

LOUGHBOROUGH UNIVERSITY

Heating Controls Scoping Review Project

For: Department of Energy and Climate Change

by

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Executive Summary

Heating system controls are seen as a potentially cost effective way of reducing energy demand in centrally heated homes. Their performance is, however, difficult to determine because the effects are directly or indirectly influenced by the energy efficiency of the dwelling itself, the heating system into which they are installed, and most importantly by the occupants of the home. The occupants use the controls to obtain the desired internal temperature and may seek improved thermal comfort from new controls, and actually use more energy. The usability of controls is therefore an important consideration.

A scoping review using systematic techniques has been undertaken to identify the evidence for the energy saving, cost effectiveness and usability of domestic central heating controls. There was particular focus on central timers, room thermostats, programmable thermostats, TRVs, TPIs, weather compensators, automation and optimisation.

Clearly defined searches of five main databases and Google Scholar revealed 1295 publications; 10 more documents were found using snowballing. These were subject to acceptance criteria and quality assurance criteria which isolated 32 UK publications for further, close scrutiny. The overseas articles have been recorded and retained.

The energy savings and cost effectiveness of controls have been determined by either: making computer models of heating systems; experiments in test houses; trials in a small number of occupied houses; or full-scale field trials. Of the articles read, very few provided direct evidence of the energy savings or cost effectiveness, though many provided evidence of their effect on indoor temperatures.

The most compelling evidence is likely to come from large scale field trials which expose controls to the full complexity of diverse, occupied homes. Such trials will also expose any unintended consequences from the installation of new controls in existing homes. The review revealed just one large-scale UK trials dedicated to understanding the performance of heating controls. This demonstrated that the introduction of a TPI controller in place of a standard thermostat, did not improve the overall efficiency of the existing, energy efficient, modulating, condensing boilers.

Clearest evidence of the energy savings and cost effectiveness of controls has come from side-by-side trials in full-size homes with simulated occupancy. For the occupancy schedule chosen, and the particular homes and weather conditions, zonal control reduced gas consumption by c12% compared to a Building Regulations compliant system. Other trials have demonstrated energy saving from adding a room thermostat, and small additional savings from adding TRVs, but the benefits of programmers and timers is uncertain.

An interface to a dynamic thermal computer model has been developed to enable the possible effects of controls to be simulated in order to inform the development of the Standard Assessment Procedure. The fidelity of the predictions is unknown.

Most studies of usability focussed on central timers, room thermostats and programmable thermostats as a single device. Few mention TRVs or automation; no studies covered usability issues relating to weather compensators or optimisation. None identified, with any robustness, the consequence of poor usability in terms of energy or cost-effectiveness.

Overall, this review has identified a dearth of evidence relating to the energy savings, cost effectiveness and usability of heating controls in the UK literature. It isn't that there are evidence gaps so much as no robust evidence at all for most controls.

Impact of different heating controls on energy saving, cost-effectiveness and usability with confidence level

Control Type	Impact on			Confidence
	Energy Saving	Cost-effectiveness	Usability	
Programmer/timer (inc. digital)	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Room thermostat	Single test. 12% gas saving compared to boiler thermostat only. Unrealistic 'weather' & house temperatures. ¹	Lack of robust evidence	Lack of robust evidence	Very Low
TRV	Single test. 30% gas saving compared to room thermostat only. Unrealistic 'weather' & house temperatures. ¹	Lack of robust evidence	Lack of robust evidence	Very Low
Weather compensation	Lack of robust evidence	Lack of robust evidence	N/A	N/A
TPI	Large field trial. TPI in place of standard thermostat. No effect on efficiency of modulating condensing boilers. ²	Lack of robust evidence	N/A	Good
Zonal control	Series of trials in one house. 12% gas saving compared to a Building Regulations compliant system. ³	Acceptable payback for cheaper systems	Lack of robust evidence	Modest
Automation incl. self-learning	Two homes only. Learning zonal control 8%-18% gas saving. ⁴	Lack of robust evidence	Lack of robust evidence	Very Low
Remote control	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A

¹ Fitton et al (2016). ² Kershaw et al (2010). ³ Beizaee et al (2015). ⁴ Scott et al (2011).

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1 Introduction

1.1 Background

The UK Department of Energy and Climate Change (DECC) is currently carrying out work to explore the evidence base for heating controls to contribute to one of the Department's key policy priorities to decarbonise heat. The suite of standard heating controls (such as timers, room thermostats and thermostatic radiator valves) and advanced heating controls (such as zonal control, learning algorithms and remote control) are currently being examined in terms of energy savings, thermal comfort, usability, accessibility and evidence gaps.

DECC commissioned this review with the aim to look for support in reviewing the evidence base for domestic heating controls in terms of cost-effectiveness, usability, energy savings and evidence gaps. In particular, DECC was looking for support for the following types of heating controls: central timers, room thermostats, programmable thermostats, TRVs, weather compensators, TPI, automation and optimisation.

1.2 Aims and objectives of the review

The aim of the research project was to collect, synthesise and assess the quality of current knowledge on domestic heating controls by undertaking a scoping review in order to meet the following objectives:

- Using systematic techniques, collect all of the previous studies on domestic heating controls from academic, grey and industry sources (UK-focused, though where evidence is poor, identify international sources where the evidence might be stronger) – the scoping review should focus on: central timers, room thermostats, programmable thermostats, TRVs, weather compensators, automation and optimisation
- Assess the quality of the previous studies, discussing the strengths and weaknesses of both those that pass and fail the quality assessment (see the quality assessment scale used in section 0)
- Synthesise previous research to determine:
 - The energy savings from each of the above heating controls
 - The usability of each of the above heating controls
 - The cost-effectiveness of each of the above heating controls (priority area)
- Discuss the current state of knowledge for each of the above heating control types and identify the key evidence gaps.

1.3 An overview of domestic space heating controls

A central heating system which is in compliance with Building Regulations Part L1B (HM Government, 2013) (Figure 1) has all the following control devices and specifications:

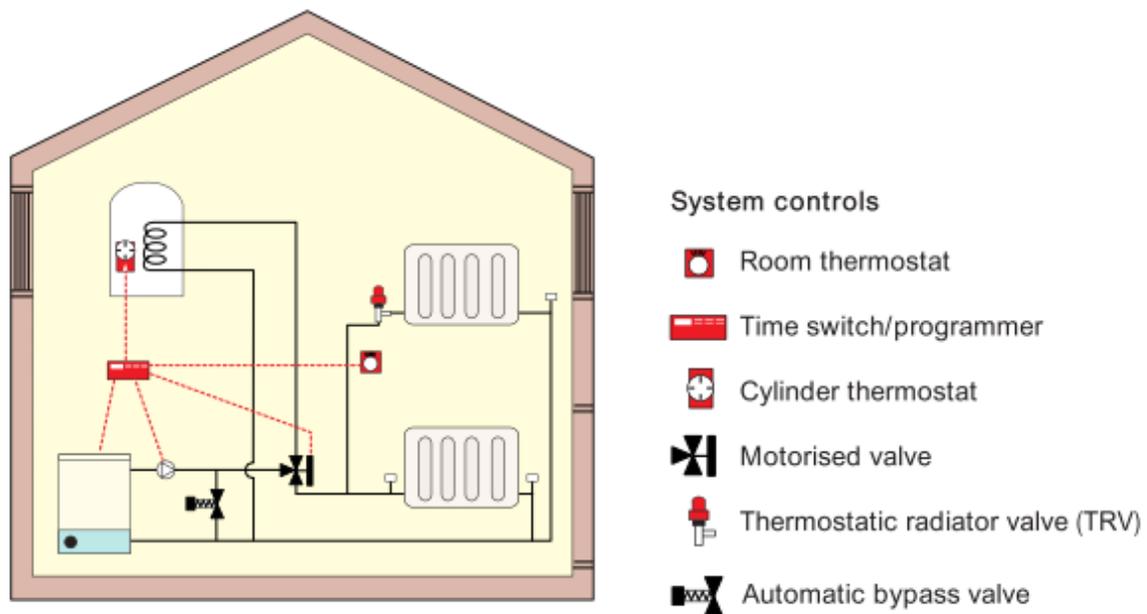


Figure 1: A standard domestic wet central heating system configuration (BRECSU, 2001)

- **Time switch (for combination boilers):** A time switch is the primary way in which the central heating system can be controlled by the occupants. It allows them to set the times at which the system will turn on and turn off.
- **Programmer and cylinder thermostat (for regular boiler with separate hot water store):** A programmer is similar to a time switch but it allows the time setting for space heating and hot water to be independent. A cylinder thermostat prevents the water in the cylinder from overheating. The programmer enables the times of hot water heating and space heating to be set typically for weekdays and weekends separately. In effect, turning the system on and off at pre-set times.
- **Room thermostat:** A room thermostat allows the occupants to control the air temperature when the heating is on. It is often located in a central area of the home such as a living room or hallway. A Programmable Room Thermostat (PRT) is simply a combined programmer and thermostat.
- **Boiler interlock:** Boiler interlock is not a control device but a wiring arrangement of the system controls (room thermostats, PRTs, cylinder thermostats, programmers and time switches) in order to prevent the boiler from firing when there is no demand for heat.

- **TRVs on all radiators, except in rooms with a room thermostat:** TRVs are used to provide a degree of temperature control in individual rooms by adjusting the water flow through an emitter and controlling its heat output.
- **Automatic bypass valve:** A bypass circuit allows a minimum flow rate to be maintained while the boiler is firing.

In addition to these control devices and specifications, which are required for the existing dwellings to comply with the Building Regulations, since 1 October 2010, every new home which is not open plan, must be divided to at least two heating zones (HM Government, 2013). This allows the living and sleeping areas can be controlled at different temperatures. If the house is less than 150 m² then these two zones can be controlled by the same timer, otherwise two timers are needed.

A number of additional advanced control devices are also sometimes used in some central heating systems:

- **Weather compensator:** A weather compensator adjusts the temperature of water in central heating systems in accordance with the outside temperature. Weather compensators are installed in order to allow condensing boilers work more effectively or for less time. Load compensators fulfil a similar task based on the measured indoor temperature.
- **Time Proportional Integral (TPI) controls:** TPI is a functionality which many of the current electronic room thermostats have. TPI use an algorithm to closely control internal temperature, eliminating the temperature swings observed with on/off controllers.
- **Zonal control:** Zonal control allows householders to heat each zone at a different time. Programmable thermostatic radiator valves (PTRVs) enable time-dependent operation of each emitter.
- **Automation:** In the last five years a new generations of 'smart' controls has emerged which enable people to control their heating system remotely by exploiting wireless connectivity. Some provide users flexibility and greater control over when they heat whilst others use embedded learning algorithms to automate the provision of heat. Some provide feedback on energy use.

The energy that is saved by controls will depend on the characteristics of the native system into which they are installed. For example, if TRVs are installed in a system without a room-thermostat, they could produce a large energy saving. If installed in a system that already has a room thermostat savings could be much less.

Controls such as compensators and TPI controllers are less influenced by occupant behaviour, but the duration, spatial extent and level of heating will have an impact on their performance. The effect of thermostats, TRVs, timers and new home automation controls are very intimately influenced by the choices made by the people living in the home.

2 Methodology

2.1 Overview

The review of the existing evidence on domestic space heating controls and their energy savings, cost-effectiveness and usability was conducted through a scoping review of peer-reviewed academic publications, reports produced by professional bodies and independent research organizations as well as central government and associated organisations such as the Department of Energy and Climate Change. The review followed guidelines developed by the Government Social Research Service which involves using a transparent and reproducible search to identify studies, and explicit and objective methods to select, extract, quality appraise and synthesise the evidence. The review was done in the following 10 stages (see Figure 2). Figure 3 shows the outcomes of this process as a flow chart.

