recommendations to promote technologies' uptake and acceptance are also very valuable: this is a necessary first step if they are to contribute to reduce emissions, and in the decarbonisation of home heating in the UK (for example), progress is badly lagging (Rosenow et al. 2020). Relatedly, recommendations to promote the integration of such technologies into users' daily lives may promote their ongoing use. Issues such as rebound effects (e.g. Druckman *et al.*, 2011; Chitnis and Sorrell, 2015) reveal that the way in which technologies are used is also relevant for reducing emissions; however, recommendations that aim to promote emissions reductions during use tend to be relatively vague.

Developing conceptualisations of *how* users learn may suggest new opportunities to influence learning about technologies' use. For example, Hargreaves, Wilson and Hauxwell-Baldwin, (2017)'s suggestion that technology design or installers might promote greater energy savings could likely be developed with an understanding of how these two elements interact with users' lives and contexts, and how this is involved in patterns of learning that may represent

greater or lesser degrees of energy saving. Parrish, Hielscher and Foxon (2021) begin to consider how users learn about a specific technology (smart hybrid heat pumps) in a particular context, and how this can suggest recommendations to promote greater emissions reductions. This paper takes this idea further by developing a set of generic learning processes that illuminate how users' learning emerges from interactions between different elements of technologies with users' lives and contexts, although identifying specific policy recommendations is out of scope of the analysis. The following section describes the methodological approach taken to address this.

3. Methodology

3.1 Overall approach: data collection and process analysis

Process analysis is well suited to analysing learning about new technologies. It involves looking for patterns within temporally ordered data, to answer questions about how and why change or stability may occur (Langley et al. 2013). While it describes a spectrum of approaches with different underlying assumptions (Langley, 1999), some offer a good conceptual fit with domestication theory. Pettigrew's (1997) approach, for example, explicitly recognises path dependence and how agency and context may be mutually shaping, which supports analysis of domestication trajectories and the relationship of household and societal domestication processes.

The approach of process analysis was applied to analyse interviews and observations with ten households, and two installers, participating in the FREEDOM Project trial (Turvey et al. 2018) of smart hybrid heat pumps (SHHP). The trial and SHHP technology are briefly introduced in Section 4.1. To investigate users' learning over time, user interviews were conducted at two time points. Initial user interviews were conducted during or following installation; in six cases it was also possible to observe the final stage of installation, where installers explained trial equipment and set up controls with users. Follow-up user interviews were conducted towards the end of the trial. Both initial and follow-up user interviews took place in users' homes and included any adult members of the household who wished to take part. Following the trial, *installer interviews* were conducted by telephone with the two lead installers responsible for setting up trial controls with the users. User interviews formed the core of the analysis and installer interviews and observations were used to gain further insights into processes identified through the analysis of user interviews. All interviews were semi-structured; Parrish, Hielscher and Foxon (2021) includes further details of how topic guides were developed and what each type of interview covered.

14 households were interviewed in total. Of these, one declined a follow-up interview, while remote control of the smart hybrid systems did not function as intended for another three. This paper analyses learning in the remaining 10 households. Table 1 summarises their composition and indicates that many interviewees had occupations relating in some way to energy or technology.

Interviewee(s) (all names are pseudonyms)	Household circumstances
Richard and Sophie	Working couple with a child at university. Richard teaches engineering at college while Sophie works for the local council.
Alan and Carol	Retired couple with adult children. Alan worked as a carpenter.
Anne and Cai	Retired couple with adult children. Cai worked as an electricity system engineer.
Jim and Rachel	Couple with adult children, one living at home. Jim works in the electricity sector while Rachel is often at home.
Ruth and Harry	Working couple. Ruth works for the local council while Harry is a toolmaker.
Clive	Couple with adult children, two living at home.
Hayley	Couple with three children. Hayley is a homemaker; husband works as a carpenter.
Nick	Single man who works in a factory producing petrol engines.
Laura	Working couple with two children. Laura is a primary school teacher.
Paul	Working couple with children. Paul works in the electricity sector.

Table 1: Description of interviewed households

Alongside diversity in household composition, the sample included homes with a range of physical structures, including for example stone cottages, brick terraced homes, and more recently constructed and better insulated detached houses and bungalows. They also included homes with a variety of material arrangements related to heating, including main sources of heating prior to the installation of the smart hybrid heat pumps (most commonly boilers fuelled by mains gas, but also including boilers fuelled by liquid petroleum gas and wood burning stoves), and the location of radiators and boiler systems.

This variety helped to reveal how material elements of homes influenced users' learning about smart hybrid heat pumps. For example, noise from night-time operation of heat pumps was

sometimes more noticeable to users because parts of their old heating system, and consequently parts of the new SHHP system that replaced it, were located near to their bedroom. Furthermore, variety in households' prior heating systems contributed to influence variety in their pre-existing routines associated with heating, which in turn helped to reveal how pre-existing routines may influence users' learning about smart hybrid heat pumps.

3.2 Steps in applying process analysis

Data analysis involved five steps, which are described in detail below.

1) Identifying outcomes of learning about smart hybrid heat pumps

Process analysis is facilitated by identifying defined 'outcomes' in the data before seeking explanations about how these arose (Pettigrew, 1997, pp. 342-344). In this analysis, the concepts of cognitive, symbolic, and practical learning (Sørensen 1996, 2006; Sørensen et al. 2000) were used to identify outcomes related to users' learning. These were identified in the data as follows:

- Cognitive: Understandings related to what the technology does and how it works.
- Symbolic: Meanings of the technology related to feelings that users communicated about the technology or symbolic understandings. Symbolic understandings were differentiated from cognitive understandings based on a judgement of whether the user could explain why they held the idea. Some interviewees communicated meanings connected to their self-identities but these did not feature prominently in this analysis.
- Practical: Uses of SHHP related to ways that users interacted with the controls; uses of heat related to the levels of heat in the home at different times and routines associated with them, such as using heating to dry laundry, caring for children, or creating a comfortable environment. 'Use' designates a *pattern* of use, so a one-off adjustment of control settings would not be identified in this category.

It should be noted that 'outcomes' do not denote a final result of domestication, but simply moments when particular understandings, meanings and uses were observed; indeed, they also changed within the trial period.

2) Identifying temporal periods of analysis

Process analysis often involves defining temporal periods to further structure analysis. This enables replication of theoretical ideas in successive time periods and supports analysis of how

processes progress and interact over time (Langley 1999; Langley et al. 2013; Pettigrew 1997). The domestication phases cannot provide this function as they do not follow a temporal progression (see Section 2). Instead, three temporal periods were identified based on discontinuities in the empirical data (Langley et al. 2013). The first of these is *uptake/installation*. Both steps are involved in technology adoption, rather than use, and users' accounts of learning were similar across them; also, it would be difficult to distinguish between them because initial user interviews were conducted during or after installation. The second period is *early use*. This was characterised by an initial period of adjusting control settings and forming routines of using SHHP. Finally, *later use* simply describes the period following early use and up until the end of the period of analysis; user interviews reveal that rather diverse processes and patterns of learning emerged in different households during this period.

3) Defining processes of learning as emerging from interactions between elements

While the prior two steps helped to *structure* the process analysis, defining processes of learning was a central *result* of the analysis. Ideas about learning processes were first identified from inductive coding of initial and follow-up user interviews. *Experiencing*, *interpreting* and *responding* emerged as higher-level themes when merging coding of initial and follow-up user interviews. Adding to these, the theme of *receiving* information was identified as part of a previous analysis (Parrish, Hielscher and Foxon, 2021).

These four themes offered a first indication of how cognitive, symbolic and practical learning occurred. The usefulness of this vocabulary was confirmed by constructing analytical chronologies: temporally sequenced written data “reaching towards theory presentation” by testing analytical vocabulary and identifying preliminary patterns and sequences (Pettigrew, 1997 p.346). The four processes were further conceptualised as emerging from *interactions* between *elements* associated with the new technology and with users' daily lives and contexts. For example, the process of experiencing was conceptualised as emerging from interactions between the elements ‘technology characteristics’ and ‘routines and material arrangements’. This approach was informed by existing notions of interaction in domestication theory, such as interactions between technologies and users, and society and households (Silverstone, 2006; Sørensen, 2006). Process analysis is particularly well suited to study interactions (Abbott 2007).

Domestication theory identifies a wide range of influences on users' learning, as reviewed in Section 2. Within this empirical analysis, the identification of specific influences on learning informed definition of more generic *elements* interacting in each learning process. This was

enabled by analysing patterns in the empirical data, which is a central feature of process analysis (Langley et al. 2013; Pettigrew 1997).

The framework of learning processes was largely informed by identifying patterns of *differences* across the interviewed households. In some cases, this was supported by users' explicit accounts of their learning about SHHP. For example, the process of *receiving* information involves interactions between 'information available to users' and 'information important to users'. This definition was informed by the accounts of different interviewees who explained how and why they sought different information about SHHP, or selectively ignored part of the information that was provided by installers. In other cases, interview analysis identified *patterns of learning processes* or *patterns of learning outcomes* (i.e. cognitive, symbolic, or practical learning). Identifying these patterns provided a starting point for further analysis to understand why they arose. For example, some interviewees described experiencing night-time heating from SHHP, while others did not. Further analysis indicated this was likely due to differences in users' pre-existing routines of sleeping with bedroom windows open or closed, and/or material arrangements such as the absence or presence of a switched-on radiator in the bedroom. Thus, this suggested that the process of *experiencing* emerged from interactions between technology characteristics, and users' routines and material arrangements; this was supported by analysing and comparing patterns within other examples of the same process. Similarly, multiple interviewees described technically incorrect cognitive understandings which they had constructed about SHHP. Further analysis indicated that these understandings were constructed because processes of *interpreting* information involve interactions between information users receive and relevant understandings they already hold.

4) Refining definitions of interacting elements from which learning processes emerge

Process analysis often involves inductive-deductive cycles by which theoretical ideas are generated, tested and refined (Pettigrew 1997). In the present study, this was aided by iteratively constructing a series of visualisations to represent learning processes across multiple households and all three temporal periods. These were drawn by hand and developed responding to the insights and questions that arose with each iteration. Visualisations can help to develop theoretical ideas by moving towards greater generalisation and abstraction (Langley 1999). In the present study, they also helped to develop the definition of learning processes by enabling longitudinal replication of theoretical ideas (Langley et al. 2013). Learning processes initially defined in the previous step were applied to learning in different

temporal phases and groups of households, which enabled the definition of elements interacting in each process to be tested, refined, and expanded on when necessary. A guiding principle was simplicity (Langley 1999); in other words, conceptual refinements aimed to define a set of learning processes which were necessary and sufficient to explain the range of patterns of learning identified in the data.

Constructing visualisations also provided a systematic approach to ‘map’ learning. This clarified what learning occurred over the three temporal periods, including certain processes and outcomes that were less immediately apparent.

5) Identifying and analysing patterns of similar learning outcomes

A further round of analysis was performed by identifying patterns of similarities in learning outcomes across the interviewed households. The observation that certain learning outcomes were similar across interviewed households, despite numerous differences in learning processes, invited analysis of how and why these outcomes emerged.

The insights enabled by this approach are discussed in Sections 4.2 and 4.3. First, Section 4.1 sets the scene for the analysis by providing background information on the FREEDOM Project trial and the technology of SHHP.

4. Conceptualising users’ learning about smart hybrid heat pumps in the FREEDOM Project trial

4.1 Setting the scene: the FREEDOM project trial

To put the coming analysis into context, this sub-section provides brief details of the circumstances in which the empirical data was collected.

The FREEDOM Project trialled a new heating technology, smart hybrid heat pumps (SHHP), which were designed to reduce carbon emissions from home heating while minimising disruption for users. It was conducted in south Wales, UK, over the heating season of 2017 – 2018, which included a period of particularly cold weather. The majority of interviewed households were heated by boilers burning mains gas: natural gas (fossil methane) supplied to homes via large scale infrastructure. Two households in less accessible locations were not connected to mains gas, and had boilers fuelled by relatively expensive liquid petroleum gas (LPG), delivered by road and stored in outdoor tanks. In all interviewed households, water heated by boilers was circulated through pipes to wall mounted radiators that transfer heat energy into rooms. So-called ‘wet’ central heating fuelled by mains gas is typical in the UK (Hanmer et al. 2019)

SHHP tested in the trial consisted of air source heat pumps together with natural gas boilers and smart controls that automated their operation. Air source heat pumps use electrical energy to raise the temperature of heat energy collected from the air via an outdoor heat exchange unit. This can create very high efficiencies because the majority of heat energy supplied is transferred from the environment, in this case the air (The Energy Saving Trust 2010). Nevertheless, switching entirely to heat pumps for home heating would require considerable expansion of electricity generation and network capacity to meet peak heat demand; hybrid systems have been proposed as an approach to avoid or defer such an expansion because they can switch from using electricity to gas at times of peak demand (CCC 2018, 2019c). Heat pumps also differ from gas boilers by tending to operate more efficiently if heating is more constant and by producing heat at relatively low temperatures (Turvey et al. 2018). Because of this, in many UK homes efficient heat pump operation would require installation of larger radiators or water-based underfloor heating to transfer heat energy into rooms, alongside building fabric insulation. Hybrid heat pumps are also proposed as a way to avoid or defer building retrofits, while also continuing to provide heating characteristics which UK users are accustomed to (Turvey et al. 2018).

Within the FREEDOM Project Trial, SHHP smart controls automated both the timing of heating operation and which fuel source was used. At the same time, users could input heating settings via a smartphone app and make adjustments using a wall mounted thermostat. The app enabled users to set up heating profiles using the labels 'IN', 'OUT' and 'ASLEEP': a temperature was set for each and they could be programmed to timings that varied for each day of the week. The app also enabled remote control of heating from a mobile device, and an 'AWAY' profile intended for extended periods away from home. Users could check and alter heating profiles via the app (including remote operation) and use the thermostat to check actual and set temperatures and make adjustments. Some, but not all interviewees also installed a supplementary app and email alert service available as part of the trial, which gave information about energy use and costs.

4.2 Developing conceptualisations of learning processes

This section tells the story of users' learning during the three temporal periods defined as part of the analysis: uptake and installation, early use, and later use. Tracing patterns of learning over these three temporal periods shows how learning varied over time as well as between different households, which supported the approach to process analysis described in Section 3.2.

Through this analysis, four learning processes were identified: receiving, experiencing, interpreting and responding. As outlined in Table 2, each of these processes emerges from interactions between two defined elements, relating to different aspects of the technology and of users' daily lives. Section 4.2 highlights evidence to illustrate how these processes of learning emerge from the interactions presented in Table 2, and how these interactions can reveal how and why different patterns of learning emerged in different households and at different times. The analysis tested and refined the conceptual definition of these learning processes by comparing instances of the same learning process across different households, and across multiple temporal periods. The contribution of the analysis within each temporal period is summarised in Table 3 at the end of Section 4.2.

PROCESSES	INTERACTING ELEMENTS	
RECEIVING:	Information available to users	Information important to users
EXPERIENCING:	Technology characteristics	Routines & material arrangements
INTERPRETING:	Information received & experiences	Meanings & understandings
RESPONDING:	Meanings & understandings	Strategies, tactics & resources

Table 2: Summary of four processes of user learning about smart hybrid heat pumps, and the interactions between elements of the technology and of users' contexts from which they emerge. The following sub-sections include empirical analysis which illustrate these four learning processes and links between them.

4.2.1 Uptake and installation: conceptualising processes of receiving and interpreting

Across all interviewed households, users' learning during the period of uptake and installation mainly involved constructing understandings and meanings about SHHP. This involved the processes of users *receiving* information, including from trial recruitment materials, installers, social networks and online research, and *interpreting* the information they received by drawing on understandings and meanings they already held and which they related to the new technology.

Receiving

The process of receiving information varied between users according to their interests and needs. For example, some interviewees explained that during handover they focussed on receiving practical information about the controls, and paid less attention to more technical details:

"I was in a rush as it is, right, app is on here, OK." (*Nick, initial user interview*)

"A new sort of system on the market that, with a heat pump. I didn't understand any of that." (*Nick, initial user interview*)

Users also actively sought information in order to learn about elements of the technology that are important to them. Nick asked installers about electricity use by the heat pump, perhaps because of his concerns about running costs:

"I asked how much electric it'd use, the heat pump. And they said for every kilowatt of electric it uses I think they said it gives you three back in heat." (*Nick, initial user interview*)

Other users sought information by conducting research online or asking knowledgeable members of their social networks. For example, Hayley was able to access advice from social networks formed by her husband, a carpenter:

"My brother-in-law, he's a plumber, we asked his advice. And also, we did ask an electrician his advice as well.... my husband's in the trade, he was asking different people. It was mainly to do with the technology itself, to see if they thought it was suitable, and their views on it basically." (*Hayley, initial user interview*)

Others used online research to gain reassurance about the SHHP technology, or about the legitimacy of the trial itself:

"I Googled just to see hybrid system, and Daikin, and whatever. And usually you get a blog site and everything, don't you, people putting their comments on. And it was pretty much positive stuff on there." (*Clive, initial user interview*)

"So often you get people trying to push solar panels, and this and that, and you think what is your motive? Because there are a lot of schemes, aren't there, that seem too good to be true, and I did wonder... but yeah, I read up and realised that it's actually a bona fide trial!" (*Laura, initial user interview*)

Meanwhile, others sought additional information because of an interest in technology as much as to learn about what to expect from the trial in their own homes:

“I just want to know a bit more in depth. Some people just want to know the basics, don't they, they don't want to get bogged down with too much information and the technical things. But I'm that way, I just wanted to know roughly what we were getting. That's why I went on the internet, to look at it... I like electronics.” (*Jim, initial user interview*)

These quotes illustrate that users' needs and interests influence their attention to information that is presented to them, for example by installers. They also influence decisions to seek additional information – in which case, strategies and resources such as performing online research or asking social networks also come into play. Thus, the process of *receiving* information can be conceptualised as emerging from the *interaction between the information that is important to users and the information that is available to them*. This process contributed to making SHHP 'work' practically and symbolically for different users: for example, by focussing on practical information needed to operate the technology, or seeking information needed to develop trust in the technology.

Interpreting

The process of *interpreting* information to construct understandings and meanings about SHHP involved existing understandings and meanings which users associated with the new technology. For example, construction of cognitive understandings was influenced by existing understandings of technical language. Some interviewees understood that the 'pump' in a heat pump acts to circulate heat around the system, in a similar way to the pump in their former heating system:

“The circulating pump off the combi boiler is using electricity to pump that system around... And the heat pump is only going from the unit in the garden to the boiler. Everything else is the same. So it's only that heat pump is the difference in electricity.” (*Cai, initial user interview*)

Similarly, a previous analysis of this data identified that many interviewees constructed cognitive misconceptions about the functioning of SHHP: that heat pumps cannot provide hot water or heat at lower outdoor temperatures. This may have resulted from users interpreting the information provided by installers, that heat pumps are less *efficient* at lower outdoor

temperatures, to construct the understanding that they are not *effective* at these temperatures (Parrish et al. 2021).

When constructing symbolic meanings, users drew on meanings constructed for previously domesticated technologies which they associated with SHHP and ideas about technological development more generally. Interviewees often associated SHHP with experiences of or ideas about “smart” technology and app-based controls. For example, Harry related the SHHP controls to technologies he already used, including online banking and his car notifying him of low tyre pressure, and concluded “everything's smart now, so why wouldn't your heating be?” (Harry, follow-up user interview).

“It's just like most things in life, it just takes the hassle away from you, doesn't it?... You don't programme Sky, do you - you don't have to set all the timers, you go record and it does it all itself, doesn't it? Any technology that takes away all the crap.” (Harry, follow-up user interview).

Other interviewees drew on more general ideas about technological development, including a sense that increased smart control is inevitable. For example, Hayley commented that:

“The house can generally keep going on its own, which is a bit scary in some ways. But, in other ways it is a good thing. You know, with technology it's crazy these days...that's the way technology is going, though, isn't it? With everything.” (Hayley, initial user interview)

These quotes illustrate how processes of *interpreting* emerge from *interactions between information received and understandings and meanings* users already hold, and which they draw upon when constructing understandings and meanings as part of endeavouring to make a new technology ‘work’. Analysis of early use will illustrate how processes of interpreting may also emerge from interactions between users’ *experiences* and understandings and meanings users already hold.

4.2.2 Early use: conceptualising processes of experiencing, responding and interpreting

In this temporal period, users developed routines of using SHHP controls and routines of using heat from the SHHP system. This practical learning involved processes of users *experiencing* the SHHP system and *responding* to their experiences. Analysis presented towards the end of this section will indicate that the process of responding was mediated by a preliminary step, of symbolically *interpreting* experiences.