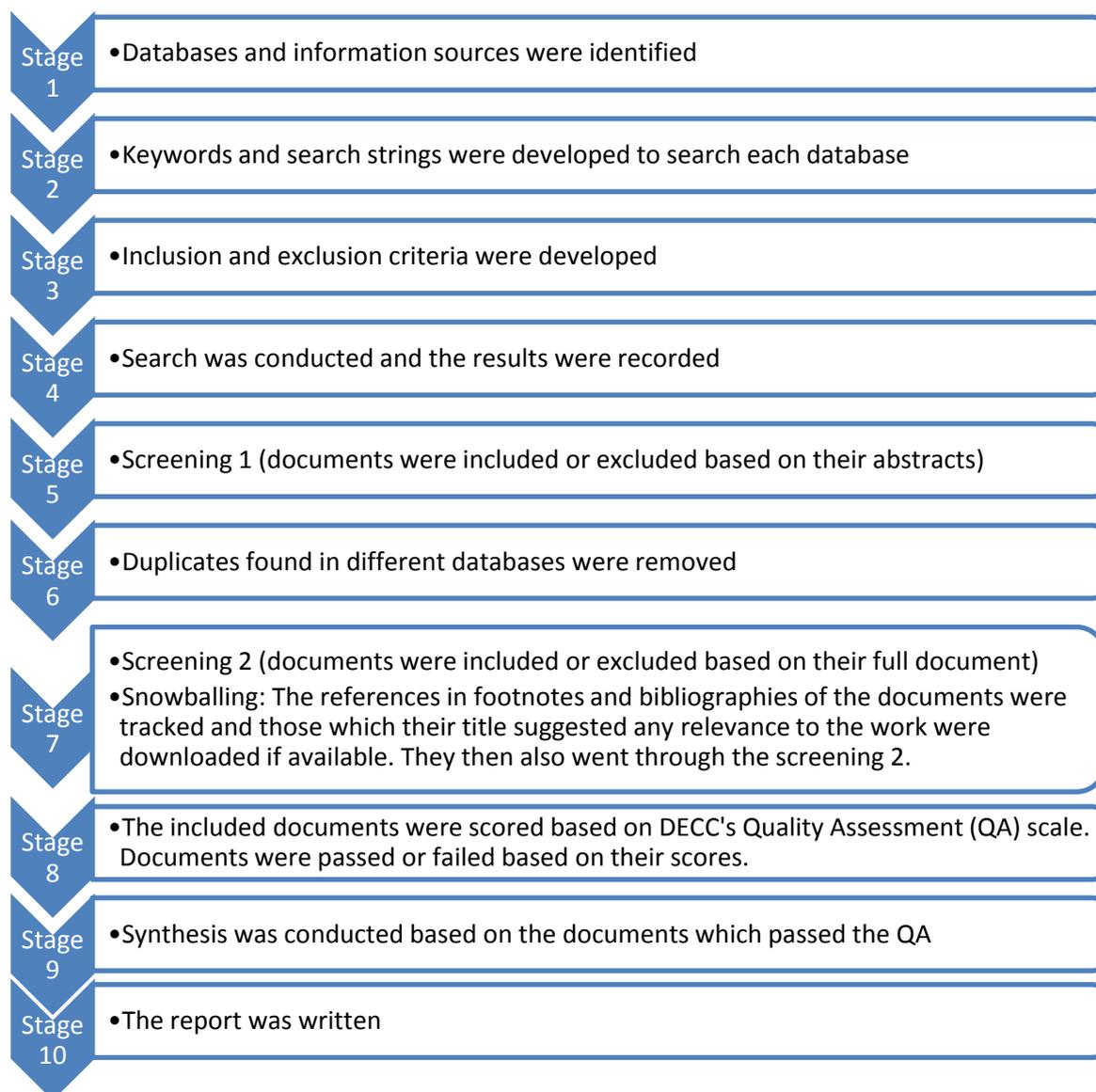


Figure 2: Flowchart showing an overview of the search methodology

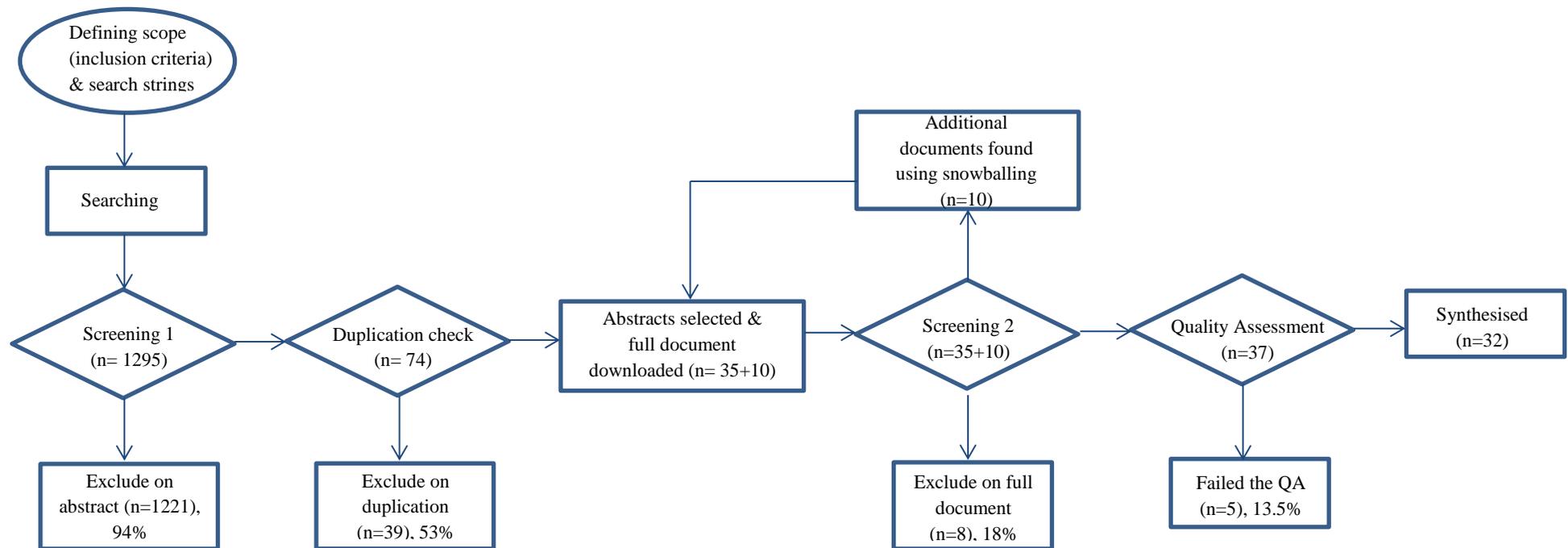


Figure 3: Flow diagram of search methodology with outcomes

Table 1 shows the percentage changes in the sample at different stages

Table 1: The percentage changes in the sample at different stages

Stage	Percentage changes (%)
Initial hits to applying inclusion criteria	83%
Applying inclusion criteria to quality assessment	97%
Quality assessment to final sample	14%
Initial hits to final sample	99.6%

2.2 Databases and sources

The search was conducted using the following databases and information sources:

- **Scopus:** Scopus is the largest abstract and citation database of peer-reviewed literature from various fields such as science, technology and social sciences. It contains over 60 million records including more than 21500 journals (4200 full open access), 7 million conference papers and 116000 books. The database is updated on a daily basis and covers “articles-in-press” from over 5000 journals. Although over 63% of its records are post 1996, the rest of articles go back as far as 1823. The database’s advanced search features and filtering options allow complex searches to be conducted and the results to be refined according to different criteria such as language, affiliation, source type, author, etc.
- **Ei Compendex (Engineering Village):** Ei Compendex is the world’s broadest and most complete engineering literature database with over 18.8 million records across 190 engineering disciplines. It covers 3639 journals and over 88000 conference proceedings. The database is updated on a weekly basis and covers “articles-in-press” from 1260 journals. 14% of its records are classified as related to civil engineering. Engineering village offers access to 12 engineering literature and patent databases including Ei Compendex. It has powerful search tools and results refinement tools for searching the database.
- **Civil Engineering Abstracts:** Civil Engineering Abstracts database includes over 1 million records of technical reports, trade journals, conference papers, books etc. from all aspects of civil engineering such as construction, energy and environmental. The database covers literature from 1966 to present and is updated on a monthly basis.
- **Google Scholar:** Google Scholar is an online, freely accessible search engine which searches a variety of sources including academic publishers, professional societies and university repositories. Google Scholar includes journal and conference papers, theses and dissertations, academic books, pre-prints,

abstracts, technical reports and other scholarly literature from all broad areas of research. As opposed to scholarly databases in which articles are indexed on specific disciplines with certain journals being included on purpose, Google Scholar is interdisciplinary which enables search within a huge range of topics all at once. Therefore, Google Scholar was used in combination with other databases in order to increase the chance of finding grey literature which may not be found if only scholarly databases had been searched.

- **Professional bodies, networks, industry & government:** Construction Information Service (CIS) is an expert knowledge online tool which provides full text access to the most comprehensive source of technical standards, legislation and technical guidance for construction industry professionals. CIS's publishing partners include professional bodies and independent research organisations such as Building Services Research and Information Association (BSRIA), Building Research Establishment (BRE), Chartered Institute of Building (CIOB), British Standard Institution (BSI) etc.

In addition to the CIS, the following organisations and networks were accessed through their websites and publication libraries and searched manually using site search engines:

- Department of Energy and Climate Change (DECC)
- TEDDINET: Transforming Energy Demand through Digital Innovation NETWORK (TEDDINET) is an EPSRC funded research network addressing the challenges of transforming energy demand in buildings. It comprises of 22 research projects with multidisciplinary teams in the development of digital technology and the exploration of how that technology is actually adopted by society to affect behaviour change with regards to energy use. The projects have already had more than 200 outputs including journal articles and conference proceedings, book chapters etc. which are all listed on the output page of the TEDDINET's website.

2.3 Keywords and search strings

After conducting preliminary searches to assess the effectiveness of different search terms, the research team agreed with DECC the strings reported in Table 2 for each database.

Table 2: Search strings used to search within each database

Database / Source	Search String / Method
Scopus	TITLE-ABS-KEY (heating OR hydronic) AND TITLE-ABS-KEY (control OR controls OR thermostat* OR remote OR zonal OR compensator OR compensation OR automat* OR tpi OR fuzzy OR trv OR (boiler AND (timer OR programmer))) AND TITLE-ABS-KEY (dwelling* OR residential OR home* OR domestic OR apartment OR hous*) AND TITLE-ABS-KEY (energy OR cost* OR usability OR user OR occupan* OR behaviour OR behavior OR interaction OR reaction OR practice) AND NOT TITLE-ABS-KEY ("heat pump" OR wind OR "Non-residential" OR "Non-domestic" OR "District" OR "Demand response" OR "CFD" OR Air-con*)
Engineering Village (EI Compendex)	(((((heating OR hydronic) WN KY) AND ((control OR controls OR thermostat* OR remote OR zonal OR compensator OR compensation OR automat* OR tpi OR fuzzy OR trv OR (boiler AND (timer OR programmer)))) WN KY)) AND ((dwelling* OR resident OR home* OR domestic OR apartment OR hous*) WN KY)) AND ((energy OR cost* OR usability OR user OR occupan* OR behaviour OR behavior OR interaction OR reaction OR practice) WN KY)) NOT (("heat pump" OR wind OR "non-residential" OR "non-domestic" OR "district" OR "demand response" OR "cfd" OR air-con*) WN KY))
Civil Engineering Abstracts	(ab(heating OR hydronic) AND ab((control OR controls OR thermostat* OR remote OR zonal OR compensator OR compensation OR automat* OR tpi OR fuzzy OR trv OR timer OR programmer)) AND ab((domestic OR residential OR dwelling* OR home* OR apartment OR hous*)) AND ab((energy OR cost* OR usability OR user OR occupant* OR behaviour OR behavior OR interaction OR reaction OR practice)) NOT ab((heat pump OR wind OR non-domestic OR non-residential OR district OR demand response OR cfd OR Air-con*)))
Google Scholar	allintitle: heating domestic control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating residential control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating home control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating dwelling control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating house control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating apartment control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer

Google Scholar	allintitle: hydronic domestic control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic residential control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic home control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic dwelling control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic house control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic apartment control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating homes control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating dwellings control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating houses control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: heating apartments control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic homes control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic dwellings control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic houses control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer
Google Scholar	allintitle: hydronic apartments control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR fuzzy OR trv OR timer OR programmer

It was not possible to use complex search strings similar to those used for searching Scopus, Engineering Village, Civil Engineering Abstracts and Google Scholar when

searching CIS, DECC and TEDDINET. This was due to the fact that their websites or publication libraries' search engines do not allow use of complex search strings.

The CIS website was searched using various identified keywords used in the search strings of other databases (Table 2) but did not result in finding any documents which met the inclusion criteria. Therefore, this database was removed from the list of databases at this point.

The DECC website was found to produce a manageable list of documents using the search term: "heating+control". This search term produced the most relevant documents compared to other search terms tested initially, which in some cases had resulted in irrelevant or an unmanageable number of results.

The TEDDINET website had a limited number of documents (around 200) which were all listed on the output page of the website. All these documents were assessed manually against the inclusion and exclusion criteria, described in the next section.

2.4 Inclusion and exclusion criteria

The research team developed criteria to select or exclude documents on the basis of abstracts (screening 1) and also full document (screening 2). These inclusion and exclusion criteria were developed based on the aim and scope of the project and also using DECC's Quality Assessment (QA) scale. They are shown in Tables 3 and 4.

Table 3: Inclusion criteria used

Inclusion Criteria
Screening 1
1. Documents that are written in English
2. Documents that are UK based
3. Documents that are available and accessible online within the project's timeframe
4. Documents that their title or abstract indicate any evidence base for one or more types of domestic heating controls in terms of either (1) energy saving (or factors contribute to energy savings such as internal temperatures or heating duration), (2) cost-effectiveness or (3) usability. The types of domestic heating controls included were: central timers, room thermostats, programmable thermostats, TRVs and weather compensators as well as more advanced heating controls such as zonal control, learning algorithms, remote control and TPI.
Screening 2
5. Documents that when read in full, meet all the criteria set for the screening 1 AND actually provide an evidence base discussed in 4.
Quality Assessment
6. Documents that score 6 or above using DECC's quality assessment scale

Table 4: Exclusion criteria used

Exclusion Criteria	
Screening 1 & 2	
1.	Documents that report new method(s) for controlling domestic space heating but do not evaluate their energy saving potential, cost-effectiveness or usability.
2.	Documents that only study the effect of heating controls on energy demand along with other energy efficiency measures (such as building fabric improvements) so that the sole effect of energy savings due to heating controls could not be isolated.
3.	Documents that are shorter version of another document which has been already included (e.g. a conference paper which has been developed into a journal paper).

During searching the databases and through snowballing, a number of documents were identified which met all the inclusion criteria for screening 1 except being non-UK based. These documents were stored separately and did not go through screening 2, quality assessment or the final synthesis. However, the list of these overseas documents is presented in Appendix A.

2.5 Quality Assessment (QA)

The reporting and research quality of the included documents were assessed using DECC's QA scale (Figure 4). Each document was scored out of total of 9 and those which scored above 6 were used for the synthesis. A sample of documents was assessed for quality by two people, to check for consistency of scoring. Whilst some minor differences were identified (for example, whether the rationale and research questions justified a score of 1 or 2), none affected the judgement of whether the document was included or not in the review. Figure 5 shows the distribution of the scores that the documents received during the QA.

<p>Reporting Quality:</p> <ul style="list-style-type: none"> ➤ 2 points: Are the rationale and research questions clear and justified? ➤ 2 points: Does the document acknowledge resource contributions and possible conflicts of interest? ➤ 1 point: Are the methods used suitable for the aims of the study? <p>Research Quality:</p> <ul style="list-style-type: none"> ➤ 2 points: Has the document been peer reviewed or independently verified by one or more reputable experts? ➤ 1 point: Do the conclusions match the data presented? ➤ 1 point: Does the author / publishing organisation have a track record in the area?

Figure 4: DECC's quality assessment scale

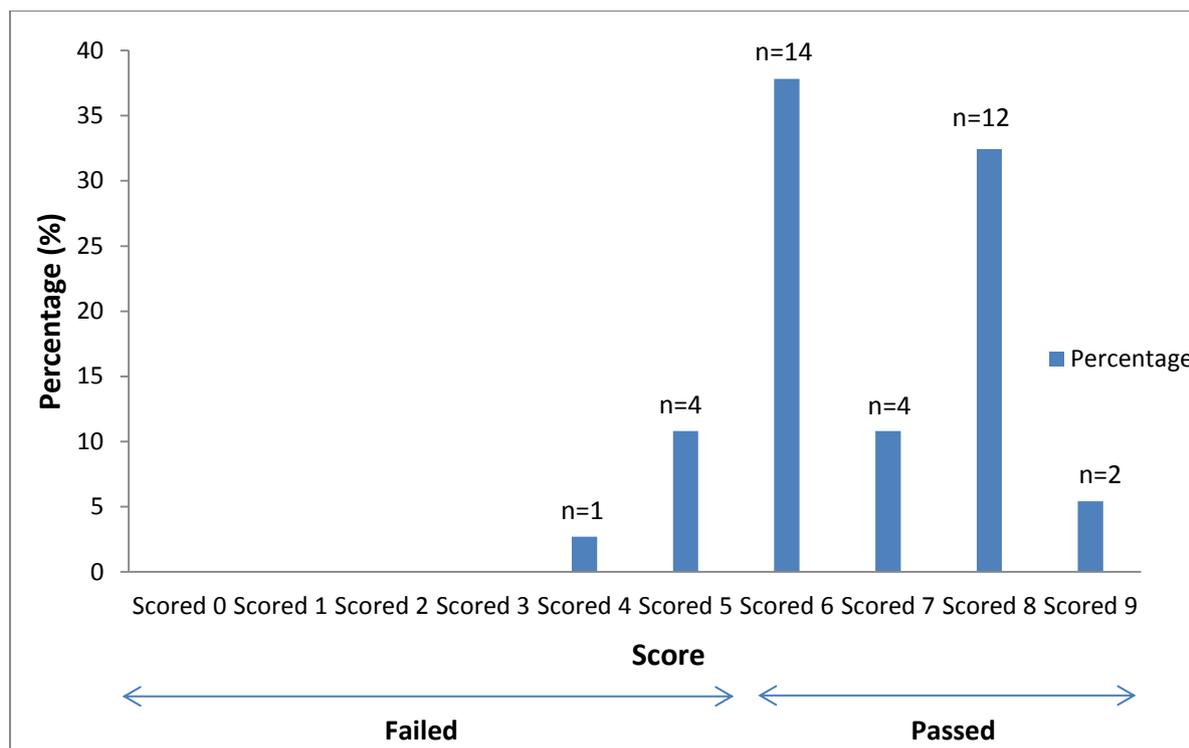


Figure 5: Distribution of the scores that the documents achieved during the QA

2.6 Synthesis

The documents that met the quality assessment were then reviewed by the appropriate expert in the team and relevant information extracted for the summary and synthesis, the results of which are presented in the next sections.

Table 5, overleaf, shows the documents which were used in the final synthesis and indicates their focus with regard to the type of heating controls, energy savings, cost effectiveness or usability.

Table 5: Classification of documents based on their focus on each type of heating controls

Document	Focus	Whole system / generic 'heating controls'	Programmer / timer (inc digital)	Room thermostat only	TRV	Weather compensation	TPI	Zonal control	Automation inc self-learning	Remote control
Beizaee et al 2015	Energy saving Cost effect.				✓			✓		
Beizaee et al 2016	Energy saving Cost effect.				✓			✓		
Boait & Rylatt 2010	Energy saving Usability		✓							✓
BRE 2013	Energy saving									
Cockroft et al 2009	Energy saving				✓		✓			
Cockroft, Samuel, & Tuohy 2007	Energy saving				✓		✓			
Combe et al 2011	Usability		✓							
Combe et al 2012	Usability		✓							
Consumer Focus 2012	Usability, Energy saving	✓	✓	✓	✓	✓	✓	✓		✓
Critchley et al 2007	Usability		✓							
Crosbie and Baker 2010	Usability	✓								
DECC 2014	Usability		✓	✓	✓					
Dimitrokali et al 2015	Usability	✓								
Ellis et al 2012	Energy saving		✓						✓	
Firth, Lomas & Wright 2010	Energy saving									
Fitton et al 2016	Energy saving			✓	✓					
Hargreaves et al 2015	Usability	✓								
Heap 1979	Energy saving									

Kelly et al 2013	Energy saving		✓	✓						
Kershaw et al 2010	Energy saving						✓			
Marshall et al 2016	Energy saving				✓			✓		
Munton et al 2014	Energy saving									
NHBC Foundation 2012	Usability	✓	✓							
Rayment, Cunliffe, & Morgan 1983	Energy saving			✓	✓					
Revell and Stanton 2014	Usability	✓								
Rogers et al 2013	Energy saving									
Rubens and Knowles 2013	Usability	✓	✓	✓	✓			✓	✓	✓
Scott et al 2011	Energy saving		✓						✓	
Shipworth 2011	Energy saving			✓						
Shipworth et al. 2010	Energy saving		✓	✓						
Stevenson et al 2013	Usability		✓	✓	✓					
Wall and Healy 2013	Usability	✓	✓					✓		✓
Number of documents with focus on each type of control (out of 32)		8	14	9	11	1	4	6	3	4
Percentage of documents with focus on each type of control		25%	43%	28%	34%	3%	12%	19%	9%	12%

In addition, Figure 6 indicates percentage of documents that focus on each of the specified heating controls.

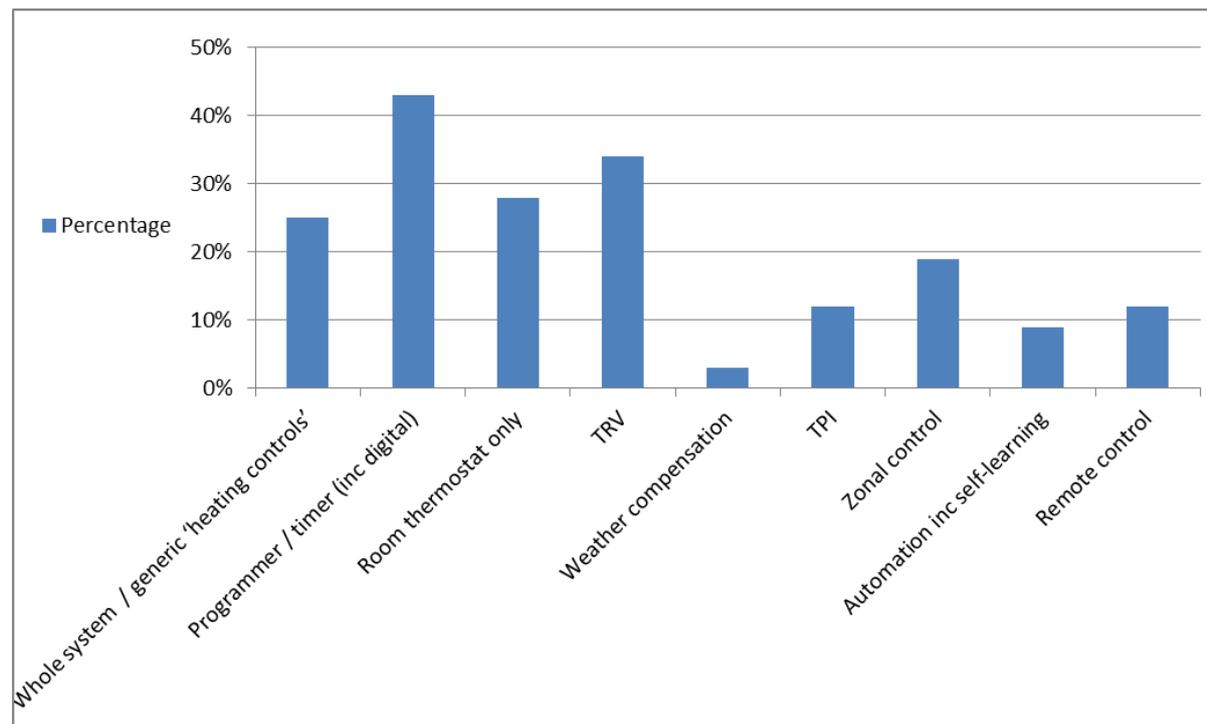


Figure 6: percentage of documents that focus on each of the heating controls

3 Main Findings

3.1 Energy Savings and Cost-effectiveness

3.1.1 Introduction

Central heating controls contribute to reducing energy demand either by improving the efficiency with which the fuel supplied to the boiler (gas, oil or other fuel) is converted to heat, or by reducing the heat demand by limiting the duration, extent and level of heating (i.e. the space temperatures) to only that which is needed to meet the thermal comfort needs of occupants.

Devices such as weather compensators, load compensators and TPI controllers are, essentially, intended to improve efficiency and require no interaction with the home occupants. The performance of these is though, influenced by the occupants through changes to the duration or level of heating. Devices that control space temperatures, such as timers, thermostats, TRVs, zonal and remote controllers, enable, or require occupant interaction, so their usability is important (see below).

Modern gas boilers are already remarkably efficient, with a seasonal efficiency (SEDBUK) rating of 90% or more, and in-use efficiencies of 80 to 90%, thus gains in the efficiency with which fuel is converted to hot water are hard won. Reducing the load on the boiler, by reducing house temperatures, the duration of heating or the spatial extent of heating, is seen as a more fruitful area for demand reduction, hence the interest in controls. However, controlling the way a house is heated has a consequential impact on boiler efficiency.

Whether energy is saved or not when a new system or control is installed, very much depends on the system that it replaces. As a benchmark, the current Building Regulations require central heating systems to have a programmer or timer, to set the periods for which heat is required, and a room thermostat and TRVs to control the temperature in the whole house and each room.

Measuring the energy savings and cost effectiveness of a control system means that the fuel used by a 'trial' system must be compared to the fuel used by some other, defined, benchmark system. Clear definitions of both the new and benchmark system are important. Whether the energy savings are cost-effective or not depends on the absolute fuel reduction, the cost of this fuel, the cost of the new system and controls, and the payback time that is deemed relevant.

Measures of temperature changes, rather than energy demand changes, can indicate a possible effect on fuel use. For example turning down a thermostat by a degree will very probably lead to an energy saving. However, the absolute saving is hard to quantify, especially if the temperature level, duration of heating and/or spatial extent of heating all change simultaneously.

To isolate the effect of a specific control component, that component alone must be the subject of a trial. If many factors change simultaneously, it is hard to quantify the individual effects precisely. This is especially so for heating controls, where the energy savings might be small. Other energy efficiency measures, such as insulation, could produce savings which are an order of magnitude greater.

When deployed in a 'real world' context, the energy effect of controls can be very hard to quantify, especially if they are controls with which people interact. The interaction will depend on many personal and social factors and the effect of any interaction will depend on the design of the heating system and the way people use it. By way of context, similar households living in similar homes can have space heating demands that vary by a factor of three or more.

Unintended consequences often manifest when interventions are made in complex systems. For example, reducing space temperatures might increase damp and mould growth, and introducing complex controls could easily result in increased energy use.

Finally, it is worth noting that the inclusion of a control technology in the (rd)SAP model should not be taken as an indication that there is good evidence to support the modelled effect of that control. The SAP method evolves, as necessary, to respond to new innovations taking the best evidence available at the time. This evidence base may well be very weak. SAP, when used for energy rating, also ignores user effects, assuming that all homes, no matter what controls are installed, will be heated to the same pattern; a pattern which, incidentally, looks increasingly out of line with the heating patterns observed in UK homes.

3.1.2 Methods of measurement

The UK literature on the energy saving and cost effectiveness of heating controls provides evidence based on four different approaches: computer modelling; trials in full-scale experimental facilities; trials in individual occupied homes; and large-scale field trials. Reviews offer compilations of the available evidence. Table 6 shows number of documents with focus on energy saving and cost-effectiveness based on their method.

Table 6: Number of documents with focus on energy saving and cost-effectiveness based on their method

Method	Number included in review
Computer modelling	4 publications
Full-scale experiments	5 publications
Small-scale trials in real occupied homes	3 publications
Large scale field trials	5 publications
Review of existing work	2 publications

1. Computer modelling

Thermal modelling, whereby the central heating system, or part of the system, is modelled and the effect of individual controls features predicted for a chosen dwelling type, heating system configuration, occupancy scenario and weather year. The credibility of such predictions relies heavily on the rigour of the model and the way that feedback from the controls to the boiler is modelled. More important are the assumptions about the interaction between the occupants and the control components and the way occupants' behaviour might change following the introduction of new controls.

Of the articles that describe modelling approaches (Cockroft et al, 2007 and 2009; Firth et al, 2010; Marshall et al. 2016), those by Cockroft and Marshall attend most closely to matters pertinent here. Firth et al. produce an estimate of the CO₂ reduction from installing TRVs across the whole English housing stock. But they used a BREDEM-based model (BREDEM-8) so the results merely indicate the outcome of the assumptions embedded therein.

The Marshall paper reports TRNSYS results for the energy savings of zonal control and TRVs. However, the controls are not modelled explicitly, but instead the house temperature and spatial extent of heating are (arbitrarily) reduced. In effect, this study represents a number of modelled what-if scenarios, which may or may not represent the real effects of the controls.

The work of Cockroft et al. (2007) is the most convincing; the ERSU Group at Strathclyde are the originators of the ESP-r model. They report the development of a controls evaluation model to allow the SAP for home energy rating to include the energy saving benefits from advanced controls. An interface to the dynamic thermal model ESP-r called ADEPT (Advanced Domestic Energy Prediction Tool) enables many combinations of house, system and control schemes to be evaluated. In effect, a model is being used to help fill the evidence gap.

The paper of Cockroft et al. (2009) focuses on the modelling methodology but does include a one-off comparison between a PI controller and a standard on/off controller. A saving of 6.2% (0.6MWh) is predicted for the house, occupancy regimen, and system in question, which would very likely be deemed cost effective.

It should be evident from this discussion that model-based estimates of saving are very valuable for triaging control options and giving a rough indication of what may be possible in practice. Modelling is also very cost effective. Predictions do however lack real-world credibility and so are not compelling; they are just too dependent on modellers' assumptions, whether these be buried in the code or introduced when the model is used.

2. Full-scale experiments

Different controls strategies have been tested in full-scale experimental houses. Such an approach enables the house to be well-characterised (fabric and ventilation heat loss), the system into which any control is introduced to be defined, and the occupant behaviour to be 'set'. Dense instrumentation of the tests is possible and operating modes that would be unethical in occupied homes can be adopted. Such tests can, in principle, detect quite small differences in energy demand due to the control intervention.

Side-by-side testing enables one house to operate as a control whilst the other can include the intervention. The houses are exposed to the same real weather over the trial period. This approach has a long pedigree in building science.

Rayment et al. (1983) report side-by-side trials conducted in 1978/79 in a pair of 1960's semi-detached homes with synthetic occupancy. In one, TRVs with remote sensing heads were used and in the other just a room thermostat. Numerous comparisons were made with the houses running in different synthetic occupancy modes. There was no reported difference between the energy used in the house with TRVs and the house with a thermostat.

Using a very similar approach to Rayment et al, Beizaee et al. (2015) and Beizaee (2016) conducted experiments in a pair of 1930's uninsulated, semi-detached houses. The homes used a two period heating regimen and had synthetic occupancy. The energy use of a building regulations-compliant central heating system was compared with energy demand of the same system but with programmable zonal thermostatic radiator valves (PTRV). The controls were set to produce the same room temperature when rooms were (assumed to be) occupied as the standard system. Energy savings of about 12% were found. Empirical modelling enabled extrapolations to other locations (with different weather conditions). This suggested similar percentage saving across the country. However, because absolute energy demand differed with location, the cost effectiveness varied. A low cost system (£120) would have a net present value over 15 years of c£1000 in all UK regions whereas a 'luxury system' with central remote programmer costing £1200 installed would not be cost effective.

Fitton et al. (2016) conducted trials in a house, representing an end of terrace, which was build inside a temperature controlled chamber. The chamber ran at a steady 5°C and the house was heated to a two period pattern. A series of three tests, each lasting 48 hours, with the measurements being made over the second 24 hours was undertaken. These covered the following: 1. Boiler thermostat at factory setting; 2. Wall thermostat added in living area; 3. TRVs added in each room, except living area. Interestingly, concerning the room thermostat, control was "not done using the device itself as the accuracy was not of an experimental quality so a calibrated air temperature gauge was

used to ensure the thermostat reflected its actual set point rather than the numeric set point on the display”.

Savings of up to 12% using the house ‘thermostat’ and 42% with the TRVs installed are reported. However, with no controls the house was running at 20 to 31°C. During the heat-on periods, with the ‘thermostat’ temperatures were between 20 and 29°C and with the TRVs between 18 and 23°C. In all the trials the internal doors were closed, which the experimenters acknowledge would increase the benefits of TRVs.