Experiencing

Experiences of ease of use and novelty associated with SHHP controls and experiences of air temperatures at home were both important for users' learning. In both cases, experiencing resulted from interactions between *characteristics of SHHP* and *users' existing routines and material arrangements*. Experiencing night-time heating provides one illustration of this interaction. Night-time operation is characteristic of SHHP technology: heat pump efficiency increases with more constant operation, and in the trial heat pump peak electricity demand was measured at 04:00am and 14:30pm (Turvey et al. 2018). However, not all interviewees experienced night-time heating in the same way. Many interviewees described experiencing warmer temperatures during the night-time, but this was not the case for Richard and Sophie: they "always have the [bedroom] window open, because fresh air's good for you" (Richard and Sophie, initial user interview). Similarly, Clive explained that "We just like a cold bedroom. Window is never closed" (Clive, initial user interview), and explained that he does not have a radiator installed in his master bedroom:

"When I was young we used to go down to my Auntie's farm.... I always remember going in the bedroom one evening, and the snow was coming in the windows, and she had about that much, the old-fashioned blankets, sheets and quilts, and eiderdowns as they called them, that thick, and I know where she's coming from now... So we don't have a radiator in there." (Clive, initial user interview)

These quotes illustrate how experiences of night-time heating may vary due to material arrangements, such as the absence or presence of radiators, and routines such as leaving windows open which relate to ideas and experience of what is comfortable and healthy. Similarly, experiences of SHHP controls varied due to users' prior routines of using apps and mobile devices. For example, Nick explained that he is "Quite clued up on apps" and found the SHHP app "so straightforward" (Nick, initial user interview). As his existing routines made his phone very accessible, Nick interacted with the app-based controls more frequently than those of his previous system:

"With my phone it's just right next to me... So I manage it a lot more now, on the app, than I would before." (Nick, initial user interview)

Conversely, Alan explained that "I've only got a clockwork phone, anyway. The others do my head in." (Alan, follow-up user interview). He also rarely used the household tablet computer. Consequently, he found it easier to use the thermostat rather than the app:

“If you're just walking by [the thermostat], saves getting the iPad out or whatever you call it. Saves getting that out and switching it on.” (*Alan, follow-up user interview*)

Other users experienced a sense of novelty or interest connected with the controls. For Harry, this was influenced by incorporating the SHHP app into his existing routine of checking social media apps on his phone:

“You do find it addictive! I get into work sometimes in the morning, and I... check my Facebook, and I check... WhatsApp, and then I usually see what the heating's doing.” (*Harry, initial user interview*)

These quotes illustrate how processes of *experiencing* emerge from *interactions between technology characteristics* (such as more constant heating and features of controls) and *users' routines and material arrangements* (such as placement of radiators, opening windows, and using apps and mobile devices). The following analysis illustrates how experiencing may be followed by processes of responding and interpreting as users endeavour to make new technologies work.

Responding

The process of *responding* describes how users took action following their experiences of SHHP. In early use, most interviewees adjusted the heating profiles input during handover to make their experience of heat from SHHP fit better with their existing routines. For example, Hayley adjusted the initial schedule to better fit her routines of caring for her family:

“We were putting it to come on a little bit earlier, so it was warm for when the children come home from school. And... we were having it to come off at 10, but we were generally up till a bit later than that, so we've changed it to come off at 11 now.” (*Hayley, follow-up user interview*)

Other households changed control settings with the aim of avoiding or reducing night-time heating which they experienced as uncomfortably warm. For example, Anne commented that “I nearly melted away last night... so I've turned the radiator in the bedroom just about off today” (*Anne, initial user interview*).

Users' actions when making such adjustments were often influenced by their understandings of SHHP or associated technologies. For example, Clive drew on his pre-existing understanding of thermostats to respond to the experience of his living room temperature increasing:

“A thermostat in a hallway is not the ideal place to put it. Usually it should go in your living area... my hallway is always colder than everywhere else... what I've had to do is reduce the temperature on that thermostat to compensate for it being colder out there, and giving me the ideal temperature in here. So it's been a bit of trial and error from that point of view, to get it just-right comfortable.” (*Clive, follow-up user interview*)

Newly constructed understandings of SHHP can also influence the ways in which users respond to their experiences. For example, Alan explained that he responded to uncomfortably warm night-time temperatures by turning down thermostatic valves (TRVs) on his bedroom radiators rather than reducing the night-time temperature setting in the app:

“I think you're defeating what you're trying to do then, aren't you? You're warming up from nearly zero, then, up to where you want it. So it's back to the old system, then, before they put this in.” (*Alan, follow-up user interview*)

In this way, Alan's response was influenced by his newly constructed understanding that more constant heating is more efficient, as well as his access to TRVs on his bedroom radiators and understanding of how they function.

These quotes illustrate how the process of *responding* can emerge from *interactions between understandings* (about how technology works, for example, the functioning of controls), with users' repertoires of appropriate *actions* (such as making adjustments to control settings) and/or *access to resources* (such as TRVs). The analysis in Section 4.2.3 further conceptualises processes of responding. However, this section first develops conceptualisations of interpreting which explain the link between users' experiences and their responses.

Interpreting

The analysis in Section 4.2.1 (uptake/installation) illustrated how interpreting may emerge from interactions between information received, and understandings and meanings already held by users. This sub-section develops this conceptualisation by considering how users may draw on existing meanings to interpret their *experiences*. This analysis starts from the observation that processes of responding sometimes involved users changing their experiences of SHHP to fit pre-existing routines, but sometimes involved users changing routines to fit those experiences.

For example, Hayley and Alan both changed their routines of using heat in response to experiences of more constant daytime heating. Alan explained that with the former gas boiler

system “because we're busy people we don't tend to have it on a lot in the day” (Alan, initial user interview). By contrast, he explained that with the SHHP:

“You come in, you can take your coat off straight away because it's not uncomfortable at 17 or 15 [°C] or whatever I've got it at.” (*Alan, follow-up user interview*)

While Alan began to use the SHHP ‘out’ setting instead of clothing to create thermal comfort, Hayley and her family simply no longer tolerated occasional periods of lower thermal comfort when they arrived home:

“With the old system, we just used to have to come in, and if it was cold, then you'd turn it up, and wait for the house to warm up. You don't have that, it is constantly a nice heat.” (*Hayley, follow-up user interview*)

These responses can be contrasted with those previously described, when Hayley and Alan changed their experiences of heating to fit their previous routines. Section 2 introduced the idea that users learn about new technologies in order to make them work in their daily lives. Observing these different ways of responding suggests that users were *interpreting* whether or not particular experiences of SHHP represent the technology ‘working’ for them. This idea follows the basic premise that processes of domestication occur as users endeavour to make new technologies work, and is supported by users’ accounts of their experiences. For example, Alan said “I think the [SHHP] system is great, because the house is never cold” (Alan, follow-up user interview). However, this appreciation of more constant heating did not extend to night-time. In common with most interviewees, Alan explained that “we don't like it too warm in the nights” (Alan, follow-up user interview). Consequently, he did not appreciate the warm night-time temperatures he experienced before turning down bedroom TRV settings:

“In the beginning, you wake up in the night and think good God, it's warm here! You're throwing your duvet off.” (*Alan, follow-up user interview*)

Similarly, Hayley described the SHHP system as “Brilliant” because “the house is never, ever cold, because it's constantly ticking over” (Hayley, follow-up user interview). She explained that the most important reason for using heating was caring for her family:

“With baths and showering in the evenings, it's nice and warm. And they do activities in the evenings, so when they come back it's warm for them. I mean, when I'm here in the day, I'm always busy, so I don't sit down and feel it really. It is generally for the children.” (*Hayley, initial user interview*)

The experience of more constant daytime heating seems to have aligned with and extended this use of heat, as Hayley also appreciated coming home to a warm home after daytime activities during the winter:

“We went up the mountain on sleighs... But then it's nice to come in to a warm house!” (*Hayley, follow-up user interview*)

Altogether, these quotes suggest that processes of *interpreting* whether or not different experiences constitute technology ‘working’ inform users’ aims when responding. This also suggests that processes of interpreting may follow processes of *experiencing*, as well as following processes of receiving as described in Section 4.2.1. However, the accounts of the two interviewed households supplied with LPG suggest that processes of interpreting information can also have important influences on processes of responding. Prior to the installation of SHHP, both households restricted their use of heat because of the high cost of LPG compared to mains gas, and both changed their routines of using heat after the introduction of SHHP. This was most pronounced in Paul’s household, where more rooms were heated after the introduction of the new system:

“Now that we've got rooms that are more comfortable to be in, the kids tend to go up to their own rooms now.” (*Paul, follow-up user interview*)

Meanwhile, Laura noted that “I'm not shouting shut the door as much” (*Laura, follow-up user interview*) to remind her children to close internal doors and stop heat being lost from rooms. She also described experiencing greater thermal comfort after the introduction of the SHHP:

“I've got a jumper on now, but I'm not feeling cold and damp, which is what we would have been.” (*Laura, follow-up user interview*)

Both households changed their routines of using heat by directly responding to meanings of SHHP as a more “efficient” and “economic” system (*Paul, initial user interview*) that would reduce the use – and cost – of LPG. Paul also described how his processes of responding were influenced by his ideas of normal ways to use heat. For example, he noted that to have formerly “huddled around here [living room] as a family” was “back to the olden days I suppose, everyone had an open fire”. However, Paul felt that this situation did not meet current standards of heating: he felt that he did not have a “usable central heating system” – one “that you can truly use for its core function, which is, you know, to warm the house.” (*Paul, initial user interview*):

“It’s terrible just warming a couple of rooms, and all having to huddle down into those three rooms, you know, because you can’t truly afford to heat those other rooms as you’d like to.” (*Paul, initial user interview*)

In addition to the idea that a modern home should have many rooms warmed by central heating, Paul’s specific temperature settings with the SHHP were influenced by norms he encountered at work:

“That seems to be the temperature that we set the office at, 21 degrees, so that seems to be a comfortable temperature for most people, I guess.” (*Paul, follow-up user interview*)

Interestingly, Laura reflected on how her household’s routines of using heat remained different from social norms even after the introduction of the SHHP. Although her heating had become more constant, Laura maintained relatively low temperature settings compared to those of other triallists she met at a focus group, and she reflected that her household’s norms may have been influenced by their established routines of heating with the LPG system:

“When I said ours was set at 17 [°C], people were like oh my God, that’s freezing! (laughing). But for us, that’s brilliant, that we can do that!” (*Laura, follow-up user interview*)

“Coming from a place where we’ve hardly been using it... we’ve got quite a low threshold I think.” (*Laura, follow-up user interview*)

This may relate to the ways in which Laura’s household had previously restricted their use of heat. By contrast to Paul’s family, who had lived with higher room temperatures in a limited number of rooms in the house, Laura described living with lower room temperatures alongside routines such as wearing jumpers and slippers and keeping internal doors closed. Through learning different ways of living with restricted heating, Laura and Paul’s households may also have constructed different ideas and experiences of what is comfortable, which help to explain their differing responses following the introduction of SHHP.

To summarise, the analysis in this sub-section proposes that processes of *responding* are preceded by processes of *interpreting* whether or not different experiences represent new technologies ‘working’. This draws on the established idea that users learn in order to make new technologies work as part of their daily lives. Furthermore, the analysis in this sub-section suggests that when interpreting what kinds of experiences represent technologies working,

users may draw on meanings of what is normal and expected derived from their pre-existing routines (for example, Hayley's routines of caring for her family) or their ideas of social norms (for example, Paul's ideas about appropriate home heating). Processes of responding may also be influenced by meanings constructed for new technologies, such as greater economy or efficiency.

Analysis of later use further develops conceptualisations of the processes of interpreting and responding.

4.2.3 Later use: conceptualising processes of interpreting and responding

The analysis of users' learning during early use illustrated how routines of using the SHHP controls and of using heat emerged from processes of experiencing SHHP, in ways that varied according to existing routines and material arrangements; interpreting these experiences by drawing on meanings of 'working'; and responding accordingly, sometimes by drawing on understandings of SHHP or other technologies. Responding may also emerge from interpreting information received about SHHP, rather than experiences.

This sub-section analyses learning in later use, and further develops conceptualisations of interpreting and responding. This analysis is divided into two parts. "Newly prominent experiences" described learning that occurred after experiences of SHHP changed suddenly due to a period of particularly cold weather; meanwhile "Passing time" describes learning that occurred more gradually as users accumulated experiences of SHHP.

Newly prominent experiences

Both Hayley and Harry began to experience low room temperatures during the period of particularly cold weather. In other households, their shared installer was observed explaining that he set the gas boiler component of the SHHP to 50°C (a relatively low setting) to increase efficiency, and Hayley and Harry's accounts also suggest this was the cause of their experiences. However, Hayley responded by immediately asking for expert help, while Harry adopted a strategy of trial-and-error. Comparing these two cases clearly illustrates how users' strategies of responding may influence learning.

Hayley explained that she experienced cooler air temperatures during the cold snap, and by checking the room and set temperatures on the thermostat she found that the system was not heating up to the set temperature. Hayley's husband then responded by contacting the installer and following his instructions to change a setting on the boiler:

"We were turning it up... when we had the cold spell, but the room temperature was going up to 18[°C], it wouldn't go any higher. So [husband] spoke to [installer], and he explained we had to go upstairs and do something on the boiler, which [husband] done, so the room temperature could come up. So that's all done now." (*Hayley, follow-up user interview*)

This illustrates that the process of responding may link back to the process of receiving: Hayley's experiences changed what information was important to her, and she sought this information using the sources available to her because of the design of the SHHP controls and the design of the trial. This focussed on receiving practical know-how rather than technical information:

"We don't know why, but for some reason the room temperature wasn't going up over 18[°C]." (*Hayley, follow-up user interview*)

This strategy may have been related to Hayley's low interest in the technicalities of the SHHP system, which she described in her account of installation. It enabled Hayley's household to change their experiences of SHHP relatively quickly and in the process they did not construct new understandings, meanings, or routines of use. This contrasts markedly with Harry's account.

Like Hayley, Ruth and Harry experienced a period of uncomfortably low evening temperatures during the cold snap, and similarly to Hayley, Harry first responded by raising the 'in' setting up to 25 degrees – a temperature involved in routines of using his former heating system:

"Ruth would say to me, it's a bit cold, turn the heating up... So I said right, I'll turn it up, to 25[°C]. And I'd sit there, and I'd think, nothing's happening. It doesn't seem to be getting any warmer. Whereas before, when we had just the gas, you'd turn it up, and the boiler would kick in, and whoomph, it would ramp up, and you'd think, that's warm, we can turn it down a bit now." (*Harry, follow-up user interview*)

Unlike Hayley, Harry adopted a strategy of trial-and-error after finding his initial response was ineffective. Harry explained that his installer advised that he might need to adjust the initial settings, because "all houses are different" (Harry, follow-up user interview), and also related this strategy to his understanding of SHHP:

"I literally just thought, it's a teething thing, you've got to get the settings right – because it's trying to work it out itself, isn't it, it's like a self-learning thing I think."

(Harry, follow-up user interview)

Harry tried a wide range of adjustments to different control settings over a period of a couple of weeks. These included actions drawn from Harry's past learning about heating systems and other technology types he associated with SHHP:

"I went and turned it off and turned it back on again. Because to me, that's always the issue, isn't it, with electronics?" *(Harry, follow-up user interview)*

"Most boilers you've got radiators and hot water... I could go downstairs, and turn that up, so when I turn the tap on the water would be hotter. And I think you can do the same with the radiators.... I did play with that as well." *(Harry, follow-up user interview)*

During this period, Harry also began *interpreting* his experiences of SHHP in ways that influenced the actions he took when responding. These processes of interpreting experiences drew upon and modified meanings and understandings of SHHP controls which Harry constructed during uptake/installation.

Harry explained that he began to re-visit understandings and meanings of SHHP following an interaction with another triallist:

"I had this guy, random bloke, knock on my door, and he said, I've noticed you've got the - what do they call it? The heat exchanger outside... and he said, I've had it installed in my house.... and he was convinced [laughing]... he said, I'm sure they're turning it down." *(Harry, follow-up user interview)*

While Harry was initially dismissive, over time he found that "it made me think, then, because we were having these little issues" (Harry, follow-up user interview). He began to feel unsure about how the SHHP system was being controlled, in part by making comparisons with familiar technologies:

"There's not a laptop downstairs running my heating system, is there? There's just a box, and I'm thinking, really? Can't be that clever. Unless it's being done remotely." *(Harry, follow-up user interview)*

Re-interpreting the SHHP controls as possibly ‘trying’ to achieve certain objectives led Harry to devise new actions to respond:

“I don't know if it wasn't explained really well, but because we've got this heat exchanger, so I assume that because that uses less energy it [SHHP system] decides, I'll use that more than the gas.” (*Harry, follow-up user interview*)

“The only thing I could think was, because it's trying to do it so efficiently – I went back on my settings, and... I tweaked them a little bit, so it came on slightly higher, or it stayed on a little bit longer, or it came on earlier, half an hour earlier, and it's almost as if that seemed to help, then.” (*Harry, follow-up user interview*)

Harry's experiences also led him to re-interpret and respond by changing the initial temperature settings. The installer initially set the ‘in’ temperature to 19 degrees, and Ruth had noted that this was perfectly comfortable. However, after the experiences described above Harry re-interpreted this ‘in’ setting as “something stupid” (*Harry, follow-up user interview*). He explained that “When we're out, I've set it at 19[°C] now” (*Harry, follow-up user interview*). This involved re-interpreting the 19°C degree setting as a *baseline* from which to raise the temperature:

"We set up like an average temperature of 19 degrees, so it's ticking over nicely, so if you do want to turn it up it hasn't got to... jump from zero to 22, it goes from 19 to 22, so it uses less energy. And that's how it was explained to me, right". (*Harry, follow-up user interview*)

Interestingly, adjusting the temperature settings involved Harry re-interpreting the setting suggested by the installer as ‘stupid’ but also drawing on understandings of why more constant heating is more efficient constructed from information received from the installer. These contrasting ways of applying information received from the installer reflect that learning within domestication occurs as users seek to make technologies work, rather than passively receiving expert knowledge or striving to develop a technically ‘correct’ understanding.

Hayley and Harry's accounts elaborate on conceptualisations of responding and interpreting in several ways. In terms of responding, they illustrate how two contrasting *strategies* of responding (asking for expert advice, or trial-and-error) can have dramatic influences on users' overall learning. They also illustrate how actions as part of responding may be based on practical know-how (such as following installers' advice or switching SHHP on and off) rather than cognitive understandings.

In terms of interpreting, Harry's account illustrates how processes of interpreting experiences may draw on existing *understandings*, constructing new understandings that feed into processes of responding. This builds on the conceptualisation of processes of interpreting experiences by drawing on existing *meanings*, as illustrated in Section 4.2.2. Harry's account also further develops this conceptualisation by suggesting how processes of interpreting experiences might ultimately lead to the construction of symbolic meanings such as mistrust. This extends the conceptualisation of interpreting whether experiences represent technology 'working', as illustrated in Section 4.2.2. Notably, these forms of interpreting experiences arose after Harry found that his initial actions to respond to discomfort, based on routines and practical know-how, did not change his experiences of SHHP in the way he expected. By contrast, Hayley's strategy of asking for expert advice meant she did not need to interpret her experiences in order to make SHHP 'work'; similarly, in early use users were able to achieve this relatively easily.

Finally, Harry and Hayley's accounts both illustrate how users may seek additional information as part of the process of responding (such as asking for expert advice, or checking technology displays for information). This reveals that processes of responding may be linked with processes of receiving as users endeavour to make technologies 'work' practically. Recalling interviewees' accounts initially presented in Section 4.2.1 reveals that similar processes of responding were at play as users sought additional information during uptake. For example, Laura said:

"So often you get people trying to push solar panels, and this and that, and you think what is your motive? Because there are a lot of schemes, aren't there, that seem too good to be true, and I did wonder... but yeah, I read up and realised that it's actually a bona fide trial!" (*Laura, initial user interview*)

Applying the concepts of interpreting and responding to this statement suggests that Laura drew on existing meanings she held about "people trying to push solar panels" to interpret information she received about the trial, and constructed the meaning that it may have been "too good to be true". She responded by seeking additional information in order to conclude that "it's actually a bona fide trial!" (*Laura, initial user interview*). This indicates that processes of responding may link to processes of receiving information as users endeavour to make new technologies 'work' symbolically, as well as practically.

Passing time

Learning also resulted as users accumulated experiences of SHHP over time. For example, accumulated experience of warmer daytime temperatures apparently led Sophie to re-interpret the remote-control functionality as unnecessary, and respond by decreasing her use of this aspect of SHHP controls:

Sophie: "The ease of being able to warm up the house in advance, if I was coming home early from work, that's something. I have done it a couple of times. But because it's always, it's never cold-cold when you come in...."

Interviewer: "Do you mean that because it never gets really cold, sometimes you might not worry too much about turning it on, because you know when you get home it's not gonna be freezing?"

Sophie: "Yes, yeah." (*Sophie, follow-up user interview*)

Similarly, with accumulated experience many interviewees stopped frequently checking or adjusting programmed settings in the SHHP app. Sophie initially remarked "I don't know how many times I've looked at it today - I've been showing people!" (*Sophie, initial user interview*), but later described how:

"I don't look at the app any more...three or four weeks?... That was probably about it, and then I lost interest in it." (*Sophie, follow-up user interview*)

Sophie explained this change occurred because the information available in the app is "the same thing every day" (*Sophie, follow-up user interview*). Similarly, Harry quickly found the SHHP app less engaging than the other apps he regularly checked on his phone:

"Something like Facebook or Snapchat's different, because it's constantly changing, isn't it? Whereas I know – because it's already set now, for the time being, I'm quite happy with the temperatures and the timings, so I probably won't look at it again until – well, perhaps, if this warm spell lasts more than a week, I might start altering things on it then." (*Harry, follow-up user interview*)

These quotes illustrate how accumulated experiences can lead to processes of re-interpreting what constitutes technology 'working' and responding by changing routines. Together with the accounts in Section 4.2.2, they illustrate how, over time, users' ideas of what constitutes SHHP 'working' can shift from the performance of frequent checks and adjustments using the app-based controls to more automated operation. However, other users' circumstances meant

they continued to interpret the information or control functionality as useful. Nick continued to use the app to adjust his heating schedule because he worked variable shift patterns and was also often away from home for social activities. Meanwhile, Laura's previous experience of the expense of heating with LPG made her anxious to know that this heat source was not operating: "I do like to know if the gas is on. Which it isn't, really, but I do like to check now and again" (Laura, follow-up user interview).