More generally, it is evident that the assumed external conditions do not reflect reality, the thermostat was not an actual commercial product, and the internal temperatures generated, especially in test 1, are not realistic for an occupied house. As noted by Fitton et al. (2016) themselves “The control of variables to create benchmark testing in order to isolate the differences between control regimes does mean that findings may not be directly translated to consumer savings under a wider variety of conditions.”

Finally, it is worth pointing out that the controls tested are already required by the Building Regulations.

The paper by Rogers et al. (2013) reports a trial of a model predictive controller used to control the output from an oil-filled electric radiator located in a test cell (a truck body). The experimental controller performed well in the test cell but poorly when presented with the thermal dynamics experienced in a real house.

The trials of Beizaee and, to a lesser extent Fitton et al, represent some of the firmest evidence of controls’ performance found in this review.

3. Small scale trials in real occupied houses

The most compelling evidence of the energy saving potential of controls is likely to come from trials in occupied houses. This exposes the controls to the full complexity of homes, their heating systems and the occupants, and the interactions between these and the new control. Occupant effects are most important when there is a human in the control loop.

The existing heating system and the way it is used defines the benchmark against which any energy savings are measured. Thus, any measurement of savings is likely to differ significantly depending on the house, heating system and occupancy context in which any new controller is deployed.

When trials are conducted in sequence, the energy savings are hard to calculate with precision because the energy that would have been used, had the house not had the controls, is unknown. Some form of model is needed to provide an estimate of this. Relatively simple empirical models based on the pre-trial (base-line) performance of the house can suffice. However, the uncertainty associated with any calculation of energy

savings is likely to be much greater with trials in real occupied homes than in test houses.

Field trials are expensive and constrained by access and ethical considerations. Thus many studies about home energy demand use cohorts of just a few homes.

Ellis et al. (2012) and Scott et al. (2011) report work undertaken in a collaboration between Microsoft and Lancaster University. Five homes, of which two were in Cambridge, UK, were monitored. One of the UK homes had underfloor heating the other wall mounted radiators. The heating pattern used in the homes is not stated. Both papers report the performance of experimental, rather than commercially available controllers. Both studies lasted 61 days alternating between a day of programmer (normal) control and a day with the controller(s). The UK homes households had two adults and one or more children.

The Ellis et al. study examined the energy to be saved by predicting the time of departure from the home. The idea was that energy could be saved if the heating switched off when people left the house rather than later when it was programmed to go off. Such control is complicated to implement of course. Using the actual gas consumption and the known occupant departure times, the energy that could be saved with a perfect controller (the Oracle) was calculated as 4-5% in the UK homes. A real controller that tried to predict departure (BigDrop) produced savings of just 1% in both UK houses and in one house turned the system off when the house was still occupied on 60% of occasions. The authors caution that these savings may not be realised in practice.

Scott et al. studied PreHeat, the potential of “occupancy sensing and historical occupancy data to estimate the probability of future occupancy, allowing the home to be heated only when necessary.” Motion sensors were installed in each room of the UK homes to identify, and learn, when each room was used. This predictive zonal controller produced reported gas savings of 8 to 18% in the UK houses. Each zone has a different heating pattern, which emerged through the learning capability of the controller rather than through pre-programming each space controller. It is also stated that the controller reduced the times when the room was in use but under heated.

The advantage of these studies is that the control days were interleaved with the intervention days, rather than running sequentially, and so savings from the controls could be estimated reasonably reliably.

These studies point towards possible future controllers which improve efficiency without the need for complex user interfaces. The savings from the zonal control (8-18%) are in line with those measured by Beizaee et al.

Boait and Rylatt (2010) report the testing of a prototype controller in one house. The controller sought to simplify heating control by learning when occupants were present

by recording electricity use and water runoff. It is, therefore, examining very similar matters to the works of Ellis et al. and Scott et al.

Clearly, whether the results observed in trials on individual homes are reproduced in other homes remains an open question. But they do identify promising technologies and potential pit falls.

4. Large-scale field trials

Large-scale field trials involving many homes can capture the full socio-technical complexity of home heating systems, occupants, weather, etc. Such trials are however very expensive and so rarely undertaken. Trials may recruit households with different characteristics, e.g. some with and some without a thermostat, or might introduce an intervention (new controls) to some homes and not to others.

To identify the effect of a particular feature, or the effect of a deliberate intervention, statistical analysis is necessary. Expertise in the application of statistics is essential to ensure that apparently significant effects are not due to factors other than the one being examined.

As noted by Heap (1979), because the energy saved by some features, such as controls, can be rather small compared to the natural variability in energy use between different homes, very large cohorts of homes might be needed.

The evidence review revealed just one completed trials which focussed specifically on heating controls (Kershaw et al, 2010). This trial, funded by DECC, examined the effect of installing TPI controllers in place of standard room thermostats in 47 of the 52 homes that provided baseline, pre-TPI, data.

The dwellings varied in age from 17 to over 150 years and were of mixed type (terraced, semi-detached and detached). All had condensing boilers, two were B rated and the rest A rated (SEDBUK over 90%), 38 were combi boilers and 14 regular boilers with a hot water cylinder; all but one house had a modulating boiler. All except three homes had a room thermostat and programmer and all but nine had TRVs on the radiators.

The TPI controllers were installed in place of the standard thermostat between December 2008 and February 2009 and the homes monitored for twelve months. 28 homes provide a whole year of data both before and after the TPI installs. Measurement included measuring the efficiency of the boiler, space temperatures and the overall energy demand of the dwelling.

The trials revealed no significant improvement in the efficiency of the heating systems after the TPI controllers were installed. Neither was there a clear improvement in the overall energy efficiency of the homes across all properties. This was because the boilers spent very little time operating with the home at the set-point temperatures. Typically, UK homes will not reach the set-point in the short morning heating period

and will only reach the set-point towards the end of the evening heating period. Kershaw et al. estimated that the homes were at the set-point, and operating under TPI control for less than 9% of the winter.

Other trials that shed light on the performance of controls examined the influence of the house, occupants and heating system on internal temperatures rather than energy demand. (Temperature is easy to measure, whereas gaining consent to measure gas use, especially at short time intervals, is difficult). These field trials did not involve purposeful interventions.

Findings from the field study of c427 homes, located across the UK, which was undertaken as part of the CaRB project, are reported in Shipworth et al. (2010), Shipworth (2011) and Kelly et al. (2013). The homes were monitored such that total gas and electricity consumption was known. The temperature in the living room and a bedroom was recorded at 45minute intervals for the period 22 July 2007 to 3 February 2008. A face-to-face questionnaire asked households structured questions about their homes' built form, heating technologies, heating practices and socio-demographics. It included a question about the thermostat set point. In all, 84% of the sample (358 households) had either gas or oil fired heating.

Shipworth et al. (2010) used data from for the three months from November to January 2008. They estimated the set-point temperature to be the average peak daily temperature recorded in the living room. The temperature traces also enabled them to estimate the duration of heating. Thermostat settings were reported by 127 households.

There was no statistical difference between the estimated thermostat setting (i.e. the average of the maximum daily living room temperatures) in homes without thermostatic control and the homes with a thermostat. Also, the duration of heating was not statistically different in homes with or without timers.

Whilst these results are interesting it is important they do not address directly the matters of energy saving and cost effectiveness. Also, the estimation of duration and extent of heating from temperatures is error prone and in any case, it is doubtful that the peak living room temperature actually represents the setting of a central thermostat.

It is also worth noting the potential for self-selection bias in that homes without a central thermostat may be inhabited by different occupants than homes with a thermostat (e.g. more or the less affluent), which could influence the results.

Shipworth et al. compared the self-reported thermostat settings of 14 (or 38) CaRB households with those reported by 111 households in the same region in 1984; there was no significant difference.

Kelly et al. (2013) used a panel method to understand the relationship between the internal temperatures recorded in the CaRB homes and the dwelling, household and heating system characteristics. "The results suggest that the mere presence of a

thermostat has the effect of reducing mean daily internal temperatures by 0.24°C on average. When thermostatic radiator valves are the only type of temperature control, they again reduce internal temperature by an average of 0.17°C, compared to homes without any control at all.” The authors note the contrast with the findings of Shipworth et al. (2010) and attribute this to the different analysis periods used and the different temperatures examined (mean daily internal temperature in Kelly et al. cf. mean daily maximum living room temperature in Shipworth et al.).

The BRE (2013) use the temperature data from the 2011 Energy Follow up Survey (EFUS) to the English Housing Survey. Loggers recorded temperatures at 20-minute intervals in the living room, hallway and main bedroom in 823 dwellings. The analysis used temperatures collected from February 2011 to January 2012 inclusive. The relationships between temperature statistics and attributes of the homes, size, age and construction are reported. The main focus of discussion concerns the appropriateness of the assumptions in the Standard Assessment Procedure. There are no conclusions with regard to internal temperatures and heating controls.

The large-scale field surveys undertaken so far have, it seems, focussed on making adventitious use of previous work to draw inferences about the effect of controls on indoor temperatures, rather than energy demand. The use of such surveys for examining heating controls could fill a substantial gap in knowledge.

5. Reviews

In examining others’ reviews, care must be taken to consider the veracity of the source from which information is drawn. Reviews can contain a mix of robust, peer-reviewed, findings, articles in trade magazines, and interviews that amounts to little more than personal opinion.

Part of the Consumer Focus (2012) report evaluated the evidence available about the energy saving potential of specific control devices. The report offered no conclusive evidence that TPI controllers save energy and suggests that ‘further research is required on the benefits of this type of control’. Likewise, evidence for benefits from weather temperature compensation was limited. Although the Building Regulations require new homes to have two heating circuits, again there was no evidence found to support this as an energy saving measure.

The review of Munton et al. for DECC (2014) echoes rather well the overall impression emerging from this review: “To date, very few UK studies have rigorously evaluated the overall effect of providing households with technologically improved heating controls in terms of energy save” and “Insufficient evidence exists about the role of consumer behaviour in potential relationships between energy savings and improved control technologies.”

3.1.3 Conclusions

Four main approaches to determining the potential energy savings from heating controls have been identified: modelling; full-scale experiments; tests in real houses; and large-scale field trials. Of the four, large-scale field trials are likely to produce the most compelling evidence of the actual effects of introducing new controllers. This is because the energy savings and cost effectiveness depend on the characteristics of the existing system and, either directly or indirectly the way that heating systems is used by the household. However, the review uncovered no UK field trials that directly measured the effect of heating controls.

The most compelling evidence to date came from side-by-side trial conducted in matched pair test houses, this produced an energy saving of c12% for zonal control compared to a Building Regulations-compliant system for the particular heating schedule used. Whether or not these savings would materialise in practice, especially given the complexity of programming such a complex control system, is unknown.

Studies of the impact of whole house thermostats, TRVs and timers/ programmers have tended to show that the first two save energy but timers/programmers may not. However, the evidence is rather mixed.

There is no robust evidence about weather compensation, load compensation, automation and optimisation.

3.2 Usability

3.2.1 Introduction

Usability is defined in latest revision of ISO 9241-11 (2015), which seeks to update the 1998 standard (ISO 9241-11:1998), as the “extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. Effectiveness is further defined as the “accuracy, completeness and lack of negative consequences with which users achieved specified goals”; efficiency as the “relationship between the result achieved and the resources used”; and satisfaction as “positive attitudes, emotions and/or comfort resulting from use of a system, product or service.”

For heating controls, usability describes the ease with which a person is able to use their heating controls; this includes turning heating on or off, adjusting the temperature or making changes to the time settings. It covers issues relating to physical interaction with heating controls which requires dexterity, vision and access, for example, as well as cognitive aspects which requires as understanding, memory and confidence.

It is not the intention of this review to summarise the usability problems that occupants have with heating controls – these are well documented in the published literature, including some of those reviewed here. There are also publications highlighting user requirements (e.g. Rubens and Knowles, 2013) and design recommendations (e.g.

Bordass et al, 2007) for improved design of controls and others identifying why users might struggle to interact effectively with their heating controls. Again, the detail is not repeated here. However, the purpose of this review is to determine the extent of the evidence and whether this covers the consequence of poorly designed heating controls.

3.2.2 Methods of measurement

The UK literature on the usability of heating controls is comparatively immature, with publications focusing on the identification of poor usability, rather than the consequences. Methods of assessment of usability include expert review against usability criteria, small-scale testing in a controlled environment and larger-scale evaluation in real world settings, usually as part of a wider intervention. As with the consideration of energy saving and cost-effectiveness of heating controls, reviews also offer compilations of the available evidence. Table 7 shows number of documents with focus on usability based on their method.

Table 7: Number of documents with focus on usability based on their method

Method	Number included in review
Reviews	2 publications
Expert evaluation	4 publications
Controlled usability assessment	3 publications
Real world usability trials	7 publications
Other approaches	1 publications

1. Reviews

Two substantial reviews were included within the selected publications from NHBC Foundation (2012) and Consumer Focus (2012). These draw on a breadth of literature and provide good summaries of the work in this area.

The NHBC report (2012) was commissioned by the NHBC Foundation to examine previous research and knowledge on occupant behaviour and user interface design in homes. An extensive literature review was conducted and information was also gathered from experts at BRE. It cites unpublished work by Hadj and Rathouse (2008) that occupants do not read user manuals and so the operation of the home systems is 'hit and miss' therefore reducing the likelihood of efficient use: "If the right controls are not in place or if occupants cannot use them as they should be used, households are limited in the way they can reduce their energy use." They also cite a Market Transformation Programme report (2006) that reports that a significant proportion of householders do not understand their heating controls, do not set them appropriately or do not use them at all, and further BRE unpublished work where occupants report

they have a 'good understanding' of how to use their heating controls, but when questioned in depth, do not use times/controls as designed. Occupants understand the controls well enough to make the system do what they need it to do, but this is not always the most energy efficient or effective way. This review identifies that many people do not know how to use their heating controls, and difficult to use controls reduces likelihood of efficient use, but provides no further qualification or quantification.

The Consumer Focus report (2012) provides an extensive review of the literature in this area, supported by follow-up interviews with stakeholders, although no details on who and how many are provided. It states that over 70 per cent of households do not have a full set of controls while 4 per cent of households have no controls at all, with rented properties being less likely to have full controls than owner-occupied properties. The report comments that consumer demand for effective heating controls is low, so there is very limited market demand. The report includes sections on usability and savings, but does not identify any significant research evidence.

There is a comment about the benefits of feedback: "Providing consumers with energy use feedback has proven successful in reducing consumption especially when introduced alongside consumer engagement programmes" but other literature (outside this review) suggests the gains are limited and not sustained. Having also not found evidence for in-situ studies that lead to significant savings, it concludes with recommendations for further research to reflect the advances in control technology and to explore the energy saving value of usable controls. There is also a word of caution over increasingly complex heating control systems: "Given the difficulty faced by consumers in understanding and using existing control systems, and especially programmers, there is a risk that zoning systems will add a further layer of complication unless they can be designed in a simple and inclusive way."

2. Expert evaluation

Several documents in the review include expert evaluation of the usability of controls, as part of a suite of methods. Stevenson et al. (2013) developed a functional usability assessment matrix to assess a range of domestic interfaces, including heating controls. These received mixed scores (6/30 for boiler controls, 15/30 for TRVs and 17/30 for room thermostat for one system from a large developer; however, 8/30 for heating and hot water controls and 24/30 for TRVs for a system from a small developer). Wall and Healy (2013), in their work for DECC, include an evaluation of five controls by two experts using a heuristic checklist. One of the controls is identified as having "wider capability to support user goals" than the other four controls. Clearly, usability is very system specific. Wall and Healy (2013) derived usability outcomes for various heating controls, and many did not reach the benchmarks set or took longer than reasonable to complete tasks. They conclude that poor usability results in a failure to engage with the heating controls, resulting in a lack of use to its fullest capacity. Combe et al. (2011;

2012) used an Exclusion Calculator to estimate the percentage of the population excluded from use of the evaluated digital programmable thermostats. This identified that between 13.5% and 18.2% of the population aged between 60 and 80 years (dependent on specific device) would be excluded from use. However, they go on to say these calculations are underestimated when compared with their user testing results, albeit with an acknowledged small sample size (n=10 older users).

3. Controlled usability assessment

Four documents in this review included some sort of controlled usability assessment. Combe et al. (2012) included 24 participants (14 younger and 10 older) undertaking a set task with three digital programmable thermostats. Wall and Healy (2013) conducted a more extensive study, asking 75 participants (from 18 – 75 years, in three bands) to undertake up to eight tasks with 3 'smarter heating controls'. In Combe et al's study, none of the older users were able to complete the programming of the thermostats. Additionally, the cognitive demands of these systems were considered using a subjective workload assessment method, based on the NASA Task Load Index, and were found to be excessive. Wall and Healy (2013) also reported difficulties by older users with controls due to lower visual acuity or manual dexterity compared to younger participants. They identified a range of barriers to use, but the work is not extended to discuss the consequences of these barriers. They note that many controls are not usable enough to allow users to reap the benefits of energy saving and that substantial finance and expertise is needed to install and set up controls correctly, which would be set against any long term savings.

Revell and Stanton (2014) explored the mental models that people have about their heating system. Using only three participants who were not typical of UK householders (although the study was conducted in the UK), they identified distinct mental models that differed significantly from the actual functioning of UK heating systems. They concluded that people do not understand their heating systems and miss out key controls (programmer, thermostat) in their descriptions, and therefore are unable to control the heating effectively. However, the small and unrepresentative sample significantly limits the meaning that can be drawn from this study.

Based on these limited studies, it can be concluded that householders struggle to understand their heating systems and to programme their heating controls; these difficulties are exacerbated for older users. However, the very small sample sizes in most studies mean the results cannot be extrapolated to the wider population. Combe et al. (2012) conclude with the comment that "one key aspect of future research remains measuring the scale of the energy savings achievable through improved user interface design."

4. Real world usability trials

This review identifies eight publications that report real world usability trials of some sort or another. Some involve large samples (e.g. DECC 2014 study in Newcastle of over 1500 social housing properties; the Warm Front study (Critchley et al, 2007) with 888 households), others much smaller (e.g. Hargreaves et al, 2015 reports initial findings from only 4 homes). The DECC Newcastle study focused on whether providing advice (in leaflet form and personalised in-home advice from a heating engineer) made a difference to gas consumption over a winter. They found that in-home advice and the information leaflet did not significantly reduce gas consumption during the trial period compared with control group (no advice). Their sample was from social housing so the authors do recognise that this is typically a low energy consuming group, so speculate that perhaps there would have been a different result, had there been more scope for reducing consumption. However, no evidence to support this assertion is presented. From a series of qualitative interviews with a sub-set of participants (n=61), they identified that advice appears to have been effective at informing residents about how to use their heating controls, but instead of reducing energy, it may have resulted in increased thermal comfort for some households. This provides evidence of wider, unanticipated well-being gains, sometimes referred to as take-back. The Warm Front study, although involving a large sample, focuses on low-income homes, and reports matters relating to the living conditions rather than use of the heating controls themselves. A sub-sample of 79 people were asked, via telephone, about attitudes and behaviours relating to, among other things, their heating and its control. They report that “a major residual problem was controlling the central-heating system. A third of all respondents over 60 [years of age] reported difficulty with programmers, with a majority of these saying they were too complicated.” This confirms the findings of others that people have difficulty controlling their heating systems, particularly older residents. Although the Warm Front team measured temperature for 1-2 weeks in two rooms, twice daily, they do not relate the comments on poor usability to temperature in those homes.

Dimitrokali et al. (2015) evaluated one particular (unidentified) home heating controller with remote control (via mobile app) over a 6 month winter period. They explored homeowners' perceptions and experiences to development recommendations for future technology and its implementation in homes. A starting sample of 203 was reduced to 71 in the post-use phase evaluation (on-line questionnaire). Just over half of the participants (59.4%) preferred to control their heating via the mobile app and this was used most to change modes, view ambient temperature and check current mode. The study found that the smart home heating controller was perceived by 71% of participants as successfully influencing and changing their home heating behaviour. However, no evidence of whether it actually changed behaviour is presented, as no baseline data (pre-installation of the new control) were collected. Self-report figures for the use of various heating control features are included (e.g. temperature increment

used in boost mode, frequency of use of the mobile app and online portal, frequency of schedule change), but as self-reported data, this is not robust. The authors also recognise that they did not include a measured link to cost or energy consumption, and that their sample is not representative of the UK population.

The research by Stevenson et al. (2013) looked at heating and hot water controls only as part of a wider study with a maximum of 45 participants. They found that the controls were not intuitive, were poorly labelled, inaccessible and required complex interaction in use. There had been limited or no hands-on demonstration of the controls at handover, although the occupants reported that they were “happy enough” with the process. Again, with such small sample sizes and lack of focus on the controls specifically, this provides no evidence pertinent to this review.

The remaining studies (Combe et al. 2011, Crosbie and Baker, 2010, Hargreaves et al., 2015) studied such small numbers of homes or primarily focused on matters other than heating controls, such that their results can only be considered as interesting. Combe et al. (2011) assessed one particular heating controller with 12 residents as part of a post-occupancy evaluation in a particular housing development. They found most users could not interact effectively with their controls and two-thirds were unable to complete the programming task that was set. Crosbie and Baker (2010) explored energy efficient housing and refurbishments rather than specifically heating controls. There was some mention of the lack of control in one of the case studies (n=4 properties). One resident had automated controls removed and the system switched to manual to regain control over when and in which rooms radiators were on, which resulted in more energy use than expected during design. Hargreaves et al. (2015) focus on interaction with smart home systems rather than heating, such that controlling the home is discussed, rather than heating controls more specifically.

5. Other approaches

Rubens and Knowles (2013) conducted a study for DECC involving diary self-reporting of heating behaviours (n=43 householders) followed by in-home, in-depth interviews with the same participants. After a period of interim analysis, a ‘long-list’ of requirements was inferred, and some emergent user types were identified. The requirements were then explored and prioritised in four ‘participatory-design’ workshops along with evaluation of three different concepts for smarter heating controls with four interviewed participants and 19 new participants. A total of five 5 heating user types (Rationers, Ego-centric, Hands off, Planners and Reactors) are identified.

No numerical data are presented in the report and there is no comment on the consequence of poor usability. The report includes speculation only about the possible types of users and what they might want from a heating control. The authors also

acknowledge that the sample is not statistically representative, so not generalisable to the population.

3.2.3 Conclusions

There is a variety of literature that reports studies into heating control usability, several of which have been commissioned by DECC. Most studies reviewed explore usability of central timers, room thermostats and programmable thermostats as a single device. Few mention TRVs or automation; no studies covered usability issues relating to weather compensators or optimisation.

None of the studies in this review identified, with any robustness, the consequence of poor usability in terms of energy or cost-effectiveness. Consumer Focus (2012) state that in situ assessments of the impact of controls are mixed. They suggest that controls can lead to significant savings but suggest further research is needed in this area. Wall and Healy (2013), who report probably the most robust usability study in this area, identify that poor controls may not support people's requirements and present potential barriers to motivating users to engage in energy saving behaviours. However, no evidence of this is presented in their report, as it was not the purpose of the study.

In short, it is known that heating controls are difficult to use, but it is not known what effect this has on heating use. None of the studies identified in this review provide robust evidence of usability in relation to energy or cost savings.

4 Overall Conclusions

From the systematic scoping review conducted of UK relevant studies, the following conclusions can be drawn:

- This review has identified a dearth of evidence relating to the energy savings, cost effectiveness and usability of heating controls. It isn't that there are evidence gaps so much as no robust evidence at all for most controls.
- Quantitative evidence has been generated from models, test houses, individual occupied homes and large-scale field trials of occupied homes.
- Whilst large-scale trials in occupied homes could provide the most compelling evidence about the impact of controls, no such trials have been reported in the UK literature.
- Adventitious use has been made of existing large-scale trials to indicate the effect of controls on room temperatures. It is not possible to infer the impact of the controls on energy demand.
- Compelling evidence is emerging from side-by-side trials in well-characterised homes with synthetic occupancy. Such trials have demonstrated energy saving from zonal control for a particular chosen occupancy regimen.
- Other side-by-side trials in experimental houses have shown that whole house thermostats can save energy as can the addition of TRVs. Whether timers and programmers save energy is unclear.
- A large-scale field study in occupied homes showed no energy savings when TPI controllers were installed in place of standard room thermostats in homes with condensing boilers.
- Usability studies focus on the requirements for users rather than the consequences of poor design. Consequently the energy impacts of a heating controller that is difficult to use are unknown.
- A large-scale field study in Newcastle showed that in-home advice and an information leaflet did not significantly reduce gas consumption compared with residents that received no advice.
- Large-scale field trials combining quantitative, measured data with qualitative surveys are needed, but these are expensive and need very careful planning.

Table 8 summarizes the evidence found regarding the impacts of different heating controls on energy saving, cost-effectiveness and usability including an indication of confidence in the figures.

Table 8: Impact of different heating controls on energy saving, cost-effectiveness and usability with confidence level

Control Type	Impact on			Confidence
	Energy Saving	Cost-effectiveness	Usability	
Programmer/timer (inc. digital)	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Room thermostat	Single test. 12% gas saving compared to boiler thermostat only. Unrealistic 'weather' & house temperatures. ¹	Lack of robust evidence	Lack of robust evidence	Very Low
TRV	Single test. 30% gas saving compared to room thermostat only. Unrealistic 'weather' & house temperatures. ¹	Lack of robust evidence	Lack of robust evidence	Very Low
Weather compensation	Lack of robust evidence	Lack of robust evidence	N/A	N/A
TPI	Large field trial. TPI in place of standard thermostat. No effect on efficiency of modulating condensing boilers. ²	Lack of robust evidence	N/A	Good
Zonal control	Series of trials in one house. 12% gas saving compared to a Building Regulations compliant system. ³	Acceptable payback for cheaper systems	Lack of robust evidence	Modest
Automation incl. self-learning	Two homes only. Learning zonal control 8%-18% gas saving. ⁴	Lack of robust evidence	Lack of robust evidence	Very Low
Remote control	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A

¹ Fitton et al (2016). ² Kershaw et al (2010). ³ Beizaee et al (2015). ⁴ Scott et al (2011).

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Appendix A: Key Overseas References

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Appendix B: Document Summary Sheets

Document Title	Predicting the diversity of internal temperatures from the English residential sector using panel methods							
Author(s), Publisher, Year	S. Kelly, M. Shipworth, D. Shipworth, M. Gentry, A. Wright, M. Pollitt, D. Crawford-Brown, and K. Lomas, Applied Energy, vol. 102, pp. 601–621, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

In this paper, panel methods are applied in new and innovative ways to predict daily mean internal temperature demand across a heterogeneous domestic building stock over time. This research not only exploits a rich new dataset but presents new methodological insights and offers important linkages for connecting bottom-up building stock models to human behaviour. It represents the first time a panel model has been used to estimate the dynamics of internal temperature demand from the natural daily fluctuations of external temperature combined with important behavioural, socio-demographic and building efficiency variables. The model is able to predict internal temperatures across a heterogeneous building stock to within ~0.71 °C at 95% confidence and explain 45% of the variance of internal temperature between dwellings. The model confirms hypothesis from sociology and psychology that habitual behaviours are important drivers of home energy consumption. In addition, the model offers the possibility to quantify take-back (direct rebound effect) owing to increased internal temperatures from the installation of energy efficiency measures. The presence of thermostats or thermostatic radiator valves (TRVs) are shown to reduce average internal temperatures, however, the use of an automatic timer is shown to be statistically insignificant. The number of occupants, household income and occupant age are all important factors that explain a quantifiable increase in internal temperature demand. Households with children or retired occupants are shown to have higher average internal temperatures than households who do not. As expected, building typology, building age, roof insulation thickness, wall U-value and the proportion of double glazing all have positive and statistically significant effects on daily mean internal temperature. In summary, the model can be either used to make statistical inferences about the importance of different factors for explaining internal temperatures or as a predictive tool. However, a key contribution of this research is the possibility to use this model to calibrate existing building stock for behaviour and socio-demographic effects leading to improved estimations of domestic energy demand.

Document Title	Central heating thermostat settings and timing: building demographics							
Author(s), Publisher, Year	M. Shipworth, S. K. Firth, M. I. Gentry, A. J. Wright, D. T. Shipworth, and K. J. Lomas, Building Research & Information, vol. 38, no. 1, pp. 50–69, 2010.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Crucial empirical data (currently absent in building energy models) on central heating demand temperatures and durations are presented. These data are derived from the first national survey of energy use in English homes and includes monitored temperatures in living rooms, central heating settings reported by participants, along with building, technical, and behavioural data. The results are compared with model assumptions with respect to thermostat settings and heating durations. Contrary to assumptions, the use of controls did not reduce average maximum living room temperatures or the duration of operation. Regulations, policies, and programmes may need to revise their assumptions that adding controls will reduce energy use. Alternative forms of heating control should be developed and tested to ascertain whether their use saves energy in real-world settings. Given the finding that detached houses are heated for longer, these dwellings should be particularly targeted in energy-efficiency retrofit programmes. Furthermore, social marketing programmes could use the wide variation in thermostat settings as the foundation of a 'social norm' programme aimed at reducing temperatures in 'overheated' homes. Finally, building energy models that inform energy policies require firmer foundations in real-world data to improve policy effectiveness. Greater coordination of data collection and management would make more data available for this purpose.

Document Title	Assessing the performance of domestic heating controls in a whole house test facility							
Author(s), Publisher, Year	R. Fitton, W. Swan, T. Hughes, M. Benjaber, and S. Todd, Building Services. Engineering Research & Technology, In Press, 2016.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	2	1	2	1	1	9	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input checked="" type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The energy consumed by domestic space heating systems represents a considerable share of the energy consumed in the UK. At the same time up to a quarter of English homes have inadequate controls on the central heating systems. Current modelling tools, and results from the limited field trials that have been carried out, are problematic due to the influence of the behaviour of occupants and variability of weather conditions. The Salford Energy House is a full-sized end terrace house built within a climate controlled laboratory. This allows a house of typical construction to be extensively analysed while completely disconnected from the unpredictability of weather conditions and human behaviour. This paper presents a series of tests carried out in the Salford Energy House into the effectiveness of installing room thermo-stats and thermostatic radiator valves. Savings of 40% in terms of energy consumption, cost and CO2 were achieved. The results should be regarded with caution in terms of their extent and application to real homes, but represent a significant contribution to the gap in current knowledge due to the ability to isolate the performance of homes from uncooperative variables, and a potential base for the development of more effective modelling tools.