Symbolic meanings associated with SHHP may also change with accumulated experiences. Hayley explained how "Just getting used to the system" meant she moved from finding the idea of smart control "a bit scary" (initial user interview) to seeing the SHHP as "like an old system... it doesn't worry me at all [now]" (follow-up user interview). This suggests that experiences over time led Hayley to re-interpret smart controls by drawing on meanings associated with her previous, familiar gas boiler.

However, symbolic meanings did not always change in a straightforward way with accumulated experience. Harry's account suggests that users may hold contrasting meanings, and perhaps also contrasting understandings, simultaneously. Harry said that "The app's really clever - it is good, the fact that you can, you know, make so many changes... whereas before you would just have a timer and a temperature" (Harry, follow-up user interview). This clearly contrasts with Harry's changed routines of interacting with controls, and he simultaneously noted that "I'm contradicting myself a bit, because.... in the back of my mind I'm thinking, well, do I really need an app on my phone to control my heating? Whereas before I would have just had a thermostat, and a timer, on my boiler, which is doing exactly the same thing" (Harry, follow-up user interview).

Altogether these quotes suggest that accumulated experiences may decisively lead to processes of re-interpreting and responding by changing routines, but that the influence of accumulated experiences on meanings and understandings of SHHP can be less clear cut. Nonetheless, they illustrate that processes of experiencing may change with passing time, as users encounter additional characteristics of the technology (for example, more constant day time heating) or as a result of users having previously changed their routines (for example, routines of frequently interacting with SHHP controls themselves changed some users' experiences of novelty and interest in the technology).

4.2.4 *Summary of learning processes*

Section 4.2 began by proposing that users learn about new technologies via four learning processes: receiving, experiencing, interpreting and responding. As outlined in Table 2, each of these learning processes emerge from interactions between elements of new technologies and elements of users' daily lives. After proposing these learning processes, Section 4.2 presented empirical analysis that illustrates how each of these processes emerges from interacting elements; how the processes may be interlinked; and how sequences of learning processes may result in cognitive, symbolic and practical learning.

Table 3 summarises how analysis across the three temporal periods of uptake/installation, early use, and later use contributed to develop the conceptualisations of receiving, experiencing, interpreting and responding. Figure 1, meanwhile, illustrates the links between the four learning processes and their relationship to cognitive, symbolic, and practical learning.

Processes of receiving and experiencing are linked to interpreting when users interpret the information they receive and their experiences to construct understandings and meanings. Thus, cognitive and symbolic learning may emerge from the processes of receiving and/or experiencing and interpreting. Interpreting may then link to processes of responding in cases where users seek additional information, or aim to change their experiences, as they endeavour to make the new technology work practically and symbolically within their daily lives. Thus, practical learning may emerge from the processes of receiving and/or experiencing, interpreting, and responding, if the actions users take as part of responding involve changes in their routines.

It is important to note that Figure 1 provides an overall summary of the relationship between the four proposed learning processes and the three types of learning outcomes and does not include a time dimension. These links may vary in different households and at different moments. For example, returning to the empirical analysis in Section 4.2.3 illustrates that experiencing may not be followed by the construction of particular cognitive understandings and symbolic meanings if, as in Hayley's case, this is not necessary for users to make the technology work; responding may not result in practical learning, for example if it involves one-off actions as part of a strategy of trial-and-error; and users may sometimes pass through multiple rounds of learning processes (from responding back through receiving/experiencing) as part of a single endeavour to make a new technology work. In this way, the framework of proposed learning processes reflects that users learn pragmatically, as part of seeking to make

new technologies work, rather than to develop 'correct' knowledge or understanding; and that the outcomes of any particular domestication process remains an empirical question.

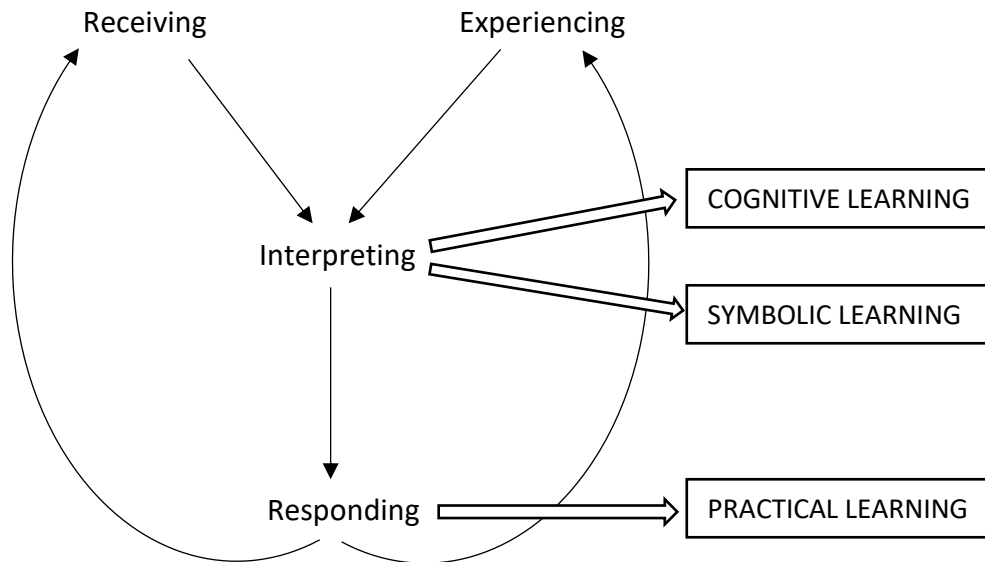


Figure 1: Links between the four learning processes and their relationship to cognitive, symbolic and practical learning. The figure illustrates overall relationships, which may unfold differently in different households and different moments in time.

Overall conceptualisation of learning processes emerging from interacting elements:	Additional elements illuminated by analysis of each temporal period:		
	Uptake/installation	Early use	Later use
	Information available to users – Information important to users	<i>(No further elements identified)</i>	<i>(No further elements identified)</i>
	EXPERIENCING: Technology characteristics – Routines & material arrangements	Technology characteristics - routines & material arrangements	<i>(No further elements identified)</i>
	INTERPRETING: Information received & experiences – Meanings & understandings	Information received – Meanings & understandings	Experiences – understandings Experiences – other meanings
RESPONDING: Meanings & understandings – Strategies, actions and resources	<i>(No elements identified)</i>	Meanings of 'working'; Understandings of technology – Actions and resources	Strategies

Table 3: Learning processes illustrated across temporal periods. This table summarises how the analysis in Sections 4.2.1 – 4.2.3 contributed to the overall conceptualisation of the four learning processes as emerging from a series of interacting elements. It summarises the particular contributions the analysis of each temporal period made to the development of these conceptualisations, and does not comprehensively identify interactions in each of these temporal periods or imply that the listed interactions always occur within similar temporal periods.

4.3 Applying learning processes to understand the emergence of similar routines of using smart hybrid heat pumps

This section identifies a number of ways in which users' learning about SHHP was *similar* across interviewed households. By contrast, the analysis in Section 4.2 was based on differences in learning outcomes between households: for example, the process of experiencing was defined by observing that some interviewed households experienced night-time heating with SHHP, while others did not, and that different households had different experiences of ease of use of SHHP controls. After describing similarities in learning across households, this section then applies the learning processes defined in Section 4.2 to suggest how and why these similar patterns of learning may have emerged. This further illustrates how the framework of learning processes may be applied to analyse users' learning. It also contributes to examine what users' learning about SHHP may "add up to when similarities and differences in patterns of use across households are examined" (Bakardjieva, 2006, p.71).

During uptake and installation, all interviewed households constructed new, positive meanings for SHHP, including efficiency, economy, comfort and ease. In this case, the observed similarity likely reflects that SHHP were previously unknown to all interviewees, and that only trial participants were interviewed (so that any non-participants who may have constructed less positive meanings were not included).

This makes it more interesting to understand the emergence of similar routines of using SHHP. During use, all interviewees who described experiencing more constant night-time heating also described changing SHHP and radiator control settings with the aim of maintaining routines of sleeping in lower temperatures. Similarly, all interviewees who described experiencing more constant day time heating also described appreciating this experience and changing their routines in response. Furthermore, domestication of SHHP often involved users decreasing their frequency of interactions with heating controls compared to their former system; although some users initially interacted frequently with SHHP controls, these initial routines typically ended after a few weeks.

The analysis in Section 4.2 indicates that routines of use typically emerged from linked processes of experiencing, interpreting and responding. Notably, processes of experiencing and responding both varied across households: processes of experiencing varied as a result of differences in material arrangements and pre-existing routines, while processes of responding varied because of the strategies and actions adopted by users. The fact that similar routines of using SHHP emerged despite this variation points to the importance of the processes of

interpreting that precede responding. The analysis in Section 4.2.2 introduced the idea that users interpret whether different experiences of SHHP represent the technology ‘working’, and that this determines whether users embrace experiences of SHHP or seek to avoid them. Observing that similar routines of using SHHP emerged across interviewed households suggests that similar ideas of what constitutes ‘working’ guided users’ interpretation of their experiences, and their subsequent responses. This is visualised in Figure 2.

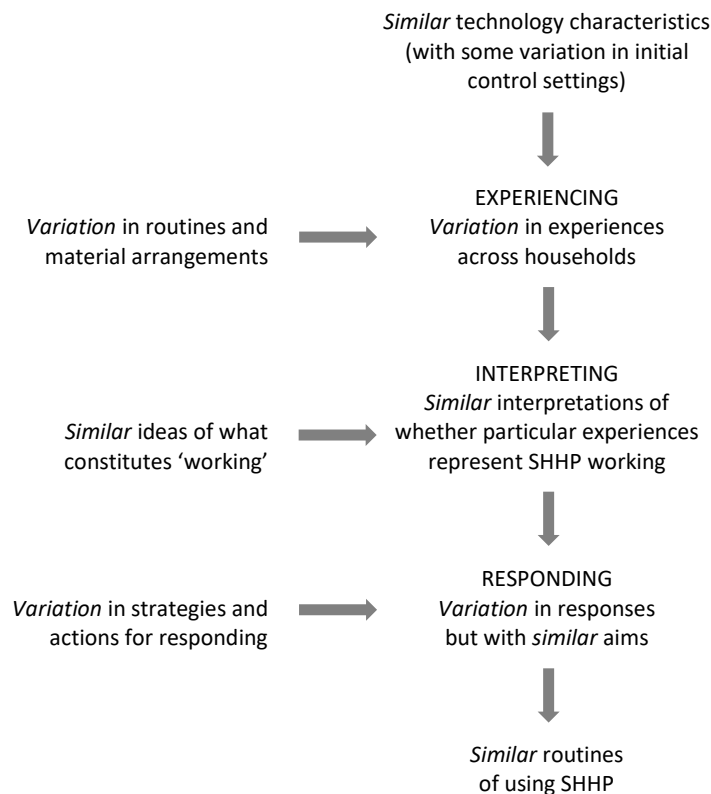


Figure 2: How processes of experiencing, interpreting and responding may explain the emergence of similar routines of using SHHP across many interviewed households.

Shared ideas of what constitutes SHHP working may have emerged in part from shared pre-existing routines relating to the timing of using heat. All interviewed households described pre-existing routines of heating during the morning and evening, with cooler room temperatures during night-time and day-time – often including times when a household member was at home during the day. These routines of heating, which are also typical across the UK (Hanmer *et al.* 2019), can explain why all interviewees who described experiencing higher night-time temperatures, also sought to avoid them: night-time heating was experienced as

uncomfortable because it differed from the routines users were accustomed to. However, users' ideas of what constitutes 'working' did not stem only from pre-existing routines: if this was the case, interviewees who experienced more constant daytime heating would not have interpreted this positively and responded by changing their routines.

As reviewed in Section 2, users may also draw on *socially circulating* meanings as part of learning within domestication; thus, socially circulating meanings might influence users' ideas of what constitutes SHHP working, in addition to their prior routines. Within the empirical analysis in this paper, this is most clearly demonstrated by Paul's account of practical learning following the introduction of SHHP (detailed in Section 4.2.2) because he explicitly related this to his ideas about normal and acceptable standards of home heating. Paul also explained that he had increased his household's use of heat in response to meanings of SHHP as more economic and efficient. However, by decreasing concerns about the cost of LPG, these meanings appear to have *enabled* a shift towards achieving 'normal' routines of using heat. This raises the possibility that other users may have drawn on socially circulating meanings when interpreting their experiences of, for example, more constant day-time heating.

Similarly, socially circulating meanings relating to automation and smart controls might contribute to explain the emergence of routines of less frequent interaction with SHHP controls. In this case, variation across households occurred because different pre-existing routines of using mobile devices and apps influenced processes of experiencing ease-of-use and responding by constructing routines of using predominantly the SHHP app, or wall mounted thermostat. Despite this variation, over time similar routines of interacting less frequently with SHHP controls emerged across most interviewed households, including those who initially interacted intensively with the app-based controls.

In some cases, decreasing interaction with controls can be explained as resulting from users' experiences of comfort with the SHHP system. For example, Rachel explained that she "used to put it [boiler] on constant" if she felt too cold while at home during the day, but during the trial she did this only on "one or two days when it was really cold" (Rachel, follow-up user interview). Meanings of intelligence constructed for SHHP might also have contributed to the emergence of such routines by suggesting that smart controls could operate home heating more efficiently than users' manual input. However, Harry's account suggests a more complex story. He began to question whether he, or the smart control system, was ultimately responsible for optimising the operation of the heating:

“It's like a self-learning thing I think, so it's trying to decide the most efficient way of heating this house. And if the most efficient way is having the heating up - like, now, I come home, and the heating was on, even in this weather.... But that's my fault for setting it a certain temperature, isn't it? It doesn't realise that it's so warm outside that you're not gonna need it this week. I don't know, I.... (laughing) it's hard to explain! Whether it was, thinking, making that decision itself...” (*Harry, follow-up user interview*)

Interestingly, Harry explained that he initially took personal responsibility for managing the SHHP system – and that his emerging routines of less frequently interacting with the SHHP app were influenced by his ideas about how actively he “should” be managing a household chore like home heating:

“You start off thinking, I’m gonna be super-efficient now, and make sure I’m running it really well. And then you get to a point where you’re thinking, pfff, is it worth it?... I’ve got loads to do, without worrying about the heating – which is how it should be, isn’t it?” (*Harry, follow-up user interview*)

As described in Section 4.2.1, Harry had previously domesticated other ‘smart’ technologies, and had constructed meanings that smart technology “just takes the hassle away from you” and “does it all itself” (*Harry, follow-up user interview*; see also Section 4.2.1). This suggests that Harry’s pre-existing routines of using smart technologies may have contributed to influence his ideas about what constitutes SHHP ‘working’.

However, users who had not previously domesticated ‘smart’ technologies similarly suggested that greater automation represented SHHP ‘working’. For example, Anne explained that “I’d like to get it [SHHP controls] to a situation where I don’t need to think about it at all, it’s set, and it will just, and that’s the aim” (*Anne, initial user interview*), while Carol remarked “If it’s tuning in to our needs, we won’t have to bother with it, will we?” (*Carol, initial user interview*). Again, this raises the possibility that socially circulating meanings may have influenced the emergence of routines of less frequently interacting with SHHP controls, as well as of more constant daytime heating. Some interviewees did refer to ideas about smart and automated technologies developing in society: for example, when discussing SHHP smart controls, Hayley remarked: “That’s the way technology is going, though, isn’t it? With everything.” (*Hayley, initial user interview*; see also Section 4.2.1).

To summarise, this section described similar routines of using heat and using controls which emerged during the domestication of SHHP across interviewed households. It also suggested

that these similarities emerged due to the influence of socially circulating meanings on processes of interpreting whether or not different experiences of SHHP represent the technology 'working'. This explanation can account for observations that similar routines of use emerged despite diversity in processes of experiencing and responding; sometimes differed from users' pre-existing routines; and appear not to be fully explained by meanings such as efficiency or intelligence which users constructed for SHHP. This analysis is necessarily more speculative than that in Section 4.2 because in most cases socially circulating meanings cannot be observed directly from interviewees' accounts of their learning about SHHP. However, it is interesting to note that Shove (2003) previously identified trends for standards of comfort and convenience to increase on a societal level alongside the deployment of new end-use technologies. This lends support to the idea that socially circulating meanings may underly the observations of increased use of heat, and decreased interactions with controls. The following section discusses how the framework of learning processes proposed in this paper may contribute to illuminate the relationship between such societal trajectories and users' learning at the household level.

5. Discussion and Conclusions

Within domestication theory, the idea that users learn about new technologies in order to make them work within their daily lives is an important part of conceptualising the co-construction of users and technologies. To further conceptualise *how* such learning emerges, this paper has applied process analysis to study users' learning about an innovative lower carbon heating technology: smart hybrid heat pumps (SHHP). This section discusses how the analysis in this paper builds on and develops existing conceptualisations of users' learning within domestication theory, begins to reflect on how these insights might be applied as part of policy to reduce residential carbon emissions through the uptake and use of new technologies, and outlines possible further work.

5.1 The relationship between the proposed framework of learning processes and existing conceptualisations of users' learning

This paper proposes a framework of four interlinked learning processes, each emerging from interactions between defined elements of new technologies and of users' daily lives, which combine to give rise to cognitive, symbolic, and practical learning. This framework builds upon several existing conceptualisations of learning in domestication theory.

The approach to develop the framework was informed by established concepts of negotiation and interaction, such as the role of users' negotiations with technology script, with other

household members, and with elements such as social norms from wider society (see, for example, Silverstone 2006 and Sørensen 2006). The framework also builds on previous work that identified influences on users' learning, as these often overlap with the interacting elements defined in the proposed framework. For example, the element 'information important to users' can be considered as one aspect of users' needs and interests, which are conceptualised as a central influence on domestication (see, for example, Sørensen, 1996, 2006); 'information available to users' may include information from advertising and authoritative voices, as identified in analyses such as Bakardjieva (2006); the potential for 'existing material arrangements' and 'existing routines' to influence the domestication of new technologies is demonstrated by analyses such as Juntunen (2014) and Judson *et al.* (2015), and so on.

These existing conceptualisations of users' learning are extended by the framework of learning processes presented in Section 4.2 of this paper. By conceptualising various influences on users' learning as elements which interact in defined ways, it provides a more systematic approach to identify how cognitive, symbolic, and practical learning emerge. This framework represents a substantial development from existing descriptions of learning processes in domestication, such as learning-by-doing (Hargreaves *et al.* 2017; Ryghaug and Toftaker 2014), learning-by-using (Juntunen 2014) or learning by trial-and-error (Sørensen 1996; Sørensen *et al.* 2000). These concepts highlight that users' learning is conceptualised as pragmatic, so that users learn in order to make technologies work, rather than aiming to develop a 'correct' or complete understanding. They also highlight that learning occurs during technology use, not only uptake. Furthermore, the concepts of practical and symbolic learning highlight that users construct routines and meanings as well as cognitive understandings. Nonetheless, these existing conceptualisations do not provide any details about *how* cognitive, symbolic and practical learning emerge from interactions between different elements of technologies and of users' daily lives.

Another approach to analyse how users learn is Aune's characterisation of four strategies by which users learned about personal computers: experimentation, tinkering, analysis and training (Sørensen *et al.* 2000). These four strategies involved different combinations of learning by trial-and-error, reading manuals and other sources of information, learning from peers, and supervised training, and were associated with different groups of users with different needs and interests (*ibid.*). The analysis in this paper similarly identifies that different users may adopt different strategies as part of learning about SHHP, such as trial-and-error or asking for expert advice. However, the proposed framework identifies this aspect of users'

learning as only one element of wider learning processes. Furthermore, the elements defined in the proposed framework are intended to be generic enough for the framework to be applicable to learning about other technologies and in other contexts, while the strategies characterised by Aune appear to be specific to the case analysed.

In addition to illuminating how users learn about new technologies, the analysis in this paper contributes to conceptualise interactions between users' learning processes and household and societal domestication trajectories. As described in Section 2, these concepts describe how users' learning about new technologies is influenced by previous domestication processes, and, in turn, may influence domestication processes in the future. Thus, they highlight path dependence in users' learning.

Defining learning processes as emerging from interacting elements can help to analyse the progression of household domestication trajectories. Figure 3 visualises how many of the interacting elements from which users' learning emerges are constructed through cognitive, symbolic, and practical learning which occurred as part of previous domestication processes. The analysis within this paper identifies various examples of such dynamics. For example, Harry's account in Section 4.2.1 indicates how meanings he constructed through previous domestications of "smart" and programmable technologies influenced his interpretation of SHHP smart controls as normal and desirable. Section 4.2.2 describes several examples of how routines of use constructed during the prior domestication of gas boilers and mobile devices strongly influenced processes of experiencing SHHP, and consequently practical learning. This includes processes of experiencing more constant daytime and night-time heating, as well as experiencing ease of use of the wall mounted thermostat or app-based controls. Furthermore, Clive, Alan, and Harry's accounts in Sections 4.2.2 and 4.2.3 illustrated how processes of responding can be informed by understandings of controls such as thermostats, thermostatic radiator valves and boiler settings which were constructed during the domestication of gas boilers. In this way, the analysis in this paper supports the findings of previous studies which highlight that prior domestications can suggest strategies and actions for practical learning (Sørensen 1994) and influence technology uptake and symbolic learning (Haddon 2006), as well as reiterating that the domestication of new technologies is influenced by previously constructed routines of use (see, for example, Sørensen, 1994; Judson *et al.*, 2015; Nyborg, 2015). Learning during the domestication of SHHP also has the potential to influence future domestication processes, although this is of course not visible in the empirical data (see Figure 3).