Document Title	Development of a methodology for the evaluation of domestic heating controls							
Author(s), Publisher, Year	J. Cockroft, A. Samuel, and P. Tuohy, Energy Systems Research Unit, 2007.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
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	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The objective of this project is to produce a controls evaluation methodology based on computer modelling of domestic housing and heating systems. The results from this project will allow the Government's Standard Assessment Procedure (SAP) for home energy rating to be further developed so that energy saving benefits of advanced controls may be recognised within the procedure, particularly in relation to maximising the benefits of condensing boilers.

The evaluation methodology takes into account typical UK housing characteristics, climate, occupancy patterns, boiler, and heating system types using the modelling tool ESP-r. Five house types, five heating system types and five control system types were agreed for analysis. House types broadly reflect the range of housing stock to which SAP will be applied. Heating system types include non-condensing and condensing boilers, regular and combi boilers, gas and oil boilers, and both radiator and underfloor heat emitters. Controls range from a basic system with a single room thermostat, through to a two-zone system with two independent thermostats. Electronic controllers are also represented, both room temperature and outdoor temperature based. The results of a selection of simulations of twenty combinations of house, system and control scheme demonstrate how choice of house size and type, burner / room control regulation mode, system operating flow and return temperature, weather compensation and choice of zoning strategy affect the zone and system temperatures, system performance, and annual energy use.

Annual heating energy consumption shows a high degree of sensitivity to factors other than inherent system efficiency. In particular, overnight rate of cool down, and fixed timer settings interact with construction and system thermal mass to affect the results in unanticipated ways.

An interface to ESP-r called ADEPT (Advanced Domestic Energy Prediction Tool) facilitates set up of any desired combinations of the defined house, system and control schemes, producing standardised outputs demonstrating control behaviour and energy use.

Suggestions for SAP / BREDEM development, using the results from the evaluation methodology are proposed.

Document Title	A method for fully automatic operation of domestic heating							
Author(s), Publisher, Year	P. J. Boait and R. M. Rylatt, Energy and Buildings, vol. 42, no. 1, pp. 11–16, 2010.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	0	2	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Complex, inconvenient and badly arranged push buttons and menus on domestic heating controls often cause users to enter unsuitable settings that result in impaired comfort and poor operating efficiency. This paper proposes a novel approach to the human interface of home heating systems that greatly simplifies the input required from the user. Time settings are derived automatically from electricity consumption and hot water use, also a temperature set point is provided that adapts to user activity levels and external temperature. Practical results from a prototype control system incorporating these methods are reported, showing useful energy savings. It is argued that this increased automation of control allows the benefits of low carbon technologies such as micro-combined heat and power, and solar hot water heating, to be fully exploited.

Document Title	Measuring the potential of zonal space heating controls to reduce energy use in UK homes: The case of un-furbished 1930s dwellings							
Author(s), Publisher, Year	A. Beizaee, D. Allinson, K. J. Lomas, E. Foda, and D. L. Loveday, Energy and Buildings, vol. 92, pp. 29–44, 2015.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input checked="" type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

A matched pair of 1930s semi-detached houses, in original condition and un-refurbished in terms of energy efficiency, were employed to measure the energy savings that might result from the use of zonal space heating control (ZC). The houses were adjoined and had the same synthetic, yet realistic, occupancy schedule, the same new central heating system, and were exposed to the same weather conditions. In one house the space heating was controlled conventionally (CC) according to minimum requirements in UK Building Regulation Part L1B for existing dwellings, whereas in the other house ZC was used to heat the rooms only when they were 'occupied'. Over an 8-week winter test period, the house with ZC used 11.8% less gas despite 2.4 percentage points drop in average daily boiler efficiency. Although zonal control reduced the mean indoor air temperature of the whole house by 0.6 °C, it did not reduce the average air temperature in rooms during the hours of active 'occupancy'. Normalisation and extrapolation of the results shows that, compared to CC, ZC could reduce annual gas demand for space heating by 12% in most regions of the UK, and that ZC would be a more effective energy efficiency measure in homes in the cooler, more northerly regions of the UK.

Document Title	How heating controls affect domestic energy demand: A rapid evidence assessment							
Author(s), Publisher, Year	A. G. Munton, A. J. Wright, P. S. Mallaburn, and P. J. Boait, DECC, 2014.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	1	1	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

This report provides findings from the Rapid Evidence Assessment (REA) of how heating controls affect domestic energy demand that the RTK Ltd delivered to the Department of Energy and Climate Change (DECC).

DECC commissioned this review with the aim of synthesising existing research evidence on how domestic heating controls affect energy demand. The objective was for the review to contribute to the Smarter Heating Control Research Programme, aimed at establishing the extent to which the introduction of smarter heating controls is likely to save energy. The review was also intended to provide evidence with which to inform a subsequent design of a possible field trial that could detect any energy reductions associated with improving control technologies.

To that end, DECC set out five detailed research questions for the REA: 1. What heating controls are installed and how do these vary across different properties and households? 2. When, why and how are new heating controls installed? 3. How do people use their heating at present? 4. What can be learnt from previous evaluations of whether heating controls affect energy demand? 5. What are the evidence gaps that should be filled?

Document Title	The role of programmable TRVs for space heating energy demand reduction in homes							
Author(s), Publisher, Year	A. Badiei, S. K. Firth and F. Fouchal, Proceedings of the 2014 Building Simulation and Optimization Conference, 23-24 June 2014, UCL, London, UK, 2014.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	1	0	2	0	1	5	Fail

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

This paper aims to investigate the potential of advanced radiator controls to reduce space heating energy demand in dwellings. The study uses Dynamic Thermal Modelling (DTM) to compare the space heating energy consumption of dwellings with programmable Thermostatic Radiator Valves (TRVs) and dwellings with conventional TRVs. Conventional TRVs can often lead to overheating or heating rooms when not required. Programmable TRVs can overcome these limitations and this study employs DTM software package, DesignBuilder to estimate the resultant heating energy savings in a semi-detached dwelling. It is found that use of programmable TRVs can lead to space heating energy savings of up to 30%, without reducing thermal comfort of occupants.

Document Title	Energy follow-up survey 2011, Report 2: Mean household temperatures							
Author(s), Publisher, Year	Building Research Establishment (BRE), DECC, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

This report presents the headline results from an analysis of the mean room temperatures derived from the 2011 Energy Follow-Up Survey (EFUS). The 2011 EFUS consisted of a follow-up interview survey and associated monitoring of a sub-set of households first visited as part of the 2010/2011 English Housing Survey (EHS). Respondents who took part in the core EFUS survey were asked if they would consent to temperature loggers being installed in their home. Temperature loggers recorded temperatures at 20-minute intervals in the living room, hallway and main bedroom in 823 dwellings. These give a dataset of monthly mean temperatures in the three rooms, in zone 2 (average of the hallway and bedroom) and in the whole dwelling (average of all three rooms); as well as mean temperatures for the heating season and temperatures recorded during extreme cold and hot weather events. The analysis presented in this report uses temperatures collected during February 2011 to January 2012 data inclusive. Analysis is based on the sample weighted to the national level, using a weighting factor specific to the temperature logger sub-sample. The results presented in this report are therefore representative of the English housing stock, with a population of 21.9 million households.

Document Title	Domestic space heating energy control via smart home energy management							
Author(s), Publisher, Year	X. Chen, S. Yang, C. Wong, P. Moore and J. Chen, Proceedings of 2015 IEEE International Conference on Mechatronics and Automation August 2-5, Beijing, China.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	1	0	2	0	1	5	Fail

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The Smart Home Energy Management System (SHEMS) is considered as an effective way to reduce energy consumption in the home environment without compromising household's comfort. Despite of the promising potential, it still lacks of convincing evidences to prove the effectiveness of such kind of home automation system. This paper reports a field trial study to reduce the energy wastage in space heating via a SHEMS. The trial result shows the achieved sustainable energy wastage reduction.

Document Title	Development and validation of detailed building, plant and controller modelling to demonstrate interactive behaviour of system components							
Author(s), Publisher, Year	J. Cockroft, D. Kennedy, M. O'Hara, A. Samuel, P. Strachan, and P. Tuohy, Proceedings of Eleventh International IBPSA Conference Glasgow, Scotland July 27-30, 2009.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

As plant modelling becomes capable of more complexity and detailed resolution, new opportunities arise for the virtual evaluation of discrete plant components such as flow control and energy conversion devices, and controllers. Such objects are conventionally developed and tested at the prototype stage in a laboratory environment. Designers now seek to use modelling technology to extend their understanding from limited laboratory test results to full building and plant system analysis. This paper describes the development of a modelling system, using ESP-r, for typical United Kingdom domestic house types with hydronic gas or oil fired central heating including radiator and underfloor heating systems, and with a variety of conventional or advanced control types. It demonstrates the ability of detailed building and plant modelling to reveal unexpected insights into how real control systems perform in combination with other plant items and in different building types, including estimation of their influence on annual energy consumption. Comparisons with measurements taken in test rooms confirm that the observed behaviour of controls is realised in practice. The authors conclude that the complex dynamic interactions that take place between the various elements that make up a real building energy system have an important influence on its overall energy performance, revealing causes of variance that cannot be identified by laboratory testing alone, or by simplistic energy assessment tools.

Document Title	Earlyoff: Using house cooling rates to save energy							
Author(s), Publisher, Year	C. Ellis, J. Scott, M. Hazas, and J. Krumm, Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, November 06-06, 2012, Toronto, Ontario, Canada.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	0	2	1	1	7	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

Home heating systems often have a significant thermal inertia, as homes stay warm after the heating is turned off for significant periods of time. We present the EarlyOff concept, whereby home heating can be predictively turned off in advance of occupants' departure, using this inertia to keep the house warm while saving energy. We use a previously gathered data set of real-time heating, gas, and occupancy readings from five houses and conduct a data-driven analysis of potential energy savings. Using an "oracle" predicting actual departure events, we show an upper bound savings of 4–12% of the gas used over the whole study period by applying EarlyOff. Using a real predictor which makes use of historical occupancy probabilities, we show savings of 1–8% of gas use.

Document Title	Combining energy efficiency measure approaches and occupancy patterns in building modelling in the UK residential context							
Author(s), Publisher, Year	E. Marshall, J. K. Steinberger, V. Dupont, and T. J. Foxon, Energy and Buildings, vol. 111, pp. 98–108, 2016.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	0	2	1	0	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The UK faces a significant retrofit challenge, especially with its housing stock of old, hard-to-treat solid walled dwellings. In this work, we investigate the delivery of heated thermal comfort with a lower energy demand through four types of energy efficiency interventions: passive system, conversion device, method of service control, and level of service demanded. These are compared for three distinct household occupancy patterns, corresponding to a working family, a working couple and a daytime-present couple. Energy efficiency measures are considered singly and in combination, to study whether multiple lower cost measures can achieve comparable savings to higher cost individual measures. Scenarios are simulated using engineering building modelling software TRNSYS with data taken from literature. Upgraded insulation of wall and roof resulted in highest savings in all occupancy scenarios, but comparable savings were calculated for reduced internal temperature and partial spatial heating in scenarios in which the house is not at maximum capacity. Zonal heating control is expected to achieve greatest savings for the working couple who had a flexible occupancy pattern. The results from this modelling work show the extent to which energy consumption depends on the appropriate matching between energy efficiency measures and occupant type.

Document Title	Basic characteristics of low-cost houses in order to reduce the energy consumption for heating- efficiency of heating plants and controls							
Author(s), Publisher, Year	R. Rayment, A. R. Cunliffe, and K. Morgan, Building Research Establishment, 1983.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

In a study of room-thermostat and thermostatic radiator valve control it is demonstrated, that for the occupancy behaviour and type of house tested that room-thermostat is as effective as thermostatic radiator valve control. Generalisation of the result is subject to a number of important qualifications. Considerable technical advances have been made, however, for the practical evaluation of heating systems and control. These are:

a) development of a matched house pair technique for the on-site evaluation of heating systems and controls, with simulated occupancy;

(b) development of a gas boiler test rig capable of continuous measurements of energy flows to the circulating water and through the flues thus enabling the transient and steady states to be investigated;

(c) development of two computer models: one for a heating appliance and one including additional simulation of a hot water radiator and temperature controls within a simple representation of a building, and further work is required to draw the full benefits from these.

Document Title	Variability of energy use for domestic space heating							
Author(s), Publisher, Year	R. D. Heap, Applied Energy, vol. 5, no. 3, pp. 179–191, 1979							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	0	2	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The level of reported variability of domestic space heating energy use is extremely high, the coefficient of variation being 20% even for groups of similar houses. In consequence, there is a need for heating systems to work effectively and economically over a wide range of energy use levels and there is also a need for large sample sizes in evaluating field results if the effects of individual factors contributing to the overall variability are to be assessed. For dissimilar houses, samples of 25 or more are necessary for the detection of individual factors and hundreds may be required for their accurate estimation. The effect on energy use of night temperature set-back is shown theoretically to be equivalent to a 212% energy saving per degree Kelvin temperature depression. The effects of more intermittent heating system operation are provisionally estimated, a 50% energy saving being estimated for a 6-h period of daily use at the required temperature. Effects of choice of internal temperature and ventilation rate on energy use are assessed. The energy savings made by such personal control strategies can be nullified by equipment deficiencies. The magnitudes of the effects of three such deficiencies (pipe or duct losses, unresponsive emitter control and upstairs overheating in mild weather) are estimated as each adding around 20% to the heating energy use of a typical house. The combined effects of energy saving strategies and equipment deficiencies make possible annual energy use figures from half to one-and-a-half times the designed level. The implications of this variability for heating system design are discussed.

Document Title	Using dynamic simulation for demonstrating the impact of energy consumption by retrofit and behavioural change							
Author(s), Publisher, Year	Y. K. Kim and H. Altan, Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28, pp. 2451–2457, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	1	0	2	0	1	5	Fail

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

In this paper, dynamic simulation software (in this case, DesignBuilder) has been used to model and to simulate a typical 1960s UK social housing in order to examine the impact of retrofit, occupant behaviour and user lifestyle on energy pattern. In terms of retrofitting study, various energy efficiency measurements have been considered such as improving level of insulations and heating system's efficiency. For the occupant behaviour influence study, three types of heating control patterns have been created such as 'Constant On', 'NCM' and 'Programmed Heating Control'. For the life style influence study, two different user patterns have been defined such as fulltime working and retired couple user groups. Results and findings of the study are further presented within the paper.