The analysis in Sections 4.2 and 4.3 of this paper also identifies how socially circulating meanings may have influenced users' learning about SHHP. Specifically, it suggests that interviewees may have drawn upon social norms and other socially circulating meanings when interpreting whether or not their experiences of SHHP represented the technology 'working'. This reflects the idea that socially circulating meanings can influence users' learning by acting as a form of script regarding the normal, expected or desirable uses of technologies (Bakardjieva 2006; Sørensen 2006). Sørensen (2006) highlights that domestication theory does not conceptualise norms regarding the proper uses of technologies as static. Instead,

“On the one hand, domestication is disciplined through expectations and norms... On the other hand, over time, a collective domestication produces new norms and expectations that influence the way the artefact is used, the meaning it signifies, and the possibilities of learning new ways of doing and thinking about it... The domestication argument, as presented here, is that norms may be understood as contested, fluid, emergent properties of developing technologies.” (Sørensen, 2006, pp.56 - 57).

This reflects the conceptualisation of co-construction of users and technologies, and the recursive relationship between domestication trajectories at the household and societal level. Social norms and other socially circulating meanings may contribute to influence users' learning, but they are also an emergent outcome of collective domestication processes through which they may eventually be transformed. In this way, what it means for a technology to 'work' can also change.

The analysis in this paper may contribute to elaborate on one mechanism underlying this recursive relationship. Figure 4 visualises how processes of learning about SHHP may be influenced by elements from both household and societal domestication trajectories, and how learning about SHHP might influence these trajectories in turn. Points 1 – 5 of Figure 4 are directly supported by the empirical analysis within this paper, while the dynamics illustrated by point 6 are speculative.

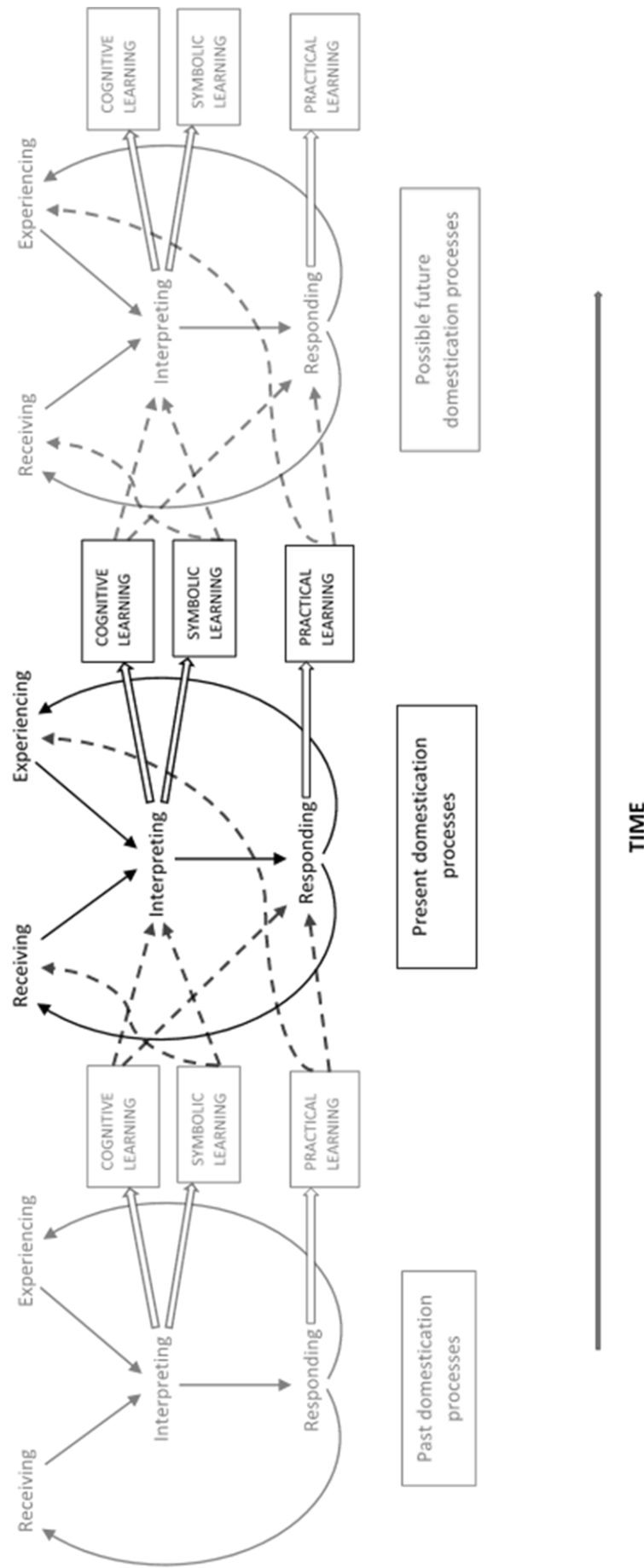


Figure 3: Visualising interactions between learning processes and household domestication trajectories. Dashed arrows indicate how cognitive, symbolic and practical learning may give rise to elements which interact as part of learning processes in later domestications. For example, understandings and meanings constructed through cognitive and symbolic learning influence processes of interpreting if they interact with information received and experiences of new technologies. Meanings constructed through symbolic learning may influence processes of receiving if they influence what information is important to users, and routines constructed through practical learning influence experiencing if they interact with the characteristics of new technologies. Strategies and actions of responding may be influenced by previous cognitive learning, for example understandings of how to use controls, and practical learning in the form of practical know-how or routines of responding to common experiences.

SHHP are visualised entering the household from the societal level because the design of new technologies is informed by designers' ideas of an ideal, or average user, which can be considered as a kind of abstraction from the range of users that might exist in different settings; this corresponds to the notion that technologies enter households from the outside (Silverstone 2006). Point (1) of Figure 4 illustrates how SHHP becomes part of household material arrangements during uptake and installation.

Following this, processes of *experiencing* SHHP emerge from the interaction of different SHHP characteristics with pre-existing household routines and material arrangements. These interactions may give rise to a variety of experiences of different characteristics of the technology, which also vary in different households. Point (2) of Figure 4 represents the emergence of this diversity of experiences.

Point (3) then illustrates how processes of *interpreting* these various experiences emerge from their interaction with meanings of what constitutes technology working, which may stem from users' pre-existing routines and/or those circulating at the societal level. These processes of interpreting influence users' aims when responding to different experiences: should the experience of the technology be changed, embraced, or simply stay the same? As illustrated by point (4), subsequent processes of *responding* may involve users changing material arrangements and/or routines as they seek to make their experiences of SHHP align with their ideas of what constitutes working.

Changes in routines and material arrangements will also change users' experiences of SHHP, as illustrated in point (5). The interview analysis presented in Section 4.2.3 illustrates that linked processes of experiencing, interpreting, and responding may sometimes occur multiple times before users succeed in making their experiences of SHHP align with their ideas of what constitutes working. Point (6) suggests what might result once this occurs. Firstly, within the household level, interpreting experiences as 'working' seems likely to reinforce the material arrangements and routines associated with these experiences, and potentially confirm users' ideas of what constitutes the technology working. Furthermore, since socially circulating meanings emerge from collective domestication processes at the household level, ideas about what constitutes technology 'working' which become established within households may also contribute to inform social norms or other socially circulating meanings.

Many empirical studies of domestication have focussed on processes that occur at the household level (Bakardjieva 2006; Haddon 2006). Empirical studies of users' learning may highlight the influence of societal level elements such as large scale physical infrastructures

and social norms (see, for example, Sørensen, 2006), but have often given less consideration to what collective domestication processes might ‘add up to when similarities and differences in patterns of use across households are examined’ (Bakardjieva, 2006, p.71). The analysis in this paper contributes to address this by conceptualising how one element of societal domestication trajectories (social norms and other socially circulating meanings) may both influence and emerge from household level domestication processes. This analysis may also have relevance for work outside of the domestication literature. Based on historical analyses, Shove (2003) identified that the adoption of new end-use technologies has been accompanied by societal trajectories of ever-increasing standards of comfort, cleanliness, and convenience. The idea that processes of interpreting and responding both draw on and feed into socially circulating meanings of ‘working’ suggests one possible mechanism by which these societal trajectories are maintained.

5.2 Policy relevance and opportunities for further work

The conceptualisations of users’ learning discussed above also have relevance for policy aiming to reduce emissions through the introduction of new end-use energy technologies in the home.

Understanding how cognitive, symbolic and practical learning emerge from interacting elements can suggest opportunities to influence users’ learning in support of policy objectives. This approach was previously demonstrated by Parrish, Hielscher and Foxon (2021), but the proposed framework has the potential to be applied more generally. For example, while Parrish, Hielscher and Foxon (2021) identified recommendations such as ensuring users of SHHP had access to thermostatic radiator valves on bedroom radiators, to avoid experiencing uncomfortably warm night-time temperatures, the proposed framework of learning processes suggests that the process of experiencing may be influenced by attending to how the design and installation of new technologies might interact with users’ existing routines and material arrangements. At the same time, insights from the proposed framework may help to identify more specific policy recommendations than others proposed in the literature. For example, Hargreaves, Wilson and Hauxwell-Baldwin (2017) and Judson *et al.* (2015) suggest that users’ learning might be influenced by technology design, installers, or users’ peers, but do not identify how changes to these influences might affect users’ learning in particular ways.

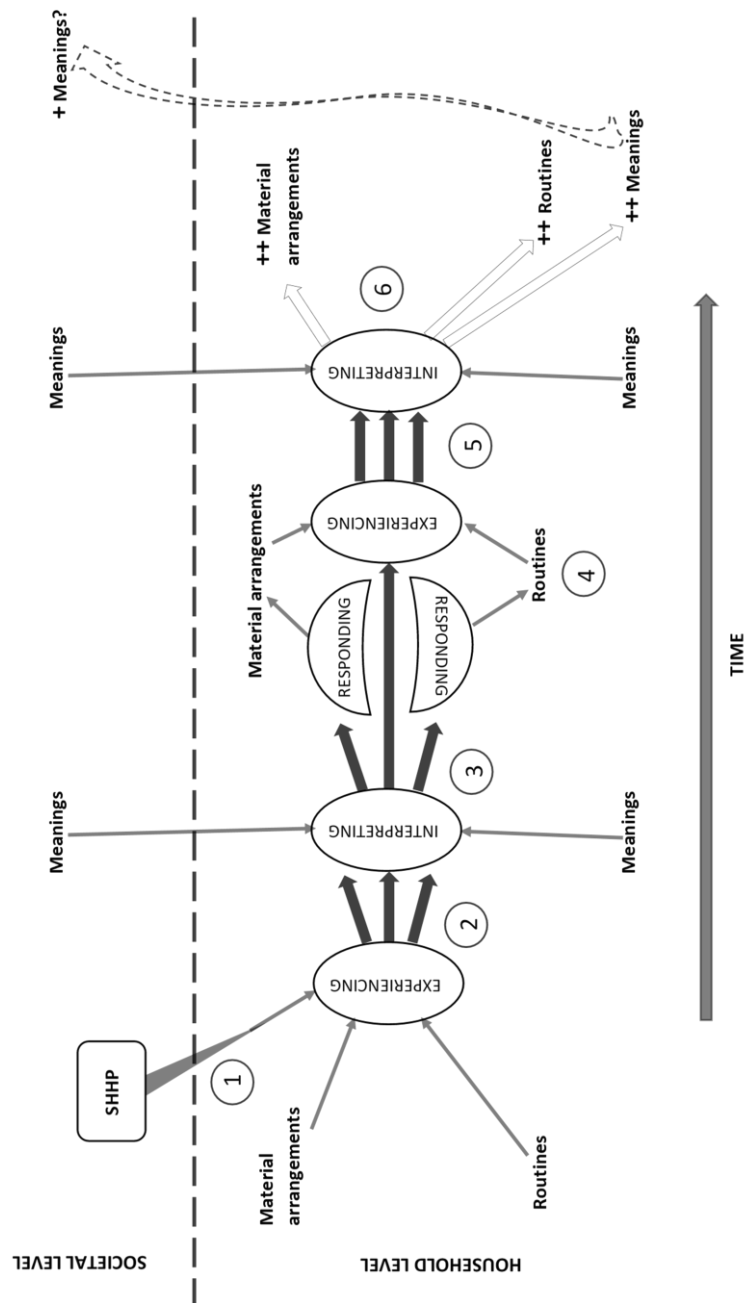


Figure 4: Visualising potential relationships between learning processes at the household level, and socially circulating meanings of what constitutes ‘working’ 1) SHHP becomes part of household material arrangements through uptake and installation. 2) Processes of experiencing different SHHP characteristics emerge from their interaction with pre-existing household routines and material arrangements. 3) Processes of interpreting whether or not different experiences constitute ‘working’ emerge from their interaction with meanings of ‘working’ associated with pre-existing routines, and/or those circulating at the societal level. 4) Processes of responding may change routines and/or material arrangements as users seek to make SHHP ‘work’. 5) Processes of experiencing change through changes in material arrangements and routines. 6) If experiences are interpreted as ‘working’, this may reinforce current material arrangements, routines, and meanings of ‘working’. Collectively, this may also contribute to meanings of ‘working’ circulating at the societal level

Understanding how trajectories of increasing comfort and convenience emerge from users' learning about new technologies also has relevance for energy policy. Concerns have been raised that trajectories of increasing demand for services may be incompatible with efforts to address climate change even alongside increases in technical efficiency (Darby and Fawcett 2018; Labanca and Bertoldi 2018; Shove 2018). It is outside the scope of this analysis to comment on how emerging routines of using SHHP might influence emissions from home heating. However, the analysis in this paper may offer more general insights into how demand for services might increase alongside adoption of more efficient and/or automated technologies (see also Darby 2018; Hargreaves et al. 2017; Shove 2018; Strengers et al. 2020, for example). This could offer a first step towards understanding how we might shift towards "good" forms of energy efficiency, "which have at their heart interpretations of service that are consistent with a radically lower carbon society" (Shove, 2018, p.786).

The framework of learning processes proposed in this paper may be generic enough to be applied to analyse users' learning about other technologies and in other contexts. However, the work presented in this paper could be usefully developed by extending the analysis to include wider samples of users and other technology types. Expanding the sample to include non-users could help to test and develop the processes of receiving and interpreting information, while involving a higher number of household members in data collection could reveal how needs were negotiated within the household. Meanwhile, SHHP represent an example of a more efficient and automated technology: as such, they were designed to substitute for a technology (gas boilers) which users had previously domesticated, and to perform emissions reductions without requiring active input from users. Indeed, the designers of SHHP tested in the FREEDOM Project trial aimed to avoid user interactions that might interfere with the intended operation of the smart controls (Stumpf et al. 2018). Applying the approach proposed in this paper to analyse learning about other technology types could usefully test and develop the framework of learning processes, as well as the analysis of their relationship with household and societal domestication trajectories. However, insights into processes of users' learning about more energy efficient and automated technologies may be particularly useful since these technology types are expected to play important roles in reducing carbon emissions from energy use in the home.

Chapter Six: Overall Discussion and Conclusions

1. Contributions to knowledge

This section begins by summarising the contributions to knowledge of the four papers presented in Chapters Two – Five. Following this, Section 1.2 reflects on the opportunities and limitations for the two problem framings adopted in the papers to address the overall thesis aim. Finally, Section 1.3 discusses broader policy implications of dominant and alternative problem framings for policy efforts to transform the UK energy system.

1.1 Contributions of papers to overall thesis aim

Overall, this thesis aims *to provide insights relevant to policy to increase UK households' contribution to reduce energy system emissions through the uptake and use of new technologies*. The four papers making up the body of this thesis contribute to the overall thesis aim in three main ways. Firstly, they provide insights that may help to predict or assess the potential for end-use technologies to reduce energy system emissions (Papers 1 and 3). Secondly, they provide insights that may help to promote the uptake of new end-use technologies intended to increase UK households' contribution to decrease energy system emissions (Papers 2 and 3). Thirdly, they provide insights that may help to understand and influence the ways in which new technologies are used (Papers 3 and 4). This section summarises how each paper contributes to address the overall thesis aim and situates these contributions within the academic literature.

Paper 1 addresses the research question,

Are modelling studies realistic about how much demand response we can really expect from residential consumers?

This paper provides a systematic review of quantitative evidence on users' engagement with residential demand response, drawn from international trial and programme evaluations. It compares this empirical evidence with assumptions by studies modelling the potential for residential demand response to increase electricity system flexibility.

Key findings include:

- Studies modelling the potential of residential demand response often assume levels of user engagement much greater than those reported by most trial and programme evaluations in the reviewed literature.

- Studies modelling the potential of residential demand response assumed flexible use of novel electrical loads, such as electric vehicles, for which little empirical evidence was identified at the time the review was conducted.
- Both modelling studies and trial and programme evaluations gave little consideration to how levels of demand response may vary at different times, but the limited empirical evidence identified suggests this variability can have important implications for the potential of demand response as a source of electricity system flexibility. To give an extreme example, if response is not achieved during annual peak demand (as reported in the UK CLNR trial, see Bulkeley *et al.*, (2015), this suggests that alternative sources of flexibility may be required at these times.

These findings contribute to the academic literature modelling the potential for demand response by suggesting that modelling studies should pay closer attention to empirical evidence on user engagement to inform modelling assumptions. For example, Globisch *et al.*, (2020) respond to Paper 1 by combining techno-economic optimisation modelling with a survey of potential users to evaluate the potential of a novel form of demand response. In particular, these findings highlight the need for further research into how levels of response might vary at different times, and the implications this may have for the potential of residential demand response as a resource for electricity system flexibility.

Paper 1 contributes to the overall thesis aim by providing insights into user engagement that may inform policy assessments of the potential for residential demand response. They suggest that policy professionals exercise caution when assessing the potential for residential demand response to increase electricity system flexibility in the UK. For example, the UK National Audit Office cited Paper 1 to highlight limited and uncertain evidence regarding the persistence of demand response over time, as part of scrutinising public spending on the UK smart meter roll out (NAO 2018). The findings of Paper 1 may also contribute to inform assumptions of studies modelling the potential of residential demand response, which can form important inputs to policy making.

Paper 2 addresses the research question,

What are the key factors affecting residential user engagement with demand response?

This paper provides a systematic review of primarily qualitative evidence on factors influencing user engagement with residential demand response. Key findings include that user engagement with residential demand response may be influenced by factors such as:

- Users' familiarity with and trust of residential demand response, associated technologies such as smart meters, and actors involved in demand response delivery.
- Users' perceptions of risk and sense of control over demand response.
- Complexity or effort involved in responding, including through manually responding to price signals or setting up and using enabling technologies.
- User characteristics and the ease with which engagement with demand response can be incorporated into existing routines.

These findings contribute to research on residential demand response by highlighting that user engagement may be influenced by factors other than time varying pricing and enabling technologies. This supports the findings of other work, such as Darby (2020) and Torriti (2019), which highlight the limitations of dominant conceptualisations of residential demand response as the result of technological artefacts and price signals. For example, Hoffmann, Adelta and Weyer (2020) cite Paper 2 as evidence that user or consumer engagement with residential demand response is affected by non-economic factors, while Sarran *et al.* (2021) cite Paper 2 as evidence that such engagement may be influenced by experiences during use.

Paper 2 contributes to the overall thesis aim by suggesting approaches to promote user engagement with residential demand response. Specifically, it suggests that user engagement with residential demand response might be supported by: a) more predictable forms of demand response around which users may be able to construct new routines; b) automation and other enabling technologies which may reduce complexity and effort; and c) sufficiently high financial incentives. It also suggests that automation and similar technologies should be designed and implemented in ways that do not increase complexity or reduce trust or perceived control. Paper 2 was based on work conducted for the UK Department of Business, Energy and Industrial Strategy (BEIS 2017), which relates to planning to support the development of smart energy systems in the UK, including potentially through informing and engaging residential users in demand response (HM Government 2017b).

Paper 3 addresses the research question,

What were the outcomes and processes of user learning about smart hybrid heat pumps in the context of the FREEDOM project trial? And what are the implications for UK heat decarbonisation policy?

In answering this question, it highlights policy-relevant outcomes of users' learning about smart hybrid heat pumps (SHHP).

Key findings include:

- Interviewees often learned that heat pumps cannot provide hot water, or space heating at lower outdoor temperatures – in other words, the functions provided by the gas boiler component of the SHHP system. This suggests that the Committee on Climate Change may be incorrect in expecting experience of hybrid systems to increase UK households' willingness to accept full heat pumps if these are rolled out in the future (CCC 2018, 2019c).
- Most interviewees were not aware that automated demand response was being tested as part of the trial; as Paper 2 indicated that transparency and trust are important for users' engagement with residential demand response, this lack of awareness may harm user engagement in the longer term.
- Some interviewees developed unintended routines of using SHHP, including bypassing the intended smart control system and intensifying routines of drying laundry on radiators, which could reduce the expected efficiency benefits on offer from SHHP.

Further policy-relevant insights are provided in the form of recommendations to influence users' learning about SHHP in support of policy objectives, which are derived from analysing how learning outcomes arose. For example, using non-technical language to explain the functioning of SHHP may help to avoid users constructing misconceptions about their functionality. Meanwhile, ensuring the presence of material elements such as thermostatic radiator valves on bedroom radiators, and spaces to dry laundry without using radiators may help to avoid unintended and less efficient ways of using SHHP while promoting the construction of positive meanings by helping to avoid discomfort. Installers may be well placed to influence users' learning because they combine knowledge of the SHHP system with face-to-face conversations with users, and surveys of the material arrangements of their homes. In this way, they may be able to tailor information provision and advise on helpful material changes according to the particularities of users' existing routines and their homes.