Document Title	A recursive modelling technique applied to the model predictive control of fluid filled heat emitters							
Author(s), Publisher, Year	D. Rogers, M. Foster, and C. Bingham, Building and Environment, vol. 62, pp. 33–44, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

Based on the recent emergence of Controlled Radiator Valve (CRV) components, the paper considers the research, development, application and benefits of a modern control methodology to improve the heating efficiency of domestic dwellings. In particular, the problem of efficient temperature control, is formulated as a model predictive control scheme employing a parameter matching technique. A key contribution of the paper is the development of an on-line modelling method, which, in contrast to previously reported techniques, requires no prerequisite knowledge of the thermodynamic behaviour of a given controlled zone and a training period of only 48 h. Moreover, it is shown that excellent performance is obtained without the normal requirements for measurements of site weather or input from other external sources of weather data, thereby reducing system cost and complexity. The proposed techniques are applied in a controlled zone using a BS EN 442 oil filled heat emitter, whose input power is closely controlled using a PWM power converter within an instrumented test cell, and also in an occupied dwelling. Results demonstrated MPC can be implemented in a dwelling with minimal per-quisite modelling and still achieve set point tracking when compared to more conventional solutions resulting in an energy saving of up to 22%.

Document Title	PreHeat: Controlling home heating using occupancy prediction							
Author(s), Publisher, Year	J. Scott, A. J. Bernheim Brush, J. Krumm, B. Meyers, M. Hazas, S. Hodges, and N. Villar, Proceedings of 13th Int. Conf. Ubiquitous Comput., pp. 281–290, 2011.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	0	2	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

Home heating is a major factor in worldwide energy use. Our system, PreHeat, aims to more efficiently heat homes by using occupancy sensing and occupancy prediction to automatically control home heating. We deployed PreHeat in five homes, three in the US and two in the UK. In UK homes, we controlled heating on a per-room basis to enable further energy savings. We compared PreHeat's prediction algorithm with a static program over an average 61 days per house, alternating days between these conditions, and measuring actual gas consumption and occupancy. In UK homes PreHeat both saved gas and reduced MissTime (the time that the house was occupied but not warm). In US homes, PreHeat decreased MissTime by a factor of 6-12, while consuming a similar amount of gas. In summary, PreHeat enables more efficient heating while removing the need for users to program thermostat schedules.

Document Title	Thermostat settings in English houses: No evidence of change between 1984 and 2007							
Author(s), Publisher, Year	M. Shipworth, Building and Environment, vol. 46, no. 3, pp. 635–642, 2011.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

Rising demand temperatures are widely blamed for UK home energy use not declining over time despite the increased efficiency of dwelling envelopes and heating technologies. The hypothesis that thermostat settings have risen over time is tested using a repeated cross-sectional social survey of owners of centrally heated English houses. No statistical evidence for changes in reported thermostat settings between 1984 and 2007 is found. Why, then, has home energy use not declined over time, despite homes apparently becoming more efficient? There is evidence that the energy efficiency of homes has not improved as much as previously assumed. Improvements in dwelling energy efficiency and increased penetration of central heating would have increased internal temperatures without occupants demanding higher temperatures. Dwelling area heated, or duration of heating, or window opening during the heating season may have increased over time, increasing temperatures or energy use.

Document Title	An investigation into usability and exclusivity issues of digital programmable thermostats							
Author(s), Publisher, Year	N. Combe, D. Harrison, S. Craig, and M. S. Young, Journal of Engineering Design, vol. 23, no. 5, pp. 401–417, 2012.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

With nearly 60% of domestic energy consumption relating to space heating, the interaction between users and their heating controls is crucial in reducing consumption. Yet, many heating controls are complex and exclude people due to the demands placed upon their capabilities in terms of vision, reach, dexterity and thinking. This study explores the scale of and reasons for user exclusion in relation to digital programmable thermostats. The Exclusion Calculator was used to estimate the percentage of the population excluded from the use of three products. Full user testing was then conducted to elicit specific usability problems of the devices. The participants were a group of 14 younger users (aged 24–44) and 10 older users (aged 62–75). The exclusion calculations underestimated the actual exclusion significantly for both age ranges ($p < 0.05$). None of the older users were able to complete the programming of the thermostats. Additionally, the cognitive demands of these systems were considered using a subjective workload assessment method, based on the NASA Task Load Index, and were found to be excessive. In conclusion, this study makes recommendations to facilitate the design of more inclusive digital programmable thermostats. It is argued that such changes could result in reductions in domestic heat energy consumption.

Document Title	Assessing the number of users who are excluded by domestic heating controls							
Author(s), Publisher, Year	N. Combe, D. Harrison, H. Dong, S. Craig, and Z. Gill, International Journal of Sustainable Engineering, vol. 4, no. 1, pp. 84–92, 2011.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	1	2	1	1	7	pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Discussed	Energy saving <input type="checkbox"/>	Cost-effectiveness <input type="checkbox"/>	Usability <input checked="" type="checkbox"/>
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Abstract / Summary

Space heating accounts for almost 60% of the energy delivered to housing which in turn accounts for nearly 27% of the total UK's carbon emissions. This study was conducted to investigate the influence of heating control design on the degree of 'user exclusion'. This was calculated using the Design Exclusion Calculator, developed by the Engineering Design Centre at the University of Cambridge. To elucidate the capability requirements of the system, a detailed hierarchical task analysis was produced, due to the complexity of the overall task. The Exclusion Calculation found that the current design placed excessive demands upon the capabilities of at least 9.5% of the UK population over 16 years old, particularly in terms of 'vision', 'thinking' and 'dexterity' requirements. This increased to 20.7% for users over 60 years old. The method does not account for the level of numeracy and literacy and so the true exclusion may be higher. Usability testing was conducted to help validate the results which indicated that 66% of users at a low-carbon housing development could not programme their controls as desired. Therefore, more detailed analysis of the cognitive demands placed upon the users is required to understand where problems within the programming process occur. Further research focusing on this cognitive interaction will work towards a solution that may allow users to behave easily in a more sustainable manner.

Document Title	Exploring homeowners' perception and experiences in using a domestic smart home heating controller							
Author(s), Publisher, Year	E. Dimitrokali, J. Mackrill, P. Jennings, S. Khanna, V. Harris, and R. Cain, Indoor and Built Environment, vol. 24, no. 7, pp. 1010–1032, 2015.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	2	1	2	1	1	9	pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Space heating in the UK is responsible for 60% of the total UK energy consumption by domestic buildings. The UK has committed to reduce heating consumption through its 'Smarter Heating Controls Research Programme', by educating people on how they heat their homes. UK utility companies have trialed smart home heating controls and claim that these packages, consisting of a smart thermostat, a mobile application and an online portal, can save energy. However, there is little robust evidence on people's perceptions and reported experiences of using smart heating controls. This study aimed to understand homeowners' perceptions and experiences in using a domestic home heating controller in order to develop recommendations for the technology and its implementation into people's homes. Perceptions and experiences were investigated in three phases focusing on (a) the pre-use phase, which collected demographic information, awareness and expectations, (b) the in-use phase, which included habits of use, and (c) the post-use phase, which addressed satisfaction, motivation and feedback. Four online questionnaire surveys (with closed and open-ended questions) were used throughout the study, supplemented with telephone interviews in the post-use phase. Together these generated an understanding of the finer nuances of perceptions towards the smart home heating controller and underpinned recommendations for future technology development. The results showed that the smart home heating controller was perceived by 70% of participants as successfully influencing and changing their home heating behaviour. In order for smart home heating controllers to be successful, more intuitive technology with additional personalised information throughout the installation and familiarisation process may be beneficial.

Document Title	Smart homes, control and energy management: How do smart home technologies influence control over energy use and domestic life?							
Author(s), Publisher, Year	T. Hargreaves, R. Hauxwell-Baldwin, M. Coleman, C. Wilson, L. Stankovic, V. Stankovic, D. Murray, J. Liao, T. Kane, S. Firth, and T. Hassan, European Council for an Energy Efficient Economy 2015 Summer Study on Energy Efficiency, 2015.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	1	1	2	1	1	7	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

By introducing new ways of automatically and remotely controlling domestic environments smart technologies have the potential to significantly improve domestic energy management. It is argued that they will simplify users' lives by allowing them to delegate aspects of decision-making and control - relating to energy management, security, leisure and entertainment etc. - to automated smart home systems. Whilst such technologically-optimistic visions are seductive to many, less research attention has so far been paid to how users interact with and make use of the advanced control functionality that smart homes provide within already complex everyday lives. What literature there is on domestic technology use and control, shows that control is a complex and contested concept. Far from merely controlling appliances, householders are also concerned about a wide range of broader understandings of control relating, for example, to control over security, independence, hectic schedules and even over other household members such as through parenting or care relationships. This paper draws on new quantitative and qualitative data from 4 homes involved in a smart home field trial that have been equipped with smart home systems that provide advanced control functionality over appliances and space heating. Quantitative data examines how householders have used the systems both to try and improve their energy efficiency but also for purposes such as enhanced security or scheduling appliances to align with lifestyles. Qualitative data (from in-depth interviews) explores how smart technologies have impacted upon, and were impacted by, broader understandings of control within the home. The paper concludes by proposing an analytical framework for future research on control in the smart home.

Document Title	Case studies of mental models in home heat control: Searching for feedback, valve, timer and switch theories							
Author(s), Publisher, Year	K. M. A. Revell and N. A. Stanton, Applied Ergonomics, vol. 45, no. 3, pp. 363–378, 2014.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

An intergroup case study was undertaken to determine if: 1) There exist distinct mental models of home heating function, that differ significantly from the actual functioning of UK heating systems; and 2) Mental models of thermostat function can be categorized according to Kempton's (1986) valve and feedback shared theories, and others from the literature. Distinct, inaccurate mental models of the heating system, as well as thermostat devices in isolation, were described. It was possible to categorise thermostat models by Kempton's (1986) feedback shared theory, but other theories proved ambiguous. Alternate control devices could be categorized by Timer (Norman, 2002) and Switch (Peffer et al., 2011) theories. The need to consider the mental models of the heating system in terms of an integrated set of control devices, and to consider user's goals and expectations of the system benefit, was highlighted. The value of discovering shared theories, and understanding user mental models, of home heating, are discussed with reference to their present day relevance for reducing energy consumption.

Document Title	The usability of control interfaces in low-carbon housing							
Author(s), Publisher, Year	F. Stevenson, I. Carmona-Andreu, and M. Hancock, Architectural Science Review, vol. 56, no. 1, pp. 70–82, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

For the same type of house, energy and water use can vary by up to 14 times between different households in low-carbon housing. This article assesses the usability of key human control interfaces in two contrasting case studies of low-carbon housing, using building performance evaluation and a usability matrix tool. It situates the discussion within socio-technical theories of habit, practice, capabilities and emergent properties in products which facilitate easy, rewarding and energy-efficient learning. Key findings reveal poor design features and occupant lack of understanding including specific aspects of centralised mechanical heating and ventilation systems. Lessons learnt and recommendations are highlighted for design guidance and policy consideration. These include a more user-centred approach to design and testing of products, and key areas of focus in relation to delivering low-carbon homes that are more controllable and therefore more comfortable.

Document Title	Usability testing of smarter heating controls							
Author(s), Publisher, Year	S. Wall and F. Healy, DECC, 2013							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

The Department of Energy and Climate Change (DECC) wished to gain insight into the usability of smarter heating controls to understand their suitability for future trials. DECC is interested in whether smarter heating controls have the capacity to support energy saving behaviours, but foresee a prerequisite of this is the ability of smarter heating controls to support easy use by consumers. Prior research suggested that people have difficulty using both standard and smarter heating controls. DECC therefore commissioned Amberlight to measure the usability of five smarter heating controls.

Two previous pieces of work provided inputs into this research:

- Rubens, S., Knowles, J. (2013). *What people want from their heating controls: a qualitative study*. A report completed by New Experience for DECC to understand what users require from their heating controls
- An unpublished technology horizon scan of smarter heating controls and their characteristics

In particular the tasks evaluated in this research were based heavily on the outputs of Rubens, S., Knowles, J. (2013). Initial research involved an expert usability review of the controls and a manufacturers survey to gather contextual and background information on each control. A review of relevant literature in the heating control and usability fields was also conducted.

Outputs of these activities were used to inform the development of a suitable test protocol using fair and representative tasks, the sample of participants recruited to take part, and metrics of usability and benchmarks against which each control's performance could be compared.

72 participants (split into two matched samples of 36 each) attended one-to-one fieldwork sessions during which the smarter heating controls were tested for how well they supported task performance related to key user requirements. Usability metrics recorded the effectiveness, efficiency and satisfaction provided by each of the smarter heating controls. Industry standards for usability testing typically acknowledge 20 users as a standard sample size for gathering usability metrics.

In addition, observed participant behaviours and feedback were recorded using field notes and later analysed to identify any barriers to use that may account for the performance of the controls during the usability sessions.

The authors have anonymised the smarter heating controls evaluated in this investigation and all related findings, to reflect the terms of informed consent entered into by participating manufacturers and the researchers. This stipulated that all data, findings and reporting would be made anonymous in any published reports.

Document Title	Measuring and modelling the energy demand reduction potential of using zonal space heating control in a UK home							
Author(s), Publisher, Year	A. Beizaee, Doctoral thesis of Loughborough University, 2016.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input checked="" type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

Most existing houses in the UK have a single thermostat, a timer and conventional thermostatic radiator valves to control the low pressure, hot water space heating system. A number of companies are now offering a solution for room-by-room temperature and time control in such older houses. These systems comprise of motorised radiator valves with inbuilt thermostats and time control. There is currently no evidence of any rigorous scientific study to support the energy saving claims of these 'zonal control' systems.

This thesis quantifies the potential savings of zonal control for a typical UK home. There were three components to the research. Firstly, full-scale experiments were undertaken in a matched pair of instrumented, three bedroom, un-furnished, 1930s, test houses that included equipment to replicate the impacts of an occupant family. Secondly, a dynamic thermal model of the same houses, with the same occupancy pattern, that was calibrated against the measured results. Thirdly, the experimental and model results were assessed to explore how the energy savings might vary in different UK climates or in houses with different levels of insulation.

The results of the experiments indicated that over an 8-week winter period, the house with zonal control used 12% less gas for space heating compared with a conventionally controlled system. This was despite the zonal control system resulting in a 2 percentage point lower boiler efficiency. A calibrated dynamic thermal model was able to predict the energy use, indoor air temperatures and energy savings to a reasonable level of accuracy. Wider scale evaluation showed that the annual gas savings for similar houses in different regions of the UK would be between 10 and 14% but the energy savings in better insulated homes would be lower.

Document Title	Targeting household energy-efficiency measures using sensitivity analysis							
Author(s), Publisher, Year	S. K. Firth, K. J. Lomas, and A. J. Wright, Building Research Information, vol. 38, no. 1, pp. 25–41, 2010.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

The Community Domestic Energy Model (CDEM) has been developed to explore potential routes to reduce carbon dioxide (CO₂) emissions and the model is used to predict the CO₂ emissions of the existing English housing stock. The average dwelling CO₂ emissions are estimated as 5827 kgCO₂ per year, of which space heating accounts for 53%, water heating for 20%, cooking for 5%, and lights and appliance for 22%. Local sensitivity analysis is undertaken for dwellings of different age and type to investigate the effect on predicted emissions of uncertainty in the model's inputs. High normalized sensitivity coefficients were calculated for parameters that affect the space heating energy use. The effects of the input uncertainties were linear and superposable, so the impact of multiple uncertainties could be easily determined. The results show that the accumulated impact on national CO₂ emissions of the underperformance of energy-efficiency measures could be very large. Quality control of the complete energy system in new and refurbished dwellings is essential if national CO₂ targets are to be met. Quality control needs to prioritize detached dwellings because their emissions are both the greatest and the most sensitive to all energy-efficiency measures. The work demonstrates that the uncertainty in the predictions of stock models can be large; a failure to acknowledge this can lead to a false sense of their reliability.

Document Title	The impact of occupant behaviour and use of controls on domestic energy use							
Author(s), Publisher, Year	NHBC foundation, BRE press, 2012.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

This review was commissioned by the NHBC Foundation to examine previous research and knowledge on occupant behaviour and user interface design in homes. An extensive literature review was conducted and information was also gathered from experts at BRE.

The review examines how energy is used in the home and how the way people behave affects their energy consumption. It explores the factors that affect energy use in the home and looks at the ways in which energy consumption can be reduced. In particular, the review examines the importance of providing guidance, feedback and information to occupants, and the role of in-home displays such as smart meters. It investigates behavioural science theories for changing behaviour and how these have been applied to energy use behaviours. It also examines the differences between energy efficiency and energy conservation and asks if energy-efficiency measures go far enough to tackle energy reduction.

Occupants control the energy used in a home through controls and user interfaces. These controls and interfaces can influence occupant behaviour. The review, therefore, goes on to explore the influence of controls and user interfaces on domestic energy use. It explores findings from previous research into how occupants typically use controls, their level of understanding and the information provided with controls. The review also compares automated and manual control systems in dwellings and their advantages and disadvantages.

The review then explores future user interfaces and 'smart homes'. It examines how occupants will interact with future homes and what interfaces they are likely to use. It highlights where smart home systems might add value and possible barriers to the widespread roll-out of smart homes. It also examines recent consumer research on the latest low energy homes and outlines the concerns of consumer groups about the technologies and interfaces installed in these homes.

The findings and recommendations are summarised at the end of this review. The review recommends further research in the areas of:

- User interface design – the development of intuitive, user friendly controls.*
- How to bring about long-term behaviour change through feedback, information, interventions and the design of controls. The impact of smart meters on long-term domestic energy use.*
- The domestic energy use of different consumer groups, the strength of the rebound effect and targeted interventions for key consumer groups. Occupant feedback on the latest low carbon and smart homes.*
- How to improve the user guides, manuals and training given to the occupants of new, low energy homes to ensure they can use the technologies installed in them efficiently and effectively.*
- The impact of smart systems and automated controls on occupant energy use, comfort and satisfaction.*

The training, maintenance, supply chain, design and build implications of future control systems.

Document Title	Enabling sustainable user interaction with domestic heating controls							
Author(s), Publisher, Year	N. Combe, D. Harrison, and C. Way, Research Students' Conference on "Buildings Don't Use Energy, People Do?" – Domestic Energy Use and CO2 Emissions in Existing Dwellings, 28 June 2011, Bath.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	1	1	0	1	1	5	Fail

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

The way we live greatly effects the carbon emissions of our homes; heating accounts for nearly 60% of domestic energy consumption in the UK. This consumption is directly influenced by occupants through the use of their control systems. Using real- world data from buildings and observational data from users this research proposes guidelines for the design of more inclusive domestic heating controls. Two user- centred studies have been completed to date; one using controls under lab conditions and the other in a low-carbon housing development. In both studies controls were found to exclude users due to the cognitive demands placed on them, therefore creating an unnecessary barrier to reducing heat energy consumption in the home. The design principles proposed aim to help designers consider user needs when designing the interfaces of heating controls and energy management systems. By designing more inclusive and usable controls considerable energy savings could be made in the domestic context.

Document Title	What people want from their heating controls : a qualitative study							
Author(s), Publisher, Year	J. Rubens, S. Knowles, DECC, 2013.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

The Department of Energy and Climate Change (DECC) has set up a programme of work to understand the potential for smarter heating controls to save energy. As part of this DECC wished to understand what people need from their heating controls so as to improve their understanding of how emerging technologies could best meet these needs. This research gathered requirements for smarter heating controls by studying how people use their existing heating controls.

The study involved diary self-reporting of heating behaviours by a sample of 43 householders followed by in-home, in-depth interviews with the same participants. After a period of interim analysis a 'long-list' of requirements was inferred, and some emergent user types were identified. The requirements were then explored and prioritised in four 'participatory-design' workshops along with evaluation of three different concepts for smarter heating controls with four interviewed participants and 19 new participants.

Document Title	Advice on how to use heating controls : Evaluation of a trial in Newcastle							
Author(s), Publisher, Year	DECC, Department of Energy and Climate Change, 2014.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

This report presents findings of a Randomised Control Trial (RCT) that aimed to test whether tailored advice from a 'trusted messenger' on how to use standard heating controls can reduce energy consumption. Commissioned by DECC, the trial was designed by the Behavioural Insights Team and implemented by Newcastle City Council with the assistance of local partners. NatGen Social Research conducted a process evaluation alongside the trial and has been responsible for integrating the results of these activities into this report.

Document Title	Consumers and domestic heating controls : a literature review							
Author(s), Publisher, Year	Consumer Focus, Consumer Focus, 2012.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Home heating systems need effective and easy-to-use controls if the Government is to achieve the energy savings expected from the Green Deal, the smart meter roll out and the heat demand reduction required by the Government's Heat Strategy.

This research draws lessons from the consumer experience of controls for gas central heating which are also relevant to the design of in-home displays, and controls for cooling, ventilation and other heating systems.

User experience of heating controls indicates that problems in using controls are widespread. Research identifies a range of problems for consumers including difficult to read displays, difficult to use buttons, lack of intuitive design, poor positioning of controls and a lack of effective supporting information and advice. As a result many users do not use their heating controls effectively or at all. Furthermore, statistics on the distribution of heating controls show a majority of consumers do not have at least one of main controls required by Building Regulations. People who are elderly or in local authority housing are more likely to find their controls difficult to use and rented properties are less likely than owner-occupied properties to have full controls.

Why have controls not adapted to meet consumer need? There are two key issues: end- user demand for effective controls is weak, and the supply chain is not responsive to consumer needs. These issues both stem in part from the lack of involvement of the consumer in the choice of controls, they are likely to be selected by the installer.

The installation of ineffective controls is a lost opportunity in terms of potential cost and carbon savings for consumers and society. By upgrading all homes to have a room thermostat and full set of thermostatic radiator valves, the Government would deliver a reduction of 4.3 mtCO₂ emissions a year. This is equivalent to 8 per cent of emissions from domestic gas and boiler space heating and roughly equal to the government's estimated potential saving figure for loft insulation.

In financial terms, installing a room thermostat could save the average household £59 per year which, combined with cost estimates from installers, makes this a highly cost efficient measure. In situ studies of the impact of controls are mixed but suggest that modern controls can lead to significant savings. Further research is, however, needed in this area.

New control technologies, including those which use smart meter data and the availability of smart phones, could provide new opportunities to drive the market for controls; however, it is unclear whether consumer demand will be sufficient to drive the development and deployment of effective, user-friendly technologies.

The report sets out principles on the design of controls and provision of information and advice and recommendations for policy makers and industry. These include the development of a central consumer information resource on controls and a standard for usability.

Document Title	Energy-efficiency interventions in housing: learning from the inhabitants							
Author(s), Publisher, Year	T. Crosbie and K. Baker, Building Research & Information, vol. 38, no. 1, pp. 70–79, 2010.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	0	1	2	1	1	7	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Technological solutions to domestic energy reduction are insufficient without the cooperation of inhabitants. It does not matter how much energy hypothetically could be saved by efficient technologies if no one wants to live in the properties, install or use efficient lighting and heating. Therefore, to improve the uptake and effectiveness of household energy- efficiency interventions, it is necessary to understand ‘why people react to particular energy-efficiency interventions in the ways they do?’ An analysis is presented of in-depth interviews with 50 inhabitants who participated in one of four domestic energy-efficiency interventions. The findings indicate that issues such as aesthetic tastes and effects on lifestyle are central to why people reject economically viable, simple and well-understood domestic energy-efficiency interventions.

Document Title	The Potential for Behavioural and Demand-Side Management measures to save electricity, gas and carbon in the domestic sector, and resulting supply-side implications							
Author(s), Publisher, Year	Enviros Consulting Ltd, Department of Energy and Climate Change DECC, 2008.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	0	0	1	0	4	Fail

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input checked="" type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

This report presents the findings of a project undertaken by Enviro Consulting on behalf of Defra. The project considers the potential for behavioural and demand-side management tools to save electricity, gas and carbon in the domestic sector, and the resulting supply-side implications.

In order to do this, we undertook a literature review and a small number of face to face and telephone interviews with industry experts. We drew together the evidence that this research highlighted to quantify three scenarios for energy use in 2020. The report also considers the ways that such outcomes could be delivered.

Document Title	Living in cold homes after heating improvements: Evidence from Warm-Front, England's Home Energy Efficiency Scheme							
Author(s), Publisher, Year	R. Critchley, J. Gilbertson, M. Grimsley, and G. Green, Appl. Energy, vol. 84, no. 2, pp. 147-158, 2007.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	1	2	1	2	1	1	8	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input checked="" type="checkbox"/>		

Abstract / Summary

Objective: To investigate explanatory factors for persistent cold temperatures in homes which have received heating improvements. Design: Analysis of data from a national survey of dwellings and households (in England occupied by low-income residents) that had received heating improvements or repairs under the Warm Front Scheme. Methods: Over the winters of 2001-02 and 2002-03, householders recorded living room and main bedroom temperatures in a diary. Entries were examined for 888 households, which had received high level heating interventions. Two hundred and twenty-two households were identified as occupying cold homes, with mean bedroom temperature below 16 °C or mean living room temperatures below 18 °C. Binary logistic regression was used to model dwelling and household features and then occupants' behaviour and attitudes in the 'cold homes' sub-set compared with the remainder of the high intervention group. Seventy-nine supplementary, structured telephone interviews explored reasons given for lower temperatures. Using graphical and tabular methods, householders preferring cooler homes were distinguished from those who felt constrained in some way. Results: Cold homes predominate in pre-1930 properties where the householder remains dissatisfied with the heating system despite major improvements funded by Warm Front. Residents of cold homes are less likely to have long-standing illness or disability, but more likely to experience anxiety or depression. A small sample of telephone interviews reveals those preferring lower temperatures for health or other reasons, report less anxiety and depression than those with limited control over their home environment. Their 'thermal resistance' to higher temperatures challenges orthodox definitions of comfort and fuel poverty.

Document Title	In-situ monitoring of efficiencies of condensing boilers – TPI control project extension							
Author(s), Publisher, Year	Kershaw, H. et al. 2010, “,” Prepared for The Energy Saving Trust, Department of Energy and Climate Change.							
Quality Assessment	Reporting Quality Score			Research Quality Score			Total Score (9pts)	Pass / Fail
	Q1(2pts)	Q2(2pts)	Q3(1pts)	Q1(2pts)	Q2(1pts)	Q3(1pts)		
	2	1	1	0	1	1	6	Pass

Quantitative Methods			Qualitative Methods				Review
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Discussed	Energy saving <input checked="" type="checkbox"/>		Cost-effectiveness <input type="checkbox"/>		Usability <input type="checkbox"/>		

Abstract / Summary

This report concludes the second phase of the ‘In-situ monitoring of efficiencies of condensing boilers and use of secondary heating’ project commissioned by the Energy Saving Trust. This phase comprised the trialling of Time Proportional Integral (TPI) controls within homes that had participated in the original Energy Saving Trust condensing boiler field trial. Laboratory trials had identified an improvement in energy efficiency from the operation of TPI controls and the objective of this phase of the trial was to assess whether similar energy efficiency savings were evident in real households. TPI controls were installed into 47 of the 52 participant trial homes. These installations took place between December 2008 and February 2009 and monitoring continued in the properties for a further 12 months. The last set of data was collected in February 2010. As with phase one of the trial, the majority of the boilers performed reliably over the period, however occupant changes and a failure of monitoring equipment resulted in some sites failing to record 12 months of consecutive acceptable data. The trial sample contains 38 combination boilers and 14 regular boilers with hot water cylinders. Monitoring of secondary heating continued through the second phase of the trials. The results from this trial have not identified a significant improvement in the heat efficiency of the heating systems from the operation of TPI controls. Periods of effective TPI control were identified from the dataset but these occurrences were not common and the authors caution against over-analysing the apparent change in performance of particular installations against the overall results of the trial as a whole. There are two fundamental prerequisites for observing the characteristics of effective TPI control: 1. The internal temperature set point must be reached 2. The boiler must be allowed to operate for a significant amount of time at the temperature set point. Failure to satisfy both of these requirements was a common observation within the trial data and in these instances no difference was observed between pre and post TPI control data sets. All but one of the trial properties had a modulating boiler. It is acknowledged that there could be potential conflicts between the logic of the TPI controller and the in-built logic of a modulating boiler. It is not possible to investigate this further from the dataset as there are insufficient non-modulating boilers to enable a comparison to be made. Analysis of daily 5 minute data has produced some good examples of TPI control. However, examples of boilers cycling on return temperature and homes being controlled by physical switching of the thermostat have also been identified. Some sites have shown an improvement in heat efficiency but other sites have seen a reduction; the majority of sites could be considered to have seen no change beyond what can be considered natural fluctuation. Some trial properties which reached their set point temperature have demonstrated the frequent cycling characteristic of effective TPI control. If the period of cycling is prolonged, there are some examples of reduced flow and return temperatures which is where the efficiency savings are expected as the boiler can remain in condensing mode for longer. However, these observations are not common. Analysis of the 5 minute data using an algorithm indicated that the TPI sites were likely to be operating under TPI control for less than 9% of total time during the months October to March 2009. When analysed as part of an overall heating system, of which the building fabric and occupant are both features, the TPI controls do not result in a clear improvement in efficiency across the trial properties. The results for the CBR and subsequent electrical analysis suggest there might be a general increase in electrical consumption with TPI controls over the mid-range heating loads tending towards a slight reduction in carbon benefits ratio. The second year of data saw a reduced proportion of heat delivered by secondary heating compared to the original trial. This was in part due to the increased use of the primary

heating system in a very cold winter. However, over the second year of the trial, double the number of properties saw a reduction in secondary heating use than saw an increase. The low proportion of heat supplied by secondary heating supports the move to stop assuming 10% of space heating is provided by secondary appliances, especially in new build properties. The results of this trial have highlighted the complexity of achieving energy efficiency savings from improvements to boiler operating systems, and how an innovative technical intervention cannot solely compensate for a poor thermal envelope or a lack of effective operation from the occupant. The efficiency of a heating system is dependent on a myriad of factors, some that can be remedied through technical developments and structural works, and others that are dependent on the less tangible factors relating to human behaviour.