The analysis in Paper 3 confirms that domestication theory can help to illuminate policy-relevant insights relating to processes of users' learning during technology use (see also Hargreaves et al. 2017; Judson et al. 2015), and that installers can influence the ways in which heat pumps come to be used (see also Gram-Hanssen *et al.*, 2016). Previous studies have suggested that installers should be trained in effective communication with users to promote energy efficient use (Gram-Hanssen et al. 2016; Hargreaves et al. 2017; Judson et al. 2015). By analysing *how* policy-relevant learning outcomes arose, Paper 3 builds on this literature by

identifying more specific policy implications relating to how users' learning might be influenced. More broadly, Paper 3 draws attention to the potential for alternative problem framings such as domestication theory to provide relevant insights for energy policy making. In this way, it contributes to calls for energy policy and related research to draw upon a wider range of problem framings, which consider problems and solutions related to daily life as well as the design and uptake of promising new technologies (see, for example, Spurling *et al.*, 2013; Foulds and Christensen, 2016; Labanca and Bertoldi, 2018; Jensen *et al.*, 2019; Royston and Foulds, 2019).

Finally, Paper 4 addresses the research question,

Taking domestication theory as a starting point, how can processes of user learning about a new end-use energy technology be conceptualised?

In answering this question, it contributes to develop conceptualisations of learning within domestication theory. The key contribution is the proposal of a framework of learning processes, each emerging from interactions between elements related to new technologies and elements related to users' daily lives:

- The process of *receiving* information about technologies emerges from interactions between information that is available about new technologies, and information that is important to users.
- The process of *experiencing* new technologies emerges from interactions between characteristics of technologies and their settings, and users' routines and material arrangements.
- The process of *interpreting* emerges from interactions between information received and experiences, and understandings and meanings users already hold. This may give rise to the construction of understandings or meanings related to the technology (in other words, *cognitive or symbolic learning*).
- The process of *responding* emerges from interactions between understandings and meanings with strategies, actions and resources available for users to act upon them. This can include seeking new information, or changing technology settings or routines in ways that change experiences. It may give rise to new routines (in other words, *practical learning*).

The analysis also identifies how these processes may be involved in ongoing trajectories of domestication at the household level, and suggests how they may contribute to the recursive relationship between domestication trajectories at the household and societal level.

Overall, Paper 4 contributes to literature on the domestication of new technologies within the tradition of Science and Technology Studies (see, for example, Sørensen, 1996, 2006; Sørensen, Aune and Hatling, 2000). More specifically, it responds to calls for the processes and dynamics of learning within domestication to be more fully conceptualised (Juntunen 2014). It also contributes to work on the relationship between learning and energy use more broadly (for example, Darby, 2006; Isaksson, 2014).

The proposed framework of learning processes suggests how users' learning about new technologies unfolds from the interaction of elements of new technologies (including information provision and technology characteristics) with various elements of users' daily lives. This is similar to the analysis of how users' learning emerged that supported the identification of policy recommendations in Paper 3. As such, the proposed framework of learning processes has the potential to contribute to the overall thesis aim by providing a generic framework to understand how users' cognitive, symbolic and practical learning about new technologies might be influenced in support of policy objectives. This would require testing the ability of the framework to explain the emergence of users' learning about new technologies within other contexts (for example, outside of a trial context, and with different groups of users) and with other types of technologies intended to reduce households' contributions to energy system emissions (for example, with non-automated technologies). It would also require additional work to develop approaches to apply the framework to influence users' learning. Furthermore, understanding interactions between household and societal domestication trajectories may suggest ways to seek to avoid increases in demand for energy services alongside the adoption of more energy efficient technologies. These and other opportunities for further work are discussed in Sections 1.3 and Section 2 of this Chapter.

The next sub-section discusses opportunities and limitations for the two problem framings adopted in this thesis to address the overall thesis aim, considering the different types of insights they can offer.

1.2 Opportunities and limitations of problem framings adopted in this thesis to address the overall thesis aim

As introduced in Section 2 of Chapter One, the idea of problem framings describes the way in which problems are conceptualised, and this can relate to both the conceptual frameworks

and methodological approaches that are employed. Problem framings are relevant to policy action to address climate change because different ways of conceptualising problems also suggest different possibilities to act. As reviewed in Section 2 of Chapter One, there is currently a debate about the dominance of certain problem framings in energy policy and related research and the extent to which insights from dominant problem framings can adequately inform action to address climate change.

The papers making up the body of this thesis adopted two problem framings to address the overall thesis aim. The problem framing adopted in Papers 1 and 2 remained close to dominant problem framings: these papers employed systematic review methodology, which has been recognised as part of evidence-based energy policy making (Sorrell 2007; Speirs et al. 2015), and used language associated with dominant frameworks, which conceptualise users' behaviour as the result of individual choice (see, for example, Wilson and Dowlatabadi 2007 for a review). Papers 3 and 4 took an alternative approach by drawing on domestication theory and process analysis.

This sub-section discusses the opportunities and challenges for each of the two problem framings adopted in this thesis to address different aspects of the overall thesis aim. It considers their potential to identify different types of influences on technology impact; to illuminate uncertainty and change over time; and to inform policy in the UK.

1.2.1 Opportunities and limitations of the two problem framings to identify influences on technology impact

The overall aim of this thesis is *to provide insights relevant to policy to increase UK households' contribution to reduce energy system emissions through the uptake and use of new technologies*. As such, it is concerned with certain *impacts* of new technologies, relating to their potential to reduce emissions directly (through, for example, increasing efficiency and making use of lower carbon energy carriers for home heating) and/or through supporting wider changes in the energy system (such as demand response to support higher penetrations of intermittent renewables). In pursuit of this aim, UK energy policy tends to focus on promoting the uptake of new technologies, without often considering their use. In other words, it implicitly assumes technological determinism, or the idea that technology impact emerges directly from technologies themselves.

Compared to dominant problem framings, the conceptual framework of domestication theory can help to identify insights into a wider range of influences on end-use technologies' impact. Firstly, it draws attention to how technology impact emerges through processes of users'

learning during *use* as well as uptake. As demonstrated by Papers 3 and 4, this can suggest new opportunities for policy to influence technology impact. For example, as an analytical framework domestication theory can help to illuminate how users' experiences of smart hybrid heat pumps (SHHP) are influenced by different ways in which the new technology interacts with users' pre-existing routines and material arrangements in users' homes, including for example elements of existing heating systems and the thermal efficiency of building fabrics. In turn, this suggests policy actions such as expanded training for technology installers to enable them to identify and address such interactions to support the effective integration of SHHP into users' lives and homes, beyond purely technical aspects of system installation. Furthermore, domestication theory can illuminate how both the uptake and use of new technologies may be influenced by diverse factors across individual, household, and societal scales. As illustrated in Paper 4, it can also illuminate how societal-level elements emerge from cumulative processes of learning within households. This differs markedly from dominant problem framings, which tend to highlight a narrower range of factors, and in particular have been criticised for conceptualising behaviour primarily in terms of individual choice while categorising social processes as exogenous 'contextual factors' that explain limitations in the explanatory power of the main model (Shove 2010).

Reflecting on the use of process analysis in Paper 4 suggests this methodological approach may help to illuminate an even wider range of insights into users' learning. Like all conceptual frameworks, domestication theory proposes a particular way to see the social world, which tends to obscure other ways of seeing (Silverstone 2006). By providing a systematic approach to trace learning processes, process analysis helped to reveal features of users' learning – such as processes of interpreting whether experiences represent 'working' – which were not apparent from thematic interview analysis conducted as part of this thesis. It is possible such aspects of learning may not be immediately apparent because researchers are also participants in societal domestication trajectories, so that some learning outcomes may appear as common sense to researchers as well as research participants.

It has been argued that systematic review methodology also has the potential to identify unexpected findings because it includes methods to reduce bias, which may help to avoid researchers perpetuating their preferred theories or theses (Petticrew and Roberts 2006). However, within the paradigm of evidence-based policy, systematic review methodology can be associated with preferences for certain types of evidence such as quantitative analyses and randomised controlled trials. This can introduce bias in the selection of research questions and evidence and the synthesis of results (Sorrell 2007). Applying the idea of problem framings to

reflect on systematic review methodology suggests that similar biases may tend to reproduce dominant problem framings. Firstly, systematic review methodology requires a well-defined research question in order to transparently define search terms, and inclusion and exclusion criteria for studies and data for synthesis. The research question and search terms may be informed by the preferred problem framings of the research team, as well as any anticipated users of the research. Since these problem framings are more likely than not to be those which are dominant in the field, this might favour the identification of studies adopting a similar problem framing. Furthermore, by definition it is likely that dominant problem framings will be more strongly represented in the literature identified. Together with potential biases introduced by researchers' training, and perceptions of what type of evidence would be most acceptable to policy professionals, this may influence the interpretation and synthesis of review findings.

The search terms for Papers 1 and 2 were designed to broadly identify *empirical* evidence on user engagement with residential demand response. These terms were successful in identifying studies adopting diverse problem framings. Bias in the selection and synthesis of findings is more likely within Paper 2 as it reviewed qualitative rather than quantitative evidence (Sorrell 2007). However, the framework of 'motivations, barriers and enablers' which structured the identification and synthesis of findings also proved broad enough to synthesise findings derived from these diverse problem framings, as the summary of contributions in Section 1.1 of this chapter illustrates. The identification and synthesis of insights from alternative problem framings was supported by adding the concept of 'enablers' to 'motivations and barriers', the concepts originally specified by BEIS. This was the result of learning during the review for Paper 1: while focussed on quantitative findings, this review included literature that described influences tending to support users' engagement with demand response (for example, spending more time at home during the day), as distinct from motivations or reasons for choosing to engage in residential demand response (for example, wanting to save money) (see, for example, Torriti, 2013). This suggested the usefulness of the category 'enablers' in addition to 'motivations' to structure the review presented in Paper 2. On the other hand, within Paper 2 review findings were synthesised into a single framework because this was expected to be more useful to the intended audience of policy professionals. By not clearly drawing attention to divergent perspectives, this may have contributed to some authors interpreting the review findings in line with dominant problem framings; for example, Todd-Blick *et al.* (2020, p.1) refers to Paper 2 to suggest that engagement with residential demand response may vary because "different types of consumers make energy-use decisions

in different ways". This interpretation of the findings of Paper 2 appears to strongly retain the assumption of rational choice by individuals.

To summarise, alternative problem framings such as domestication theory can illuminate a wider range of influences on the impact of new technologies, including processes of use as well as uptake and the recursive relationship between influences at the household and societal level. Reflecting on the methodological approach of process analysis suggests it may help to identify further relevant insights. Systematic review has the potential to identify diverse and unexpected insights; however, certain features of the methodology may contribute to reproduce aspects of dominant problem framings.

1.2.2 Opportunities and limitations of the two problem framings to illuminate uncertainty and change over time

Historical analyses (for example, Shove, 2003) have illustrated how technologies and societies co-evolve, so that technology impacts ultimately emerge from this process of co-construction rather than directly from technologies themselves. Identifying technology impacts as emergent also highlights that they are inherently uncertain (Geels et al. 2018).

By contrast, much UK energy policy seems to assume that the impacts of policies and of new technologies can be largely predicted in advance, and that current ways of life will be maintained in the future (Labanca and Bertoldi 2018; Shove 2018). For example, when recommending the roll out of smart hybrid heat pumps (SHHP) the Committee on Climate Change recognised uncertainties relating to technological development of either hydrogen or full electrification for home heating. However, they suggest that households might help to deal with this uncertainty by adopting different heating technologies at different points in time, once their techno-economic desirability can be better assessed (CCC 2018). This suggests an assumption that households' uptake and use of new technologies will proceed in a relatively predictable way, which can help to manage the unpredictability of technology development. Similarly, the recommendation is based on assumptions about gas and electricity use by SHHP drawn entirely from techno-economic optimisation modelling (CCC 2018, 2019c; Imperial College 2018). Empirical evidence from the FREEDOM Project trial relates only to users' *acceptance* of SHHP, not how they are used or how this might evolve over time (CCC 2018, 2019c; Turvey et al. 2018). Furthermore, while the CCC more recently cited empirical evidence that the use of the heat pump component of hybrid systems may vary between 63 – 6%, they suggest that this could be addressed through standards for smart control systems and their operation as well as changing the relative cost of electricity and gas (CCC, 2020, p.78). Again,

this assumes that technologies will have predictable impacts if properly designed and implemented alongside the right economic incentives, while overlooking how users' learning might contribute to unintended forms of use.

The problem framings adopted in Papers 1 and 2 arguably align with this way of thinking. Systematic reviews can be useful to highlight areas of uncertainty which relate to a lack of research in a particular area (Petticrew and Roberts 2006). However, this implies that uncertainty can be reduced with more complete information and does not recognise forms of uncertainty resulting from future changes which cannot be predicted in advance.

Paper 1 does identify certain ways in which users' engagement with residential demand response may change over time. It notes that individual users participating in residential demand response might learn to respond better, or stop responding through 'fatigue', and also that user engagement with residential demand response might vary because of its history of deployment in different countries. However, neither systematic review methodology nor concepts from dominant problem framings applied in the papers provide a means to understand *how* such changes might occur. Interestingly, some authors citing Paper 1 invoke uncertainty around future change to justify maintaining very optimistic assumptions about future engagement with residential demand response (Aloise-Young et al. 2021; Hoffmann et al. 2020). This essentially ignores the main finding of the paper (that highly optimistic assumptions about engagement with residential demand response are not supported by the empirical evidence) by suggesting that higher levels of engagement are simply a matter of time.

By comparison, both domestication theory and process analysis can offer insights into how change occurs over time as technologies, users and wider society are co-constructed. Importantly, both approaches offer resources to understand how societal level changes emerge from collective micro level processes. This differs from dominant problem framings which focus on explaining micro level changes (such as the decision to purchase a new more energy efficient technology), and may conceptualise how social context influences these changes, but offer no conceptual resources to understand wider societal change.

Understanding how wider societal change may emerge is relevant to the overall thesis aim because it highlights that the impacts of new technologies may not proceed as anticipated in policy scenarios. It may also suggest ways to influence users' learning about new technologies, which contributes to the emergence of wider societal changes. As illustrated in Paper 3, this might involve seeking to promote users' learning which supports the intended operation of

new technologies while avoiding learning which might challenge it. However, as suggested in Paper 4, it may also offer potential to go beyond this by seeking to influence processes by which demands for energy services are co-constructed with the uptake and use of more energy efficient or smart automated technologies.

To summarise, dominant problem framings tend to assume that society will not continue to change and that technologies will have predictable impacts. The application of systematic review methodology as part of evidence-based policy making can align with such assumptions by implying that uncertainty stems mainly from a lack of evidence. By contrast, by highlighting processes of co-construction and emergence, alternative problem framings indicate that technological impacts are inherently unpredictable. However, they can also suggest opportunities to influence processes involved in technology-society co-construction along certain directions and not others.

1.2.3 Potential and challenges for insights from the two problem framings to be applied by UK energy policy professionals

The summary of contributions in Section 1.1 illustrates that insights relevant to the overall thesis aim can be supported by both problem framings adopted by the papers within this thesis. Furthermore, the discussion in Section 1.2.1 echoes many other authors by suggesting that the relative complexity of alternative problem framings such as domestication theory can help to identify new opportunities for policy making (see, for example, Spurling *et al.*, 2013; Sorrell, 2015; Wilson, Crane and Chryssochoidis, 2015; Watson *et al.*, 2020). However, the potential for different types of findings to influence policy making may also be influenced by their compatibility with practices involved in policy making and the politics of what constitutes 'evidence' (Denzin 2010; Hampton and Adams 2018; Shove 2010; Sorrell 2007).

Systematic review methodology has been recognised by UK policy professionals, including in the area of energy policy and related research (GSR 2013; Sorrell 2007; Speirs *et al.* 2015). This recognition may provide an opportunity to communicate research findings with policy professionals. Indeed, Paper 2 was based on work conducted for BEIS, which specified systematic review as the methodology to be followed. The use of language and concepts drawn from dominant problem framings within Paper 1 and 2 may offer a further opportunity to communicate research findings, as unfamiliar language can make research less useful to inform policy (Hampton and Adams 2018).

By contrast, more complex alternative problem framings may face resistance because they are felt not to offer sufficiently clear guidance on exactly which actions policy makers should take

(Hampton and Adams 2018; Shove 2010; Watson et al. 2020). Relatedly, methodological approaches such as process analysis which are helpful to study domestication may connect poorly with preferred standards of evidence in current practices of energy policy making. Hampton and Adams (2018) identify a preference for generalisable, reproducible, and hence often quantitative evidence to inform energy policy (Hampton and Adams, 2018). Similarly, Sorrell (2007) identifies that energy policy professionals may place more value on approaches which aim to establish direct causal relationships between dependent and independent variables by controlling as far as possible for other variables. By contrast, process analysis involves tracing interactions between a diverse set of elements or factors as they unfold, including across multiple levels of analysis, and does not provide a means of testing causation. Furthermore, it is likely to identify features that are case-specific as well as those that might be more generalisable, and neither process analysis nor domestication theory offer a defined approach to identify whether some factors are more important than others.

The next sub-section draws on the reflections across Section 1.2 to discuss the wider implications of dominant and alternative problem framings in the context of efforts to transform the UK energy system and to effectively address climate change.

1.3 Policy implications of dominant and alternative problem framings

The summary of contributions presented in Section 1.1 of this Chapter illustrates that both problem framings adopted by the papers within this thesis can support insights relevant to the overall thesis aim. However, the discussion in Section 1.2 identifies important limitations in the *types* of insights that dominant problem framings can provide. Because they focus on conceptualising the influence of a relatively narrow range of factors (for example, substituting technological artefacts or changing price levels) dominant problem framings may not identify important influences on the uptake and use of new technologies. Furthermore, dominant problem framings do not provide conceptual or methodological resources to understand how technology and society may co-evolve over time or the forms of uncertainty this implies. On the other hand, it may be challenging for insights from alternative problem framings to inform energy policy. Insights from dominant problem framings may be more able to influence UK energy policy because the very features which create these limitations also create understandings of change and forms of evidence which are more closely aligned with current practices of policy making in the UK. This sub-section discusses some practical implications of dominant and alternative problem framings when considering the urgent need for policy action to address climate change.

Alternative problem framings such as domestication theory highlight that engagement with new technologies may continue to change over time. One immediate implication is that it may be useful for technology trials to include follow-up contact with households over longer periods of time, to develop a more complete picture of user engagement with the new technology by providing more opportunities to capture emergent outcomes of users' engagement with new technologies as well as other changing influences on engagement (such as different weather conditions influencing engagement with home heating). On the other hand, in principle alternative problem framings suggest that user engagement with new technologies would remain as potentially an open-ended process rather than being 'finished' at any particular point in time. Indeed, as discussed in Paper 4 emergent processes of learning about new technologies may also contribute to wider societal changes, which also have implications for further learning. In other words, alternative problem framings suggest that the impacts of new technologies remain in principle uncertain.

Reflexive policy making describes one way in which policy makers could work with this uncertainty as part of policy making processes, and many authors have called for more reflexive approaches to policy making to address challenges relating to different aspects of sustainability (for example, Voß and Kemp, 2006; Scoones *et al.*, 2007; Shove, 2018; Molas-Gallart *et al.*, 2021). Such an approach could better accommodate insights from alternative problem framings by explicitly acknowledging deep uncertainty and providing a framework to proactively recognise emergent outcomes and adjust governance practices accordingly.

Adopting more reflexive policy making may require greater humility about the extent to which policies can 'manage' social change (Shove 2010) and greater willingness to accept political responsibility for making decisions by recognising that these cannot always be 'objectively' supported with quantitative evidence (Stirling 2010). It would also require some form of ongoing monitoring to support decision making. However, this seems likely to be more difficult to achieve with regards to emerging ways in which technologies are used in daily life, as opposed to monitoring technology uptake through, for example, data on sales or installations.

One route to achieve ongoing monitoring might involve periodic evaluations of the type conducted as part of a technology trials, such as focus groups with users or interviews in their homes. Another approach may be to involve local actors such as installers or community energy groups in monitoring and feedback about relevant developments, perhaps alongside other forms of ongoing engagement such as supporting users to effectively integrate new technologies into their daily lives. Such an approach might support more continual monitoring

than periodic evaluations while also benefitting from tacit knowledge about local people and their contexts (Martiskainen and Nolden 2015). On the other hand, it may be that such types of ongoing engagement focus mainly capture emergent outcomes that users consider to be *problematic*: for example, users might contact installers to ask for help if their experiences of new technology do not match their expectations. However, as discussed in Paper 4 (Chapter Five of this thesis), engagement with automated and/or more energy efficient technologies may also increase demand for energy services in ways that are not experienced as problematic, but which may have implications for action to address climate change. Labanca and Bertoldi (2018) suggest that reflexivity about such issues needs to involve technology users, or practitioners, themselves. Reflection and deliberation amongst grassroots initiatives, such as community energy groups, or within households could avoid the need for centralised data collection and monitoring, as well as politically unpopular attempts to govern such issues from the top down.

While more reflexive policy approaches could help to accommodate insights from alternative problem framings, policy professionals may also benefit from a pragmatic approach to identify clear-enough insights from more complex problem framings which can offer initial guidance for policy action. For example, Watson *et al.*, (2020) developed a framework to present insights from social practice theories to policy professionals in a more manageable way that helps to identify the diverse opportunities for policy intervention these insights suggest. The framework has attracted interest amongst policy professionals, and Watson *et al.*, (2020) suggest the approach could be equally applicable to other complex and relational theories of social change. In a similar vein, Molas-Gallart *et al.* (2021, p.9) propose a governance framework based on a 'stylized' view of transitions theory, which also supports reflexivity.

However, efforts to change policy practices imply, at best, a time delay, and may also evoke political resistance (Shove 2010; Stirling 2010), while action to address climate change is urgently needed. Even actions which have been emphasised by dominant problem framings, such as deploying more energy efficient technologies, are much too slow. For example, a recent report pointed out that at current rates of heat pump deployment it would take 700 years to achieve levels commensurate with net zero emissions (Rosenow et al. 2020). Insights from dominant problem framings are recognised as useful to achieve technological change, even by proponents of alternative problem framings (see, for example, Foulds and Christensen, 2016; Labanca and Bertoldi, 2018; Shove, 2018). Furthermore, technological change is obviously not mutually exclusive to actions suggested by alternative problem framings: rather, alternative framings highlight interconnections between technological

change and wider considerations such as users' learning, the trajectories of social practice, and the development of large-scale physical infrastructures alongside sets of codified and tacit rules. Given the urgency of action to address climate change, could insights from dominant problem framings usefully be combined with those from alternative problem framings?

Several authors have suggested that insights from different problem framings can and should be combined when addressing complex problems (for example, Scoones *et al.*, 2007; Sorrell, 2015). Some approaches have drawn on insights from dominant and alternative problem framings to create a single conceptual framework (for example, Stephenson *et al.*, 2010; Sweeney *et al.*, 2013). Others have created frameworks that compare conceptual problem framings so that policy professionals may select those most appropriate to a particular application (for example, Chatterton, 2011). However, approaches such as these have been criticised for altering insights from alternative problem framings to fit with assumptions underlying dominant problem framings, in the process losing much of their value (Shove 2010, 2015). Reflecting on how some authors interpreted the findings of Papers 1 and 2 of this thesis also suggests that research users may tend to interpret research findings in line with the assumptions of dominant problem framings, even if the findings challenge these assumptions. Furthermore, considering problem framings as ways of *conceptualising problems* suggests the limitations of selecting conceptual approaches according to "what works" (see also Denzin, 2010; Morgan, 2014). An implication of the dominance of certain framings is that problems will often be conceptualised in the ways they suggest. In this sense, it may be self-fulfilling that dominant problem framings appear to be tools that 'work' for a given application. However, this also implies a lack of awareness of other aspects of the problem, which may be equally relevant to the overall aim, but which are not illuminated by dominant problem framings (as Section 1.2.2 of this Chapter suggests). As Royston and Foulds (2019, p.23) put it, dominant problem framings "put blinkers" on the knowledge available for policy making. In response to this concern, some scholars suggest a focus on simply changing the ways in which policy professionals understand problems, rather than aiming to generate direct policy impacts in the near term (see, for example, Shove 2015).

Insights from alternative problem framings may also be applied with the aim of increasing the effectiveness of actions suggested by dominant problem framings, such as the uptake of new more efficient technologies. For example, Wilson, Crane and Chryssochoidis (2015) suggest that low uptake of home insulation installation stems from a disconnection between the design of existing policy instruments, which are based on financial subsidies, and the underlying reasons why homeowners might engage in home renovation. They propose that

insights based on theories of social practice could help to illuminate when and why renovations happen, and in this way usefully inform policy to increase the uptake of insulation measures.

An ambitious series of studies has identified a diverse range of influences on how and why households use home heating in the UK (Mallaband and Lipson 2020; Sovacool, Osborn, Martiskainen, Anaam, et al. 2020; Sovacool, Osborn, Martiskainen, and Lipson 2020). Similarly to Wilson, Crane and Chryssochoidis (2015), these studies identify a wide variety of influences on UK households' use of heat, and find that cost is not necessarily the most important influence. They propose that the design of lower carbon heating technologies and policies to promote their uptake must start by considering users' existing needs and desires, such as comfort and caring for household members, if lower carbon heating technologies are to widely displace established gas boilers. They also propose the concept of 'heat as a service' to simplify households' uptake of new lower carbon heating technologies. By suggesting implications for technology design and business models, as well as policy instruments, this approach goes beyond that proposed by Wilson, Crane and Chryssochoidi (2015). However, it arguably remains focussed on *aims* suggested by dominant problem framings, namely increasing technology uptake. This can clearly be useful given the low uptake of technologies such as home insulation and lower carbon heating systems. However, it does not consider technology use, or how new technologies and users' routines might co-evolve.

The insights suggested by Paper 3 of this thesis differ from dominant problem framings by considering learning during use (rather than focussing on technology uptake) and by highlighting that this is inherently uncertain. Nonetheless, they remain focussed on how users' learning might be influenced to support existing objectives of designers and policy makers – in other words, aiming to avoid users' learning that can be considered as a 'risk' to the intended operation of the technology. This approach is common amongst studies that apply the concept of users' learning to identify policy implications related to heat decarbonisation (Isaksson 2014). Similarly, Royston and Foulds (2019) identify that when insights from the social sciences and humanities are employed in energy research, this typically comes late in the research process as part of seeking to improve essentially technological change: alternative problem framings do not typically contribute to inform the *aims* of energy research, or of policy action.

The discussion in Paper 4 of this thesis touches upon one example where alternative problem framings could suggest wider opportunities for policy to reduce emissions. It has been argued that trajectories of increasing demand for energy services mean increases in technological

efficiency are insufficient to address climate change, and may even be counterproductive if they contribute to maintain or escalate levels of demand (Darby and Fawcett 2018; Labanca and Bertoldi 2018; Shove 2018). The analysis in Paper 4 suggests that increasing demand for comfort and convenience provided by heating technologies may emerge through processes of *interpreting* whether experiences represent technology ‘working’, which draw on socially circulating meanings of ‘working’, which themselves form part of trajectories of increasing service demand. In turn, this suggests the possibility that the emergence of increasing levels of demand might be avoided, or perhaps even reversed, if meanings of ‘working’ which are currently socially dominant could be challenged alongside the uptake of new technologies in ways that influence subsequent learning about technology use. Of course, such a change is likely to be far from straightforward. Amongst other issues, attempting to introduce meanings that diverge from socially circulating ideas of what is desirable may harm technology uptake.

A possible approach to overcome this conflict might draw inspiration from the findings of the Horizon 2020 ENERGISE project (Vadovics and Goggins 2019). In this research project, households were found to reduce demand for home heating and laundry after they were invited to challenge themselves to experiment with reducing their levels of demand for these energy services by providing themselves with comfort and cleanliness through other means. Perhaps extending an invitation to experiment with demand alongside the introduction of new, more energy efficient technologies could draw greater attention to the contribution demand makes to energy costs and emissions, and the limits of purely technical approaches such as energy efficiency, without reducing the appeal of new technologies or presenting a risk to their uptake.

The discussion in Section 1.1 of this Chapter suggests that installers can have important influences on users’ learning. However, installers may quite understandably focus on creating satisfied customers, which may make them unwilling to challenge users’ routines (see, for example, Gram-Hanssen *et al.*, 2016). Community energy groups may have greater potential to support social innovations such as changes in routines, alongside technical innovations such as the adoption of new technologies. This can result from tacit knowledge of the local community, including the needs and interests of different members, but also from a sense of empowerment associated with challenging dominant models of energy supply (Martiskainen and Nolden 2015). These features may enable peer-to-peer learning, including sharing experiences of new technologies and advice about how to incorporate them into existing practices (see also Judson *et al.*, 2015). They might also support deliberation about how new technologies could be used, and challenge practices where appropriate (see also Labanca and

Bertoldi, 2018). Interestingly, Sørensen (1996) suggests that increasing users' awareness of their own role in shaping the impacts of new technologies might also generate a sense of empowerment, and more reflective forms of learning.

To conclude, the urgent need to effectively address climate change calls for rapid action, but also deep change. This may create tension between striving for more rapid action informed by dominant problem framings, despite their various limitations, and endeavouring to change policy practices to fully reflect the implications of alternative more complex problem framings. While this discussion has suggested that insights from both dominant and alternative problem framings may be useful to inform policy action in line with the overall thesis aim, it also reiterates that dominant problem framings are limited in their ability to illuminate influences on technology impact, and deep uncertainty associated with technology and society co-construction. As a result of these limitations, insights from dominant problem framings may be less effective in promoting technology uptake, and entirely overlook emergent processes during technology use.

This discussion also suggests that that a key issue of dominant problem framings is not only the types of actions they can inform, but the way in which their dominance obscures awareness of other relevant issues. Echoing, for example, Denzin (2010) and Morgan (2014), this cautions against over-reliance on "what works?" as a principle to guide the selection of policy interventions or conceptual and methodological approaches. Evidence syntheses such as systematic reviews are likely to be limited by how problems and actions have previously been conceptualised, as this defines the evidence available for synthesis. Similarly, asking "what works?" as an approach to select appropriate methodological or conceptual approaches skirts over the ways in which dominant problem framings influence research or policy aims. Overall, this discussion suggests that becoming aware of the limitations of dominant problem framings and the concerns illuminated by alternatives represents a necessary first step towards more effectively drawing on insights from alternative problem framings. This endeavour might usefully engage with households, grassroots groups, and other actors beyond national-level policy making.

2. Opportunities for further work

This thesis suggests several opportunities for further work. The framework of learning processes proposed in Paper 4 would benefit from further work to test and develop its applicability in other contexts and to other technologies. For example, applying the framework to analyse users' learning about new technologies outside of a trial could help to test or

develop its applicability when users did not interpret the technology as still under development, and where users and installers may be less engaged with learning or supporting learning about new technologies. It would also be helpful to test or develop the framework by applying it to analyse users' learning about other technologies and types of technologies.

Smart hybrid heat pumps represent an example of an energy efficient and automated technology: in other words, the technology is designed to replace an existing technology, and reduce energy system emissions without active input from users. It would be useful to test the framework's potential to explain users' learning about other more efficient and/or automated technologies, for example electric vehicles or smart appliances delivering demand response. It would also be useful to test the framework's potential to explain users' learning about technologies that are designed to require more active input from users, for example in-home displays, or even technologies that are not intended to reduce energy system emissions at all.

Further conceptual work could also include elaborating processes by which increased demand for energy services might be co-constructed with the uptake and use of new more energy efficient technologies. This could usefully include analysing users' learning about other examples of energy efficient and/or automated technologies in other contexts. As part of this, it may be helpful to focus on how certain households' routines of using energy technologies come to differ from social norms, and also to consider the potential influence of negotiations and shifting responsibilities between household members. It could also be helpful to extend the analysis to consider how users might also be guided by ideas of what constitutes 'working' when constructing meanings of new technologies, and employing these meanings during technology use.

The thesis also suggests opportunities for further work on the *practical* implications of understanding users' learning about new technologies intended to reduce energy system emissions. Working with policy professionals could consider whether and how the learning processes proposed in Paper 4 might provide a generic framework to support understanding and action in UK energy policy. Meanwhile, working with grassroots groups or directly with households could explore approaches to deliberate, challenge, and potentially create less resource intensive patterns of use, alongside the introduction of new energy efficient and/or smart automated technologies. Such work has the potential to transcend current policy formulations by also considering changes in energy use without changes in technology, and changes in consumption to reduce embodied emissions beyond the UK energy system.

Appendices

Appendices to Paper 1

Appendix A: Search approach

Evidence on residential consumer engagement with demand response

In all cases, citation trails from reviewed reports and papers were followed where it was felt that this would be productive. The search was confined to English language publications, and those which were available free of charge or through existing Imperial College journal subscriptions.

The literature review began by reviewing relevant references for HubNet smart metering position papers, and BEHAVE conference 2014.

Academic literature

The database Science Direct was searched using the following terms:

(pilot OR trial OR test) AND ("demand response") AND (residential OR "mass market" OR domestic) AND electricity

The results were filtered to journal articles, published after 1989.

The titles and abstracts of these results were used to select studies which appeared to include empirical evidence (including in the form of a review or meta-analysis), and which may have included residential customers. Some further results were then eliminated after consulting the full paper (the primary reason being that the title and abstract did not make clear that commercial or industrial response rather than residential response was under consideration).

Grey literature

The search engine Google was used to search the following terms:

(pilot OR trial OR test OR programme OR program) AND ("demand response" OR "demand side response" OR "direct load control") AND (residential OR domestic) AND electricity

The top 100 search results were reviewed, to select those that included, or made reference to, examples of empirical evidence of residential consumer experience of demand response.

Many of the top 100 results consisted of sites of demand response vendors, or utility news sites, and so referred to examples of trials or programmes without including the results of these. In some cases, the name of the trial or programme was not clear (for example, only the

utility or the location was referred to), and further Google searches were used to identify the names of trials and programmes.

Where these searches did not identify the empirical results of trials or programmes, further searches were made including the name(s) of the trial/programme, utility or organiser where known, and 'results' OR 'findings' OR 'evaluation' OR 'impact'. The top 10 results for each search were reviewed. Quantitative or qualitative results were noted, including those presented within reviews, provided that the review included details of the trial or programme. Where calculated costs and benefits were reported rather than the raw results, these were not included.

A large number of results were identified in the US, many of which comprised utility run-DLC programmes, and in some cases it was not clear that results were publicly available. Therefore, searching for results was restricted to cases where there was believed to be a high probability that results had been publicly reported and analysed. This included: programmes and pilots that had already been cited in the academic literature; programmes and pilots that had been undertaken in response to regulation on demand response or dynamic pricing (which the initial search results made reference to in Ontario, California, Illinois, Pennsylvania, New York, and Ohio); and those that had been undertaken in connection with, or analysed by public sector bodies or consultancies involved in demand response research.

A number of larger sources of evidence were identified in the top 100 search results, which were searched individually. These were Navigant, Vaasa Ett, Brattle Group, Ofgem, EPRI (whose results were limited to the past 5 years due to the large number), smartgrid.gov, and ec.europa.

Modelling studies illustrating potential benefits

Network

The database Science Direct was searched using the terms:

('demand response' OR 'demand side management') AND benefits AND ('network investment' OR 'network reinforcement')

The results were filtered for journals on the topics of energy or electricity, and for the topics of distribution networks or smart grids.

Results were then selected based on the abstracts, to include papers that described potential benefits of demand response (rather than, say, how DR may be impacted by regulation).

The database IEEE Xplore was searched with same search terms. Results were not filtered, and results selected based on the abstracts as those that were focussed on DR specifically, and that were not too narrowly focussed technically or highly specific (e.g. describing a specific model or control strategy).

VRE integration

The database Science Direct was searched using the term:

('demand response' OR 'demand side management') AND benefits AND (wind OR solar OR PV OR renewable OR intermittent OR variable)

The results were filtered for journals on the topics of energy or electricity, and filtered for the topics of demand side management or demand response.

The database IEEE Xplore was searched with the same term, and the results were not filtered.

Results from these searches were selected based on the abstracts, to exclude any that focussed specifically on islands or microgrids, or that focussed on describing a specific model or control strategy.

Appendix B: Evidence reviewed

Trials and programmes reviewed

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
ADDC "Powerwise smart metering trial" (Powerwise 2015)	Abu Dhabi	trial	2012 - 2013	400 treatment, 200 control
Ameren Illinois "Power Smart Pricing" (CNT Energy 2008, 2012, 2013; Elevate Energy 2014; Navigant 2011b; Violette et al. 2010; Violette and Klos 2009)	Illinois	programme	2007 - present	500 in 2007; 13,739 in 2013
Ameren Missouri "CPP and TOU trial" (RLW Analytics 2004, 2006)	Missouri	trial	2004 - 2005	250 treatment, 488 control
Anaheim "CPR trial" (Wolak 2006)	California	trial	2005	71 treatment, 51 control
Australia "Integral energy trial" (Frontier Economics and Sustainability First 2012)	Australia	trial	2006 - 2008	900 treatment, 360 control
Austria "Smartgrids Salzburg" (Kupzog et al. 2013)	Austria	trial	NK	10 buildings
BC Hydro "TOU/CPP pilot study" (Chi-Keung et al. 2013)	British Columbia	trial	2007 - 2008	1,717
BGE "Smart Energy Pricing Pilot" (Ahmad Faruqui and Sergici 2009)	Maryland	trial and programme	2008	1,021 treatment, 354 control
CAISO "Flex Alerts" (Braithwait et al. 2014; Hummer, Firestone, and Zentai 2008)	California	programme	2007? To present	State-wide information campaign
California "ADRS" (Automated Demand Response System pilot) (Rocky Mountain Institute 2006)	California	trial	2004 - 2005	122 treatment, 104 control in 2004, 98 treatment, 101 control in 2005
California "SPP" (Statewide Pricing Pilot) (Charles River Associates 2005)	California	trial	2003 - 2004	1,759
Cambridge "DLC vs IHD" trial (Pelenur and Cruickshank 2013)	UK	trial	NK	14
CL&P "Plan-it wise pilot" (CL&P 2009)	Connecticut	trial	2009	1,251 treatment, 200 control
ComEd "CAP" (Customer Applications Pilot) (EPRI 2011, 2012a)	Illinois	trial	2010	8,000

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
ComEd "Energy smart pricing plan" (Allcott 2011)	Illinois	trial	2003 - 2006	693
ComEd "RRTP" (Residential Real Time Pricing) (Navigant 2011a)	Illinois	programme	2007 - present	over 10,000 in 2010 (up from ~500 in 2007). For analysis: 8151 treatment, 872 control
ConEd "CoolNYC" (ConEd 2012)	New York	programme	2012 - present	3,619 devices installed in 2012
Con Ed "DLC trial" (Egan-Annechino, Lopes, and Marks 2005)	New York	trial	2002	1,752
ConEd "DLC programme" (ConEd 2012)	New York	programme	2002 - present	expects 23,056 devices by end of 2012
Denmark "DR by Domestic Customers using Direct Electric Heating " (Kofod 2007)	Denmark	trial	2003 - 2005	25
DTE "smartcurrents" (DTE Energy 2014)	Detroit	trial	2012 - 2013	1,915
Duke Energy "Power Manager" (Energy 2013)	Ohio & Kentucky	programme	'mid-90's' - present	42,597 in Ohio, 9,086 in Kentucky in 2012
Duquesne "Watt Choices" (Navigant 2014a)	Pennsylvania	trial	2012 - 2013	1,474
EDF "Millener" (Bouly de Lesdain et al. 2014)	Reunion	trial	NK	over 100 interviews
EDF "Tempo" (VTT 2004)	France	programme	pilot 1989 - 1992; programme - present	800 in pilot. More than 300,000 in 2004
Energy Australia "Strategic pricing Study" (A Faruqi and Sergici 2009)	Australia	trial	2006	650
Energy demand shifting in residential households: the interdependence between social practices and technology design (Bourgeois et al. 2014)	UK	trial	NK	19
First Energy "consumer behavior study" (EPRI 2013)	Ohio	trial	summer 2012, ongoing	533
Florida Gulf "RSVP/GoodCents Select" (Borenstein, Jaske, and Rosenfeld 2002)	Florida	programme	2000 - present	2,300 by end of 2001

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
Germany "eTelligence" (Agsten et al. n.d.)	Germany	trial	2008 - 2012	650
GPU trial (A Faruqui and Sergici 2009)	New Jersey	trial	1997	NK
Green Mountain Power "eEnergy Vermont" (Blumsack and Hines 2013)	Vermont	trial	2012 (ongoing)	2,565
Hydro One "TOU trial" (Hydro One 2008)	Toronto	trial	2007	250
Idaho "Time of day" (Idaho Power 2008)	Idaho	trial	2005 - 2007	85 treatment in 2006
Intelliekon (Intelliekon 2011)	Germany, Austria	trial	2008 - 2011	1,114 treatment, 977 control
Ireland "CBT" (Customer Behaviour Trials) (CER 2011)	Ireland	trial	2010	4,375 treatment, 1,000 control
Laredo "Customer Choice and Control trial" (Hartway et al. 1999)	Texas	trial	1994 - 1997	650 treatment, 325 control
LIPAedge "DLC trial" (Crossley 2010)	New York	trial	2001 - at least 2005	20,400 on programme. Performance monitored for 400 units
Marblehead Municipal "energysense" (GDS Associates 2013)	Massachusetts	trial	2011 - 2012	500
Mercury Energy "TOU trial" (Thorsnes et al. 2012)	New Zealand	trial	2008 - 2009	400 treatment, 55 control
Metropolitan Edison (Met Ed) "residential demand reduction programme" (ADM Associates, Tetra Tech, NMR Group, and Metropolitan Edison Company 2013)	Pennsylvania	trial	2012 - 2013	17,154
Netherlands "powermatching city" (Bliek et al. 2010; Wiekens et al. 2014)	Netherlands	trial	2007 - 2014	40 (25 in phase 1)
Netherlands 'Your Energy Moment' (Kobus and Klaassen 2014)	Netherlands	trial	2012 - 2014	251
Newmarket Hydro "TOU pricing pilot" (Navigant 2008)	Ontario	trial	2006 - 2007	220 in analysis
Northern Ireland "Powershift" (Owen and Ward 2007)	Northern Ireland	trial	2003 - 2004	100 treatment, 100 control

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
Norway "EFFLOCOM trial" (end user flexibility by efficient use of IT) (VTT 2004)	Norway	trial	2003 - 2004	10,895
Norway "MBDR project" (Saele and Grande 2011)	Norway	trial	2007	40
OG&E "Positive Energy Together" (Silver Springs Networks 2011)	Oklahoma	trial	2010	3,000
OG&E "Smart Study TOGETHER" (Williamson and Shishido 2012)	Oklahoma	trial	2010 - 2011	3,000 yr 1, 6,000 yr 2
Olympic Peninsula "Gridwise testbed" (Chassin and Kiesling 2008; Hammerstrom et al. 2007)	Washington	trial	2006 - 2007	116
Ontario "peaksaver programme" (Berghman and Perry 2012; S. George et al. 2013; George and Perry 2011; KEMA 2010a, 2010b)	Ontario	programme	data 2009 - 2012	~180,000 DLC devices, nearly all on residential AC units
Ontario "smart price pilot" (IBM Global Business Services and eMeter Strategic Consulting 2007)	Ontario	trial	2006 - 2007	373 treatment
Ontario "TOU regulated price plan" (Faruqui et al. 2013)	Ontario	programme	2005 - present	over 90% of Ontario
PECO "smart AC saver" (Navigant 2012, 2013, 2014b)	Pennsylvania	trial	2012 - 2014	78,651
Penelec "Residential demand reduction programme" (ADM Associates, Tetra Tech, and NMR Group 2013)	Pennsylvania	trial	2012 - 2013	10,906
Penn Power "Residential demand reduction programme" (ADM Associates, Tetra Tech, NMR Group, and Pennsylvania Power Company 2013)	Pennsylvania	trial	2012 - 2013	2,661
PG&E "DR contingency reserves trial" (Eto et al. 2012; Sullivan et al. 2009)	California	trial	2009	2,000
PG&E "smart AC" (George et al. 2010; George, Hartmann, and Perry 2012; S. George, Perry, and Malaspina 2011; KEMA 2008, 2009; Mike Perry et al. 2013)	California	programme	2007 - present	over 10,000 by end of 2007 - vast majority residential

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
PG&E "smart rate" (George et al. 2010; S. S. George et al. 2011; George and Perry 2011; Hartmann et al. 2012; Michael Perry et al. 2013)	California	programme	2008 - present	>10,000 in 2008
PG&E "TOU programme" (George et al. 2010; S. S. George et al. 2011; Hartmann et al. 2012; Michael Perry et al. 2013)	California	programme	2008 - present	2008: ~10,000 end of 2012: 78,000
PowerCents DC trial (Wolak 2010)	Washington	trial	2008 - 2009	857 treatment, 388 control
PPL "peaksaver programme" (The Cadmus Group 2014)	Pennsylvania	trial	2012 - 2013	43,637
PSE "TOU trial" (A Faruqui and Sergici 2009)	Washington	trial	2001 - 2002	~300,000 placed on programme, NK how many opted out.
PSE&G "Mypower Pricing" (Violette, Erickson, and Klos 2007)	New Jersey	trial	2006 - 2007	539 Educate only, 424 automation technology, 450 control
Sala Heby Energi Elnät AB (Bartusch et al. 2011; Bartusch and Alvehag 2014)	Sweden	trial	2006 - 2012	159, but analysis of 95 due to technical issues
SCE "DR contingency reserves demonstration" (Eto et al. 2012)	California	demonstration	2008	nearly 800 in phase 2
SCE "DR contingency reserves trial" (Eto et al. 2012)	California	trial	2009 - 2010	3,255 AC units (residential and small commercial)
SCE "Save Power Days" (S. George, Bode, et al. 2011; S. S. George, Schellenberg, and Churchwell 2013; Nexant 2014b)	California	programme	2012 - present	~600,000 default 205, 890 opt-in, in 2013
SCE "Summer Discount Plan" (Eto et al. 2012; S. George, Bode, et al. 2011; S. S. George et al. 2013)	California	programme	25 + years, ongoing	322,000 in 2008
SDG&E "reduce your use" (Braithwait et al. 2012; Nexant 2014a)	California	programme	2011 - present	2,907 treatment, 2240 control
SDG&E "smart thermostat pilot" (KEMA 2006)	California	trial	2002 - 2005	3,936 units in 2005

Trial/programme name	Location	Programme/ Trial	Dates	No. of participants
SDG&E "Summer Saver" (George, Churchwell, and Oh 2014; S. George, Perry, and Woehleke 2011; Holmberg and Perry 2013; Malaspina and Perry 2012)	California	programme	2009 - present	23,602 residential in 2013
SMUD "Residential summer solutions" (EPRI 2014; Herter and Okuneva 2014)	California	trial	2011 - 2012	265 in 2011, 313 in 2012
SMUD "SmartPricing Options" (Potter et al. 2014)	California	trial	2012 - 2013	8,609
Spain "ADDRESS project" (Abi Ghanem 2014)	Spain	trial	NK	NK
SVE "empower" (Power System Engineering 2012)	South Dakota & Minnesota	trial	2011 - 2012	<600
Trento Province "TOU regulated price" (Torriti 2012, 2013)	Italy	programme	2010 - 2011	1,446 in analysis
UK "CLNR" (Customer lead network revolution)" (Bulkeley et al. 2014, 2015; Phillips et al. 2013; Sidebotham 2015)	UK	trial	2012 -2014	628 TOU, 128 smart wet goods, 34 heat pumps
UK "EDRP" (Energy Demand Research Project) (AECOM 2011)	UK	trial	2007 - 2010	SSE: 1,352 treatment (TOU, possibly with other incentives) EdF: 194 treatment (TOU)
UK "Low carbon London" (Carmichael et al. 2014; Schofield et al. 2014)	UK	trial	2013	1,119 treatment, 4381 control
UK "Northern Isles New Energy Solutions" (NINES) (Coote and MacLeman 2012)	UK	trial	2010 - 2012	6 homes
West Penn Power "Energy Savers Reward Programme" (ADM Associates, Tetra Tech, NMR Group, and West Penn Power Company 2013)	Pennsylvania	trial	2012 - 2013	23573
Xcel "energy pilot" (A Faruqui and Sergici 2009)	Colorado	trial	2006 - 2007	2,349 treatment, 1,350 control

Table B1 Trials and programmes reviewed

Surveys, interviews and focus groups reviewed

Study name	Location	Study type	Date	Number of participants
2010 EPRG Public Opinion Survey: Policy Preferences and Energy Saving Measures (Platchkov et al. 2010)	UK	Online survey	2010	2,038
2013 EPRG Public Opinion Survey: Smart Energy – Attitudes and Behaviours (Oseni et al. 2013)	UK	Online survey	2013	1526
Consumer acceptance of smart appliances (Mert et al. 2008)	UK, Italy, Germany, Austria, Slovenia	Surveys and focus groups	Not stated	2907 (surveys only)
Consumer Experiences of Time of Use Tariffs (Ipsos MORI 2012)	UK	Interviews	2012	5,914
Dynamic electricity pricing—Which programs do consumers prefer? (Dütschke and Paetz 2013)	Germany	Online survey	Not stated	160
Introducing a demand-based electricity distribution tariff in the residential sector: Demand response and customer perception (Bartusch et al. 2011)	Sweden	Interviews	Not stated	10 families, 19 family members
Smart Grid Consumer Survey – Navigant Consulting (Vyas and Strother 2013)	US	Online survey	2013	1,084
Smart grids, smart users? The role of the user in demand side management (Goulden et al. 2014)	UK	Focus groups	Not stated	72
Social barriers to the adoption of smart homes (Balta-Ozkan et al. 2013a)	UK	Focus groups	Not stated	~60
The development of smart homes market in the UK (Balta-Ozkan et al. 2013b)	UK	Focus groups	Not stated	~60 (the same focus groups as the paper above)
Transforming the UK energy system – public values, attitudes and acceptability – synthesis report. UKERC. (Parkhill et al. 2013)	UK	Survey and focus groups	Not stated	2441 (survey only)

Table B2 Surveys, interviews and focus groups reviewed

Appendix C: Results of studies only reporting response in metrics other than % change in power or energy

All studies of time-of-use/critical peak pricing, critical peak pricing, or critical peak rebate reported results using the metrics of % change in power or energy and so these types of demand response are not represented in this appendix.

Study names are as per Appendix B. See Appendix B for full list of references.

DR type	Study name	Response reported
TOU	Trento Province "TOU regulated price"	Peak shifting clear in morning, new peak created in middle of day, but evening peak shifted forwards and became higher than before.
RTP	ComEd "RRTP" (Residential Real-time Pricing)	"RT-10 alerts generate small hourly savings on the order of 0.0 to 0.08 kW per hour in the mid afternoon to early evening hours, but there is no good statistical evidence that alerts called outside these hours generate savings." RT-10 households also exhibit load shifting on non-event days, which RT-14 customers do not.
	ComEd "Energy smart pricing plan"	50 – 80 W lower consumption per customer on average during higher price hours (mid-afternoon). 5 – 14% additional reduction in daytime during high price alerts.
	Ameren Illinois "Power Smart Pricing"	-4.3% own price elasticity overall. Summer: average reduction of 0.15kW per customer from noon – 5pm, and 0.23kW per customer from noon – 5pm on high price alert days.
dTOU	UK "Low Carbon London"	On average, 0.05kW per household - both reduction for high price periods and increase during low price periods. Decrease in demand was higher during winter, but increase in demand was little affected by time of year.
DLC	PG&E "DR contingency reserves trial"	Up to 84%. Differences attributed to differences in AC use and communication signal strength.
	SCE "DR contingency reserves trial"	Not stated
	SCE "DR contingency reserves demonstration"	Not stated
	SDG&E "smart thermostat pilot"	0.02kW – 0.49kW per AC unit; average 0.3kW.
	ConEd "DLC trial"	1.1kW per AC unit on average
	Laredo "Customer Choice and Control trial"	1.95kW per AC unit on average
	LIPAedge "DLC trial"	15,852 MW – 16,273 MW on aggregate

DR type	Study name	Response reported
DLC	Duquesne "Watt Choices"	0.465MW on aggregate
	Metropolitan Edison (Met Ed) "residential demand reduction programme"	7.45 MW on aggregate
	Penelec "Residential demand reduction programme"	5.35MW on aggregate
	Penn Power "Residential demand reduction programme"	0.93MW on aggregate
	West Penn Power "Energy Savers Reward Programme"	5.86MW on aggregate
	PECO "smart AC saver"	51.3 MW reduction in phase 1; 71.1MW reduction in phase 2, on aggregate
	PPL "peaksaver programme"	16.83 MW on aggregate
	CAISO "Flex Alerts"	2008 - 222 - 282 MW based on self-reported behaviours. 2013 - not statistically significant (issue of coincidence with DR of PG&E)
	Duke Energy "Power Manager"	36 – 49 MW in Ohio; 8.7 – 12 MW in Kentucky (2012 results)
	ConEd "DLC programme"	1 – 1.4kW per AC on average (2012)
	Denmark "DR by Domestic Customers using Direct Electric Heating"	5.3 -2.5 kW per house (depending on temperature – of between -8 to +11 degrees C average daytime temperature).
	UK "CLNR"	2.5kW from DLC of heat pumps
	Norway "MBDR project"	1kWh/h for customers with standard electric water heaters; 2.5kWh/h for customers with electric space heating.

Table C1 Results of studies only reporting response in metrics other than % change in power or energy

Appendix D: Persistence

Studies were considered to offer evidence on persistence if they included text that described enrolment and/or response over time, and/or presented results for enrolment and/or response for two or more years using the same reporting metrics.

The most common metric for response used by these studies was average change in power demand. Percentage changes in response were calculated for studies reporting response using this metric. For both response and enrolment, percentage changes express the change in response or enrolment over the given number of years, as a percentage of response or enrolment levels in the baseline year. Percentage changes are reported across the total period reported, and if greater, the largest change between consecutive years is recorded in the 'notes' column. Where studies reported response as a % rather than an average change in power demand, the % responses across different years were included in the 'notes' section.

Enrolment and response have been judged as stable if they changed by 10% or less across the reported, or were described in a way that indicated they were stable in the study text.

Study names are as per Appendix B. See Appendix B for full list of references.

DR type	Trial Name	reporting period	Increase/ decrease/ stable	% change	notes
TOU	Sala Heby Energii Elnait AB - RECRUITMENT	2005 – 2012	NK	NK	-
	Sala Heby Energii Elnait AB - RESPONSE	2005 – 2012	stable	NK	"six years after the implementation households still respond to the price signals of the tariff by cutting demand in peak hours and shifting electricity consumption from peak to off-peak hours." (pg. 55, (Bartusch and Alvehag 2014)).
	UK "EDRP" (EDF TOUT) - RECRUITMENT	2009 – 2010	NK	NK	-
	UK "EDRP" (EDF TOUT) – RESPONSE	2009 – 2010	decrease	NK	"any initial effect is eroded over the first few quarters" (pg. 44, (AECOM 2011)).
	PSE&G "MyPower Pricing" (TOU) – RECRUITMENT	2006 – 2007	NK	NK	-

DR type	Trial Name	reporting period	Increase/ decrease/ stable	% change	notes
	PSE&G "MyPower Pricing" (TOU) – RESPONSE	2006 – 2007	stable	NK	"participants consistently lowered their on-peak demand in response to price signals across two summers. During the summer there were daily reductions in demand from 1:00 p.m. to 6:00 p.m. on weekdays due to the on-peak prices in the TOU rate" (pg. 20, (Violette et al. 2007)).
	SMUD "Smart Pricing Options" (TOU) - RECRUITMENT	2012 - 2013	stable	-9%	Customer attrition for most plans equalled roughly 25% over the course of the two summers, with the majority of this attrition resulting from customers who moved rather than from those who actively dropped out of the pricing plans. Dropout rates ranged from 4%-9% across different trial treatments. (Potter et al. 2014)
	SMUD "Smart Pricing Options" (TOU) – RESPONSE	2012 - 2013	stable	NK	Across all participants, and all three DR types included in the trial, no changes in response between the two years was statistically significant. Given the high attrition rate due to moving, response persistence was analysed for customers who stayed on the trial across both years. For opt-out TOU pricing with and without IHD offer, and opt-in TOU pricing without IHD offer, responses persisted across the two years. For opt-in TOU pricing with IHD offer, there was a drop from 0.24kW response per customer to 0.2kW per customer [17%], which was statistically significant at the 95% confidence level. (Potter et al. 2014).
CPP	PSE&G "MyPower Pricing" (CPP) – RECRUITMENT	2006 – 2007	NK	NK	-
	PSE&G "MyPower Pricing" (CPP) – RESPONSE	2006 – 2007	stable	NK	"participants consistently lowered their on-peak demand in response to price signals across two summers. ...When critical peak days were called, customers reacted to the CPP rates and created even more demand reduction during the 1:00 p.m. to 6:00 p.m. period " (pg. 20, (Violette et al. 2007)).
	Ameren Missouri "CPP and TOU trial" - RECRUITMENT	2004 - 2005	NK	NK	-

DR type	Trial Name	reporting period	Increase/ decrease/ stable	% change	notes
CPP	Ameren Missouri "CPP and TOU trial" – RESPONSE	2004 - 2005	increase	18%	Responses reported for CPP tariff only
	Ameren Missouri "CPP and TOU trial" – RESPONSE WITH PCT	2004 - 2005	decrease	-34%	Responses reported for CPP tariff only
	SMUD "Smart Pricing Options" (CPP) - RECRUITMENT	2012 - 2013	stable	-9%	Customer attrition for most plans equalled roughly 25% over the course of the two summers, with the majority of this attrition resulting from customers who moved rather than from those who actively dropped out of the pricing plans. Dropout rates ranged from 4%-9% across different trial treatments. (Potter et al. 2014)
	SMUD "Smart Pricing Options" (CPP) – RESPONSE	2012 - 2013	stable	NK	Across all participants, and all three DR types included in the trial, no changes in response between the two years was statistically significant. Given the high attrition rate due to moving, response persistence was analysed for customers who stayed on the trial across both years. For opt-out TOU pricing with and without IHD offer, and opt-in TOU pricing without IHD offer, responses persisted across the two years. For opt-in TOU pricing with IHD offer, there was a drop from 0.24kW response per customer to 0.2kW per customer [17%], which was statistically significant at the 95% confidence level. (Potter et al. 2014).
TOU-CPP	California "SPP" – RECRUITMENT	2003 – 2004	stable	NK	"turnover among treatment customers is almost exactly the same as turnover among control customers, suggesting that relatively few customers dropped off the experiment because of the treatment itself" (pg. 28, (Charles River Associates 2005))
	California "SPP" – RECRUITMENT	2003 – 2004	stable	NK	"turnover among treatment customers is almost exactly the same as turnover among control customers, suggesting that relatively few customers dropped off the experiment because of the treatment itself" (pg. 28, (Charles River Associates 2005))

DR type	Trial Name	reporting period	Increase/decrease/stable	% change	notes
TOU-CPP	SMUD "Smart Pricing Options" (TOU-CPP) - RECRUITMENT	2012 - 2013	stable	-9%	Customer attrition for most plans equalled roughly 25% over the course of the two summers, with the majority of this attrition resulting from customers who moved rather than from those who actively dropped out of the pricing plans. Dropout rates ranged from 4%-9% across different trial treatments. (Potter et al. 2014)
	SMUD "Smart Pricing Options" (TOU-CPP) – RESPONSE	2012 - 2013	stable	NK	Across all participants, and all three DR types included in the trial, no changes in response between the two years was statistically significant. Given the high attrition rate due to moving, response persistence was analysed for customers who stayed on the trial across both years. For opt-out TOU pricing with and without IHD offer, and opt-in TOU pricing without IHD offer, responses persisted across the two years. For opt-in TOU pricing with IHD offer, there was a drop from 0.24kW response per customer to 0.2kW per customer [17%], which was statistically significant at the 95% confidence level. (Potter et al. 2014).
	SMUD "Residential Summer Solutions" (TOU-CPP) – RESPONSE	2011 - 2012	stable	NK	"For all treatments, non-event peak and event peak savings stayed level or improved in the second year" (pg. 39, (Herter and Okuneva 2014)). (The trial included multiple DR types but did not report recruitment figures for each DR type separately.)
	OG&E "smart study together" (TOU-CPP) - RECRUITMENT	2010 - 2011	increase	105%	The trial involved a second round of recruitment in the second year of the trial
	OG&E "smart study together" (TOU-CPP) – RESPONSE	2010 - 2011	increase	NK	Analysis compares responses by two different consumer groups: those recruited during the first and during the second year of the trial. Authors suggest there "could be an indication that those customers who have more experience with the rate are learning how to respond better", but that "the PCT is not as conducive to learning and improving price responsiveness over time" compared to manual responses enabled by information from IHD or web portal. The description suggesting a learning effect and increased response applies to both types of pricing included in the trial. (pg. 4-11, (Williamson and Shishido 2012))

DR type	Trial Name	reporting period	Increase/decrease/stable	% change	notes
VPP	OG&E "smart study together" (VPP) - RECRUITMENT	2010 - 2011	increase	104%	The trial involved a second round of recruitment in the second year of the trial
	OG&E "smart study together" (VPP) – RESPONSE	2010 - 2011	increase	NK	Analysis compares responses by two different consumer groups: those recruited during the first and during the second year of the trial. Authors suggest there "could be an indication that those customers who have more experience with the rate are learning how to respond better", but that "the PCT is not as conducive to learning and improving price responsiveness over time" compared to manual responses enabled by information from IHD or web portal. The description suggesting a learning effect and increased response applies to both types of pricing included in the trial. (pg. 4-11, (Williamson and Shishido 2012))
DLC	California "ADRS" – RECRUITMENT	2004 – 2005	decrease	-20%	-
	California "ADRS" – RESPONSE	2004 – 2005	decrease	NK	The reported response fell from 51% to 43%. The reduction is mostly attributed to lower control group loads in 2005, even though temperatures were higher in 2005.
	SMUD "Residential Summer Solutions" (DLC) – RESPONSE	2011 - 2012	stable	NK	"For all treatments, non-event peak and event peak savings stayed level or improved in the second year" (pg. 39, (Herter and Okuneva 2014)). (The trial included multiple DR types but did not report recruitment figures for each DR type separately.)
Info only	SMUD "Residential Summer Solutions" (info only) – RESPONSE	2011 - 2012	stable	NK	"For all treatments, non-event peak and event peak savings stayed level or improved in the second year" (pg. 39, (Herter and Okuneva 2014)). (The trial included multiple DR types but did not report recruitment figures for each DR type separately.)
TOU, CPP	Idaho "TOD" – RECRUITMENT	2006 – 2007	stable	-4.60%	The trial included time of use and critical peak pricing but did not report recruitment figures for each DR type separately.
	Idaho "TOD" – RESPONSE	2006 - 2007	NK	NK	-

DR type	Trial Name	reporting period	Increase/decrease/stable	% change	notes
TOU-CPP, DLC, info only	SMUD "Residential Summer Solutions" - RECRUITMENT	2011 - 2012	stable	-5%	"90% of the 2011 Summer Solutions participants signed up again for Summer Solutions 2012"... "5% of the 2011 participants dropped out of the study". (pg. 14, (EPRI 2014)). The trial included multiple DR types but did not report recruitment figures for each DR type separately. Response figures were reported for each DR type and can be found in the relevant sections of this table.

Table D1 Trials reporting recruitment and/or response over multiple years

DR type	Programme name	reporting period	Increase/decrease/stable	% change	notes
TOU	PG&E "Time of use tariff" – RECRUITMENT	2009 - 2012	increase	17%	The increase in enrolment reflects recruitment to a new TOU tariff (E6). Older TOU tariff (E7) closed for recruitment across all 4 years. Greatest % change between consecutive years: +24% (2011 - 2012).
	PG&E "Time of use tariff" – RESPONSE	2009 - 2012	stable	0%	Average kW responses identified for study years 2009 and 2012 only. Average % responses varied from 9.6% to 12% over the four years. In 2012 the reported results included participants in a new TOU tariff (E6). Older TOU tariff (E7) was closed for recruitment across all 4 years.
CPP	PG&E "Smart rate" – RECRUITMENT	2008 - 2012	increase	688%	Stopped actively marketing in 2010 due to regulatory uncertainty. Greatest change between consecutive years: +239% (2011 - 2012).
	PG&E "Smart rate" – RESPONSE	2008 - 2012	decrease	-33%	Largest change year-to-year: -23% (2008 - 2009).

DR type	Programme name	reporting period	Increase/ Decrease/ stable	% change	notes
CPR	SDG&E "Reduce Your Use" – RECRUITMENT	2012 - 2013	increase	32%	Customers were recruited on an opt-out basis and could opt-in to receive alerts of critical peak periods. This analysis reflects opt-in to alerts rather than total enrolment. 2011 was a pilot year and was excluded from this analysis.
	SDG&E "Reduce Your Use" – RESPONSE	2012 - 2013	stable	9%	Only one event was called in 2013, on a Saturday. The % change was calculated comparing reported response for this event with the average responses for events on Saturdays in 2012. Considering the average of all events in 2012, the change is +33%.
	SCE "Save Power Days" - RECRUITMENT	2012 - 2013	NK	NK	Customers were recruited on an opt-out basis and could opt-in to receive alerts. Opt-in to alerts was reported for 2013 only.
	SCE "Save Power Days" – RESPONSE	2012 - 2013	stable	NK	"Opt-in and default PTR percent impacts were similar to the 2012 impacts" (Nexant 2014b).
VPP	EDF "Tempo" - RECRUITMENT	NK	NK	NK	-
	EDF "Tempo" – RESPONSE	NK	stable	NK	"consumption reduction is more or less stable over the years"
DLC	PG&E "Smart AC" – RECRUITMENT	2007 - 2012	increase	1390%	Greatest change in consecutive years: +690% (2007 - 2008).
	PG&E "Smart AC" – RESPONSE	2007 - 2012	decrease	-54%	Greatest change in consecutive years: +127% (2010 - 2011; suggests increase likely due to changes in control strategy).
	SDG&E "Summer Saver" – RECRUITMENT	2009 - 2013	stable	-4%	Greatest change in consecutive years: -6% (2011 - 2012).
	SDG&E "Summer Saver" – RESPONSE	2010 - 2013	increase	20%	Only ex-ante results identified for 2009. Greatest change in consecutive years: +27% (2011 - 2012).
	SCE "Summer Discount Plan" – RECRUITMENT	2010 - 2012	decrease	-12%	Reported as number of accounts called during events rather than number of consumers enrolled. Number of accounts called not identified for 2011.

DR type	Programme name	reporting period	Increase/ Decrease/ stable	% change	notes
DLC	SCE "Summer Discount Plan" – RESPONSE	2010 - 2012	decrease	-64%	Began to operate as price responsive rather than emergency programme in 2012. Level of response not identified for 2011.
	Ontario "Peaksaver" – RECRUITMENT	2009 - 2012	increase	28%	Reported as number of control devices rather than number of participants. Suggests not all devices are notified to central reporting so true numbers may be higher. Greatest change in consecutive years: +36% (2009 - 2010).
	Ontario "Peaksaver" – RESPONSE	2010 - 2012	stable	-6%	2009 events were carried out purely to test measurement and verification procedures, so were excluded from this analysis. In 2010 and 2012 a proportion of events were called to test measurement and verification procedures, and these were excluded from this analysis. In 2012, the methodology was changed to include comparison with control groups. Greatest change in consecutive years: +51% (2010 - 2011).
RTP	Ameren Illinois "Power Smart Pricing" – RECRUITMENT	2007 - 2013	increase	2648%	Not actively marketed in 2007 due to regulatory uncertainty. Relatively little marketing in 2011 and 2012 due to regulatory uncertainty: 5% and 8% recruitment in these years. 12% recruitment in 2013 after active marketing resumed.
	Ameren Illinois "Power Smart Pricing" – RESPONSE	2008 - 2010	stable	0%	Level of response identified for 2008 - 2010 only. Over this period the response was constant, but average response fell by 13% in 2009 and rose again in 2010.

Table D2 Programmes reporting recruitment and/or response over multiple years

Appendix E: The impact of enabling technologies on response

Study names are as per Appendix B. See Appendix B for full list of references.

	Study name (further details in parentheses where applicable)	Reported response levels (%)				Change in response with enabling technology (%)		
		No enabling technology	information	automation	Information + automation	information	automation	Information + automation
sTOU	CL&P "Plan-it wise pilot"	3.10		3.10			0.00	
	Hydro One "TOU trial"	3.70	5.50			1.80		
	Newmarket Hydro "TOU pricing pilot"	4.70		0.00			-4.70	
	Ireland "CBT"	8.80	11.30			2.50		
TOU-CPP - day to day	DTE "smartcurrents" (cool weather)	0.00	0.00	9.07	10.57	0	9	11
	DTE "smartcurrents" (hot weather)	0.00	0.00	26.02	24.94	0	26	25
	BGE "Smart Energy Pricing Pilot"	1.76	4.38			3		
	PSE&G "Mypower Pricing" (hot summer days, with AC)	3.00		21.00			18.00	
	Xcel "Energy pilot" (with AC)	8.21		10.29			2.08	
	OG&E "Smart Study TOGETHER"	10.03	16.84	29.37	25.73	6.81	19.34	15.70
	PowerCents DC trial	13.00		24.00			11.00	
CPP	Green Mountain Power "eEnergy Vermont"	14.30	11.10			-3.20		
	CL&P "Plan-it wise pilot"	16.10		23.30			7.20	
	SMUD "SmartPricing Options" (opt in)	20.90	25.10			4.20		
	Xcel "Energy pilot" (with AC)	38.42		44.81			6.39	
TOU-CPP - critical events	BC Hydro trial	9.20		30.70			21.50	
	DTE "smartcurrents"	12.60	17.45	44.51	43.02	4.85	31.91	30.42
	Mypower Pricing (PSE&G) (with AC)	17.00		47.00			30.00	
	OG&E "Smart Study TOGETHER"	19.80	25.58	38.80	30.60	5.78	19.00	10.80
	BGE "Smart Energy Pricing Pilot"	21.00	27.00			6.00		
	Xcel "Energy pilot" (with AC)	28.75		54.22			25.47	
	Australia "Integral energy trial"	37.00	41.00			4.00		
CPR	Green Mountain Power "eEnergy Vermont"	5.40	5.70			0.30		
	CL&P "Plan-it wise pilot"	10.90		17.80			6.90	
	BGE "Smart Energy Pricing Pilot"	20.94	26.83	32.95		5.89	12.01	-20.94
	First Energy "Consumer Behavior Study"		11.00	8.00				
VPP	OG&E "Smart Study TOGETHER"	11.72	10.99	35.94	28.29	-0.73	24.22	16.57
	OG&E "Smart Study TOGETHER" (critical peak event)	14.52	13.40	32.15	30.78	-1.12	17.63	16.26
	OG&E "Positive Energy Together" (IHD)		11.00	33.00	28.00			
Average change in response with enabling technology:						2.5%	14.9%	13%

Table E1 The impact of enabling technologies on response

Appendices to Papers 3 and 4

Appendix F: Consent form for initial and follow-up user interviews

FREEDOM PROJECT: CONSENT FORM FOR INTERVIEW AUDIO RECORDING

I understand that agreeing to take part means that I am willing to:

- Be interviewed by the researcher
- Allow the interview to be audio recorded

I understand that any information I provide is confidential, and that no information that I disclose will lead to the identification of any individual in the reports on the project, either by the researcher or by any other party. I understand that all interview materials will be stored in a password-protected computer.

I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the Data Protection Act 1998.

Name(s):

Date:

Signature(s):

Appendix G: Information sheet for installer interviews**PARTICIPANT INFORMATION SHEET***Study title*

How might user engagement with new technologies contribute to a low carbon transition in the UK?

Invitation

You are being invited to take part in this research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

The study aims to consider how residential users engage with new technologies that are intended to reduce carbon emissions from energy use at home. If the uptake or use of such technologies differs significantly from designer or policy maker expectations, they may not contribute to decarbonisation in the intended way. Insights into different factors that influence uptake and use of such technologies could contribute to achieving decarbonisation of residential energy use in the UK.

Why have I been invited to participate?

You have been invited to participate as an expert involved in the FREEDOM Project. Interviews with residential users participating in the FREEDOM Project form an important part of this University of Sussex research project. As an expert involved in the project you have interacted with trial participants in different ways and helped to inform them about the trial technology. Interactions with experts are one factor which can be important in influencing how new technologies are used. Your insights into users involved in the trial, and into the intended use of the trial technology, would be used to complement findings from the user interviews.

Do I have to take part?

The decision of participating in this study is up to you. If you decide to take part, you will be asked to sign a consent form. You are also allowed to withdraw at any time and without giving any reason.

What will happen to me if I take part?

If you decide to participate, you will be asked to be part of an interview lasting around 30 minutes. Questions will refer to your interactions with trial participants, and the use of the trial technology.

What are the possible disadvantages and risks of taking part?

This study does not imply any risk or disadvantage for participants. Interview questions will relate to your general experiences of the FREEDOM Project and your answers will be anonymised. Interviews will be kept as short as possible.

What are the possible benefits of taking part?

We believe that your participation is beneficial for this study and hopefully its findings would be helpful to policy makers and others involved in promoting new technologies to decarbonise residential energy use.

Will my information in this study be kept confidential?

We will preserve the anonymity of your participation. You will not be identified in any report or publication. Data collected about you will be stored coded or anonymised on a password protected computer.

What will happen to the results of the research study?

The findings of the research may be published in the form of a PhD monograph, academic journal papers, academic conference papers and/or posters, blog posts, policy briefings and other forms of dissemination.

Who is organising and funding the research?

This research is being conducted by a doctoral researcher at the Science Policy Research Unit (SPRU), University of Sussex. The project is funded by the Economic and Social Research Council (ESRC).

Who has approved this study?

The research has been approved by the Social Sciences & Arts Cross-Schools Research Ethics Committee (C-REC) at the University of Sussex.

Contact for Further Information

For further information or any concerns about the way in which the study has been conducted, please contact:

Doctoral Researcher
Bryony Parrish T: +44 (0)7867948336 E: b.parrish@sussex.ac.uk

Supervisors	
Tim Foxon E: t.j.foxon@sussex.ac.uk	Benjamin Sovacool ¹⁴ E: b.sovacool@sussex.ac.uk

The University of Sussex has insurance in place to cover its legal liabilities in respect of this study.

We are very thankful to you for your time in reading this information sheet and taking part of our study.

Date

_____.

¹⁴ Benjamin Sovacool was part of the supervisory team for this thesis in its earlier stages.

Appendix H: Consent form for installer interviews



CONSENT FORM FOR PROJECT PARTICIPANTS

PROJECT TITLE: How might user engagement with new technologies contribute to a low carbon transition in the UK?

I agree to take part in the above University of Sussex research project. I have had the project explained to me and I have read and understood the Information Sheet, which I may keep for records. I understand that agreeing to take part means that I am willing to:

(please tick)

- ☐ Be interviewed by the researcher
- ☐ Allow the interview to be audio recorded
- ☐ Allow the use of direct quotations from the interview

I understand that any information I provide is confidential, and that no information that I disclose will lead to the identification of any individual in the reports on the project, either by the researcher or by any other party. I understand that all interview materials will be stored in a password-protected computer.

I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalised or disadvantaged in any way.

I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the Data Protection Act 1998.

Name:

Signature:

Date:

Appendix I: Topic guide for initial user interviews

Introduction

Thanks for offering to help with my research. I'm doing a PhD at Sussex and I'm interested in what people **think** about new technologies for heating, and how they are **used** as part of people's daily lives. I expect to **publish** findings from these interviews, but they will be **anonymous**. If you want to you can ask me to **remove** all or part of what you tell me from my research. Nothing will change for you if you decide to do that. But please let me know within 2 months.

Is it OK for me to **audio-record** the interview so I can concentrate better on what you're saying instead of on taking notes? – **consent** form for audio-recording.

House & household information

- How many people in house – ages of any children. Any adults retired or over 65? Any pets?
- House type and age – number of bedrooms. Cavity wall insulation?
- How long at this address?
- When are people usually at home? What times are people out at work or school?

First, I'd like to ask a bit more about the installation process

1) How do you **feel** about the installation process (so far)?

- Interactions with **installer** – in the home, in communication
- **Logistics**
- **Physical** installation – impact on home?
- Anything **unexpected**?

2) **Where** has the new heating system been installed? (inside and outside).

- How was the position **decided**? (customer input? Explanation from installers?)
- How do you **feel** about where it is?

3) Did your **installer** give you any specific **information** about the new system? (DEPENDS ON OBS).

- What to **expect** from **using** the technology
- **Advice** – how to use the controls, how to use heating, dos and don'ts
- **How it works** – HP, hybrid, smart control

4) Did you ask the **installer** any **questions**?

- What did you ask about?
- Why? (or, why not?)

5) Is there anything else the installer could have done to help?

6) Have you looked for **information** about the technology **anywhere else**?

What kind of information? How **helpful** was it, why?

- Trial leaflets/PassivSystems staff
- Internet
- People you know: Neighbours, friends – perhaps also in trial? Professionals – e.g. plumbers

Now I'd like to ask you about how you became part of this project.

7) Tell me about the time when you **first heard about the trial**

- **Who** from? **What** did you hear about it?
- What did you **think** about that?

8) What made you **decide to take part** in the trial?

- **Motivations** – what do they think is good about the **technology** or the **trial**? Do they expect benefits for **themselves or others**?
- **Any concerns?** – about the technology or the trial. Since they are taking part – are these concerns small compared with other factors, or did something reduce these concerns? What?
- Did you talk about it in the **household**?

9) This hybrid heating system is a **new technology**.

- How do you feel about technology in general? Experience?
- What do you usually **think** about new technologies?
- Have you **tried** out any new technologies before?

10) Does it make any difference to you that the **one part of the new technology is a gas boiler**?

- Would you have decided to take part **if the project only used heat pumps**?

11) What do you think about the **automatic controls** that the system uses?

12) Do any other members of the **household** have any **different feelings** about starting the trial?

Finally, I'd like to ask about how you usually heat your home.

First I'd like to ask about your old heating system, and how you controlled it.

13) What kind of heating system did you have?

- Combi boiler or water tank?
- Any heating other than gas boiler?
- Controls and their location – timer, thermostat, thermostatic radiator valves?

14) How did you **control** your old heating system?

- At boiler (on/off, timer), using thermostat, at radiator – why?
- **How often/when** – why?
- **Who** in the household did this – why?

15) Can you remember when you **first started** to control your heating in that way?

- Has this **changed** over the years/in different homes (including as a child)? How and why (not)?
- When you first started, did you: learn from **other people** (who, when?); follow **instructions** (where from?); **trial and error**? Were any instructions available?

Now I'd like to ask about how you usually heat your home.

16) What temperature do you like your home to be at different times?

- **Times of day**; types of **activities**; **seasons**.
- **Why is heating important** at those times?
- Are there any times that you **prefer your home to be cool**? When/why?
- Does **anyone else** in the household prefer it to be warmer or cooler? How do you **decide** on how the heating is used?

17) Is there **anything else you do to stay comfortable** at home apart from controlling the heating? Why? When did you first start to do this?

18) Do you ever use the heating for **anything other than keeping warm**? – pets; laundry; avoid dampness/condensation.

19) What do you **expect it will be like to use** your new heating system? Do you expect it to **change anything** about how you heat your home, **or not really**?

20) The new heating system could also help to **reduce global warming emissions** from the **British energy system**. Is that something you've thought about, or not really?

Close: Thank you very much! Is it OK for me to get in touch in the New Year and invite you to participate in a **second interview**? Is it OK for Clare to contact you to ask whether she can use **data from heating controls** for her research? While I'm here, is there anything I can help with?

Appendix J: Topic guide for follow-up user interviews

Introduction

- thank you for taking time to speak to me again. Remind of what I'm working on – and anonymous publication. Like last time, is it OK if I record? Consent form for recording.

Opening question

The last time we spoke, you'd had the system for about x days. **Thinking back over the last few months, please can you tell me a bit about your experiences of living with the system?**

- Have you noticed anything different compared to your old heating, or not really?
- Has anything changed because of the new system?
- Have you changed anything about the new system?
- Good or bad experiences?

(Probes only if necessary to start people talking – mostly lead into **QUESTIONS MATRIX** – see below)

Communicating about the technology outside the household

Have you talked about the technology with **anyone outside the household?**

- Who? When/how? (e.g. f2f, social media...)
- Why did you talk about it?
- What did you talk about?

Expectations and summing up

Overall, how does the system **compare to your expectations at the start of the trial?**

- Heating home; controls; cost; anything else (physical kit)

Do you **plan to keep the new system** after the end of the trial? **Why/why not?**

If so, what do you **expect from the system in the future?**

To sum up, please could you **pick a few words to describe your new heating and old heating systems?**

Has your experience made you think any differently about **new technologies or green technologies in general?** Would you think about **investing in anything else?**

Close

Thank you! Anything I can help with, or you'd like to tell me about while I'm here?

Questions Matrix

	Differences or similarities compared to old system	Over the months since new system installed:		Feelings about new system	Ideas about new system
		Changes in practices & household relations	Learning & interactions in and out of household		
Using heat in the home	More or less comfortable? • Why? • When? At specific times of day? Over changing seasons? Overall?	Changes in use of heating? • To keep warm, dry laundry etc.? • Changes to anything else?	How and why did the change happen? • Feature of new system, or something else? • Sudden or gradual? What steps were involved?	How do you feel about the way the new system heats your home? Why? Does anyone else in the household feel differently?	Any ideas about why it might be different to old heating? After this experience, would you consider having a heat pump without a boiler?
Controls	How do you have the temperatures and timings set in the app? • Times of day, days of week • Change in app (go to A) or leave set? (go to B) C) Is the way you use the controls different or similar to your old heating? • If different – how? • Why do you think this is?	A) How do you interact with the controls? • Which controls? Why? • Where are you? What are you doing? • Whose job? Why? • Changed over time? (go to C)	B) Since first set up with installer, have you changed the settings in the app? • What changes, over time? • Why? E.g. Seasons? Household circumstances? Adapting system to suit? • Who? Inside and outside the household • Steps involved?	How do you feel about the different controls? How easy is it to control the heating in the way you want? Does anyone else in the household feel differently?	Any ideas about why controls designed like that? Are there any other features of the controls you'd like to have seen?
Smart controls			Have you noticed: - when the boiler and the heat pump are working? - the smart controls changing the heating? • How can you tell? • What times have you noticed this?	How do you feel about the smart automated controls? • Trust: of objectives? Of organisations responsible? Does anyone else in the household feel differently?	Any ideas about: - why the heat pump and boiler run at certain times? - why the smart control changes the heating? • What's your understanding? • How did you work that out? • Is it important to you to understand?
Physical kit	Anything you particularly notice? • Noise, breeze, taking up space, visual impact? • Changed over time? Start noticing things, or get used to them?	Has anything you do at home changed because of the new heating units? • How, why?		How do you feel about them overall? Does anyone else in the household feel differently?	
• Heat pump and boiler units • New pipes • controls					

Appendix K: Topic guide for installer interviews

1) Please can you describe any ways in which you've interacted with customers over the course of the trial?

- *Methods of communication, e.g. telling, writing, showing*
- *Which types of information, and why? Any information that you wouldn't share? Does this vary between customers?*
- *How easy to communicate this information to different customers? Did they check understanding?*

2) Please can you tell me a bit about how the system works, and how you think it should be used?

Probes on the role of the heat pump and gas boiler in the hybrid system:

- *What times would each be running, and why?*
- *What job does each part do?*
- *Which is main/secondary heat source?*
- *What's the benefit of the system working in that way? Are there any risks?*

Probes on the use of controls:

- *In which combination, to do which jobs?*
- *At what times?*
- *Does it depend on the type of customer or the situation?*
- *What's the benefit of the system working in that way? Are there any risks?*

3) Can you imagine the system being used in any different ways?

- *Different how?*
- *Why might that happen? Because of technology, users, both?*
- *Impact on efficiency, or other objectives e.g. demand response?*

Appendix L: Coding structure for initial and follow-up user interviews

Main coding themes	Supplementary coding themes*
• Context - Household circumstances - Ideas about self re: technology - Ideas about self re: environment - Material details relevant to heating in home • Getting involved in the trial - Finding out about the trial - Reasons to participate • Installation - Feelings about installation and installers - Feelings about position of trial technology - How positions decided - Position of trial technology • Experiences of trial technology - Breeze - Comfort - Day time heating - Displays and information - Ease of use of controls - Night-time heating - Noise - Novelty - Physically occupying or changing space - Problems - Radiators - See fan moving - Visual and aesthetic • Making sense - Gratitude - 'Is it me?' - Media - Observation of technology - Other trialists - Related ideas - Trial technology 'thinking' • Responding - Adaptations to space - Getting used to it - Looking for information - 'Playing' - Users against trial technology - Users cooperating with trial technology • Outcomes - Meanings associated with trial system - Understanding of technology - Use of controls - Using heat and related practices	• Expectations and concerns • Household dynamics • Ideas and feelings about trial and trial organisers • Imagining • Innovative or 'green' tech in general • Installers • Manufacturer • Norms about heating • Running costs • Smart control • Social network • Up-front cost • What information people want • What people want from heating system * these themes supplemented the main coding structure by providing additional information and/or being coded at the same time as codes within the main structure. For example, the sub theme 'looking for information' in the main structure might be co-coded with 'installers' or 'social network' if the interviewee sought information from these sources.

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